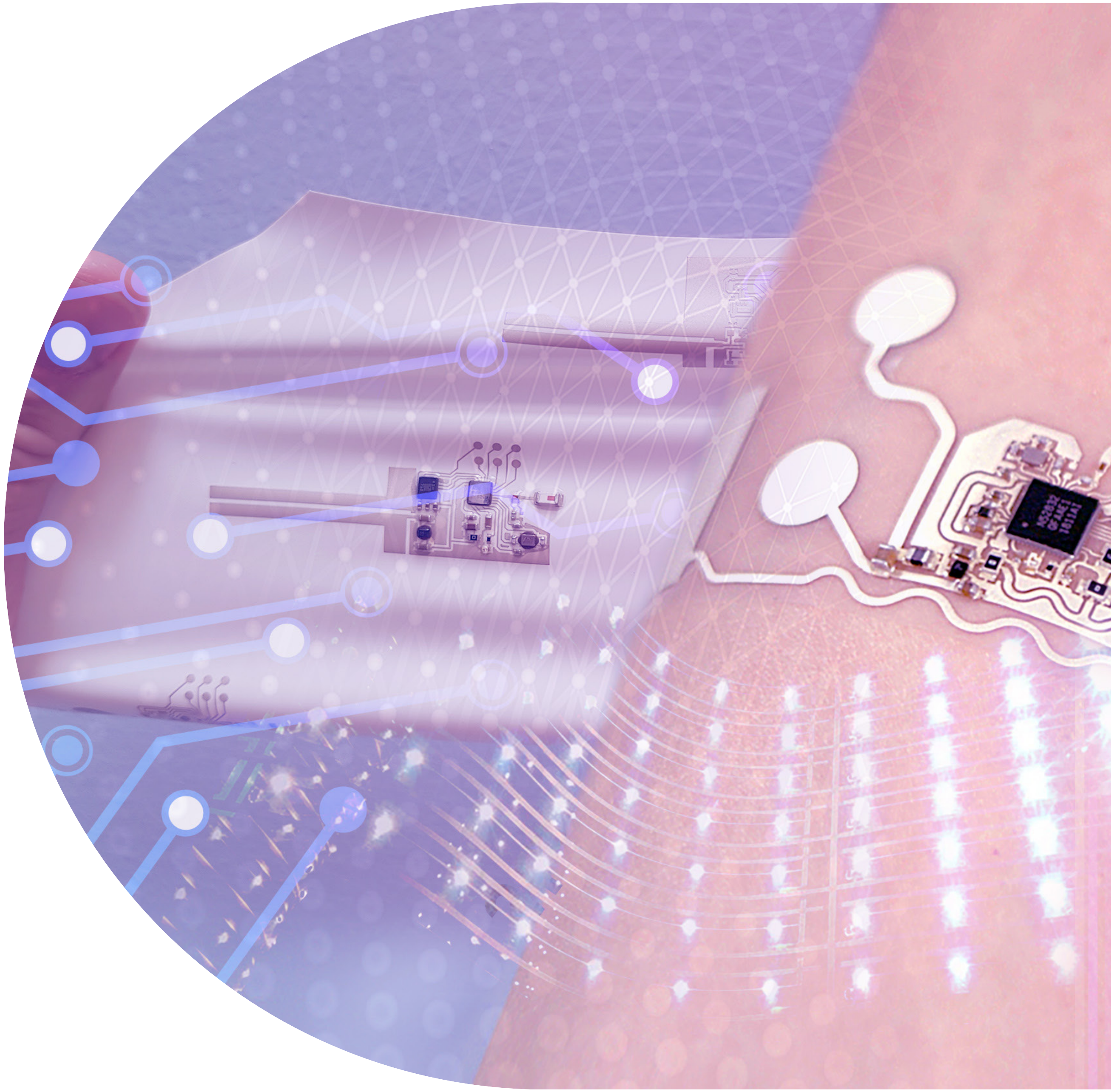
Printed Intelligence Handbook



PrintoCent

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Printed Intelligence Handbook, the third revised edition was published in 2026 by PrintoCent, at a joint effort by PrintoCent founding members, VTT, Oulu University of Applied Sciences and University of Oulu and PrintoCent industry members.

The second edition of this book - Introduction to Printed Intelligence; Handbook for technology training and coaching was published by PrintoCent in 2019. The first edition of this book - Printed electronics & diagnostics products; PrintoCent Designer's handbook was published by Neficon Finland Oy in 2015.

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Foreword

Dear Reader,

Printed Intelligence (PI), encompassing printed electronics, hybrid integration, and diagnostic solutions, has evolved from a promising concept into a transformative technology platform shaping multiple industries. Today, PI enables lightweight, flexible, and sustainable solutions that integrate electronic, optoelectronic, and sensing functionalities into surfaces and structures where they have never existed before. From wearable health sensors to energy harvesting and structural electronics, these innovations are redefining product design and user experience.

Why does this matter? PI offers clear competitive advantages:

- Design freedom and miniaturization for next-generation devices
- Cost efficiency and scalability through roll-to-roll and additive manufacturing
- Sustainability and material savings, aligning with global green initiatives

The business potential is enormous. PI is driving growth in sectors such as healthcare, automotive, IoT, UXVs, electronics, and autonomous energy solutions. Emerging applications are opening new revenue streams and creating opportunities for both start-ups and established corporations.

This handbook is your gateway to understanding and leveraging these opportunities. Whether you are an entrepreneur seeking to disrupt markets or an R&D team member in a global enterprise, you will find here the state-of-the-art knowledge, design principles, and practical examples needed to accelerate innovation and commercialization.

Join us in shaping the future of electronics – flexible, sustainable, and seamlessly integrated.

Kari Rönkä
Chairperson of PrintoCent

Satu Väinämö
Director, PrintoCent

January 2026

Contents

1

PRINTED INTELLIGENCE AND PRINTOCENT

1.1 Introduction to Printed Intelligence

Printed Intelligence revolutionizes electronics industry

Printed Intelligence (PI) represents not just an incremental step in the evolution of electronics, but a fundamental revolution in the field. Unlike traditional electronic systems that rely on bulky, rigid circuit boards, PI introduces ultra-thin, flexible, and even stretchable systems. These advanced systems challenge the limitations of conventional electronics by enabling integration directly into different materials. As a result, electronic functionality can now be seamlessly embedded within everyday objects, creating interactive experiences that were previously impossible.

This transformation is reshaping the way electronic systems are designed, manufactured, and deployed. By merging the adaptability of printed electronics with the computational capabilities of conventional components, PI forms the foundation of Flexible Hybrid Electronics (FHE). FHE is an emerging technology that brings together the best aspects of both printed and traditional electronics, and it is set to revolutionize industries including healthcare, energy, mobility, and defense.

Flexible Hybrid Electronics

Today, Flexible Hybrid Electronics combines the flexibility and scalability of printed electronics with the high performance of silicon-based components. This hybrid approach enables the creation of thin, lightweight, and conformable devices that can adapt to complex surfaces. FHE enables the integration of electronics into materials such as textiles, plastics, paper, and even directly onto the skin. Furthermore, the use of roll-to-roll manufacturing processes supports low-cost and high-volume production, making these innovations accessible for a wide range of applications.

As a result of roll-to-roll manufacturing, this is a truly scalable approach that delivers not only commercial feasibility but also consistent quality that is a major advantage. However, the downside is that sufficient manufacturing volume is required, which often doesn’t occur. To address this challenge, sheet-to-sheet processes are also available.

Some examples

- **Wearables** have evolved from simple fitness trackers to sophisticated platforms integrating biochemical, optical, and stretchable sensors for real-time health and wellness monitoring. FHE enables ultra-thin, soft, and biocompatible electronics that conform to the human body, supporting unobtrusive monitoring and long-term comfort.

- **Diagnostics** are leveraging breakthroughs in spectroscopy, AI, and flexible electronics resulting in rapid, point-of-care solutions. Technologies such as printed biosensors and microfluidic platforms enable the rapid, low-cost, and scalable production of diagnostic devices, including glucose sensors, infection detection strips, and multiplexed biochemical analyzers

- **Automotive and transport** sector is undergoing a profound transformation towards lightweight, energy-efficient, and intelligent vehicles and systems. FHE's unique combination of lightweight design, integration freedom, and sustainability supports the global drive toward smarter, safer, and greener transport. FHE changes vehicle design e.g. by merging lightguides, sensors, and control interfaces into vehicle structures.

- **Modern unmanned vehicles (UXVs)** equipped with advanced printed sensors, lightweight energy solutions, and AI-driven analytics are used for applications ranging from precision agriculture and infrastructure inspection to security and environmental monitoring. Printed electronics contribute to reduced weight and increased design flexibility, enhancing the capabilities of automated vehicles like drones across various use cases, including environmental monitoring, logistics, and defense.

- **Smart Surfaces and Built Environments** are being redefined through printed intelligence that embeds sensors, adaptive controls, and energy-efficient functionalities directly onto walls, windows, and furniture. These smart surfaces enable efficient heating control, real-time environmental monitoring, and adaptive lighting - seamlessly integrating intelligence into building materials for improved comfort, efficiency, and interactivity.

- **Autonomous energy solutions** benefit from printed batteries, supercapacitors, and photovoltaics that power remote sensors and devices without external infrastructure. Combined with printed batteries, they enable fully autonomous systems such as various IoT systems. These components are lightweight, flexible, scalable, and suitable for integration into wearables, vehicles, and infrastructure.

Looking Ahead

As we move towards 2030, Printed Intelligence is becoming a cornerstone of smart, sustainable product design. It will empower industries to rethink how electronics are integrated, used, and recycled.

A strong market pull is now driving printed intelligence from research into commercial reality. Demand for connected, lightweight, and sustainable electronics is accelerating across multiple high-growth sectors — including wearables and smart textiles, diagnostics and healthcare, mobility, smart surfaces, and intelligent packaging. These domains share a common need for innovative form factors and ultra-thin, flexible, scalable, and stretchable intelligence, which traditional electronics manufacturing cannot easily deliver. Printed Intelligence fills this gap by enabling functional integration directly into product forms, reducing system complexity, and supporting the circular design models to provide reliable and continuous data sources for AI.

The PrintoCent, through its industrial members, pilot factory, training programs, and innovation events, will continue to lead this transformation, fostering cross-sector collaboration and accelerating the industrialization of sustainable electronics.

This handbook is your gateway to that future. It offers practical insights, design guidelines, and real-world examples to help you exploit the full potential of Printed Intelligence.

1.2 PrintoCent Business Environment

PrintoCent is an industrial cluster set to boost innovation and industrialization of Printed Intelligence. PrintoCent was established to speed up the commercialization of the Printed Intelligence research results. Starting from 2020 focus has been shifted to facilitating in the industrialization of Printed Intelligence. From the start, there has been strong co-operation with global industrial leading companies in the materials, electronics, manufacturing and machinery, testing and application sectors. New innovations have grown into businesses within these companies and through start-ups.

PrintoCent has a strong base in Oulu, Finland, due to the pilot scale manufacturing facilities built and upgraded during the past 20 years, and the know-how built in the regional research organizations and companies in close proximity. PrintoCent is led by VTT Technical Research Centre of Finland Ltd, and the operational team includes the other founding members - University of Oulu, Oulu University of Applied Sciences and Business Oulu. These institutions provide strategic leadership and operational support, ensuring the cluster's continued success and development.

Today, more than 500 printed intelligence experts are available in PrintoCent in research and industry organizations in Oulu region. Despite strong regional base, PrintoCent has a wide global reach with its 40+ international industry member companies, and other partners forming the PrintoCent Cluster. The other partners include SME and LSE companies globally, other clusters in the region and globally, funding agencies, R&D partners and other organizations.

PrintoCent Industry Cluster

The PrintoCent Industry Cluster (PIC) brings together member companies globally, forming a dynamic ecosystem that spans the entire value chain of printed intelligence. This ensures comprehensive expertise and effective collaboration throughout multiple domains. The cluster includes global industrial companies, each representing different stages from materials development to the delivery of end products, thereby enabling the effective commercialisation of novel products and services. As printed intelligence is an enabling technology, the cluster's members represent a wide range of industries, including health and wellbeing, mobility, the built environment, and connectivity. This diversity highlights the broad applicability and impact of printed intelligence across multiple domains.

Cluster members comprise start-ups, SMEs, and large-scale industrial companies from around the world. Each member engages in a three-year program designed to foster collaboration and innovation. Figure 1.2.1 illustrates the current positioning of PrintoCent cluster members along the value chain, which spans from materials to product owners. Cluster will continue to grow as new members join throughout the program to strengthen the cluster's reach and impact.

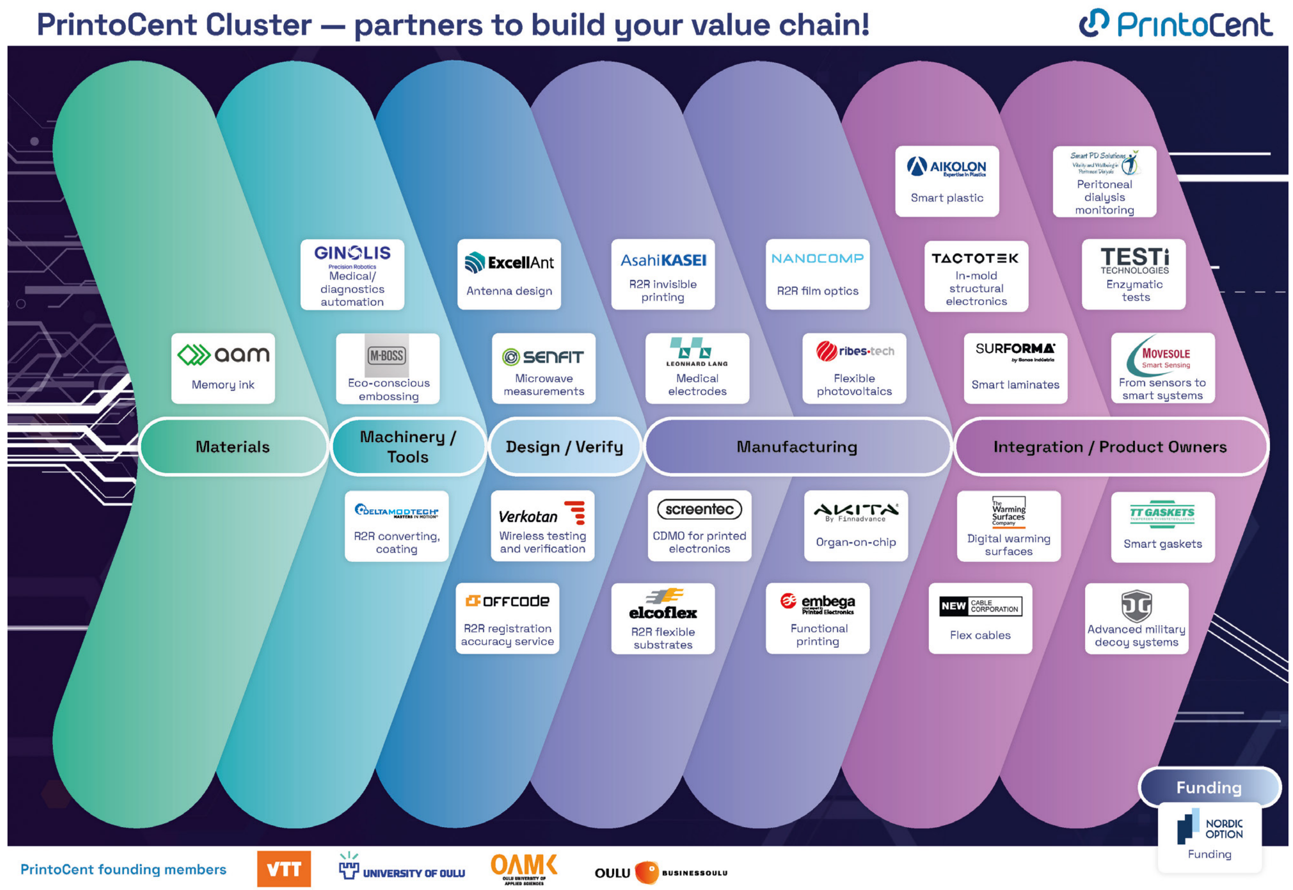


Figure 1.2.1. PrintoCent cluster along the value chain (2025)

In 2025, the composition of members by company type consists of 50% start-ups, 40% small and medium-sized enterprises (SMEs), and 10% large-scale enterprises. In terms of geographical distribution, 50% of members are based in Oulu, 25% are located elsewhere in Finland, and the remaining 25% are from international regions including Asia, Europe, and the USA.

At the heart of PrintoCent lies a collaborative network of companies, working closely with the founding organisations to accelerate innovation in the field of printed intelligence. By integrating research excellence with industrial collaboration, PrintoCent can transform breakthrough ideas into commercial products and innovative services, thereby reshaping the future.

Industrialization

Bringing deep technology solutions, such as printed intelligence, to the market is a time-intensive process. The Oulu area has a longstanding tradition in the field of printed intelligence, supported by decades of research and expertise. The region has made significant investments in both research and education, establishing piloting environments that facilitate hands-on innovation, piloting and testing. These ongoing efforts are now focused on accelerating the industrialization of printed intelligence, further solidifying Oulu's position as a leader in this advanced technology domain.
https://www.printocent.net/

Figure 1.2.2. PrintoCent's route from research to industrial growth
© VTT

1.3 PrintoCent Pilot Factory

The PrintoCent Pilot Factory is a world-class innovation hub for printed electronics, located in Oulu, Finland. It brings together the cutting-edge expertise and facilities of VTT Technical Research Centre of Finland Ltd, University of Oulu (UO), and Oulu University of Applied Sciences (OAMK) to support the development, prototyping, and pilot-scale manufacturing of next-generation printed, flexible, stretchable hybrid electronics. https://www.printocent.net/printocent-pilot-factory

Specializing in roll-to-roll (R2R) processing, PrintoCent offers a comprehensive suite of services that span the entire value chain—from concept design and material selection to pilot production and technology transfer. The factory is equipped with advanced printing and coating technologies, complemented by supporting processes such as nanoimprint lithography, hot embossing, laser etching, injection moulding, and lift-off techniques. With additional post processing, hybrid and structural electronics integration and testing facilities, PrintoCent Pilot Factory covers the whole development and manufacturing chain from vision to proof of production of novel products and tech transfer. With industrial network the development can be transferred under industrial controlled environment for commercial manufacturing. Or dedicated manufacturing specification can be formulated for technology blocks that can be used for investment project on each need.

PrintoCent's capabilities enable the fabrication of thin-film active components including printed solar cells, transistors, sensors, indicators, power sources, and flexible circuit boards. These can be integrated into complete systems using hybrid integration, in-mould electronics, and structural electronics processes. Also, thick film printing technologies are used to generate circuits used in various application areas.

Beyond technical development, PrintoCent also supports business development, offering consultation and commercialization services to help companies bring printed intelligence solutions to market.
Its multidisciplinary team and facilities provide:

- Research and development (R&D) services at laboratory scale for ink and process development, component design, and demonstrator manufacturing mainly in sheet-to-sheet (S2S) environment.
- Roll to Roll (R2R) pilot-scale services for process upscaling, component prototyping, and pilot production.
- Post-processing and hybrid integration including laser and die cutting, pick-and-place assembly, and in-mould integration for plastic electronics or various converting (layering) methodologies.

The PrintoCent community enables the creation of flexible smart systems and plastic-integrated devices, offering:

- System-level concept design and feasibility analysis
- Optical and thermal simulations
- Prototype and demonstrator manufacturing
- Reality check on maturity level of the device
- Manufacturing approach analysis in combination of cost estimate on various volumes
- Technology transfer to industrial partners

By partnering with PrintoCent Pilot Factory, customers gain access to:

- Multidisciplinary expertise and state-of-the-art facilities
- Seamless integration of printed and hybrid electronics
- Low-risk pathways for scaling up production
- Support in identifying new business opportunities
- End-to-end assistance from concept to commercialization

Figure 1.3.1. Focus areas of PrintoCent

1.3.1 Roll-to-roll proof of manufacturing

PrintoCent Pilot Factory offers a unique in-house competence from material formulation and process development of pilot-scale roll-to-roll production to multi-technological knowledge of applications and systems. We also have a world-class, award-winning roll-to-roll capable pilot factory for printing, component assembly and post processing.

MAXI Roll-to-roll printing line

- 4 interchangeable printing units: forward and reverse gravure, rotary silk screen, flexography and slot die coating
- Plasma treatment, lamination, hot embossing and die cutting units
- Drying units (air, UV)
- Automatic registration system
- Max. web width 300 mm
- Max. web velocity 30 m/min

ROKO Roll-to-roll printing line

- 1 interchangeable printing unit slot: forward and reverse gravure, reverse gravure, rotary silk screen, flexography, knife coating
- Plasma substrate treatment and lamination units
- Drying units (air, UV, IR)
- Lift-off, paste etching, solvent lamination and ultrasonic washing processes
- Max. web width 300 mm
- Max. web velocity 10 m/min

SILKO Roll-to-roll elastomer replication line

- 2 component silicone elastomer (“PDMS”) replication
  - Microfluidics as main application
  - Opportunities to upscale micromechanics fab from lab proto-type
- Wet deposition, layer thicknesses tens to hundreds of µm
- Up to 300 mm web widths
- Further processing
  - Printing, laser ablation
- Multilayer capability

EVO component assembly tool

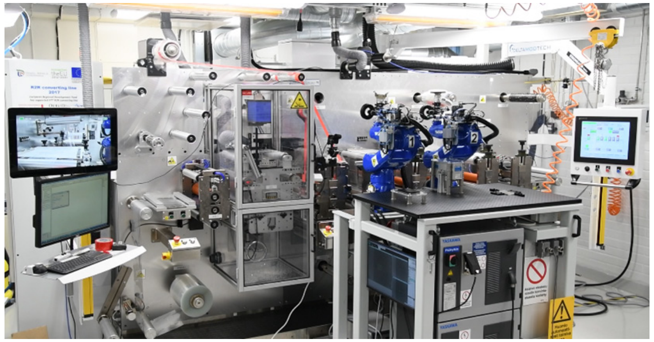
- Assembling flexible, silicon and SMD components on printed back-plane
- Die attach, flip chip, multichip: chip-size down-to 100 µm, up to 100 mm
- Die pick from wafer, waffle pack, gel pack and tray
- Max. working area 300 x 200 mm
- Adhesives dispensing & stamping (ICA, ACA, NCA), flux dipping
- Adhesive curing by thermo-compression (max. 350°C and 7500g) and UV curing (max. 14000 mW/cm² with mercury lamp)
- Highest accuracy ± 10 um @ 3 Sigma

LAKO Roll-to-roll component assembly line

- Automated stop-and-go hybrid integration line for flexible, stretch-able and bio-based continuous substrates
- All process steps on the same run
    - Conductive adhesive (ICA) dispensing for electrical bonding (jet and screw valves)
    - Pick-and-place of SMD components (tape feeding, component size from 01005” to 74 x 74 mm)
    - Heat-curing in a reflow oven (up to 250°C)
    - Non-conductive adhesive dispensing for encapsulation, side-bonding, underfill and coating
    - UV curing equipment (<100 mW/cm² at 365 nm) (top and bot-tom side irradiation)
- Working area 400-500 mm x 290 mm (MD x TD) in each process equipment

DELTA Roll-to-roll converting line

- 6 interchangeable converting unit slots: die- and kiss cutting (top and bottom), lamination and slitting.
- 6 winders enable simultaneous lamination of up to 4 webs.
- CO2 laser, max area 280 × 280 mm², web speed up to 5 m/min.
- 2 industrial robot arms
- LED and Hg UV-units
- Automatic registration system
- Max. web width 340 mm
- Max. web velocity 90 m/min
- 2 industrial robot arms
    - Max. payload: 8 kg
    - Repeatability: ± 0.01 mm
    - Synchronised with the converting line and laser.
    - Operation modes (pick-and-place): tray-to-web / web-to-tray; multi indexing of web-to-web
    - Machine vision system for high accuracy alignment.
    - Tooling: grippers: mechanical, adhesive, vacuum, needle; dispenser with UV fiber curing; hotplate pressing; ultrasonic welding, and soldering iron station



ENKELI Injection moulding machine

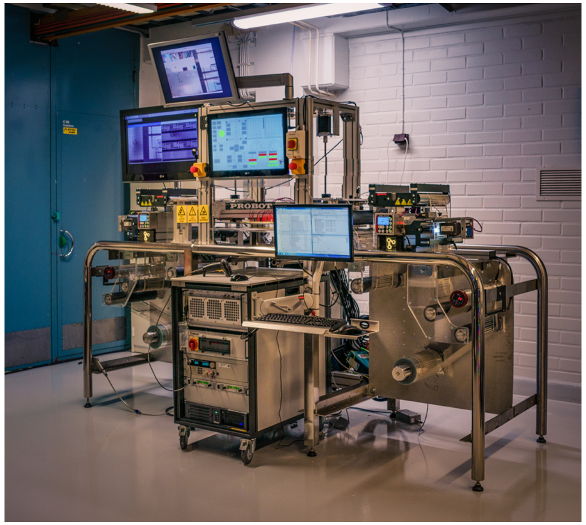
- 2 injection units: ø 30 mm and ø 40 mm screws
- Clamping force 120 tn
- 2-shot moulding capability with rotation plate of 700 mm
- Wide range of thermoplastics including special high-temperature grades
- Foil integration options: In-Mould-Labeling (IML) and In-Mould-Decoration (IMD)
- R2R feeder included

PRECO Roll-to-roll die-cutting tool

- Four Post Hydraulic Press
- 40 Ton Capacity
- Shock Pads
- Standard 17” (431.8mm) Daylight (Includes 2” (50.8mm) bolster plate
- Platen Area of 12”/302mm Deep and 24”/609mm Wide
- Target-to-Cut Accuracy +/-.001” (.025mm)

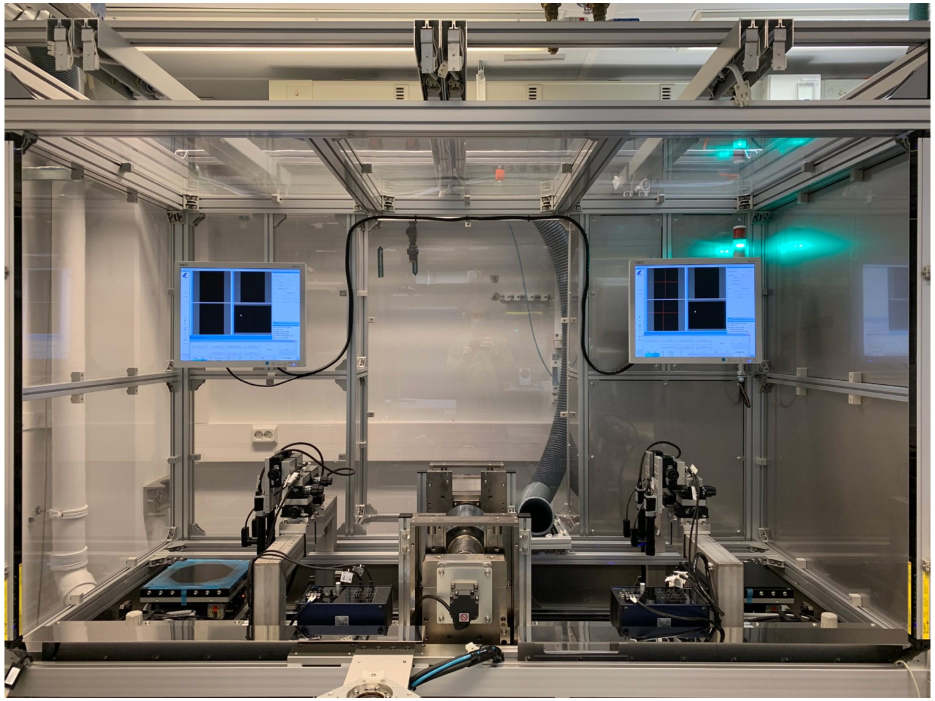
TESLA Roll-to-roll testing line

- Automated stop-and-go functional testing line for continuous rolls including printed and hybrid electronics
- Testing area 408 mm x 290 mm (MD x TD).
- 400 arbitrarily configurable test pins.
- Available test applications:
- Open and short circuit testing
- LCR measurements
- Current and voltage measurements
- OPV characterization (IV-curve)
- LED and OLED functionality testing
- On-the-fly test results storage on a data base.
- Systematic quantification of quality, yield and tolerances through-out the roll at industry-relevant volumes.



Reverse offset printing (ROP) system

- High-resolution µm-level printing
- Linewidths down to 0.5 µm demonstrated
- 8” sheet-to-sheet processing (19 cm x 19 cm)
- Printing speed 5 mm/s – 150 mm/s (down to 1 mm/s possible)
- Ink application by slit-coater
- Suitable inks include metal NPs, polymers, metal oxides
- Automated overlay alignment system having approx. ±2 µm alignment accuracy



1.3.2 Diagnostics Pilot Environment

PrintoCent Pilot Factory provides qualified diagnostics test development services to global companies operating in the health, environment and veterinary sector. The services include development of fabrication of disposable sensors, including lateral flow test strips, integrated microfluidic devices and optofluidic sensors, electrochemical sensors. We can further support in pre-clinical testing.

DIANE Diagnostics pilot line

- Development and pilot manufacturing of next generation point-of-care diagnostics
- Clean room with controlled environmental conditions
- Temperature +22°C ± 2°C; humidity 20 RH% ± 5 RH%
- Application examples:
- Lateral flow assays, molecular diagnostics, opto-fluidic chips, microfluidic sensors, electrochemical sensors, and integrated sensors
- Lateral flow assay manufacturing capacity with 1000-2000 test strips per week.

1.3.3 Medical Device Pilot Environment

The medical device pilot enables the production of small and middle-size prototype series for pre-clinical studies using the most advanced electronic, photonic, microelectronic and microfluidic components and integration manufacturing technologies following ISO-13485 practises. These enable the development of comfortable-to-wear, skin-like wearable sensors combined with wireless communication and data processing functionalities.

Key application focus areas for the pilot line include preventive monitoring of cardiovascular diseases, metabolic syndromes and early cancer detection and recurrence as well as rapid diagnostics.

Main capabilities:

- Pilot Manufacturing Accuracy and Repeatability: Ensuring high precision and consistency in production.
- Increased Sheet Size: Accommodating larger sheets up to 500 mm × 500 mm.
- Patch-to-Patch Quality Control: Implementing rigorous quality checks for each patch.
- Design Verification and Design for Manufacturing: Enhancing design processes to ensure manufacturability.
- MDR Compliance: Meeting the requirements of the Medical Device Regulation.
- New Material Testing: Focusing on sustainable manufacturing practices.

Our key infrastructure comprises of

- State-of-the-art ISO7 cleanroom
- Flatbed Computer-to-Screen (CtS) screen exposure system
- Flatbed automatic screen printer
- UV and IR belt oven
- Automatic component assembly line for large area flexible PCBs
- Picosecond UV Laser for cutting, structuring and drilling of flexible PCBs
- High precision press flat die cutter
- Advanced Sub-Micron Bonder for photonics packaging
- Printed electronics printing and assembly
- Photonics packaging capabilities
- Characterization capabilities: Surface profilometers, Scanning Electron Microscope, High capacity 3D X-ray Microscopy
- High-precision dispenser for bioreagents
- Lamination capability for multilayer integration

https://www.vttresearch.com/en/technology-infrastructures/medical-device-pilot

1.3.4 Battery Laboratories

VTT has developed competences and applied battery facilities for research and development of energy storage since 2010. The research laboratories enable comprehensive experimental work on battery cells, modules and packs, as well as battery management systems and thermal management. These facilities are integrated with dynamometer facilities enabling experimental work not just on batteries, but also on heavy-duty vehicles, drivetrains and engines under the same roof. With our high-power battery emulator, we can test electric vehicle prototypes on the dynamometer even without a real battery installed in the vehicle.

VTT has also recently built competences for battery safety testing at cell level. Having tested hundreds of batteries, we can provide state-of-the-art knowledge, foresight and experimental research services. The backbone of these services is experimental work combined with modelling capabilities and tools.

Battery assembly and characterisation:
https://www.vttresearch.com/sites/default/files/2023-10/FactSheet_BatteryAssembly_v2.pdf

https://www.vttresearch.com/en/ourservices/battery-technologies

Battery technology development environment

The infrastructure will consist of a dry room laboratory, a general chemical and characterization laboratory and a battery testing laboratory. The environment enables battery manufacturing covering the entire chain from processing battery chemistry to manufacturing functional cells and testing the performance.
The estimated date of completion of the environment is in fall 2026.
Planned equipment and capabilities include:

- Dry room with very low humidity conditions (dew point below -40°C)
- Battery manufacturing and assembly
- 3D printer, silk screen printer, blade coating
- Roll-to-roll line
- Material preparation and handling

https://www.oulu.fi/en/projects/battery-technology-development-environment-enabler-for-just-transition

1.3.5. PrinLab - Development Laboratory for Printed Intelligence

PrinLab is a printed electronics R&D and small-scale manufacturing laboratory offering RDI and educational services from design to prototyping and testing. PrinLab provides access to SMEs, researchers and product developers to participate in the development and testing of printed electronics applications while enabling co-operation between universities, research facilities and PrintoCent stakeholders. PrinLab offers experts and cutting-edge equipment for printing and testing prototypes, and training new professionals.

PrinLab´s capabilities include e.g.:

- Flatbed and rotary screen printing
- Inkjet and dispensing
- R2R flexo, gravure and hot embossing
- Laser cutting and engraving
- Surface profilometry
- Electrical measurements
- Development and testing of electrochemical assays
- Environmental testing

www.oamk.fi/prinlab

2

DESIGN CONSIDERATIONS IN PRINTED AND HYBRID ELECTRONICS

2.1 Design flow in printed electronics

Introduction

From electronics designer's perspective Printed Electronics resemble partly conventional PCB design, where discrete components are placed and routed together. Partly it resembles custom integrated circuit (IC) design, where components are created and modified as needed, routed together and the behavior and interaction of components and routing is analyzed. Printed Intelligence covers a very broad range of emerging and rapidly developing technologies. Design methods and tools are still in early stages. Also, special technologies e.g. biochemical and optical technologies require new kind of approach to the design flow.

How does Printed Electronics design differ from conventional PCB or IC design?

One definitive advantage of printed electronics is that it makes possible large area designs. The measures can be in meter scale versus decimeters in PCB and millimeters in IC design. The design tools must support large area and at the same time the possible small dimensions of the discrete components. It's possible to make larger surfaces functional on the unique approach of printed electronics since it utilizes additive manufacturing. You only add functional parts where they are needed. Whereas usually in traditional electronics manufacturing you remove the areas that are not needed. Therefore, especially parts where only small area of total surface is functionalized this approach is beneficial.

Graphic images can be printed on the same substrate with the functional components. Often it is simpler to print graphics and electronics separately and combine the functionality and graphics by laminating layers together. The challenge is that graphics designers use different design systems and file formats than electronics designers. The dimensions and registration of both layers need to match.

Flexibility brings another dimension in electrical and mechanical design. Bending and stretching will affect the component and wiring properties and may introduce reliability issues. Special care is needed when discrete hard components are assembled on flexible and even stretchable substrate. Additional glop top coating, lamination or a local substrate stiffener may be needed.

Printed components have often lower performance than discrete or silicon integrated components. Designing routing for a copper-based PCB is rather straightforward. Very sensitive signals or high frequency or high current signals need special attention. Printed conductors have typically over ten times higher resistance than the copper wires on the PCB. This forces careful layout planning together with schematic design.

It is also possible to have several conductor types in one design – e.g. etched copper wires and printed silver wires. The design tools may not support this, and the designer must find a way to manage the situation.
One feature of printed electronics is that documented design rules and design guidelines are missing. This book is intended to partly help with this problem.

What is needed in Printed Electronics design?

For feasibility evaluation the following data should be available

- Data of component and material availability, performance, reliability and restrictions
- Instructions for material and process (and manufacturer) selection
- Data for cost estimation
- Design examples of similar applications

In an ideal situation the following things should be available for actual design work

- Design rules for components, wiring, assembly and testing
- Design software and a design kit including
  - schematic symbols for components
  - simulation models for components
  - layout symbols for components
  - electrical rules check
  - integration of mechanical and graphics design data
  - correct output file formats or reliable format converters
- For complex designs (large number of transistors)
  - comprehensive component library
  - automated layout tools
  - back-annotation of layout parasitics (e.g. wire resistances, capacitances and inductances) to the simulator
  - layout versus schematic check

Proper process documentation and design kits are in an initial state and not yet mature and comprehensive enough to support electronic design automation (EDA) tools for printed electronics. Most of the design tools and practices are developed in-house in different foundries to fit their specific needs.

Design rules

Design rules describe the electrical and physical characteristics for the available devices and components. To be able to create reliable design rules production process needs to be stabilized. Process stabilization is iterative work and requires a lot of characterization runs and data analysis. Process documentation and characterization data generated in stabilization phase is the basis for the design rule manual that describe reliable devices and components for printed electronics design.

Process design kits

Process design kits (DK) are based on the design rules and define the component/device design characteristics for a specific EDA tool. Design kits are foundry and process specific, and they include schematic symbols, simulation models, layout rules, verification rules, reliability rules, etc. Additionally in printed electronics we need to consider new design possibilities such as hybrid designs, 3D, flexibility, decorative design and their effects on electrical characteristics.

2D design

In low complexity 2D design the normal PCB design tools work well. Wire resistance needs to be included in the design, but a designer can do that manually by inserting extra resistors for simulations.

For more complex designs it would be better to use some EDA system intended for integrated circuit design. They offer more flexibility for automated layout, design rule check and back annotation of parasitic effects to the simulator. Some moderately priced IC design systems exist, and free open-source tools are also available.

Free-form and 3D effects

The origins of printing techniques and the future applications of printed electronics require new considerations and tools to be handled in the industry standard electronics design flow.

The flexibility of the printed circuits requires the effects of bending to be considered during design as shown in Figure 2.1.2. Measurements of screen-printed passive components (resistors, capacitors and inductors), indicate a possible change in components' primary electrical parameters in the order of 5%, which is roughly like the variation caused by temperature, supply voltage and process variations in traditional IC manufacturing processes and thus should also be taken into consideration during design phase.

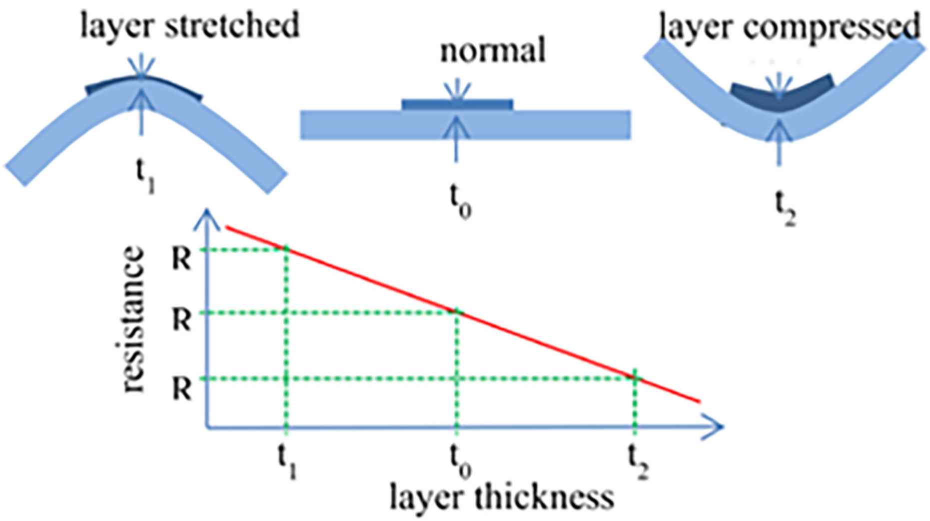


Figure 2.1.2. Effect of bending a resistor (resistive layer) – thickness changes due to direction of bending, which leads to the change of resistance.

However, there is a lack of a tool, which can combine the 3D shape information (from a 3D design software) and the knowledge of the sensitivity of printed components to shape deformation caused by bending. The following steps would be needed to create support for bending effects in a design system.

1. to create knowledge on the behavior of different components as they are bent

2. to develop a reliable method to predict the change of the electrical performance of a printed circuit when it is wrapped in an arbitrary shape

3. to automate the process of back-annotating the effects of bending on electrical properties to the printed electronics design flow, so that it can be used during simulation before manufacturing, increasing the probability of 1st manufacturing run success

The shape of components will be dictated not only by the electrical requirements but also by artistic ambitions, which requires links between the graphical and electrical design. For example, the possibility to design OLED- based displays into almost any desirable shape, can lead to functional (electrical and lighting) problems as shown in Figure 2.1.3, if not considered during design and simulation.

To support the dealing with arbitrary shapes it is needed

1. to gather knowledge on the electrical behavior of components with arbitrary shape

2. to develop automatic methods and tools to back-annotate shape related effects on electrical behavior of components to the printed electronics design flow

3. to develop methods to reduce the effects of arbitrary shape to the electrical properties of components without compromising the artistic representation of the component

Similar effects can be found in printed solar cells, in which case the artistic representation is not the reason for arbitrary shape but the need to cover all empty areas to maximize the power output.

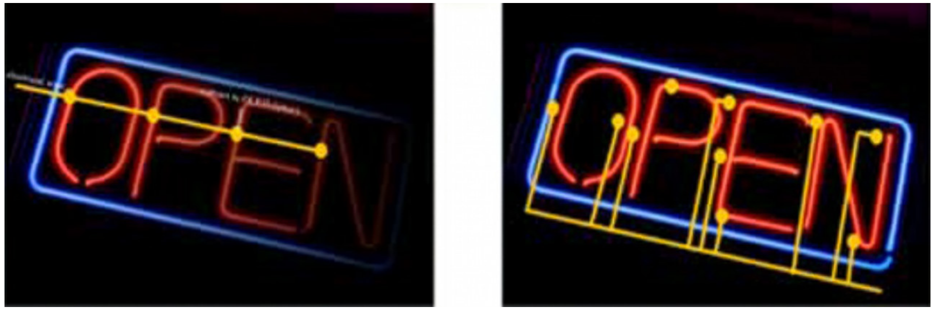


Figure 2.1.3. (a) Poorly designed electrical wiring leading to non-uniform OLED lighting and (b) an optimized wiring providing uniform lighting. This effect is hard to predict for complex shapes without an automatic link between graphical and electrical design and simulation.

Some practical recommendations on Design Flow, tools and file formats

As EDA tool, it is recommended to use 3D PCB editor with support for flex and rigid-flex multilayer PCBs. It is preferable if the EDA tool can handle graphical pdf files in cases where certain images will be transferred as functional designs, e.g. the new OPV shapes. Recommended file formats are Gerber RS-274X and .DXF. Also, other formats can be used in most cases. Tools such as CAM350, Altium Designer 19-> or PADS layout can be used for finalizing layout design and design rules checking. The output file format is dependent on the manufacturing process to be used:

- **S2S screen printing: Gerber RS-274X or .PDF** needed for screen exposure
- **R2R screen and flexo printing: .PDF** needed for screen exposure
- **R2R gravure printing: .DXF** needed to gravure cylinder engraving
- **Inkjet printing: 1-bit BMP file** or almost any image file, **or .PDF**
- If **graphical printing** houses are involved, they are typically using **.PDF** file format

When 3D mechanical shapes combined with electrical, optical and graphical layers, 3D CAD, such as IronCAD, SolidWorks or AutoCAD tools are used. In this case the input data needs to be in .DXF format and output .ICS is recommended. When several layers (electronics, mechanics and graphics) need to be combined, it is recommended to agree a common zero-point of individual designs helping the combining.

In EDA and CAM tools any .DXF to Gerber and Gerber to .DXF conversions should be avoided due to high risk of getting faults due to the incompatibility between file formats.

2.2 IMSE® (In-Mold Structural Electronics)

Design and Manufacturing Flow

The article is based on the PrintoCent handbook, previous edition, 2019, author Antti Keränen.

In-Mold Structural Electronics (IMSE®) is a breakthrough technology that integrates printed electronics and conventional electronics directly into thin, molded plastic structures. The result is conformal electronics—three-dimensional, functional, lightweight, and reliable solutions bringing real, customer-validated added value for a wide range of industries and applications. TactoTek develops and licenses IMSE technology to the global ecosystem of manufacturers and brands. As a foundation of the scalable licensing business, TactoTek has the strongest IP portfolio in the field - 50 patent families and over 300 granted patents globally (2025).

Automotive is one of the leading industries adopting IMSE technology. As the automotive interiors are transforming from driver-centric vehicles into multimodal spaces, IMSE is an enabler of this transition – turning decorative surfaces into living, smart surfaces that communicate through light, sense, and interaction.

By replacing bulky, flat PCB assemblies and multi-layer mechanical and optical structures, IMSE enables unprecedented design freedom and simplifies system integration. IMSE parts can deliver high-quality and high-efficiency illumination solutions, such as light lines (see Figure 2.2.1), surface illumination, and solutions e.g for lit emblems or door trims depicted in Figure 2.2.2. Also, additional features can be integrated, such as touch controls, sensing features, and antennas. Various finishes can be applied in the process, including decorative plastic, in-mold labeling film, natural wood, and stone; parts can also be 'wrapped' with natural or synthetic leather, fabric, or other materials, allowing for a wide range of visual and tactile aesthetics.

Sustainability is an inherent part of IMSE. The technology reduces plastic use and PCB size, streamlines the supply chain that ultimately leads to reduced greenhouse gas emissions. In collaboration with partners, TactoTek is also developing novel recycling approaches to recycle both electronics and plastics of integrated IMSE parts at high recycling yield to obtain fully circular IMSE.

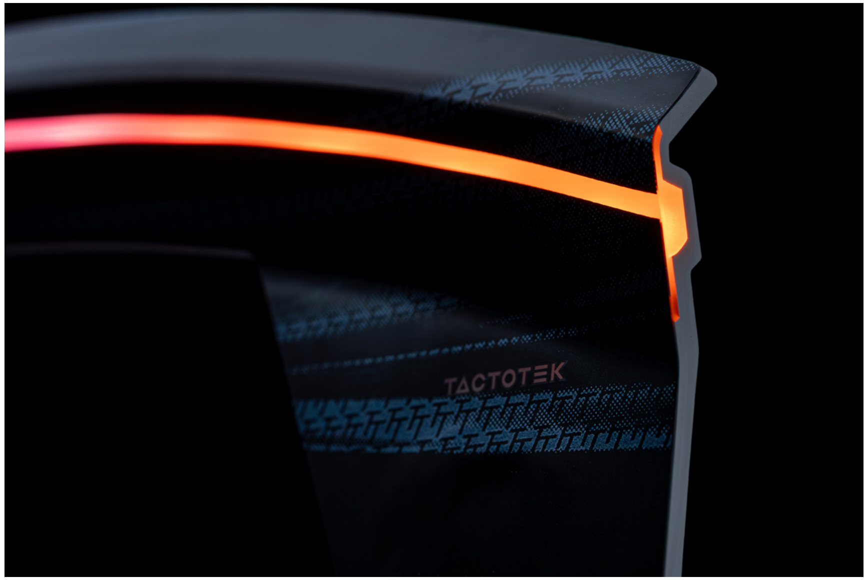


Figure 2.2.1. Example of a light line built with IMSE technology—a thin, encapsulated structure that can be applied to 3D surfaces for many applications.
© TactoTek

Figure 2.2.2. Example of edge-to-edge surface lighting with IMSE technology. Surface lighting can be used for dynamic ambient lighting as well as warning lighting.
© TactoTek

IMSE Part Structure

IMSE parts integrate electronic functions directly within the cosmetic surface. Discrete components such as LEDs are attached to a substrate and overmolded with transparent or translucent plastic, which serves as an efficient light guide. This allows thin, space-efficient lighting solutions with a minimized LED count and power consumption.

Light propagation in the IMSE part can be controlled through structural and material choices. Customized designs allow light to be directed, diffused, blocked, and efficiently coupled in and out without additional optical components. Beyond lighting, IMSE structures can integrate additional features, such as touch sensors and other sensing capabilities.

There are several variations of IMSE structures, and the structure is always selected based on the application requirements. Molding is a process that can be applied in different ways to create the necessary optical, electrical, and mechanical interfaces for IMSE applications, such as in-mold connectors. An IMSE structure can be created by molding over a single substrate, between two substrates, or through multiple molding shots with different materials, depending on the design requirements. Each method allows for integrating essential components within the structure to ensure it performs as needed.

Successful IMSE design relies on recognizing how various materials and components perform and interact throughout the process — from layering them together, shaping them into three-dimensional forms, and finally molding them into one unified structure.

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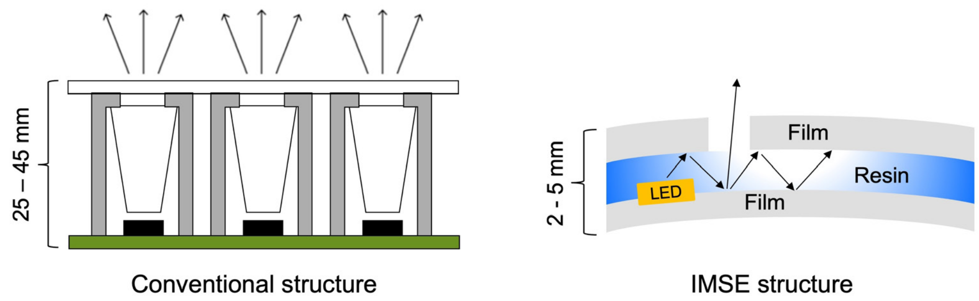

Figure 2.2.3. Comparison of conventional and IMSE illumination structures.
© TactoTek

IMSE System Elements

The base for an IMSE system is the printed, formed, and molded IMSE part. Most IMSE designs have a connector interface for a small external control electronics board. The small control electronics board/PCBA incorporates the hardware and software for driving the functional features in the IMSE part.

The control electronics board may have components and software for host communication, power supply components, etc. The control electronics board may also have an application-specific connector or wireless communications for connecting the IMSE part to a host system. IMSE also allows for integrating SiP (System-in-Package) within the product's plastic structure, minimizing the need for an external control board.

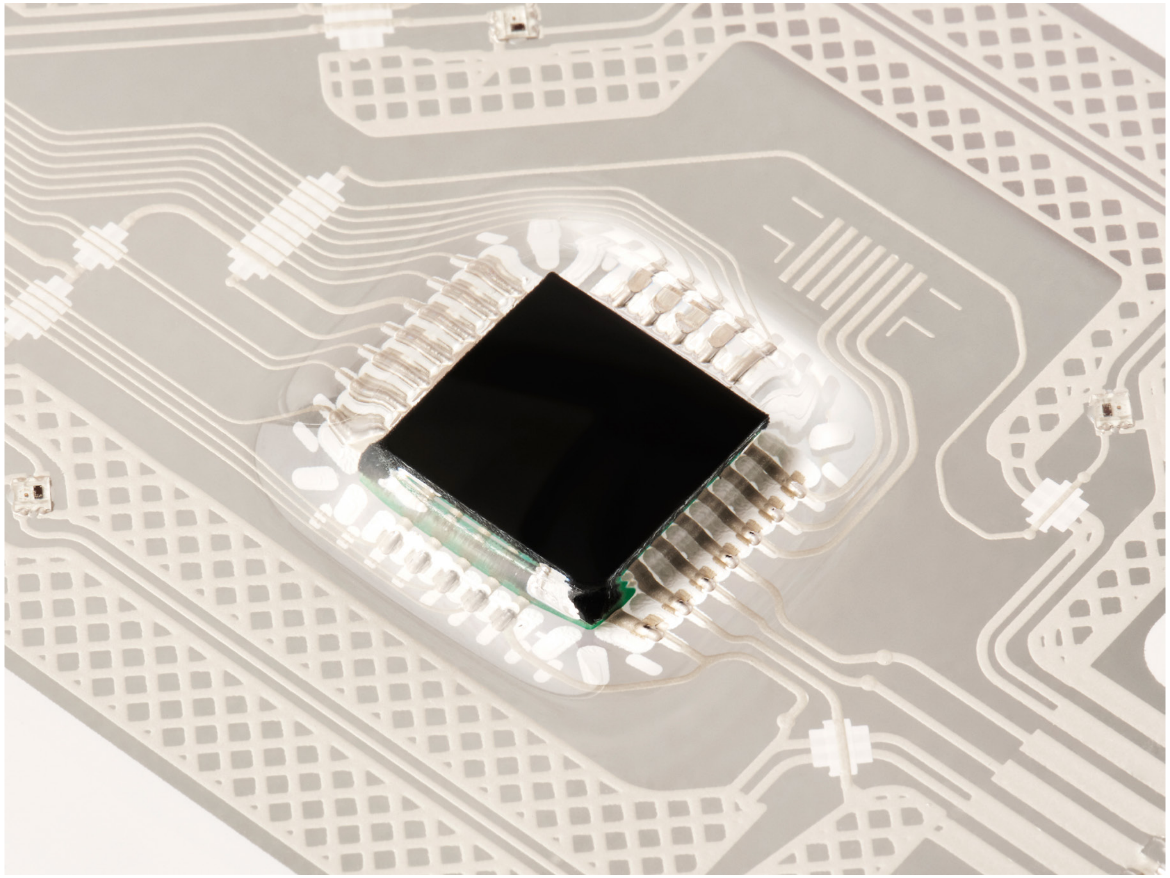

Figure 2.2.4. Example of sophisticated system electronics, IMSE SiP, integrated into the IMSE part.

IMSE Design Is Multi-Disciplinary

IMSE requires an evolution in electronic product design. Since mechanical and electronic functions are built into a single structure, design work becomes inherently multidisciplinary. Teams that might traditionally work in sequence instead collaborate in parallel, ensuring that decisions in one area align smoothly with the others. Depending on the part's features, IMSE design typically involves the following disciplines, as presented in Figure 2.2.5:

- Mechanics design
- IMSE electronics design (schematics and printed electronics layout)
- Illumination design
- Tooling design (molding/forming/cutting)
- Control electronics design (hardware and embedded SW)
- Printed graphics design (if needed)
- Antenna design (if needed)

Responsibilities can be distributed in different ways depending on the organization—one designer may cover several areas—but close, continuous collaboration remains essential. A change made in one discipline often affects others: for example, relocating an LED may require adjustments to the mechanical and electronics designs, and any change in the 3D shape of the product must be reviewed by other disciplines.

Effective IMSE development also depends on compatible CAD and simulation tools. A wide range of simulation methods is applied throughout IMSE design to ensure efficient workflows and high-quality design outcomes. Many IMSE design rules and methods are already integrated into the design tools created by TactoTek's partners, helping teams collaborate smoothly across disciplines.

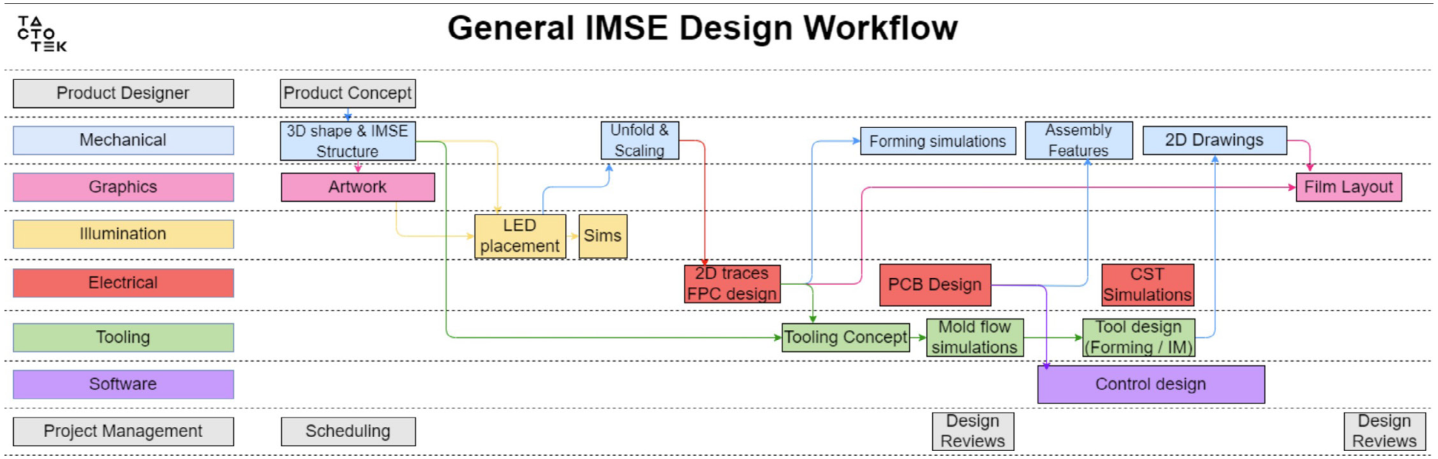

Figure 2.2.5. General IMSE Design Workflow
© TactoTek

IMSE Design and Manufacturing Are Closely Linked

IMSE manufacturing differs notably from conventional electronics, and these differences influence the design work. Designers need a solid understanding of how manufacturing processes and materials affect their decisions. For example:

- The final part shape determines component placement and the selection of optimal conductive inks.
- Printing capabilities define the minimum and maximum widths of conductor traces.
- The location of the injection-molding gate affects both component layout and routing of conductive traces.

Understanding the core IMSE manufacturing process steps helps clarify these relationships. The IMSE production flow—printing, surface mounting, forming, and molding (Figure 2.2.6)—consists of well-established steps that use standard mass manufacturing methods with standard machines from the printing industry, electronics industry, and plastic industry. What makes IMSE unique is how these mature processes and methods are integrated together in a unique way.

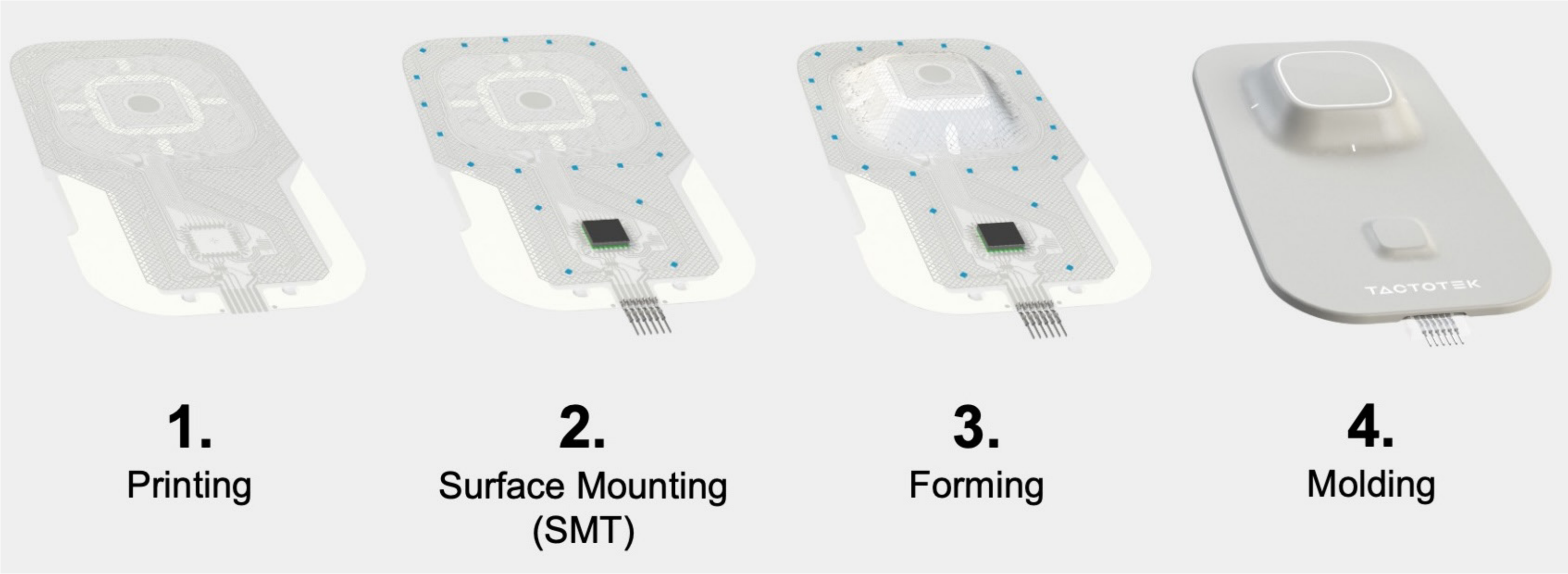

Figure 2.2.6. IMSE manufacturing process steps. © TactoTek

Printing

Printing is the first core IMSE process step. Printing is used to prepare circuitry, other functional layers, and also decorative layers (when needed) onto a plastic substrate such as polycarbonate or another suitable substrate material. Circuitry is typically screen-printed using silver-based conductive inks. If cross-overs are needed in the circuitry, then multiple layers of dielectrics are also screen-printed to insulate at crossover locations. Typically, the printed circuitry is located on the surface of the substrate that faces inside the molded structure, such that the circuitry is being encapsulated by the plastic resin when the part goes through the molding process.

Functional films are similar to a PCB assembly: both include a substrate with conductors and surface-mounted components (Figure 2.2.7). However, printed conductor traces in IMSE differ from solid copper traces in PCBs. The key differences are:

Conductive inks, especially with elongation properties do not conduct electricity as well as solid materials such as copper. Therefore, printed conductor traces in IMSE have much higher electrical resistance than PCB traces. This affects overall current-carrying capabilities, trace width, schematics, and layout design.

Polymer substrate materials tend to shrink during the IMSE manufacturing process, and this must be accounted for when creating schematics and printed electronics layouts.

IMSE Technology enables transformation from flat, 2D designs into 3D form, adding some special elements to the electronics design.

Multilayer circuits are also created differently in IMSE than in PCBs. IMSE multilayer designs have several conductive layers on top of each other (Figure 2.2.8). In multilayer IMSE circuits, dielectric layers are printed only at locations where traces cross, which affects the layout design.

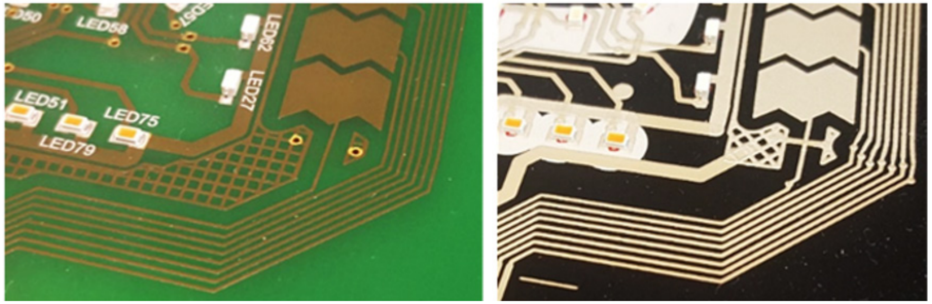

Figure 2.2.7. The printed circuit board on the left and the IMSE functional film on the right each include a substrate with conductors and surface-mounted components.
© TactoTek

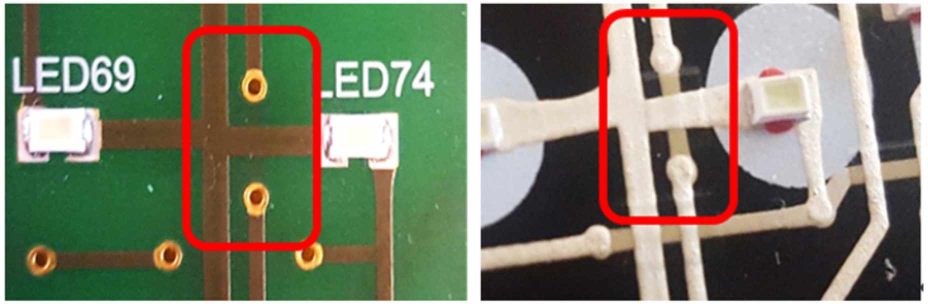

Figure 2.2.8. The PCB multilayer design on the left is concealed within the structure, while the IMSE multilayer design on the right shows visible conductive and dielectric ink layers.
© TactoTek

Surface Mounting (SMT)

Surface mounting technology (SMT) is the second core IMSE manufacturing process step. Components such as LEDs are placed and bonded—mechanically and electrically—onto 2D functional film(s) using standard, high-speed 2D pick-and-place equipment. The output is a 2D substrate with printed circuitry and components (functional film). IMSE surface mounting uses conductive and structural adhesives instead of solder paste in a reflow soldering process. Adhesive curing temperatures typically remain below 130 °C. However, adhesive bonding requires a different component footprint than soldering, which affects layout design.

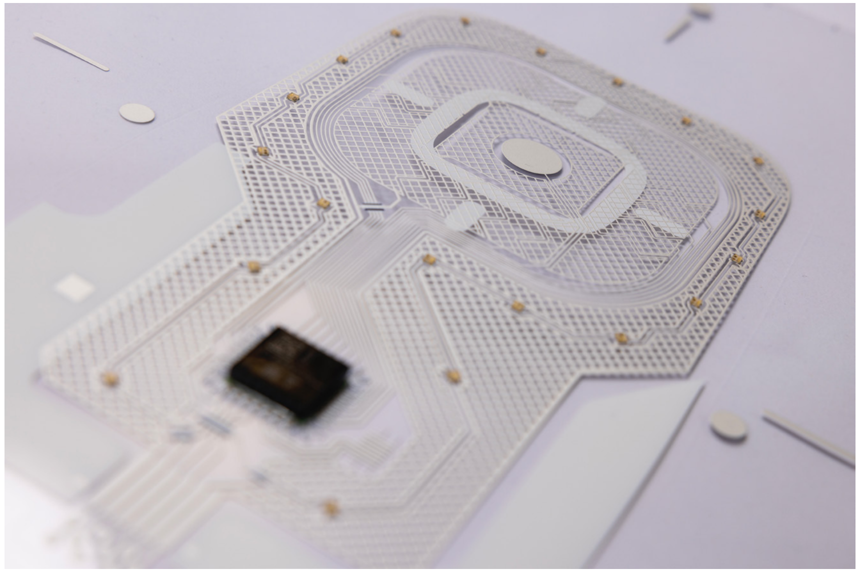

Figure 2.2.9. Printed circuitry and electronic components (LEDs and SiP) on a plastic substrate.
© TactoTek

Forming

Forming is the third core IMSE process step; it is not used in conventional electronics manufacturing but is used for the cosmetic surfaces of some electronics assemblies. In this process, the 2D functional films having circuitry and components on top and decorative films (if any) are forced into a 3D shape, for instance, by using high air pressure with the so-called Niebling process. The outputs are 3D-shaped functional films having printed circuitry and components and, when required, 3D decorative films or cosmetic surface materials (Figure 2.2.10). By enabling 3D-shaped, electronically active parts without full-sized PCBs and their associated assembly structures, IMSE offers far greater design freedom.

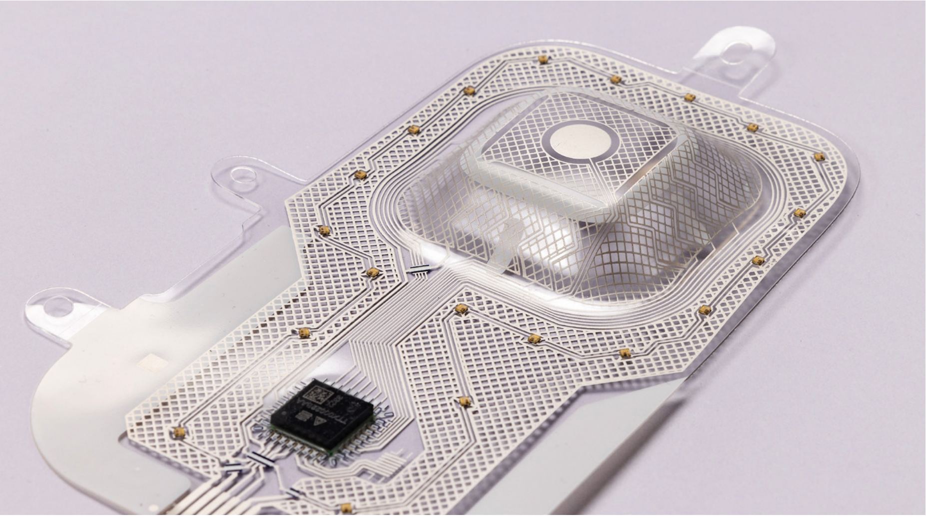

Figure 2.2.10. A formed functional film with circuitry and components (LEDs and a SiP).
© TactoTek

Molding

Molding is the fourth core IMSE manufacturing step. During molding, the 3D formed film(s) are used as inserts in a molding tool. Plastic resin, such as PC, is injected on top of the functional film, resulting in an ultra-thin, single-piece, molded part. In the case of two separate films being used, the molding is prepared between the films. The output is a strong and durable structure in which electronics are encapsulated within plastics. As mentioned earlier, the plastic structure has a dual function. It brings mechanical integrity and also forms a light guide.

The injection-molded polymer protects the electrical components from harsh environmental conditions such as mechanical impacts, vibration, moisture, and dust. It also protects the circuitry from oxidation.

IMSE manufacturing also typically includes pre-assembly and final assembly of control electronics. These processes are not IMSE-specific.

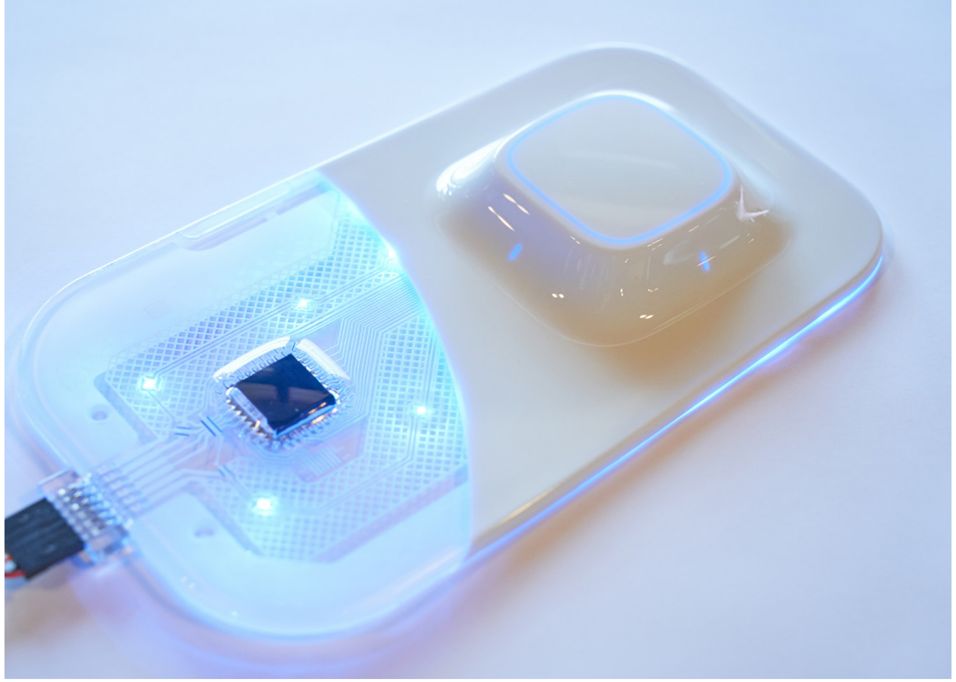

Figure 2.2.11. The molded IMSE part encapsulates printed circuitry and rigid electronic components within the plastic structure, bringing mechanical integrity. The molded structure also acts as a light guide.
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Sinivaara H., Heikkinen M., Simula T., Ahola T., Apilo P. 2025. IMSE® Enabling Innovative Automotive Applications. 29p. Available at: https://www.tactotek.com/resources/imse-enabling-innovative-automotive-applications

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2.3 Cost Considerations

Practical Validity Statement:

Much of the cost structure and material pricing information in this section reflects real-world practice in printed and hybrid electronics manufacturing. However, actual costs can vary significantly depending on market conditions, production scale, and technology maturity. Users should treat these figures as indicative, not absolute, and always verify with current suppliers and market data.

Key Cost Drivers in Printed Electronics

1. Materials Costs

- **Substrates:**
  Selection depends on temperature stability, mechanical and dielectric properties, chemical resistance, and dimensions. For example, a 500 m PET roll (30 mm wide, 125 µm thick) costs about €500 (€2.8/m²).

- **Conductive Inks:**
  Silver ink is a major cost factor. Prices for micro-particle silver ink range from €1,500–€3,000/kg, while nano-particle inks can reach €3,000–€10,000/kg in small quantities. Large-volume purchases may lower costs, but the global silver price directly impacts ink pricing. Emerging copper inks promise lower costs (down to €100/kg), but silver remains dominant. Copper inks have not yet fully penetrated the market, although their availability and the range of vendors offering them have increased. Copper inks are mitigated in rigid structures already but remain in small volumes in flexible and stretchable solutions. Conductive ink selection and the combination of the inks is highly dependent on intended use case and environment.

- **Other Inks:**
  Dielectric inks (~€100/kg), resistive inks (~€300/kg), and copper pastes (~€400/kg).

- **Active Components:**
  For devices like OPVs and OLEDs, material costs can be up to 85% of total costs, with barrier foils and adhesives being the largest contributors. Better barriers increase both cost and product lifetime.

2. Manufacturing Costs

- **Preparation and Tooling:**
  Costs depend on complexity, number of layers, and chosen printing technique. Tooling (e.g., flexo plates, gravure cylinders, rotary screens) ranges from €200 to €2,000 per layer, with delivery times from days to weeks.

- **Facility and Personnel:**
  Layout design, operator costs, and facility usage are significant. For example, a pilot run may require €1,200 for layout, €3,400 for a day's use of a printing line with two operators, plus material and tooling costs.

- **Yield and Volume:**
  High production volumes are essential for cost efficiency. Production yield, layout design, and process variations all impact final costs.

3. Assembly and Integration

- **Bonding Methods:**
  Standard soldering isn't feasible for flexible substrates; conductive adhesives and thermode bonding are used instead. Preparation work for pilot runs can be extensive and sometimes more time-consuming than the run itself.

- **Line Capacity:**
  Tack time for assembly steps (dispensing, pick & place, curing) limits throughput and affects costs. Complex products require more steps and reduce effective capacity.

- **In-mould Integration:**
  Injection moulding for integrating functional films involves significant investment (€200k+ for machinery, €10k+ for tooling). Cycle times and tooling complexity affect amortization and unit costs.

Highlight: Raw Material Cost Increases – Silver and copper price trajectory

The cost of silver, a key ingredient in conductive inks, has surged dramatically in recent years:

- **Early 2020s:** Silver moved from the $15–$20/oz range, spiking near $28 in 2020–2021 due to COVID-driven safe-haven buying and physical shortages.
- **2024:** Prices flirted with $30 and hit $34.80 by October, influenced by geopolitical tensions and tariff concerns.
- **2025 Boom:** Silver broke records, reaching over $50/oz by late 2025, with seeing it surpass $65/oz, driven by a perfect storm of factors.

The cost of copper, a key ingredient in replacement for silver based conductive inks, has also been increasing

- **2020:** Averaged around $6,174/metric ton.
- **2021:** Reached a peak average of $9,317/metric ton.
- **2024:** Averaged $9,142/metric ton, with a Q2 2024 high near $9,750/ton.
- **2025** (Early/Mid): Prices surged, with some forecasts seeing averages around $8,200/ton, but hitting record highs driven by supply shortages and green energy demand, with Q2 2025 over $9,500/ton.

Impact:

Silver has experienced a dramatic surge in value, climbing from an average of $17.50 per ounce in the early 2020s to $65 per ounce by late 2025—a staggering increase of approximately 271%. In contrast, copper has shown more moderate growth, rising from $6,174 per ton in 2020 to $9,500 per ton in the second quarter of 2025, representing about a 54% increase.

These price trajectories has a direct and substantial effect on the cost of silver- and copper-based inks and, consequently, on the overall cost structure of printed electronics. Manufacturers must closely monitor silver and copper prices and consider not just other alternative materials (such as carbon/graphite inks) to mitigate cost risks but also consider more traditional manufacturing methodologies like subtractive copper or aluminum etching. When considering these alternatives ones must understand that they are not one to one compatible, performance and processing conditions may vary a lot and bring also total cost variance.

Final Note

While the cost predictions and figures presented are valid in practice, they are subject to rapid change due to market dynamics, especially raw material price volatility. Always consult up-to-date sources and suppliers for current pricing and cost structures.

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https://www.macrotrends.net/1470/historical-silver-prices-100-year-chart

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2.4 Sustainability in printed intelligence

The electronics industry relies on manufacturing processes that are energy and material intensive and on materials of which many are rare, valuable, hazardous or critical. The global material consumption is increasing rapidly, which will eventually lead to a shortage of virgin materials. At the same time, only less than 9% of global resources are circular. Furthermore, electronic and electric waste (e-waste) is one of the fastest growing global waste streams. Recycling is limited – globally 20%, in the EU 40% – because material recovery from the electronic devices is a challenge due to use of multiple materials and some in small fractions. Also, because unused devices are not returned from the users to circulation or the devices are not designed for recycling.

Sustainable development combines environmental, economic and social considerations to meet the needs of present generations without jeopardising the ability of future generations to meet their own needs. Circular economy is one opportunity for increasing sustainability. It aims to extend the lifetime of the products, valorise the end-of-life products and to keep the materials in circulation as long as possible. Figure 2.4.1 shows how the different circularity strategies – R strategies – can be implemented in the electronics value chain.

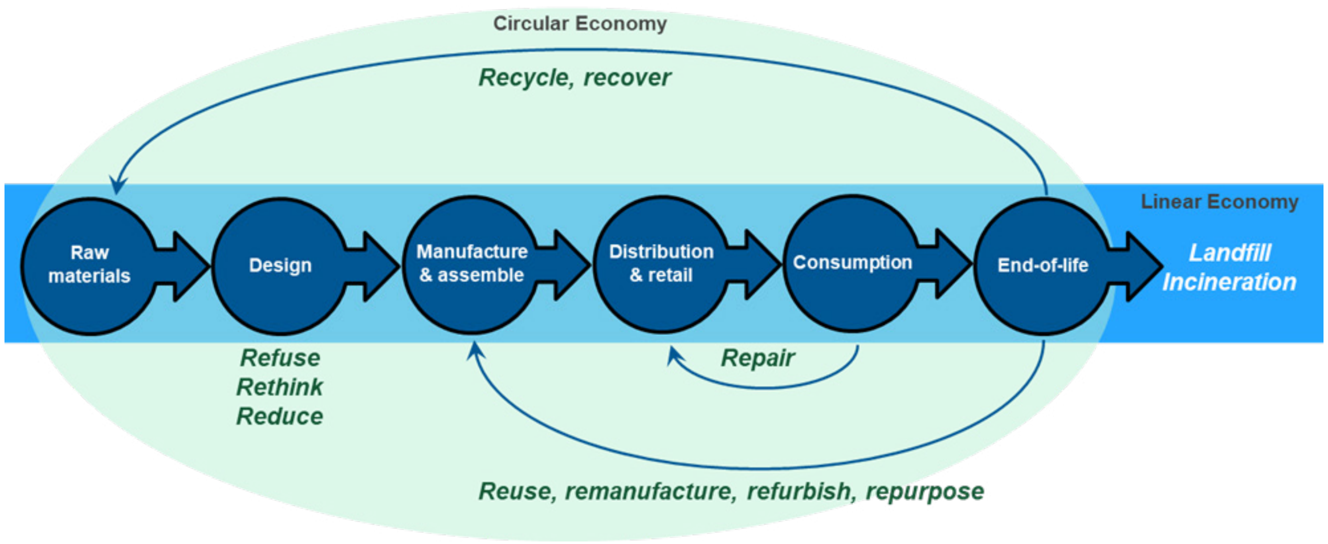

Figure 2.4.1. The different circularity strategies in the electronics value chain as opposed to linear economy.

Sustainability – required by legislation

There are different global, EU-level and national sustainability agendas and regulations that target also the electronics industry. The United Nation's Sustainable Development Goals (SDGs) are adopted by all the member countries. They cover comprehensively all three categories of sustainability and are now slowly being implemented by the governments, cities and companies in their action plans.

The EU has an extensive regulatory framework on sustainability in the electronics industry.

Authorisation and Restriction of Chemicals REACH (EC 1907/2006) aims to protection of human health and the environment through the better and earlier identification of the intrinsic properties of chemical substances.

Restriction of Hazardous Substances in Electrical and Electronic Equipment RoHS Directive (2011/65/EU) aims to prevent the risks posed to human health and the environment related to the management of e-waste.

Waste from Electrical and Electronic Equipment WEEE Directive (2012/19/EU) contributes to sustainable production and consumption addressing environmental and other issues caused by the growing number of discarded electronics in the EU. The goal is to prevent the creation of WEEE, use resources efficiently, and retrieve secondary raw materials through re-use, recycling and other forms of recovery.

Battery Regulation (EU 2023/1542) entered into force in 2023. Its aim is to minimise the environmental impact of the growing battery sector. It contains, for example, rules for waste batteries that will calculate and verify the rates of recycling efficiency and recovery of materials.

The most recent regulatory activity in the EU is Regulation on Ecodesign for Sustainable Products (ESPR) that is a framework for making sustainable products the norm on the EU market and for reducing their overall environmental and climate impacts. It is targeting any physical good placed on the market with some exceptions, such as food and feed. Product-level rules are being developed. The regulation aims also to empower consumers for the green transition. Digital Product Passport (DPP) is one of the cornerstones in the regulation to provide value chain transparency and product traceability to allow users to make environmental sustainability benchmarking.

There are also EU regulations on energy labels, ecolabels, corporate sustainability reporting and use of conflict minerals.

Environmental sustainability

Environmental sustainability is linked to low environmental impact or footprint of products. In the electronics industry it is often referred to as green electronics. LCA (Life Cycle Assessment) is a standardised and EU-recommended method used for quantification of the environmental sustainability. There are examples in the literature how the printed electronics can contribute to lowering the environmental impact of the electronics manufacturing. Since LCA calculations are always case-specific, no universal conclusions can be drawn from them. However, the existing assessments indicate that the strengths of the printed electronics arise from the use of more sustainable materials and lower energy consumption of the manufacturing process compared to etching based processes.

In one example a four-layer PCB (Printed Circuit Board) manufacturing can lower its environmental impact with over 80% when using flexible substrates and printed silver ink instead of subtractive manufacturing processes, as shown in Figure 2.4.2. The biggest reduction comes from less use of chemicals and electricity. The remaining environmental impact is mostly associated with the use of silver as the conductive material and with the consumption of the process energy. Replacement of silver with copper- or carbon-based inks can decrease the environmental impact with additional 80-90%, as shown in Figure 2.4.3. Printed electronics allows usage of flexible and thin substrates that can also be bio-based or renewable, such as cellulose- or biopolymer-based ones. Although the role of the substrate in the overall environmental impact is low, they can allow new end-of-life management opportunities, such as recycling or even composting or biodegradability, when feasible from the use case perspective.

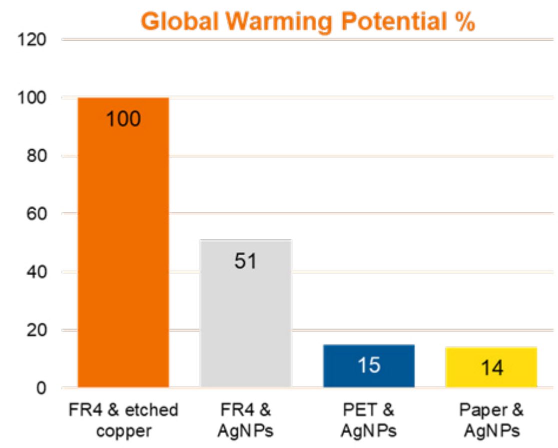

Figure 2.4.2. Global warming potential of different material and process combinations for manufacturing a PCB board. FR4 with etched copper is a baseline, while the other bars represent printing of silver nano-particle ink on different substrates. (adapted from [4])

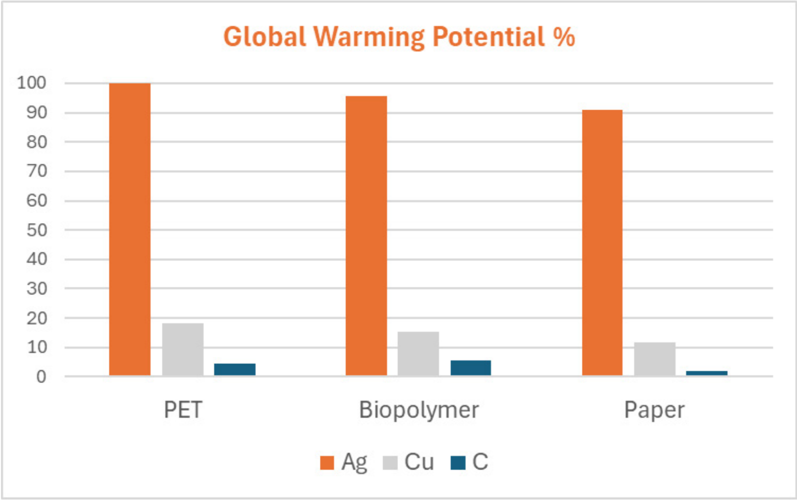

Figure 2.4.3. Global warming potential of different ink-substrate combinations in printed electronics. The bars include impact of materials, electricity and end-of-life incineration. Silver ink on PET is the baseline. (adapted from [5])

Social and economic sustainability

Social sustainability is linked with people's well-being, equity and inclusion, access to essential services, human rights and work-life balance. Printed intelligence is an enabling technology to many new innovations that can address the social aspects. For example, the affordable diagnostic tests or wearable sensors that can be used outside point-of-care, have positive impact on well-being of citizens by allowing the patients to recover at home, stay connected to the healthcare professionals and avoid constant travelling between home and healthcare facilities. Another example is printed smart labels attached to packaging for monitoring product conditions during logistics, retail and storage. These technologies can contribute to decrease in misplaced shipments, decrease in food waste and increase in food safety.

Economic sustainability can be achieved from circular business models (CBMs), efficient supply chains, company policies supporting sustainability or investments on renewable energy and materials. CBM defines how an organisation creates, delivers, and captures value through strategies that extend product life and close material loops. CBMs in printed electronics support product reuse and extended use through modular architectures and resource-efficient additive manufacturing. To enhance circular traceability, DPPs record material composition, usage details, and recovery steps, supporting the return, reuse, and recycling of components. In addition, printed electronics further enable service-based business approaches such as leasing and product-as-a-service (PaaS) models. These approaches maintain product functionality throughout use, improve material efficiency, and reduce waste generation. Wearable sensors can be upgraded with AI-based data analysis to create user profiles, assist mobile nursing personnel, and improve healthcare efficiency. These digital and modular functions enhance circular value creation by connecting sustainable materials, logistics networks, and energy-efficient printing to achieve environmental and economic benefits. Table 2.4.1 shows the CBM value dimensions and related circular and economic dimensions for printed and hybrid electronic products.

Table 2.4.1. General CBM value dimensions for printed and hybrid electronic products.

CBM Value Dimension	Sub-value elements	Description	Circular and Economic value
Value Proposition Products and services that reflect the organization's vision while ensuring economic, environmental, and social benefits	Product	Electronic device combining reusable and single-use parts	• Reduced material and energy demand • Reusable and upgradable components
	Service	Sensor-based monitoring and connectivity services using data collection and cloud/mobile platforms for identification, tracking, and analytics	• Enhances service continuity and supports PaaS • Extended product use; improved utilization and data-driven value creation
Value Delivery Systems and relationships that bring these offerings to users in line with sustainability goals	Target customer & users	• Healthcare sector • Electronics industry • Smart & intelligent packaging	Broad cross-sector applicability and market potential.
	Value delivery processes	• Choosing sustainable materials • Manufacturing process (Roll-to-roll) • DPP-based traceability and product information • Subscription-based access for remote use • Original Equipment Manufacturer (OEM) networks and sector-specific partners	• Quality, transparent lifecycle data, efficient market access • Reduces CO2 emissions

Table 2.4.2.

CBM Value Dimension	Sub-value elements	Description	Circular and Economic value
Value Creation Organizing resources, activities, and partnerships to address sustainability requirements	Key partners and stakeholders	Ink and substrate suppliers, printing partners, collaboration among OEMs, recyclers, assemblers, digital platform providers	• Shared design and material reuse • Efficient resource use and joint development
	Value creation processes	• Eco-design guided by LCA principles • Integration of LCA data to support products design • Higher resource efficiency and extended product lifetime	Higher resource efficiency and extended lifetime
Value Capture Revenues and costs managed while contributing to environmental and social outcomes	Revenues	Service-oriented models such as leasing or PaaS generate income while promoting reuse of electronic parts	• Modular design • Shared platform • Service- and data-based income enhancing long-term value retention
	Cost	• Material efficiency through sustainable choice of ink, substrate, and additives • Energy-efficient manufacturing and reuse of electronic parts	Reduces manufacturing impact and end-of-life costs through resource utilization across the product lifecycle

Company examples

M-Boss creates colours, patterns, and functionalities by patterning material surfaces on the nano- and microscale. For example, colourful surfaces on paper or plastic can be made without printing inks, and anti-reflective plastic surfaces can be created without adding chemical layers. The M-Boss hot embossing process has very low LCA values because it produces no waste chemicals or VOCs (Volatile Organic Compounds), and renewable energy can be used. The next step in enhancing sustainability is to use biodegradable substrates, like those M-Boss uses in its biodegradable glitter products for cosmetics. These products are home compostable and disintegrate into water without creating any microplastic waste.

New Cable Corporation's ultimate objective is to design and offer flat, flexible cable and harness solutions that save space, weight, material, and cost. We aim to ensure that our products use the sustainable technology best suited to project requirements. Our sustainability assessment consists of environmental, economic and social aspects of the solution and its design and manufacturing process. This is ensured by a Sustainability, cost, and risk Assessment (SCRA) carried out throughout all projects. SCRA is an iterative sub-process that begins with the first customer inquiry and is being revised at every level. Data collected and its revisions are inherited at every level of the project. Relevant aspects and learnings of the assessment will be used in the development of corporate processes and management. SCRA process was carried out in the UNICORN EU-project where sustainable automotive electronics were developed. The best impact score was reached with the flat connectorless design cable with the die-cut and lamination production technology. Aluminium and partially recycled PET were used and this combination shows also the biggest potential cost wise.

Screentec Oy is a contract manufacturer of custom disposable medical electrodes and other printed electronic products. The amount of different kind of measurements made using medical electrodes will increase in the future and as the electrodes are most commonly single-use electrodes, Screentec has focused the past three years to develop and test material stacks to make more sustainable medical electrodes. With the help of EU and BF funded project Sustronics, Screentec has so far manufactured ECG, EEG and Bio impedance electrodes which have been made using more sustainable materials, have high enough quality to make needed functional measurements, can achieve wear time up to 24 hours and are also cheaper than similar electrodes using currently commonly used material stack. This development work has also already resulted first order for custom disposable medical electrode made from more sustainable materials.

Summary

SWOT (Strength, Weakness, Opportunity, Threat) analysis of printed intelligence from sustainability perspective is presented in Table 2.4.3.

Table 2.4.3. SWOT analysis of printed intelligence covering the three levels of sustainability.

Strengths	Weaknesses
Environmental • Small energy consumption: additive method • Small production waste • Compatibility with bio-based, renewable and abundant materials **Economic** • Maintenance and use costs of infrastructure: no clean rooms • Scalable production **Social** • Limited exposure to harmful chemicals	**Environmental** • Technically equal alternatives to silver and PET **Economic** • Large volumes often needed for economic viability • Yield at sufficient level with the new materials **Social** • Some reliance on toxic volatile solvents, specifically in machinery cleaning
Opportunities	**Threats**
Environmental • Small product footprint: benefits in logistics and transportation • Design for the environment possible • Suitability for recycling **Economic** • Implementation of circular business models • Sustainability as a competitive edge **Social** • Enabling novel product concepts that improve well-being and quality of life (e.g. healthcare)	**Environmental** • Silicon-based components overcome the environmental benefits from the printed parts • Total biodegradability difficult to achieve **Economic** • Bio-based and renewable materials remain more expensive than the fossil-based ones **Social** • End user acceptance if product price is higher or performance lower than with the non-sustainable alternatives

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2.5 Ecodesign

The importance of the design phase is emphasised by the fact that even 80% of the environmental impacts of a product are specified during its design phase. Ecodesign is a principle that considers the products' environmental impacts already during the design and development process aiming for minimised environmental footprint throughout the product life cycle. Therefore, all stages of a product life cycle and value chain should be considered. Ecodesign expects use of materials with less environmental impact, use of fewer materials in manufacturing, use of fewer resources during manufacturing, and generation of less pollution and waste at all stages, for example. In practice, this can mean decrease in use of materials or substitution of materials with more sustainable alternatives or designs with less process steps and compatibility with processes consuming less resources. Printed electronics has capabilities to meet many of these ecodesign requirements.

During a design phase it is often difficult to implement a full LCA, because enough data is not yet available. Therefore, methods that are designed for a more streamlined approach can be helpful in decision-making to assess the impact of the different design choices. VTT has developed a method – Greentool – to assess sustainability of flexible electronic devices during design phase holistically by taking into account all three aspects of sustainability: environment, social, economy. Greentool has seven main criteria that each contain several subcriteria i.e. the data points for benchmarking. Each subcriteria gets a scope between 1-5 as compared to the baseline. The scores are summed up and can be presented in a spider-web graph. Greentool has been used for electronic smart labels, wearables and batteries benchmarking. Figure 2.5.1 shows an example of the wearables benchmarking. Similar to the other test cases, the raw materials and manufacturing have the biggest differences between the baseline and the printed concepts, thus highlighting the importance of the design and manufacturing phase. The observations are also in line with the LCA assessments explained in Section 2.4.

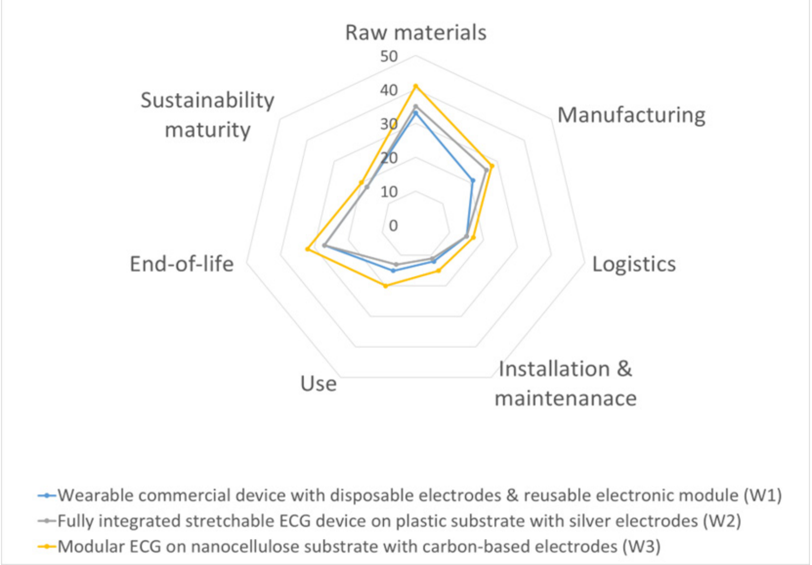

Figure 2.5.1. Greentool benchmarking for the different wearable concepts. W1 is the baseline and W2-W3 are printed concepts.

3

PRINTING AND HYBRID INTEGRATION METHODS AND MATERIALS

3.1 General about printing and coating methods

There are several methods for the deposition of functional materials onto flexible substrates. Printing methods, such as flexography, gravure, rotary screen, offset, reverse offset, and inkjet, allow direct patterning of the layers. Coating methods, such as reverse gravure, roll-, knife-, spray-, and slot-die coating, are typically used in applications, where continuous stripes or full coverage of functional layers is needed. Hot embossing is an imprint technology used to manufacture optical features and microfluidics. Other roll-to-roll (R2R) compatible patterning methods include lift-off, etching, thermal imprinting, and UV imprinting. These methods combine printing/coating methods with other processing methods, such as washing, evaporation, and imprinting.

All these methods can be used in sheet-to-sheet (S2S) processes, but the focus of this chapter is in the R2R processes with high production volumes. As an exception, reverse offset printing (ROP) is mainly a S2S process but is described here due to its importance in the manufacturing of certain printed components like TFTs and transparent electrodes.

Conventional printing methods

The operating principle of flexography is shown in Figure 3.1.1. Flexography uses soft and flexible printing plates where the image elements are raised above the non-image areas, forming a relief of the desired printed pattern. Printing ink is applied onto the image elements via an anilox roller having small ink-transferring cells engraved/etched evenly onto its surface. The surface of the anilox roller is flooded with ink from an ink reservoir or from a fountain roller. Excess ink is then wiped off with a doctor blade so that the ink remains only in the cells. Ink is then transferred onto the plate and further onto the substrate. The layer thickness can be adjusted by changing the volume of the cells of the anilox roller.

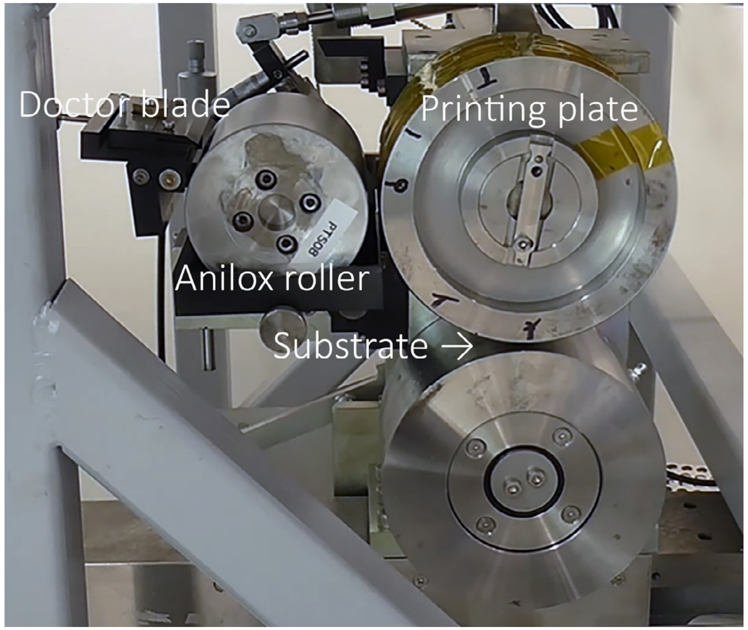

Figure 3.1.1. Flexographic printing process

Gravure printing process is presented in Figure 3.1.2. The image elements are engraved/etched into the surface of a metallic printing cylinder whereas the non-image areas remain at the original level. To ensure uniform ink transfer, the cells are always separated by cell walls even in the case of solid tones. Therefore, some ink spreading is always required to reproduce full coverage.

The printing cylinder rotates in an ink fountain and picks up ink onto its surface. Excess ink is removed from the non-image areas by a doctor blade so that ink remains only in the cells. The ink is then transferred onto the substrate.

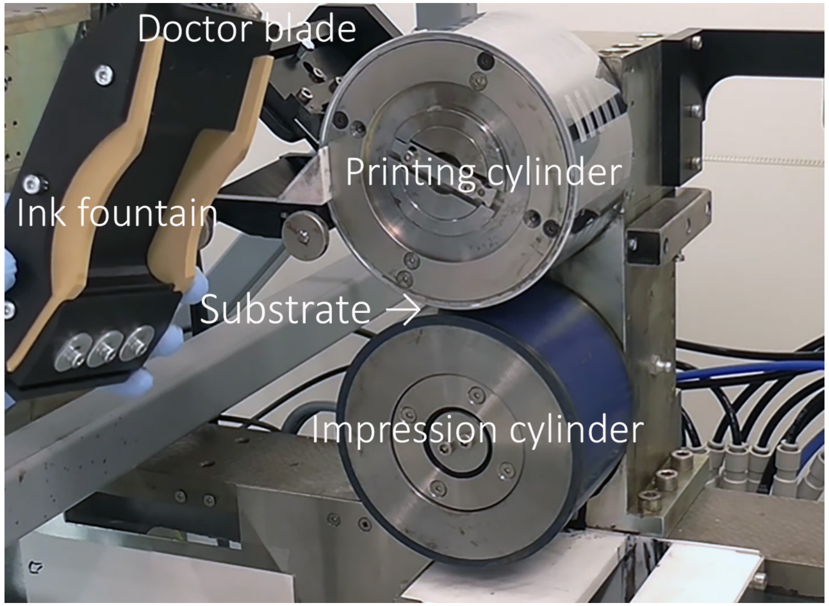

Figure 3.1.2. Gravure printing process

The layer thickness can be adjusted by changing the engraving/etching parameters of the printing cylinder affecting the cell volume. Rotary-screen printing (Figure 3.1.3) is a push-through process where the ink is pushed through the openings of the fine fabric screen made of metal or polyester threads. The non-image areas of the screen are covered with photopolymer emulsion. The ink is applied inside the rotating cylindrical screen. A stationary squeegee, which is located inside the screen, is slightly pressed against the screen, thus pushing the ink through the screen openings onto the substrate. The layer thickness can be adjusted by changing the mesh count of the screen.

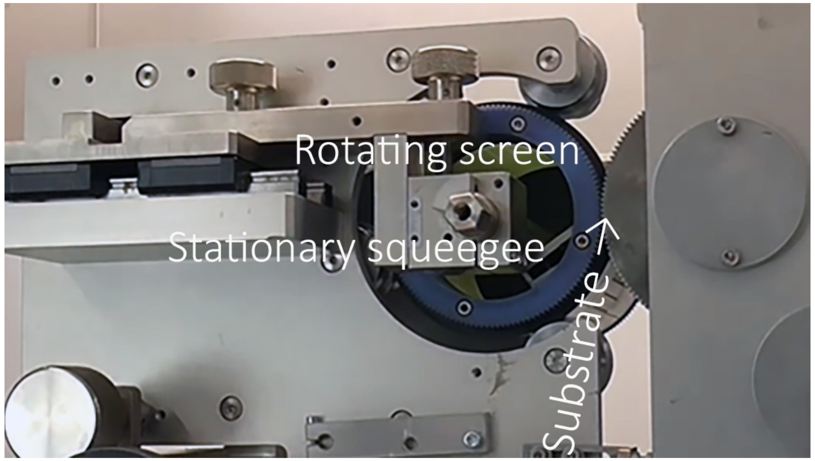

Figure 3.1.3. Rotary screen printing process

Table 3.1.1 and Table 3.1.2 compare the different printing methods. Gravure printing is a suitable method when using low viscous inks. In addition, the registration accuracy and detail rendering demands can be high. Wide variety of solvents can be used in gravure printing because of the metallic printing cylinder.

Very corrosive liquids can harm the chrome plating, though. The other significant limitations are the high cost of the printing cylinder and the demands for ink rheology. Gravure printing has been used to print active, semiconducting, and dielectric layers of organic photovoltaics, transistors, and sensors.

Flexographic printing is typically used when the ink viscosity is a bit higher than in gravure, and high detail rendering and edge definition are required. The printing plates are cheap, but the chemical resistance of the plates is poor, thus limiting the selection of the ink solvent. Flexography has been often used for the printing of thin conductor layers.

Rotary screen printing is a potential method when the layer thickness target is high, and the ink has high viscosity. The high layer thickness enables the manufacturing of conductive layers with low sheet resistance. However, the detail rendering is poorer than with flexography and gravure. It should also be pointed out that there is a wide variety of commercially available functional inks. Rotary screen printing can be used to manufacture multi-layer passive components containing conductive, resistive, and dielectric layers.

Table 3.1.1. Performance of the different printing methods

Method	Minimum feature size	Layer thickness	Ink viscosity
Gravure	20 - 80 µm	20 nm - 12 µm	<200 mPa·s (low)
Flexography	30 - 80 µm	50 nm - 8 µm	<500 mPa·s
Rotary screen	70 - 100 µm	1 µm - 100 µm	>1 mPa·s (high)
Inkjet	20 - 100 µm	< 1 µm	4 - 20 mPa·s (very low)
Dispensing	40 - 150 µm	20 µm - 200 µm	1 mPa·s · 1000 mPa·s

Table 3.1.2. Advantages and disadvantages of the different conventional printing methods

Method	Advantages	Disadvantages
Gravure	• Good detail rendering • High registration accuracy • High production speed • Precise ink application	• Expensive tooling with long delivery times • Edge raggedness • Missing dots (non-transferring cells) • High nip pressure needed → can be detrimental during overprinting • Solid tones reproduced via ink spreading • → ink rheology important to achieve uniform layer coverage
Rotary screen	• Sharp and well-defined edges • Good detail rendering • Cheap tooling • Low nip pressure → no damage to the underlying layers • Easily adjusted ink transfer amount	• Limited chemical resistance of the plates → limited ink choice • Poorer registration accuracy • Difficult to achieve fine details and solid tones in a single printing pass
Flexography	• Thick layer (lower resistance of conductors) • Wide selection of commercial functional inks available • Moderate tooling costs • Very low printing pressure	• Limited resolution • Only for high viscous ink • Low printing speed • Screen blocking

Reverse Offset Printing, ROP

Reverse-offset-printing (ROP) is a novel printing method capable of forming features at µm-level and with µm-level alignment accuracy, well beyond the capabilities of conventional printing methods. In the ROP process (Fig. 4.) a roll of polydimethylsiloxane (PDMS) is coated with a low-surface tension, low viscosity ink. The ink solvent is partially absorbed by the PDMS and partially evaporated, leading to a semi-dry condition of the ink where the viscosity and the cohesion are high.

A relief pattern containing the negative image of the desired pattern is brought in contact with the semi-dry ink, removing the ink from unwanted areas on the PDMS. Finally, the positive pattern left on the PDMS is transferred onto the receiving substrate. ROP can be per- formed as roll-to-plate (sheet process) or in a roll-to-roll process. In the roll-to-plate reverse offset-printing, either the cliché and substrate plate move underneath a stationary roll or the PDMS roller rolls over a stationary cliché and substrate plates. The roll-to- plate approach al- lows higher alignment accuracy, which is important in TFT applications. ROP-equipment has been scaled up to at least 5G size substrate size (1100 x 1300 mm) in industry.

Patterning of the ink in the semi-dry state, allows high patterning reso- lution. Resolution is limited by the manufacturing accuracy of the cliché and ink properties and edge definition (sharp edges with almost vertical sidewalls). ROP does not suffer from substrate wet-ink interactions that can lead to uneven cross-section profile of printed features in conventional printing techniques. The thickness is defined by the coating of the PDMS and ink properties, allowing good thickness control and uniformity, with characteristics resembling those attainable with photolithography.

ROP was initially proposed for wirings and gate electrodes for amor- phous silicon (a-Si) thin-film transistors (TFTs) in the flat-pan-el-display industry. ROP has mostly been used to print metal nanoparticles (Ag, Cu) for Source/Drain electrodes in organic TFTs (OTFTs) and metal oxide TFTs (MOTFTs), antennas and metamate- rials, and transparent metal mesh electrodes. ROP has been used to print semiconductor layer and polymer dielectrics for OTFTs. The nanoparticle inks and polymer inks have high cohesion when the solvent leaves the system.

Reverse Offset Printing, ROP

In slot-die coating process the ink is pumped from an ink reservoir into the coating head. The coating head consists of two metallic halves, one of which has an inlet and ink manifold/groove for the ink.

The two halves are separated by a metal shim that defines the size of the lip gap, determines the coated width and the number of coated stripes, and ensures the ink flow out of the coating head.

The ink is pushed through the lip gap onto the substrate by means of the pumping pressure. A small gap is kept between the lip and the substrate. It is also possible to pattern rectangular shapes by turning the pumping on and off controllably. A wide range of ink viscosities can be used in the slot-die coating. The pumping speed, ink viscosity, shim thickness, coating speed, and lip-substrate gap determine the layer thickness. The achieved layer thickness ranges from tens of nm to hundreds of µm. The minimum width of the stripes is typically in a millimeter scale. Slot-die coating is a process where all the different parameters need to be carefully optimized to obtain uniform layers.

In the reverse gravure coating process a an engraved/etched cylinder is used for coating. This method can only reproduce continuous stripe patterns in the printing direction. The coating cylinder rotates in an ink reservoir and lifts ink on its surface. The doctor blade wipes off the excess ink after which the ink is transferred onto the substrate. The substrate and the printing cylinder move in the same direction, thus making the smoothness and evenness of the coated film better than in gravure printing. The speed difference between the substrate and the coating cylinder plays also a major role in the layer homogeneity. Reverse gravure coating uses rather low viscous inks. The layer thickness is typically from 10 nm to 1 µm. The minimum width of the coated stripes is in millimeter scale.

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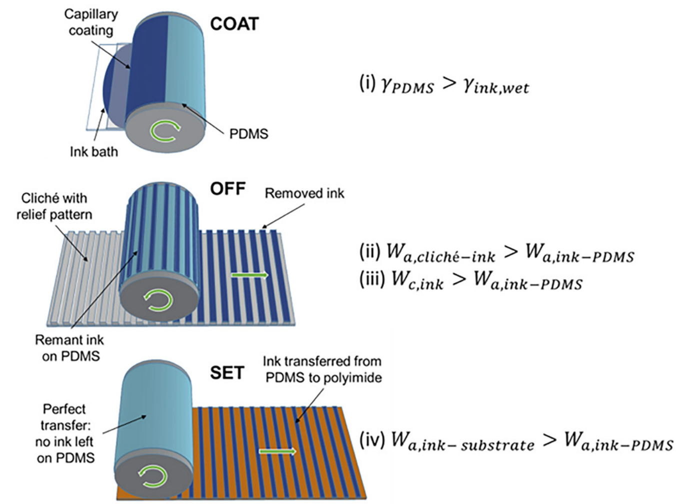

Figure 3.1.4. Principles and steps of reverse-offset printing technique.[L3.1]. Details on flat bed screen printing can be found from practical guide.

Coating methods

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Hot embossing

Hot embossing is mainly used to manufacture microfluidics and optical features onto flexible substrates. A metal shim contains the desired features. The shim is welded onto a metal sleeve to enable R2R processing. The sleeve is then heated and pressed against the substrate. The impression cylinder can also be heated. The hardness of the impression cylinder is selected according to the substrate

and the desired feature sizes. The shim features are copied onto the surface of the substrate by means of heat and pressure. The minimum feature sizes are <1 µm in the case of optical features and from 100 µm to millimeters in the case of microfluidics.

Digital printing methods

Inkjet and dispensing methods are two widely used digital printing techniques in printed electronics enabling precise, flexible, and additive deposition of functional materials onto various substrates. The main benefit of using digital printing is the freedom of design and material efficiency, enabling the low cost of trying new things, without the need of acquiring a tool (screen, plate, etc.) for printing.

Inkjet printing

Inkjet printing is an attractive deposition tool to complement the traditional processing methods used in printed electronics and in microelectronics fabrication. Its maskless, digital and non-contact nature provides many benefits, such as savings in processing steps and material usage, production flexibility and scalability to large areas. The required low jetting viscosity (< 20 mPa·s) of inkjet printable fluids translates to dry layer thicknesses up to ~1 µm, with minimum feature sizes in the range of 20 to 100 µm.

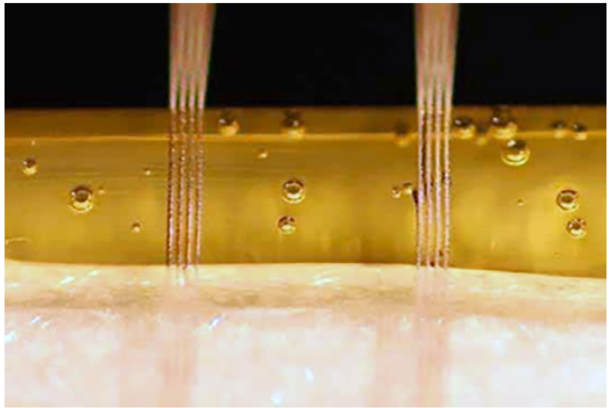

Figure 3.1.5. Example of inkjet printed conductor over a step (step height 700 µm, Ag electrode width/pitch 50 µm, 5 printed layers, resistivity 8.8 × 10-8 Ωm)
©VTT

In addition, inkjet printing can be utilized in the integration of e.g. silicon and polymer or paper-based systems, such as for hybrid large-area, flexible devices, which are out of the scope of traditional clean room processing.

Dispensing

Dispensing is a direct-write digital printing technique used in printed electronics for depositing functional materials such as conductive inks, adhesives, and encapsulants. Unlike inkjet printing, which relies on droplet ejection, dispensing involves the controlled extrusion of material through a nozzle, typically driven by pneumatic, piezoelectric, or other mechanical systems.

This method is particularly suited for high-viscosity inks and thick-layer applications, enabling the fabrication of robust conductive traces, dielectric barriers, and multilayer structures. Dispensing systems offer precise volume control and can accommodate a wide range of inks, making it ideal for prototyping and low-volume production of flexible and stretchable electronics.

Although the resolution of dispensing is typically lower than that of inkjet or aerosol jet printing—typically in the range of 40 - 150 µm—it excels in applications requiring mechanical durability and material versatility.

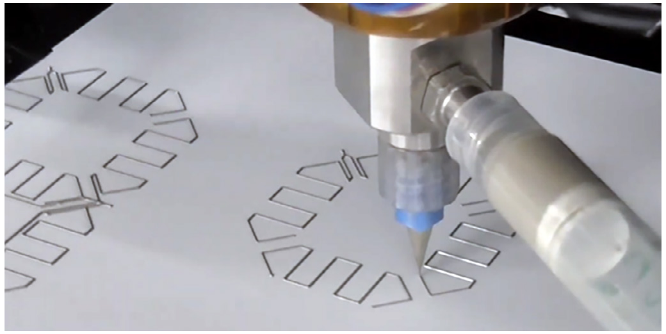

Figure 3.1.6. Example of dispensed silver conductor ©Oamk

Applications

In printed electronics, inkjet printing has been used for the deposition of conductive and insulating inks based on both organic and inorganic materials. For instance, fully inkjet-printed TFT fabrication has been demonstrated, and high-performance transistors have been obtained using inkjettable metal oxide semiconductor ink. This fabrication path could limit costs and enable production of customizable, large area electronics. In addition to direct patterning of multilayered functional devices, inkjet lends itself to the controlled coating of uniform films and for direct patterning of masking materials. VTT has formulated inkjet fluid formulations based on e.g. carbon, metal oxides and metal nanoparticles.

In microelectronics integration applications inkjet offers a leap to maskless patterning and selective coating to complement traditional micro-fabrication processes, such as wire bonding and electroplating.

Inkjet is used to deposit metal nanoparticle ink for creating vertical electrical interconnection. In addition, the process of inkjet printing of metal nanoparticle ink for creating an over-edge electrical interconnection from substrate to chip has been studied.

Dispensing is highly adaptable to complex geometries and non-planar surfaces, making it suitable for applications in wearable electronics, biomedical sensors, and conformal circuits. Its ability to handle viscous inks also enables the integration of functional materials with high particle loading, such as silver pastes and conductive adhesives.

3.2 Printed electronics materials

In principle, virtually all solid and liquid materials can be utilized within the field of printed intelligence. A brief overview of printable materials and commonly used substrates was provided in the previous version of the handbook. This chapter will now shift focus to the sustainability aspects of materials used in printed electronics.

SSbD (Safe and Sustainable by Design) is a framework developed by the European Commission to support the development of chemicals and materials that are safe for human health and the environment, while also being sustainable throughout their entire lifecycle. This approach has driven efforts to replace hazardous substances used in printed electronics, such as PFAS compounds and to reduce reliance on critical raw materials. It also promotes the integration of biobased and transient materials into printed electronics, aligning innovation with environmental and safety goals.

PFAS materials, or per- and polyfluoroalkyl substances, are fluorine-containing compounds, such as the well-known TEFLON, that exhibit unique properties including thermal, radiation (UV), and chemical stability, low surface tension, water and oil repellency, high mechanical strength, and excellent dielectric characteristics. These attributes make PFAS highly attractive for use in printed electronics. However, these same properties also contribute to their environmental persistence. PFAS compounds do not readily degrade and may transform into stable end products that accumulate in wildlife and humans. In response to these concerns, five European countries submitted a PFAS restriction dossier in 2023. The European Union is expected to implement comprehensive restrictions, either a full ban or application-specific exemptions, both with a defined transition period.

CRM (Critical Raw Materials) are substances that are economically and strategically important but have high risk of supply distribution or have few or no viable alternatives in their applications. These materials are essential to produce advanced technologies such as batteries, semiconductors, renewable energy systems, and printed electronics.

Table 3.2.1 Most used CRM in printed electronics and their application areas

CRM	Application
Silver	electrically conductive inks
Indium	transparent conductive films
Gallium, Tellurium	semiconductors, optoelectronic devices
Rare earth materials	magnets, sensors, display technologies
Lithium, Cobalt, Nickel, Graphite, Manganese	batteries

Printed electronics are a key area where CRMs are being substituted with biobased, carbon-based, or transient materials, aligning with SSbD framework.

Biobased materials are derived from renewable biological sources and are increasingly used to replace fossil-based substrates, polymers, and inks in printed electronics. Biobased substrates are e.g. bio-PET, PLA (polylactic acid), CAP (cellulose acetate propionate), regenerated cellulose and nanocellulose. Bio-PET is usually 30% biobased sourced from sugarcane, corn or other biomass and PLA is made from renewable agricultural sources. CAPs cellulose is derived from wood pulp or cotton linters but modified with propionic acid esters that can originate from fossil sources. Regenerated cellulose and nanocellulose are derived from natural cellulose.

Table 3.2.2 Biobased substrate materials in printed electronic applications

Biobased material	Printed electronic applications	Key properties
Bio-PET	Substrates for flexible circuits, sensors, and displays	Transparent, thermally stable, partially biobased, compatible with roll-to-roll
PLA	Substrates for biodegradable sensors, smart packaging, and wearables	Biobased, thermoplastic, optically clear, good thermal and dielectric stability
CAP	Substrates for flexible hybrid electronics, dielectric layers	Biobased, thermoplastic, optically clear, good thermal and dielectric stability
Regenerated Cellulose	Substrates for eco-packaging electronics, RFID tags, and low-power circuits	Biodegradable, flexible, transparent
Nanocellulose	Substrates for wearable sensors (e.g. ECG patches), barrier layers, and printable conductors	High mechanical strength, lightweight, printable, biodegradable

Transient materials in printed electronics are engineered to disappear, dissolve, or degrade after serving their intended purpose. These materials are particularly valuable in applications requiring temporary functionality, such as medical implants, environmental sensors, security devices, and wearable technologies. While some biobased materials may exhibit transient behaviour, not all are inherently transient. Silk fibroin, rice paper, polyvinyl alcohol (PVA), poly(lactic-co-glycolic acid) (PLGA), and cellulose are commonly used as dissolvable substrates. In addition, certain metals (Mg, Zn, Fe), metal oxides (ZnO, MoS2, MgO, SiO2), and polymers (PVA, wax, polyanhydrides) can function as transient components in printed electronics, serving roles such as conductors, insulators, encapsulation layers, or active materials. Most transient materials are designed to dissolve in water or biofluids, or to biodegrade under environmental or physiological conditions, enabling safe and controlled disintegration.

Figure 3.2.1. Biodegradable solar cell module

3.3 Flexible Hybrid Electronics

Hybrid integration concept in printed electronics enables the combination of printed, flexible components with traditional silicon-based microelectronics to create versatile, scalable, and high-performance electronic systems. It also enables new form-factor flexible product structures, and furthermore, seamless integration of novel optical, electrical, and mechanical features from 2D into 3D plastic products.

With hybrid system integration approach, industrial product designers gain more design freedom but also reduce complexity, volume, and cost of product systems. The hybrid technology truly combines the best of both worlds – the unique large area and arbitrary form factor of printed organic electronics and the high performance of conventional inorganic electronics devices. In addition, the utilisation of roll-to-roll manufacturing in the printing, assembly, and converting of flexible hybrid electronics systems enables cost-competitive production of 3D plastic products known also as structural electronics.

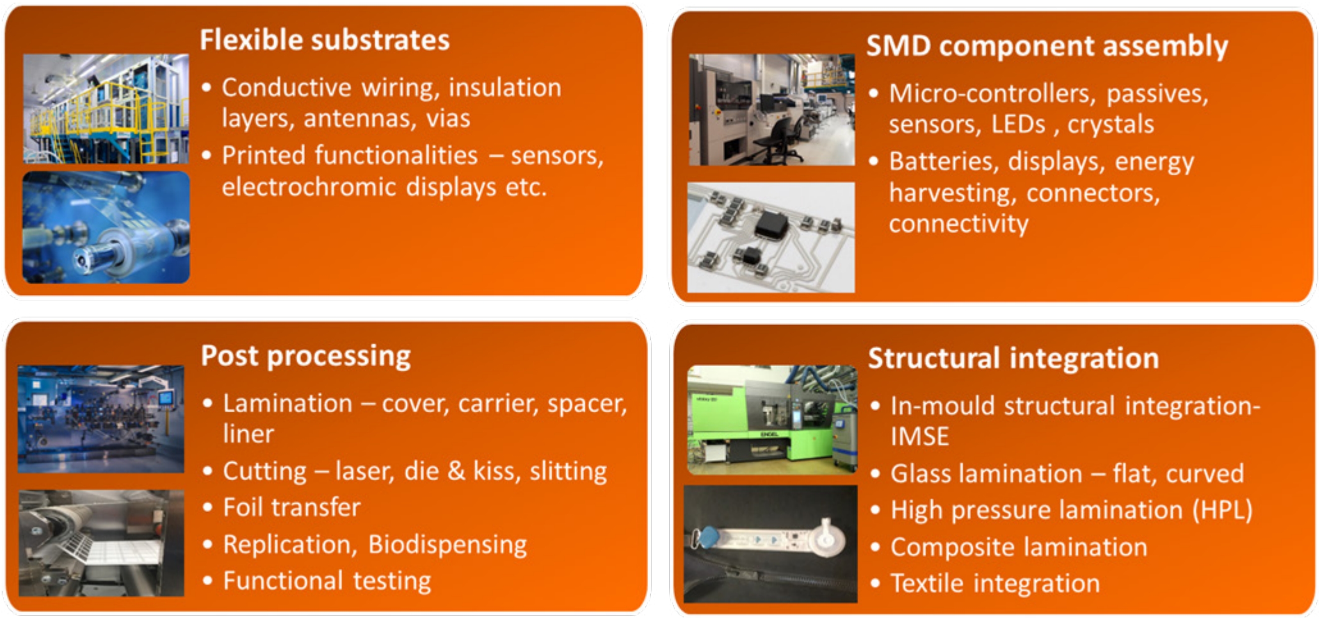

Figure 3.3.1. Hybrid Integration manufacturing concept.

The hybrid integration concept is based on seamless combination of roll-to-roll printing, component assembly, lamination, foil forming, and in-mould-labelling processes. Hybrid in-mould integration technology as part of a product design enables

- Design freedom, new form factors
- Large-area scalability
- Lower product complexity
- Compact, lightweight designs
- Seamless integration
- A simplified manufacturing value chain
- Environmental benefits by reducing material waste and carbon footprint.

Key functionalities in hybrid in-mould integration are:

- Indicator lights, displays
- Backlights
- Capacitive touch switches
- Optics
- Sensors
- Power sources and storage
- Si-based microprocessors, memories, etc.

Potential areas of application for hybrid system integration include:

- Automotive & Aviation interiors
- Medical, healthcare and wearable consumer products, stretchable electronics
- nteractive packaging, point-of-sale and signage
- Smart textiles
- Industrial sensors, agricultural sensing
- Consumer electronics and interior design products

Case examples

In automotive interiors, such as overhead consoles, significant reductions in weight, volume and cabling can be achieved with in-mould integrated, thin form-factor lighting and signage, touch sensors and other electronics elements.

Figure 3.3.2. Hybrid in-mould integrated lighting, signage and proximity sensor product demonstrator. More info: www.tactotek.com

Integration of 3-axis accelerometer, gyroscope, Bluetooth data streaming on flexible and comfortable substrate would enable realization of ultra-compact stick-on wireless sensor patch for unobtrusive motion sensing and recording.

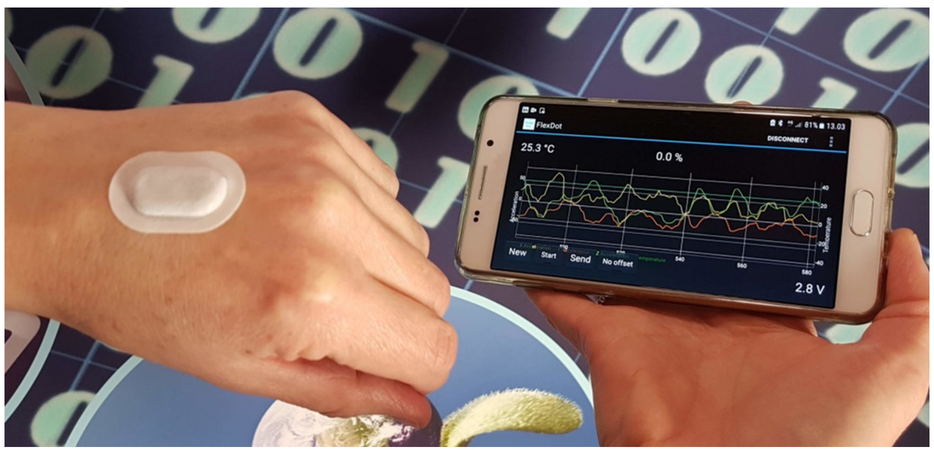

Figure 3.3.3. FlexDot ultra-compact stick-on wireless sensor patch.

Offcode, VTT and Ynvisible have created NFC powered visual user interface demonstrator in the Printocent community. The demonstrator shows in a simple manner the benefits of flexible printed electronics and its capabilities to be integrated in different everyday items and objects.

Figure 3.3.4. NFC powered visual user interface.

Textile electronics integration is demonstrated by a LED display integrated on a stretchable TPU substrate with printed wiring and laminated with textile. The display consists of 5*17 RGB LED matrix with 10 mm pitch.

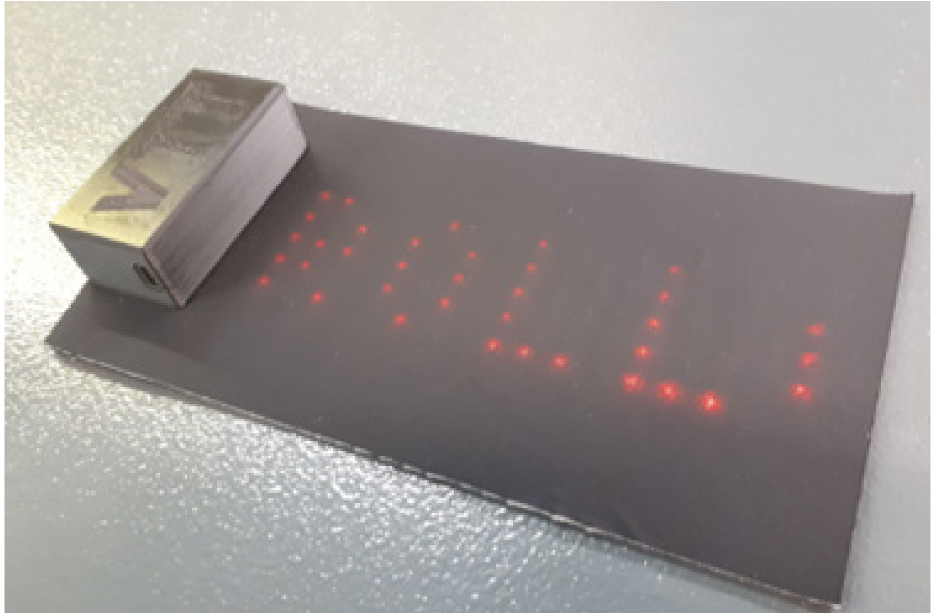

Figure 3.3.5. Textile integrated RGB-LED module.

Fully printed OPV integrated into a wristband that works in parallel to the battery source to prolong the longevity of the energy supply. With the wristband's display providing feedback of the OPV's operational power level. Bluetooth connection is established for data reading in a mobile phone.

Figure 3.3.6. Energy harvesting wristband.

Fully roll-to-roll (R2R) manufactured microfluidic device (Ultrasensitive plasmonic device for early cancer diagnosis.) with integrated fluid actuation, printed biomolecules and printed electrodes for high-volume, low-cost manufacturing.

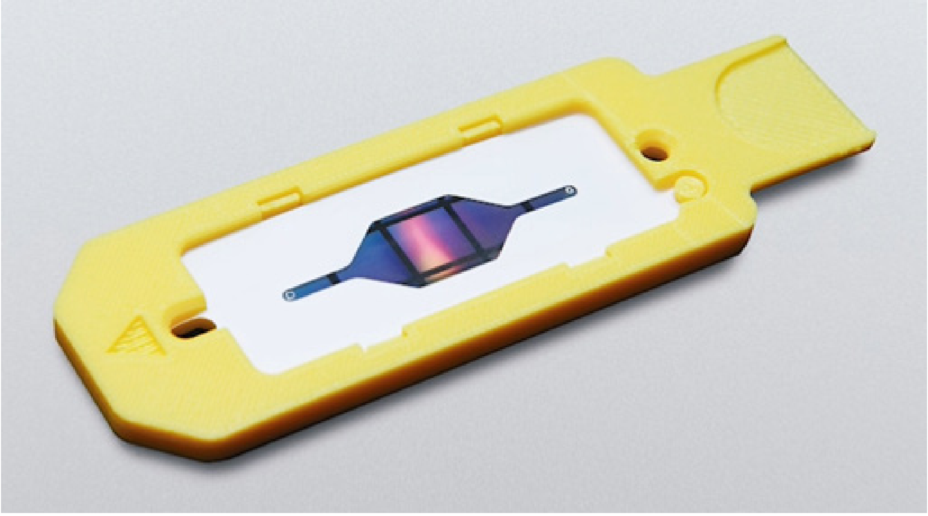

Figure 3.3.7. Ultrasensitive Plasmonic device

A wearable, adhesive-free, smartwatch-compatible sweat-rate sensing device made with simple prototyping techniques by integrating a reusable 3D printed sweat collector with a fluidic layer.

Figure 3.3.8. Tape-free 3D printed wearable sweat rate monitoring device

PrintoCent

3.4 Large-area assembly and bonding

Introduction

Roll-to-roll (R2R) printing enables additive manufacturing of electrical circuits on flexible substrates at high volumes. Further, incorporating large area printed electronics with surface mount devices (SMDs) results in flexible hybrid electronics (FHE) with improved performance and functionality. The subsequent assembly and bonding processes can be performed either S2S or R2R in format to achieve heterogeneous integration over large areas.

Assembly and bonding lines

PrintoCent pilot factory includes assembly and bonding lines for developing and pilot-manufacturing FHE applications by using surface mounting technology (SMT). Mounting component-on-flex, chip-on-flex and flex-on-flex with various interconnection technologies create the framework for applications exploiting large are with high performance. PrintoCent pilot factory operates three unique lines (MECHA, LAKO and EVO) illustrated in Figure 3.4.1 and the following chapters describe the main processes available with these lines.

Figure 3.4.1. Assembly lines MECHA, LAKO and EVO.

Interconnection technologies

One of the main design parameters in FHE integration is choice of interconnection technology. The available options include adhesive bonding technology and low temperature soldering. The consideration regarding bonding method should cover the following aspects:

- temperature tolerance of substrate and other sensitive devices
- material of printed circuitry
- number and type of components
- component package
- component pitch

The first option to interconnect surface mounted devices (SMDs) on flexible printed circuit boards is isotropic conductive adhesive (ICA). The adhesive is conductive to all XYZ-directions and thus requires individual dots or area over the footprint of flex circuitry. Applying ICA can be done with a dispensing robot by using a screw, needle or jet valve, or by screen/stencil printing. These methods enable feature sizes down to 200µm allowing pitches of 400-450µm in components to be assembled. A typical choice for ICA material is a silver-based epoxy requiring 100-120°C curing temperature for 15-30 minutes. Also room-temperature curable ICAs are available, but their curing times increase to hours or a day. ICA process is the backbone in large-area FHE with wide component spectrum. The process is available with all PrintoCent pilot factory assembly and bonding lines (MECHA, LAKO and EVO).

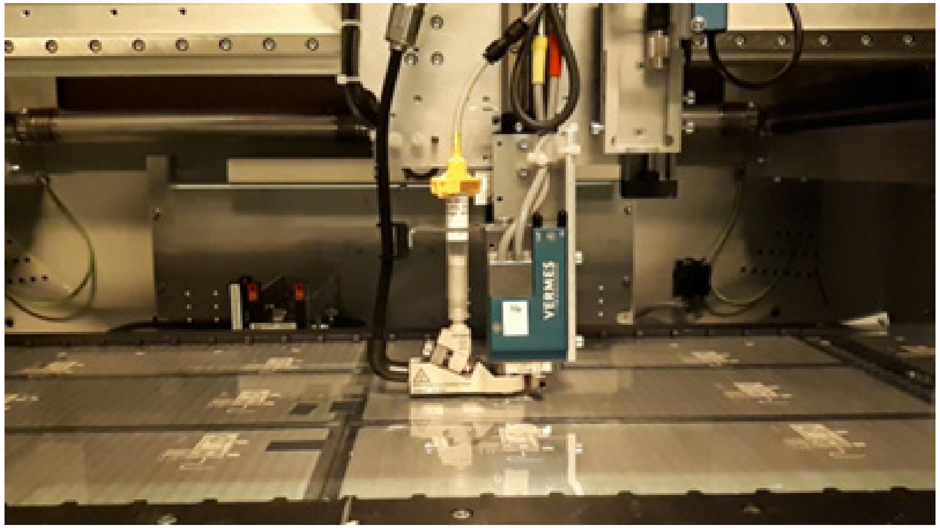

Figure 3.4.2. Dispensing ICA with a jet valve on printed circuitry

Electrical interconnections established by ICA shall be incorporated with non-conductive adhesive (NCA) to enhance mechanical bonding between component and substrate. The alternative options for this purpose include side-bonding or edge-bonding after component assembly or underfilling a component before or after assembly. The main application method for NCA is dispensing with screw or needle valve due to non-planar surface. The available material options include heat and UV curable adhesives. Curing profile with heat curable NCAs should adhere temperature and time used with ICA. In case of UV curing, intensities up to hundreds of mW/cm2 are usually required and illumination all over adhesive without shadow areas is a necessity. NCA process is available with all PrintoCent pilot factory assembly and bonding lines (MECHA, LAKO and EVO).

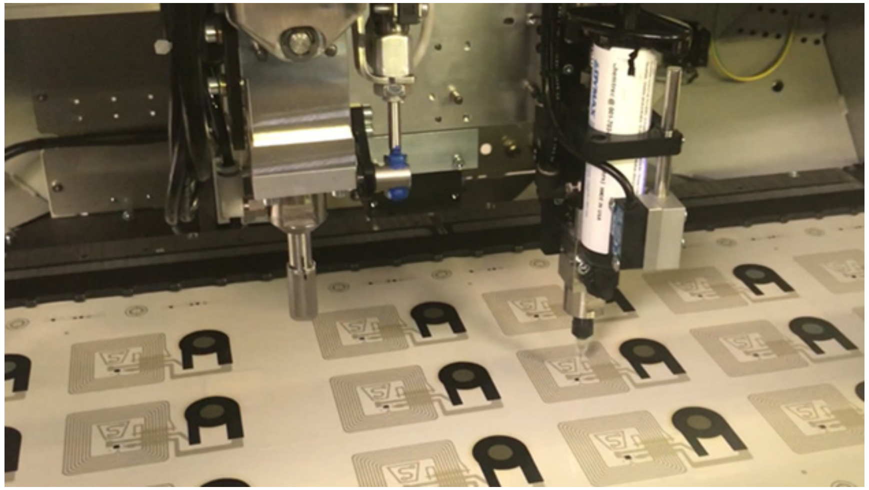

Figure 3.4.3. Dispensing NCA with a needle valve around chips.

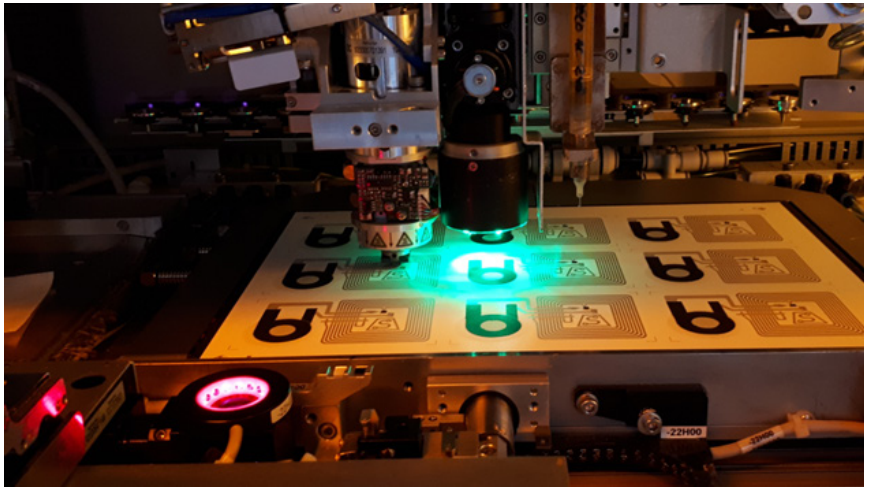

Figure 3.4.4. Thermode curing an ACA interconnection.

In case of components with short distances between interconnection areas, or high pitch, anisotropic conductive adhesive (ACA) is a feasible option. Concentration of conductive particles in such an adhesive is low and thus the material is conductive only in Z-direction. This characteristic enables continuous adhesive area over several pads at printed footprint. Thus, the method allows bonding components with pitch down to tens of micrometers. Applying ACA is usually done by dispensing. The bonding process is performed with a special tool, thermode, providing sufficient heat and pressure on a component. Representative curing parameters are 180°C and 200g, for instance. The tooling might be accompanied by heating plate (60°C as an example) below the bonding area. Due to higher adhesive volume over the footprint, ACA process doesn't mandate additional mechanical support for the component integration. The process is available with PrintoCent pilot factory EVO bonding machine.

Yet alternative interconnection technology in flexible electronics is low temperature soldering. This bonding method enables solid electrical contacts between SMDs and PCB by various solder alloys but requires high temperature tolerance and preferably bulk metal conductors. Possible solder alloys for FHE include SnBiAg, which requires about 180°C temperature in reflow profile. Moreover, Indium-based solder alloys feature lower melting temperatures. Solder paste is typically applied by stencil printing but dispensing is also applicable. The process is available with PrintoCent pilot factory MECHA and LAKO assembly lines.

Component assembly

Pick-and-place machines perform component integration by using automated assembly heads and special tools. In MECHA and LAKO assembly lines the main operation mode is tape feeding of SMDs to the machine. The assembly heads equipped with multiple nozzles can handle components from 0402 size (metric) up to 74 x 74 mm. The maximum throughput is 27000 components per hour (CPH) with the smallest nozzles. MECHA assembly line features also tray option and stick feeding for odd-shaped and custom devices. EVO assembly machine provides more versatile pick-up options, and components can be pick-and-placed from wafer, waffle pack, gel pack and tray. EVO machine has the capability to handle bare die chips and features flip-chip process.

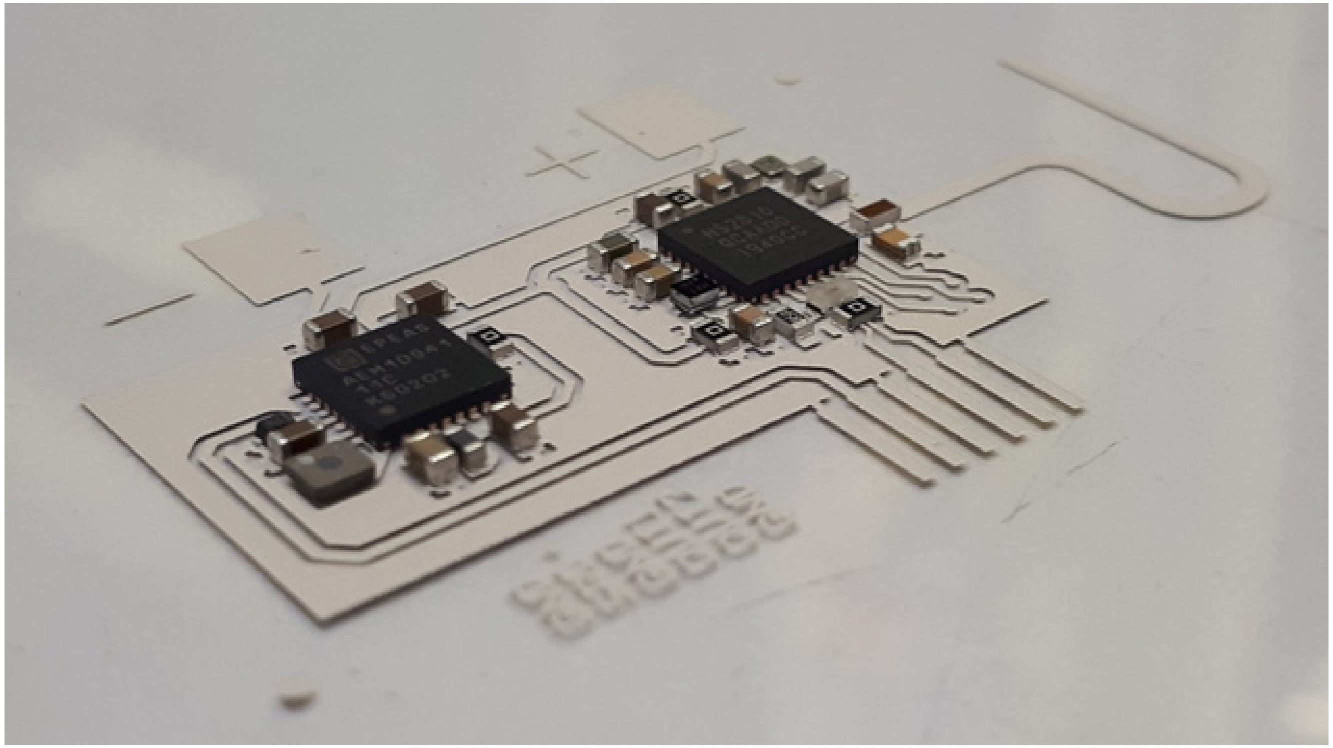

Figure 3.4.5. Multicomponent assembly on flexible substrate.

Fiducials

To guarantee successful assembly and bonding process, the use of substrate, module and component level fiducial marks are recommended. The marks are created during the same manufacturing process as conductive wiring and component footprints. These shapes are recognized by the camera systems of assembly lines and used for the global and local positioning. The closer fiducial marks are to component footprints, the more accurate assembly process will be. As an example, the design rules and recommended fiducials to be included in the layout for EVO machine contain

- Substrate marks for each work sheet
- Place 2 x 2 mm sized cross shaped (+) fiducials into the corners of the substrate (good contrast and edge quality important)
- Same fiducials are recommended also in the corner of each module. However, differentiation from the substrate fiducials recommended such as additional dot for easier programming
- Component specific squares are highly recommended for every component bonding position needing special accuracy in assembly, such as bare die flip chip components. 2 - 4 points recommended for centralized definition, such as in Figure 6. The optimum size is 2 x 2 mm (+/-0.4 mm). Avoid any other same shape and size marks within 15 mm area around the fiducial mark. The optimum distance from the edge of the chip component to the mark is 1 mm when chip size is less than 1 mm and 2 mm when chip size is larger than 1 mm
- Clearance area without components in the layout needed for the substrate indexing clamp feeder. The clearance area needs to be open throughout the total web width, clearance width recommended 100 mm, absolute minimum 5 mm

Substrate handling

MECHA assembly line is dedicated to automated sheet-based processing over a large area. The line utilizes special carriers for handling up to 500 x 500 mm flexible sheets for the needed process in FHE integration tasks. LAKO assembly line features R2R operation mode with capability to handle continuous webs with 300 mm width. However, assembly processes are performed in stop-and-go mode over 410 x 290 mm sized working areas. EVO assembly machine is a standalone unit and substrate handling with this machine is performed manually. The maximum working area with EVO is 300 x 200 mm.

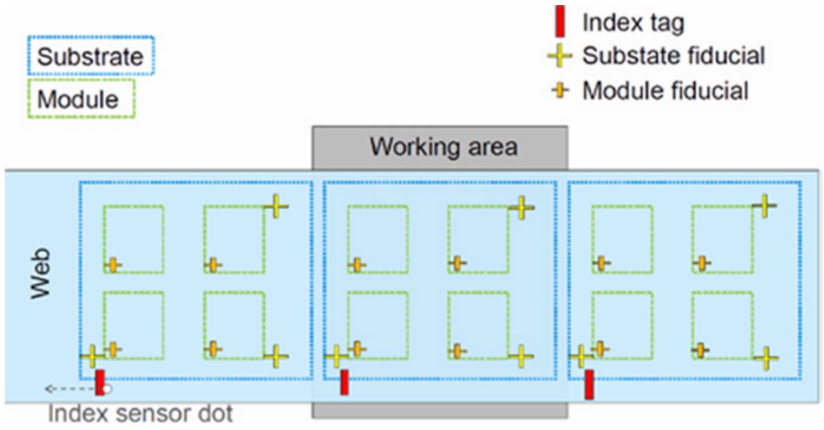

Figure 3.4.6. Recommended index tags and fiducials used with R2R EVO 2200 assembly and bonding line.

3.5 Roll-to-roll postprocessing and converting

Roll-to-roll (R2R) converting is a continuous manufacturing process where flexible materials — such as plastics, metals, textiles or papers—are unwound from a roll, processed through various stages (e.g., coating, printing, laminating), and rewound into a finished roll. This method enables high-throughput production with consistent quality and is widely used in industries like packaging, electronics, energy, and healthcare. The efficiency and scalability of R2R systems make them ideal for producing large volumes of functional materials, including flexible circuits, solar cells, and printed sensors.

Web handling refers to the control and movement of flexible materials. Key aspects include tension control, which ensures consistent force across the web to prevent wrinkles or breaks; web guiding, which maintains proper alignment; and speed synchronization, which coordinates the motion of rollers and processing units. Effective web handling is critical for maintaining product quality, minimizing waste, and enabling high-speed, continuous production. An advanced automatic registration system ensures precise alignment of patterns and layers during high-speed operation. This capability is critical for maintaining print-to-cut accuracy and minimizing waste in complex designs.

Figure 3.5.1. DELTA R2R converting line

Modular converting unit design

The system incorporates six interchangeable converting unit slots, enabling rapid reconfiguration for diverse processes with the maximum web width of 340 mm:

- Die-cutting and kiss-cutting (top and bottom): For precise cutting of substrates and adhesive layers.
- Lamination: Facilitates bonding of multiple layers for composite structures.
- Slitting: Ensures accurate width reduction and edge quality.

This modular approach supports customization for different product requirements and minimizes downtime during changeovers.

Equipped with six winders, the system enables simultaneous lamination of up to four webs. This feature is essential for producing multilayer constructions such as flexible circuits, barrier films, and sensor assemblies. Independent tension control ensures uniform bonding and dimensional stability across all webs.

Laser processing integration

Laser technology allows intricate patterning without mechanical stress, making it ideal for precision applications in electronics and medical devices.

A CO_2 laser unit provides non-contact cutting and engraving with:

- Maximum processing area: 280 × 280 mm2
- Wavelength: 10.6µm

A pulsed fiber laser provides laser marking solutions with

- Maximum processing area: 110 × 100 mm2
- Wavelength: 1060-1080 nm
- Web speed: up to 5 m/min

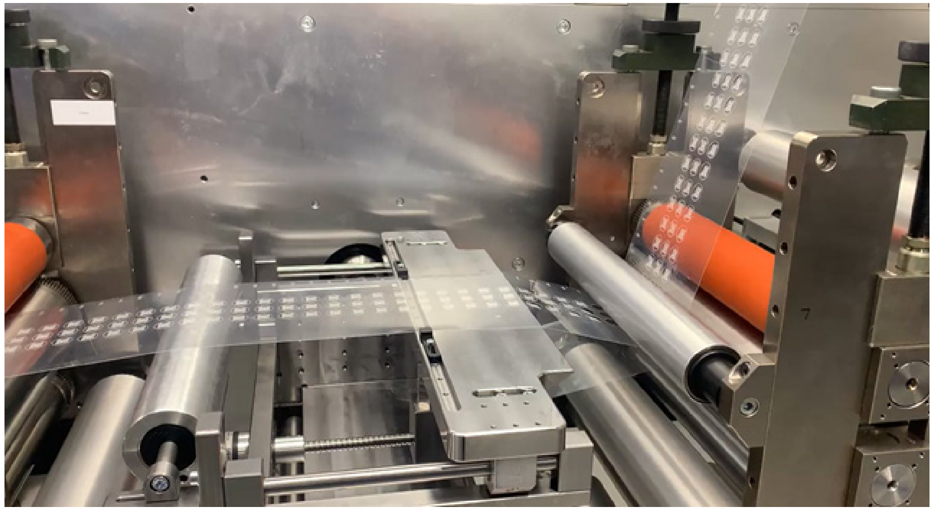

Figure 3.5.2. Laser marking of QR codes.

Figure 3.5.3. Mass-producible diagnostics platform

Robotic automation

Two industrial robot arms are integrated for automated material handling, tool exchange between converting stations and loading/unloading of substrates. Robotic automation reduces manual intervention, enhances quality consistency, and supports continuous operation in high-mix production environments. It is fully synchronized with the converting line and laser for coordinated operations with repeatability of ± 0.01 mm. Operation modes includes: Tray-to-Web and Web-to-Tray pick-and-place and multi-indexing of web-to-web for precise odd shape component placement.

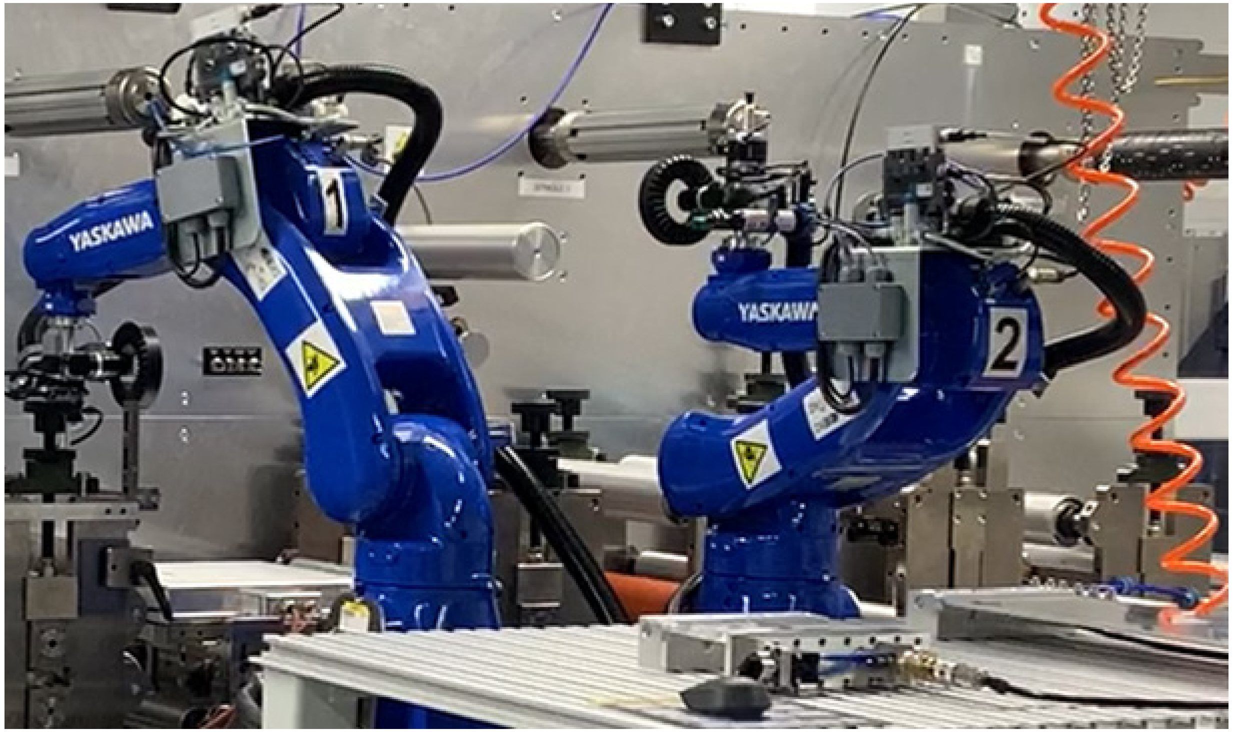

Figure 3.5.4. Robotic arms

The list of converting tools

- Continuous flow dispensers
- Hotplate pressing tool
- Ultrasonic welder
- Soldering iron station
- Flexography printing unit
- Area scan camera inspection
- UV lamp and fiber curing tools
- Rotary Hot Stamp System/Hot Roller
- Vacuum heated table
- 13” Shear Slit Module (5 Knives)
- Rotary die cutting
- Dual bullnose system
- Grippers: needle, flat suction cup

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3.6 Cables and connectors for printed electronics

Interconnections for printed electronics

Printed electronics substrates can be connected to flexible or rigid PCB by using both female and male array connectors. Several printing technologies, such as screen printing, inkjet printing and aerosol jet printing can be applied to pattern contact areas for interconnects. Electrically Conductive Adhesives (ECAs) are typically applied to ensure contacting between component contacts and substrate contact pads. ECAs are also applied to ensure reliable permanent interconnections between flex to flex and flex to rigid electronic substrates. Detachable interconnections for printed electronics apply several connector technologies are listed in following chapters.

1. Crimp and Snap Connectors

Two main connector types are commercially available for flexible foil connecting. First type, so called crimp connector, has metallic bars, see Figure 3.6.1. Crimp connector can be applied to connect flexible printed substrate to a rigid PCB, see Figure 3.6.2.

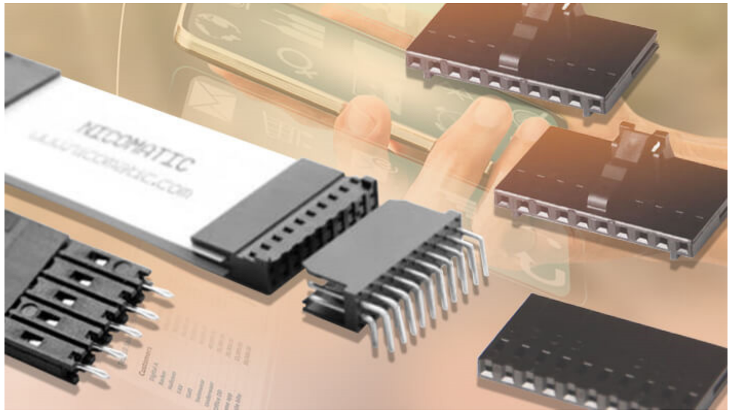


Figure 3.6.1. Examples of crimp connector contacting (Nicomatic)

Figure 3.6.2. Example of crimp connector manual assembly tool (left) and dedicated machine (right) for connector assembly (Nicomatic)

Crimp connector is typically applied to connect operational power and data lines to flex PCB from mother PCB. Crimp connector manufacturers include Nicomatic, SMK corporation, TE Connectivity and Axon' Cable.

In the assembly process the bars are pressed through the foil contacts and twisted parallel to the substrate surface on the opposite side of the flexible substrate. Isotropic Conductive Adhesive (ICA) can be applied to improve conductivity of joints. Non-Conductive Adhesive (NCA) can be applied to increase mechanical reliability of the contact.

A Snap Connector (SC) is a type of electrical connector designed to make electrical connections for data and power lines quickly and easily. It can be used to electrically tap into a wire in mid-span without cutting or stripping the wire. Example of Snap Connector is shown in Figure 3.6.3.

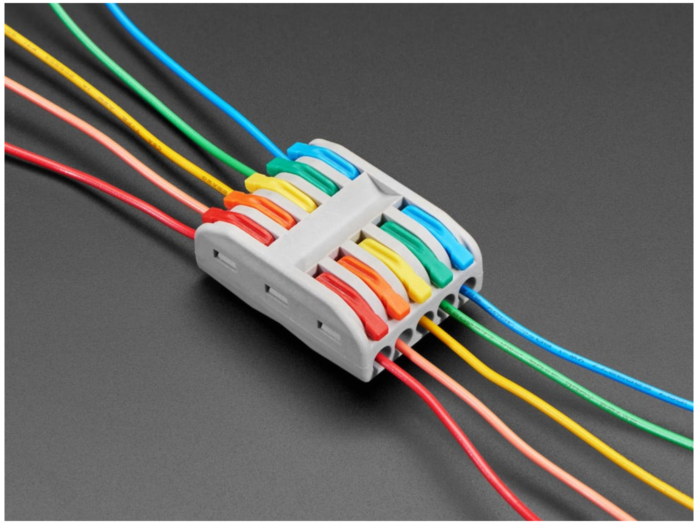


Figure 3.6.3. Example of 5 x 5 type Snap Connector (Adafruit)

One of the most significant features of a Snap Connector is that it is easy to install. It has a spring-loaded mechanism that allows for quick and secure connections without the need for tools or crimping. This makes it a time-saving and cost-effective solution compared to traditional wire connectors.

2. Flexible Flat Connector (FFC) and Flexible Printed Circuit Connector (FPC)

Another main type for interconnections applied with printed electronics is FFC/FPC applied typically on thin and flexible printed substrate PCBs. Molex, Hirose Electric, Würth and Amphenol are main manufacturers for FFCs. One example of FFC is shown in Figure 3.6.4.

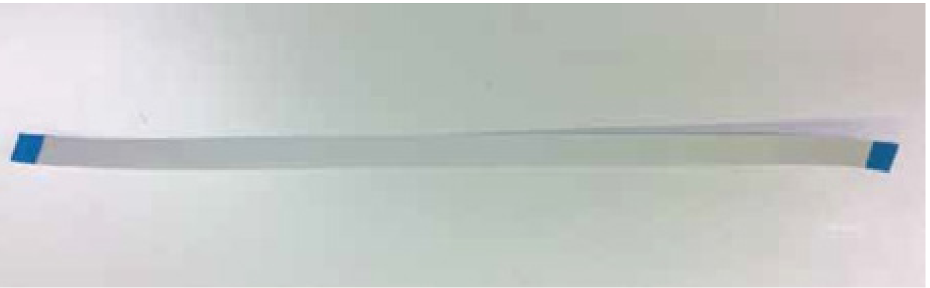


Figure 3.6.4. Flat Flex Connector (FFC) example

FFC connectors can be assembled on printed flexible substrates using ICA on silver printed tracks or solder bonding on copper printed tracks. In applied connector assembly process compatibility with substrate, printed material and adhesive/solder material need to be achieved to guarantee functionality and reliability of system. As an example, PET substrate with copper paste/ink printed circuitry require applying of low temperature soldering process and applicable material in component bonding process. This is due to oxidation layer developing on top of printed copper layer. Copper paste/ink oxidation of printed surface layer will compromise joint reliability, if hermetic sealing of connector contacts to substrate contacts is not achieved in applied bonding process. Hermetic sealing in bonding process can typically be achieved using soldering process, which generates intermetallic compound between component contacts and printed layer contact pads.

When applying component assembly on silver ink/paste printed substrates, oxidation is not causing contacting or reliability challenges because printed silver ink/paste surface layer retains high conductivity even when oxidized.

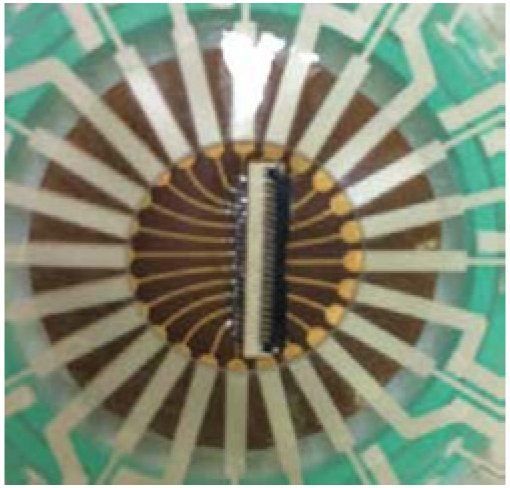


Figure 3.6.5. An example of a FFC contacting on flexible printed substrate

3. Zero Insertion Force (ZIF) connectors

Zero Insertion Force (ZIF) connectors are commonly used for flex-to-flex and flex-to-rigid connections. Manufactures like Hirose, Molex and TE Connectivity offer compact, multi-pin connectors with locking mechanics. Connectors support high-frequency signals (up to 15 GHz) and are compatible with thin substrates like paper or polymer films.

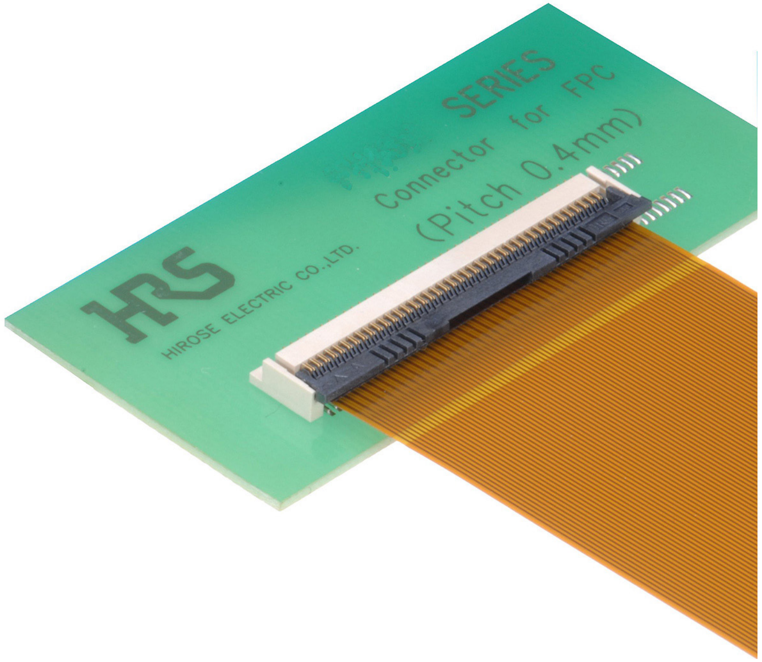


Figure 3.6.6. Zero Insertion Force (ZIF) connector contacting to flat cable (Hirose Electric)

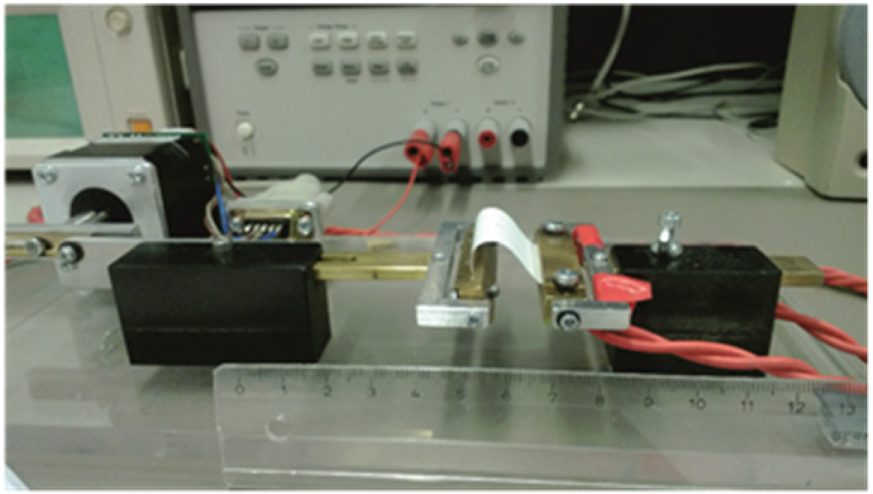
4

PROCESS CONTROL AND QUALITY CONTROL, TESTING

4.1 Reliability testing

Introduction

Conformance to specifications over time is based on reliability in any electronic design. General characteristics of a reliable product include not only fewer field failures or lower risk of recall, but also better design that are easier to manufacture, less material scrap and product rework. In printed electronics, established reliability test methods from conventional electronics may give misleading results because they are developed for different structures and materials, or are based on irrelevant accelerating factors. Thus, there is a need for new test methods which take relevant stresses into consideration. These are typically realized by custom solutions but specific standards regarding reliability testing of printed electronics are also under development.



Bending tests

A characteristic feature in printed electronics is flexible substrates allowing curved or non-planar structures. However, this attribute exposes flexible electronic applications to mechanical stresses and may lead to reliability issues. There are various test setups to assess bending reliability of printed electronics, but Figure 4.1.1 shows two possible approaches based on stepper motors and dedicated mechanics. In the first setup, moving holder exposes the sample under test to free bending with radius below 10 mm. The second test equipment rolls the sample under test over a cylinder. Bending radius vary from 15 to 40 mm within this setup. Both in-house built test systems feature online electrical measurements for detailed analysis.

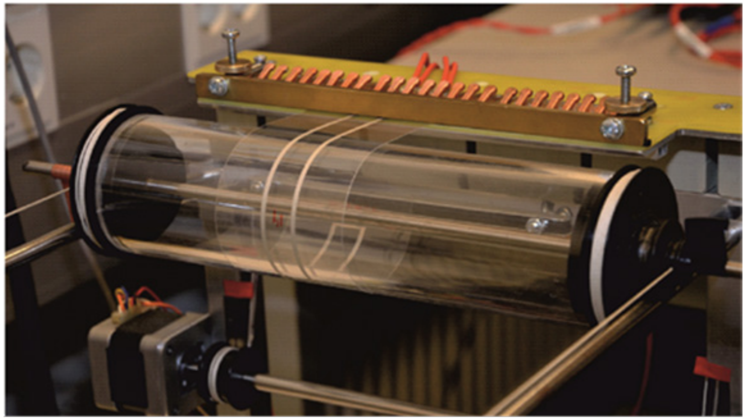


Figure 4.1.1. Test equipment for free bending and rolling tests.

Stretching tests

Stretchable substrates enable free-form and multidimensional use conditions for printed and hybrid electronics. One-dimensional linear elongation is the baseline for stretching reliability assessment but may be accompanied by torsional movement to mimic realistic operational environment of systems on elastic substrates. Available test routines for stretching test include maximum elongation and cyclic stretching. An important feature in stretching test setups includes online electrical characterization, which enables thorough analysis on electrical properties under mechanical stresses, including changes over a cycle or stretch. The key issue in reliability of stretchable electronics with component integration is found to be close to the rigid-stretch interface at printed structures.

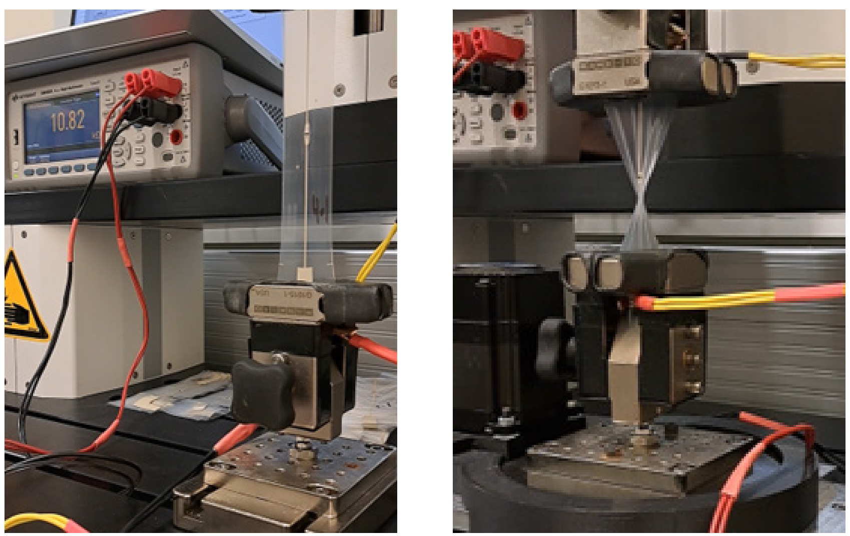


Figure 4.1.2. Test setups for linear elongation and combined stretching and torsion.

Adhesion tests

Adhesion between separate layers is a critical factor in multilayer laminates in printed electronics. Adhesion properties can be quantified by motorized test stand according to standardized routines for 25mm wide sample strips. The test procedure features constant movement at pre-defined velocity to peel layers apart from each other while recording force with a gauge. The most common peel strength test setups include both 90 degree and 180 degree methods.

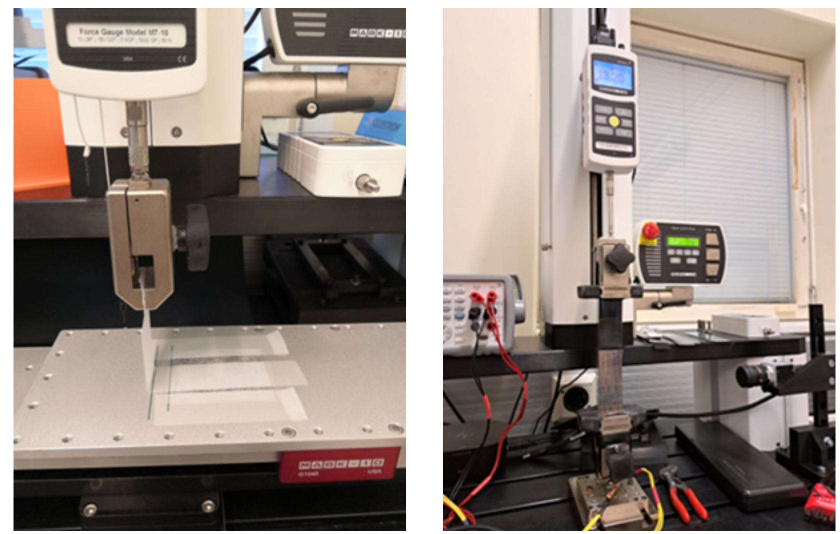


Figure 4.1.3. 90 and 180 degree peel strength tests.

Bonding strength tests

From mechanical durability and reliability perspectives, adequate bonding strength of rigid SMDs on flexible substrates is a necessity. Pull-test setup enables quantification of adhesive bonding strength and to optimize process parameters in printed and hybrid assemblies. The setup includes grips to grab over component under test and force gauge to record the needed force to detach this component from a substrate under upwards-going motion perpendicular to substrate. The corresponding setup is shear test but there the movement is directed parallel to substrate. The destructive test method features a shear jig to push an assembled component from its footprint while the required force is recorded.

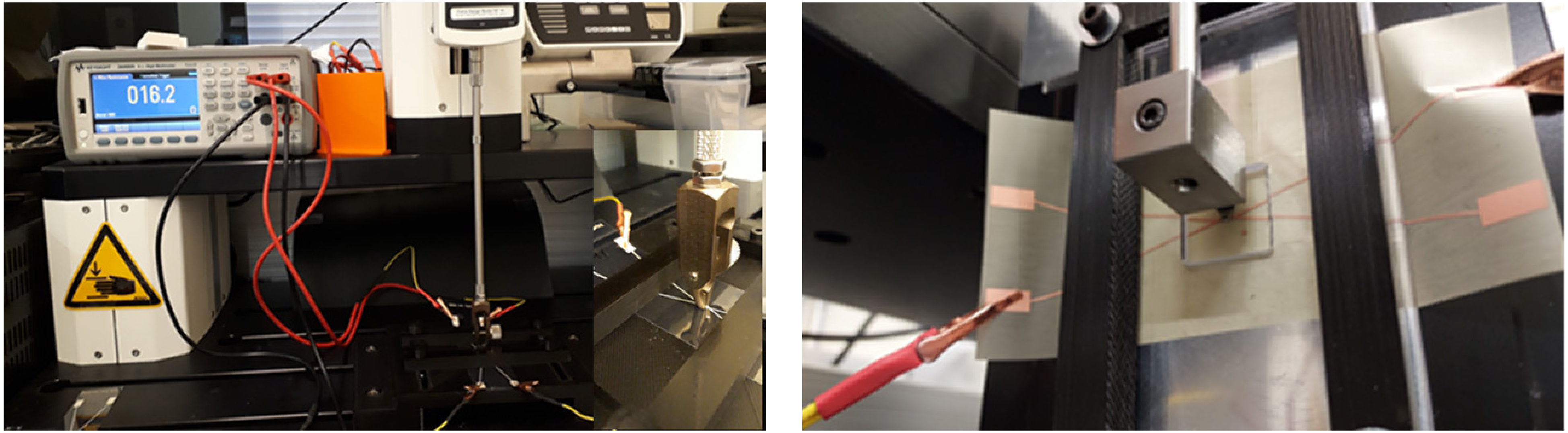


Figure 4.1.4. Pull and shear test to assess bonding strength.

Environmental tests

Accelerated lifetime testing at elevated temperatures or under changing conditions is a well-known reliability test method and feasible also in printed and flexible electronics. However, test profiles with printed or organic electronics shall be set according to relevant operating conditions and considering the materials used in devices under test. The available environmental tests include temperature cycling, temperature/humidity test and accelerated weathering including sunlight-relevant light exposure.

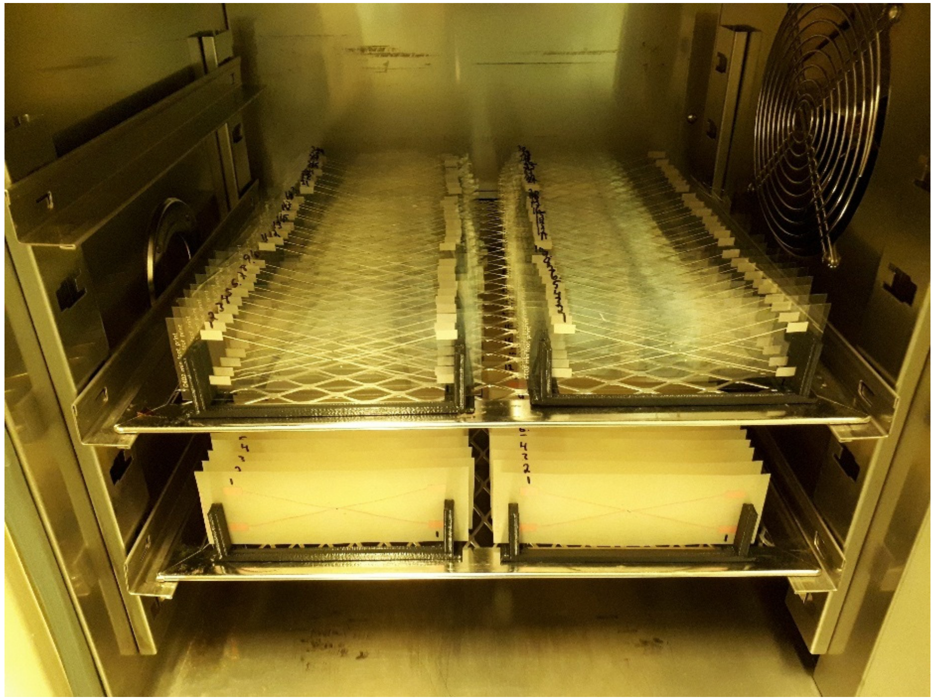


Figure 4.1.5. Test samples placed in an environmental chamber.

Publications

T.Happonen, M. Paakkolanvaara, Stretching reliability of SMD electronics integrated on elastic fabric, IEEE ETEXTILE 2024, DOI: 10.23919/E-Textiles63767.2024.10914309

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T.Happonen "Reliability studies on printed conductors on flexible substrates under cyclic bending" http://jultika.oulu.fi/Record/isbn978-952-62-1242-5

5

PRINTED COMPONENTS

5.1 Printed Conductors

Materials, Methods, and Key Characteristics

Printed conductors form the foundation of printed electronics, enabling diverse applications such as antennas (e.g., RFID tags), wiring, electrodes, user interfaces, and keyboards. These conductors are created using various printing methods, with rotary screen printing being the most common due to its ability to produce thick, highly conductive layers with low sheet resistance. For applications that require thinner layers, such as in stacked electronic structures, flexographic or gravure printing offers an alternative with reduced material costs.

Circuit board construction is widely used in printed electronics, facilitating the integration of passive components like resistors, capacitors, and inductors in the same manufacturing process. On-demand methods such as inkjet printing allow for point-to-point connections, particularly useful for short traces or last-step modifications.

Printed conductors are typically made from:

- Metal particles — Primarily silver, but copper, gold, or aluminum are also used, available in micro/nanoparticle inks or as nanowires.
- Particle-free metal inks — Such as ionic silver solutions.
- Carbon-based materials — Including graphite and graphene, which offer lower costs and good stability but reduced conductivity.
- Conductive polymers — Used for specialized applications.

Silver-based metal inks are the most common choice for high conductivity, though cost can become an issue in designs with dense conductor patterns. Sometimes, blends of metal and carbon are used to balance performance and affordability.

Printed conductors typically achieve sheet resistances from a few to several tens of milliohms per square for layers thicker than 5 µm. Thinner layers, such as those produced by flexography, yield higher resistance values. While printed conductors cannot match the low resistivity of bulk metals (e.g., silver's ~1.6×10^{-8} Ω cm), advanced formulations using nanoparticle inks can approach $3–9\times10^{-6}$ Ω cm.

Several factors influence the final conductivity, including ink composition, layer thickness, curing temperature, process speed, printing pressure, and substrate compatibility. Post-processing, such as heating or calendaring (applying heat and pressure), can further improve conductivity by enhancing particle contact.

Designers should be aware of practical limitations: printed conductors may have higher resistance and less precise detailing compared to etched metals, and issues such as silver migration or copper oxidation require careful encapsulation. Soldering to printed silver is difficult, often necessitating more expensive adhesives or specialized assembly methods.

For optimal design, recommendations exist for conductor widths and spacings, and printed insulators are required wherever wiring crosses occur. Overall, the choice between printed and traditional (etched) conductors depends on the desired balance of cost, performance, and application-specific requirements.

Accuracy control for roll and sheet processed printed electronics on flexible plastic substrates, Välimäki, M. K., Jansson, E., Von Morgen, V. J. J., Ylikunnari, M., Väisänen, K. L., Ontero, P., Kehusmaa, M., Korhonen, P. & Kraft, T. M., Apr 2022, International Journal of Advanced Manufacturing Technology. 119, 9-10, p. 6255-6273. https://doi.org/10.1007/s00170-022-08717-z

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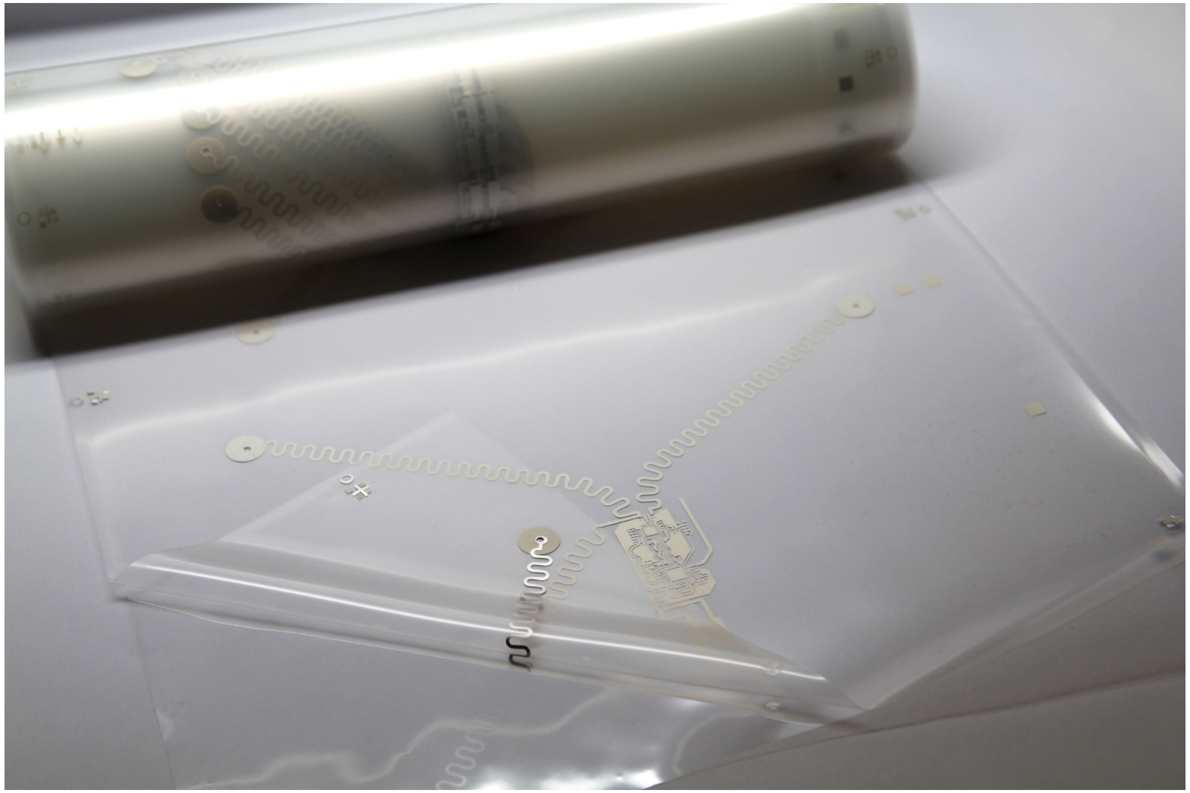

Table 5.1.1. Design rules for VTT pilot printing

	SILVER CONDUCTOR DESIGN RULES FOR VTT R2R		
	Design Class		
	Recommended	Can be used	For special cases
A, E	500 µm	200 µm	100 µm
B, C	100 µm	80 µm	60 µm
D	1. mm	10 mm	5 mm
F	100 µm	80 µm	60 µm
G1, G3, G4	10 mm	10 mm	5 mm
G2	5 mm	3 mm	2 mm

Where:

A= Minimum conductor line width B= Minimum conductor line spacing
C= Minimum component pad spacing to conductor line
D= Minimum component pad spacing to module
E= Minimum component pad size
F= Minimum component pad spacing
G= Minimum conductor line or component pad spacing to:
G1= WEB edge
G2= repeat length edge
G3= die cutting edge
G4= slit edge

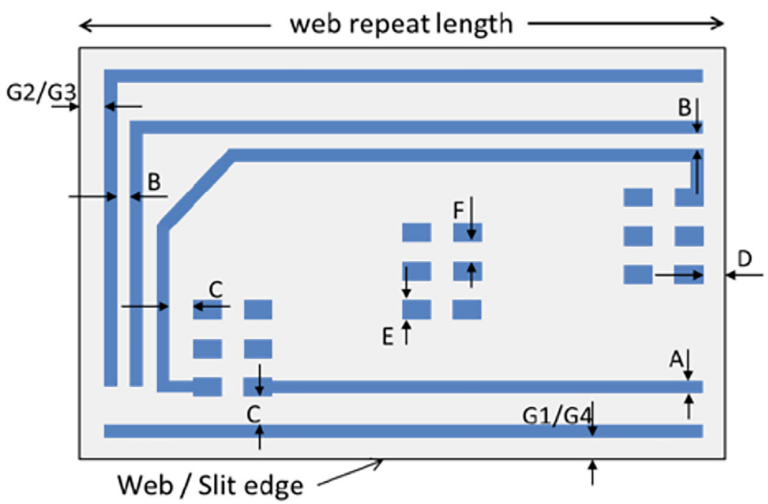

Figure 5.1.1. Printed silver connectors on TPU

5.2 Flexible Metallic Conductors

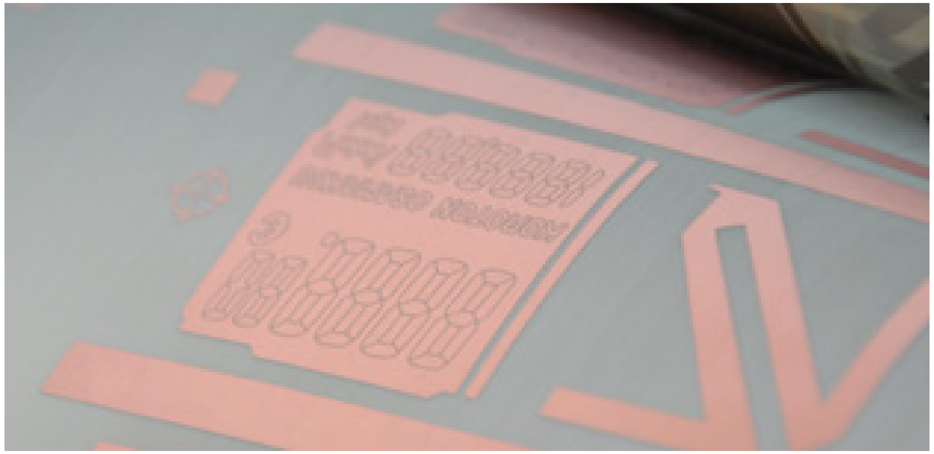

Figure 5.2.1. Screen printed copper circuit

Introduction

The most common method of manufacturing metallic conductor circuits is based on a metal laminate, which is patterned and etched. The circuit pattern can be created by various printing methods: screen, flexo, gravure or ink-jet and also using photolithographic method for very fine lines. After pattern printing the circuit is etched and the resist stripped off. Additional conductive polymer layers can be printed on top of the copper circuit to form multilayer structures.

In Flexible Printed Circuits (FPC), polyimide (PI) is widely used as a substrate due to its high temperature resistance. This is only needed if high temperature processes like reflow or sintering are used for component assembly. In PrintedElectronic applications polyimide is often replaced by polyester (PET) and other low temperature thermoplastic substrates. PET is mainly used for lower price but also for other good mechanical and electrical properties. Due to its low glass transition temperature, standard soldering process cannot be used and alternative joining methods like, SnBi-solder, isotropic and anisotropic adhesives as well as crimping must be used instead.

Metallic conductors have better conductivity and price performance than directly printed tracks, especially when circuit covers more than 8% with silver paste and more than 20% with copper paste. All process residues can be recycled. As process temperatures are kept below 100 °C, very large areas can be produced with high accuracy. This feature emphasizes the price performance of metallic circuits over conductive polymer circuits where high curing temperatures cause considerable shrinkage.

Substrate structures

Aluminium is used in applications where weight and low cost are more critical than maximum conductivity.

Copper is the ideal conductor metal for high-power applications, high-frequency circuits and where performance is paramount.

With either material laminates are mainly 3-layer types with adhesive between conductive metal layer and substrate. Usually Al-layer is 9 or 18 um and copper-layer is from 12um to 70um (1/3 oz to 2 oz). PET layer thickness is typically between 23um to 125um.

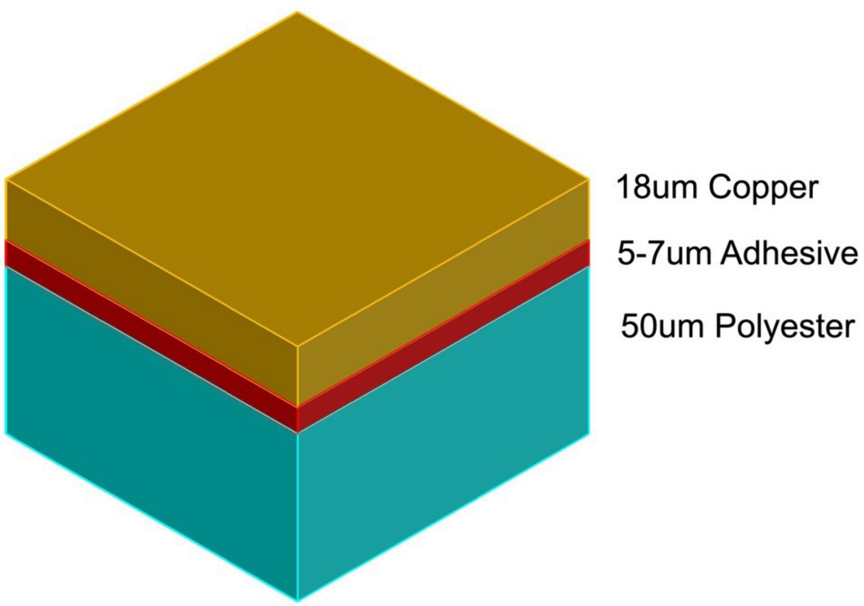

Figure 5.2.2. Example build-up of 3-layer Cu/PET -laminate

There are two types of copper foils
- electrodeposited (ED)
- Rolled and Annealed (RA)

RA copper is used for a higher flexural life, but it also has a higher price.

Both copper types are used on polyimide (PI) substrates. Due to the higher price of PI, typical thickness is 25 um or lower. PI laminate can be 2-layer, which means that copper is directly casted or sputtered on PI substrate. 2-layer material is used in Chip on Film circuits due to its better accuracy and bonding characteristics.

There are also special substrates like PEN, PEEK, PC, TPU and special metals like German Silver, which can be used when specific features are required.

In special applications, it is also possible to transfer etched circuits to substrate materials which would not normally withstand processing. For example, an etched copper circuit can be transferred to a paper substrate, thereby achieving a highly recyclable circuit structure.

Pattern developing

Screen printing is the most versatile printing method in developing circuit patterns in low and medium volume applications. Gravure is used on RFID applications where volumes are high. Phototolithographic dry film method is used when line/space is 100 um or below or when production yield requirement is very high. Typical line/space dimensions for Cu/PET circuits are:

Pattern type	Small scale production	Mass production
Printed etch resist	80/80 um	100/100 um
Dry film	50/50 um	60/60 um

Table 5.2.1.

Surface treatment

Aluminium is the most difficult surface to contact due to isolating oxide layer on the top. It cannot be soldered in standard process and Al-oxide prevents a good adhesive joint unless adhesive particles are pressed mechanically through the oxide layer. Crimping is a similar method where conductive layer is pressed mechanically through the oxide layer.

Due to the slow oxidation process, copper can in some cases be contacted without surface treatment, but usually the contact surfaces are protected from oxidation by various methods, for example:

- Immersion gold
- Immersion silver
- Electroplated Ni/Au
- OSP (Organic Solderability Preservative)
- Printed polymer ink (Ag or carbon)

Figure 5.2.3: Immersion silver plated led circuit pads

Printed Conductor Characteristics

Metallic copper has very good conductivity compared to polymer inks. Silver is a better conductor than copper in metallic form but conductivity is only 1/10 compared to copper when silver is mixed with polymer binders.

Metal	Resistance @ 20 °C
Silver	0,0159·10−6 Ωm
Copper	0,0168·10−6 Ωm
Gold	0,024·10−6 Ωm
Aluminium	0,028·10−6 Ωm

Table 5.2.2.

Copper foil has good bendability when the bending radius is more than 6 x foil thickness. With a large bending radius, flex life of 1 million times can be achieved with RA type copper. It can also be embossed, a feature that is useful in making conductive bumps (dimples) on copper pads. The nickel and gold plating must be added after embossing to make the dimple structure more rigid.

Back end processing

1. Adding layers

Low cost multi layer structures can be manufactured by adding polymer layers on top of the printed and etched copper tracks.

A dielectric layer is needed on the copper to make a multi layer structure. Typically the dielectric layer is printed twice to prevent pin holes. Conductive polymer ink is printed over the dielectric layer.

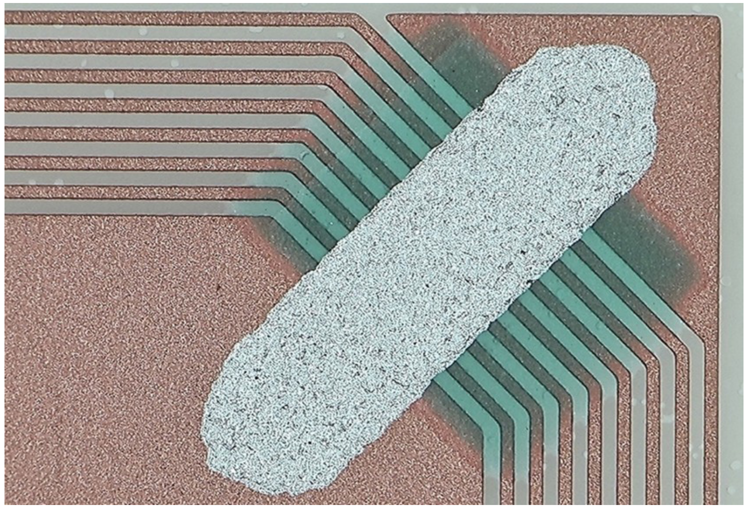

Figure 5.2.4. Silver bridge printed on copper HF antenna to form double layer structure

2. Soldering

As the recommended maximum process temperature for polyester-based circuits is 150 °C, they cannot be soldered in elevated temperatures which are needed in SAC solder process. Thus lower temperature solders like SnBi are used instead. Manual soldering or laser soldering is also possible to minimize the melting area and avoid the substrate warpage.

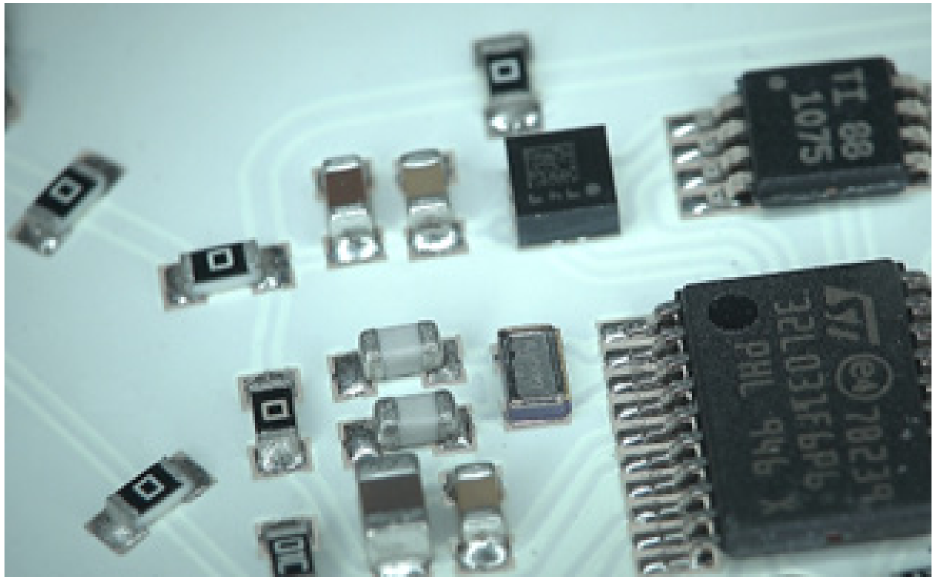

Figure 5.2.5. Low temperature reflow process is used to solder components on Cu/PET smart label circuit.

3. Adhesives (ACP, ACF, ICA)

Adhesive joints are an important connection method for Printed Electronics substrates as adhesives can also be printed roll-to-roll. Bonding temperatures are normally 170-190 °C, but there are also low temperature adhesives on the market. However, standard ACF can be used in low resolution joints as long as the circuit structure is not broken in bonding.

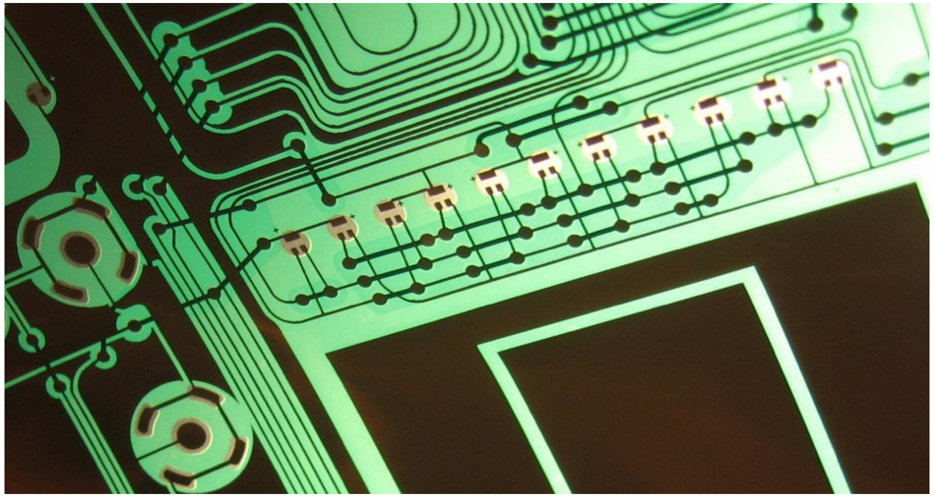

Figure 5.2.6. Two layer membrane circuit using copper and and silver layers. Components are assembled by adhesive.

4. Crimping

Crimping is a very reliable and low cost connection method for metal and polymer tracks.

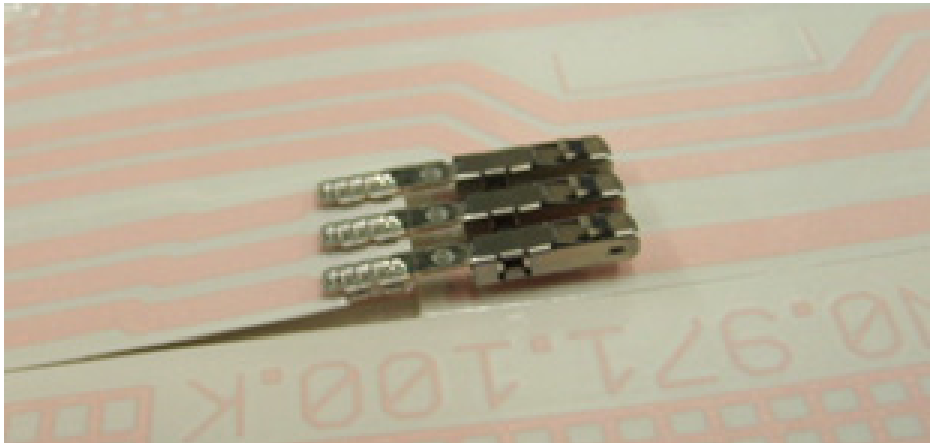

Figure 5.2.7. Crimped connector on 70 um copper track

5.3 Flexible Transparent Conductors

Introduction

Flexible transparent conductors are crucial in printed electronics, powering devices such as solar cells, OLEDs, and touch screens. Traditionally, transparent electrodes are made of indium tin oxide (ITO) on PET films, but ITO's rising cost, brittleness and Indium as CRM limit its use in flexible applications. This has driven the search for new materials and fabrication techniques.

Key Requirements & Applications

Applications differ in their need for transparency and visibility of electrodes:

- Solar cells can tolerate visible electrode grids if overall transparency remains high.
- OLEDs and touch screens require electrodes to be nearly invisible, necessitating extremely thin, often submicron, lines.

Promising Materials and Methods

Conducting Oxides:

- ITO remains standard but is limited by cost and flexibility.
- Alternatives like oxide-metal-oxide (OMO) multilayers (e.g., ZnO, AZO) offer better flexibility and comparable conductivity and can be patterned using similar techniques as ITO.

Conducting Polymers:

- PEDOT:PSS is widely used for its conductivity and transparency but is sensitive to moisture and acidity, which may impact device longevity.
- Carbon-Based Materials:
- Graphene and carbon nanotubes promise excellent conductivity and transparency; however, challenges in processing (aggregation, loss of properties in dispersions) remain unresolved for large-scale use.

Metal Nanowires:

- Silver nanowires can be deposited via solution processing and have shown effectiveness in commercial organic photovoltaics, boosting conductivity and device performance.

Printed and Embedded Grids:

- Direct printing of metallic nanoparticle inks creates grid electrodes but is limited by print resolution (typically >20 µm lines).
- For finer, invisible grids (<10 µm lines), advanced methods like direct writing, reverse offset, or nanoimprinting are being developed.
- Embedding metal lines within substrates minimizes short-circuit risks and is emerging in commercial products (e.g., Vewflex® embedded grids).

Evaporation and Lithography-Based Grids:

- Evaporation methods, though slower, allow for ultra-thin and highly conductive electrodes, suitable for devices where smoothness is critical.
- Roll-to-roll lithography enables sub-micron, invisible electrode grids, important for applications demanding clarity and minimal visual intrusion.

Summary & Outlook

No single method or material meets all requirements for every application. In the near term, alternatives compatible with existing production lines, such as OMO films, are likely to replace ITO. Over time, performance, cost, and sustainability will drive which technologies dominate the market. Continued advancements in materials science and processing methods are paving the way for robust, flexible, and transparent conductors that will power the next generation of electronics.

Self-aligned metal electrodes in fully roll-to-roll processed organic transistors, Vilkman, M., Ruotsalainen, T., Solehmainen, K., Jansson, E. & Hiitola-Keinänen, J., 2016, Electronics. 5, 1, 10 p.

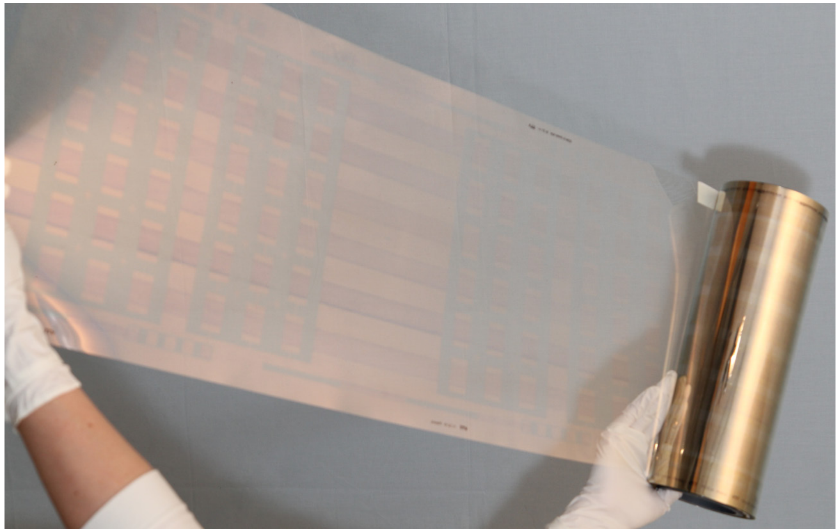

Figure 5.3.1. Printed SnO2 on patterned ITO

5.4 Capacitors, resistors and inductors

Resistors and Capacitors

Printed electronics allow for the creation of basic passive components such as resistors and capacitors by using specialised inks and design techniques. This summary outlines the essential design rules, structures, and performance factors for printed resistors and capacitors.

Design and Structure

Printed Resistors:

- Made by adding a layer of resistive ink to conductive structures.
- Resistivity is set by ink type and resistor size; larger layouts (millimetre scale) improve accuracy and yield.
- Typical thicknesses are in the micron (µm) range and depend on printing method.

Printed Capacitors:

- Simple capacitors use lateral ‘finger’ designs, ideal for picofarad (pF) capacitances.
- For higher capacitances (nF range), use stacked structures: a dielectric layer sandwiched between two electrodes.
- A minimum of 5 µm thick insulation is recommended to prevent shorts; high-quality print and materials are crucial.
- Two layers of dielectric can help avoid failures from pinholes.

Component Characteristics

Performance Factors:

Uniformity and thickness of printed layers greatly affect component performance thus proper manufacturing parameters must be fixed case by case. Resistor inks resistivity typically range from 0.1 Ω·cm to 10 Ω·cm and they are usually carbon-based. Commercial products are often delivered as components where the mixing ratio determines the resistivity.

Printed resistors are sensitive to bending, which can alter resistance by up to 50%. Most changes are reversible after straightening, but some permanent deformation is possible depending on materials. Consequently, these limits lead to practical printed capacitor capacitance range from pF level up to around 50 nF. In special cases µF level could be reached.

Environmental Effects:

Temperature increases can raise the dielectric constant (Ɛr), resulting in up to 40% higher capacitance between 25°C and 75°C. Moisture also affects permittivity, and both temperature and moisture changes must be considered in design.

Printed passive components are highly influenced by material choices, layer quality, and environmental conditions. Careful design and manufacturing are essential to ensure stable, reliable electronic performance.

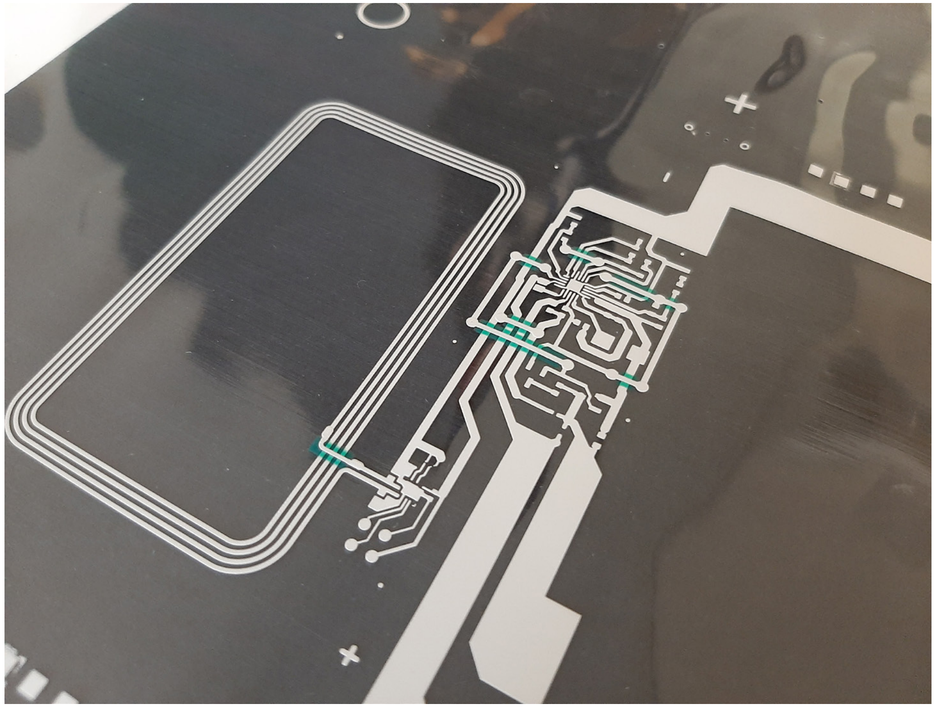

Figure 5.3.1. Printed multilayer circtuiry on plastic substrate

5.5 Printed Antennas

Antennas are essential components in radio and telecommunications, responsible for transmitting and receiving electromagnetic waves. When transmitting, an antenna converts electrical signals from a transmitter into radio waves. When receiving, it collects radio waves and translates them back into electrical signals for the receiver. There are two main types: omnidirectional antennas, which broadcast equally in all horizontal directions, and directional antennas, which focus energy in specific directions.

Printed antennas, manufactured through printing processes, have become popular for their low profile and cost-effectiveness, especially in applications requiring compact designs. They are typically planar (flat), making them suitable for integration with modern electronic devices.

Structure and Types

Printed antennas often use simple structures, like the slot antenna. A basic slot antenna consists of a narrow slot in a conductive surface and a microstrip line on the opposite side of the substrate. By altering the slot's dimensions and microstrip placement, engineers can tune the antenna's bandwidth. Variants include L-shaped slots for size reduction and wide-slot designs with tuning stubs to increase bandwidth. While most printed slot antennas produce linearly polarized waves, more complex structures—like dual-spiral slots—can generate circular polarization used in satellite communications.

Wire antennas, another major type of planar printed antenna, are commonly loop-shaped and serve well at lower frequencies, such as those used in NFC (Near Field Communication).

3D antennas

3D antennas represent a significant advancement in antenna design, leveraging three-dimensional geometries to enhance performance characteristics such as gain, bandwidth, and radiation pattern control. Unlike traditional planar antennas, 3D antennas utilize volumetric structures, enabling more complex current distributions and electromagnetic interactions. 3D antennas are typically constructed using techniques such as:

- Folded structures: Wire or patch elements arranged in three dimensions.
- Conformal geometries: Antennas mounted on curved surfaces (e.g., cylinders, spheres).
- Metamaterials and 3D printing: Allowing intricate designs with tailored electromagnetic properties.

Key benefits of 3D antennas include:

- Enhanced Gain: 3D structures can focus energy more effectively.
- Compact Size: Efficient use of volume allows miniaturization without sacrificing performance.
- Beam Steering: Some 3D arrays support dynamic beamforming for applications like 5G and radar.
- Multi-functionality: Integration of multiple antenna types (e.g., dipole + patch) in one structure.

3D antennas are increasingly used in:

- Wireless communications: Especially in MIMO systems and mmWave bands.
- IoT and wearable devices: Where space and shape constraints demand conformal designs.
- Aerospace and automotive: For robust, high-performance antennas on curved surfaces.
- Medical devices: Implanted or wearable antennas requiring compact and efficient designs.

Materials and Manufacturing

Key material properties for antennas are electric permittivity, metal conductivity, and loss tangent, all of which affect performance at different frequencies. While traditional printed circuit boards (PCBs) are common substrates, alternatives like polyethylene terephthalate (PET), polyimide (PI), paper, and glass are also used, depending on the application. The substrate's dielectric constant, thickness, and surface roughness play important roles in antenna effectiveness.

Most printed antennas use silver-based conductive inks due to their high performance and relatively low manufacturing costs. Other materials, such as copper, gold, and silver-carbon nanotube composites, have been explored but are less common. After printing the metallic pattern onto the substrate, a sintering process (heating) is used to enhance conductivity—though even the best printed antennas typically reach only 50–70% of the conductivity of bulk silver.

Production methods include screen printing, gravure, inkjet, aerosol jet, and direct ink writing. Some designs require additional printed dielectric layers for more complex structures.

Performance Characteristics

Antenna efficiency (η) is a key parameter, measuring the ratio of power radiated to power supplied. Printed antennas tend to have lower efficiency than conventional ones due to limited metal conductivity and losses in plastic substrates. The quality factor (Q-factor) describes an antenna's bandwidth: lower Q indicates a wider bandwidth. Slot antennas can achieve ultra-wideband performance in the 1–12 GHz range, while wire loop antennas are often used at lower frequencies, such as the 13.56 MHz typical for NFC applications.

In summary, printed antennas offer a flexible and cost-effective solution for many modern wireless devices, balancing simplicity in design with new materials and manufacturing techniques to meet a wide range of application requirements.

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Near-Field UHF RFID Transponder with a Screen-Printed Graphene Antenna, Jaakkola, K., Sandberg, H., Lahti, M. & Ermolov, V., Apr 2019, In: IEEE Transactions on Components, Packaging and Manufacturing Technology. 9, 4, p. 616-623. https://doi.org/10.1109/TCPMT.2019.2902322

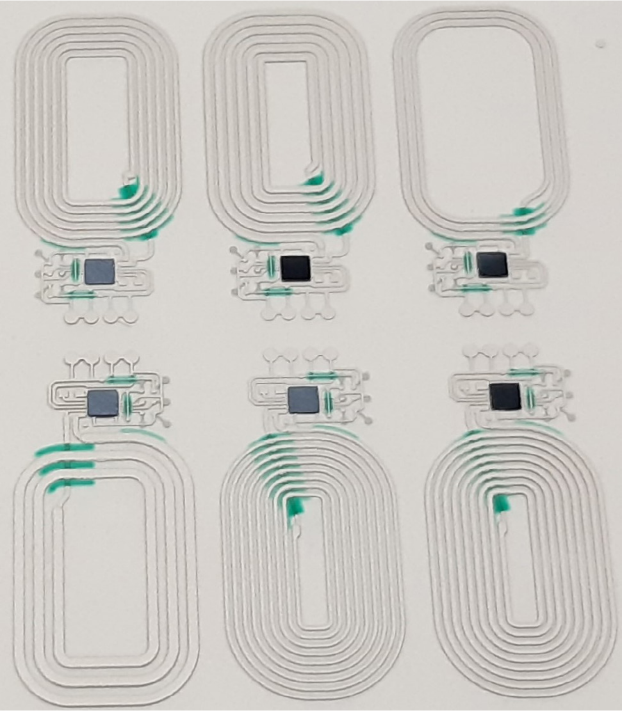

Figure 5.5.1. Screen printed NFC antennas

5.6 Printed and Flexible Transistors

Transistors are fundamental components of modern electronic devices, enabling complex functions. High-performing printed and flexible transistors require precise control over thin films, layer registration, and device structure, making their manufacture challenging—these multilayer devices are considered the "holy grail" of printed electronics.

Materials, Structure and Fabrication

Thin-film transistors (TFTs) consist of four layers, namely gate electrode, gate dielectric, semiconductor, and source/drain (S/D) electrodes (Figure 1). Fabrication of TFTs requires at least three different type of materials (conductive, semiconductive and dielectric) and high-resolution and precise patterning to form a pinhole and defect-free multilayer structures. The current in the semiconducting channel located between the S/D electrodes is controlled by the gate electrode that is separated from the channel and S/D with the gate dielectric. In general, the electrical performance and the operation frequency of the TFTs is dependent on the channel dimensions (smaller the better), charge carrier mobility of the semiconductor (e.g. chemical and crystal structure), operation voltage (thin gate dielectric), and parasitic capacitances (high overlay accuracy between layers), contact resistance (clean interfaces). These pose challenges for fabrication of flexible TFTs using printing technologies.[1] Printed TFTs can be either p-type (hole carrier) of n-type (electron carrier), where p-type devices are typically based on organic semiconductors (OTFTs) or carbon nanotubes (CNTs) and n-type transistors generally use metal oxide materials. Emerging 2D materials like graphene and MoS_2 also show promise. Organic materials offer low-temperature processing compatible with various flexible substrates and ready scalability to roll-to-roll (R2R), however, they need careful consideration of solvent orthogonality to avoid dissolving previous layers of the stack and are sensitive to ambient conditions. Oxide-based materials offer higher performance and stability, albeit they usually require higher processing temperatures. TFT materials may be directly applied as inks, solutions or dispersions, or as chemical precursors (e.g. metal salts) that require some post-processing to form the functional films. Recently, a hybrid approach has gained momentum, where high performance and device uniformity can be obtained using a combination of high-resolution print-patterning and low-temperature vacuum deposition.

Applications for flexible TFTs

Printed and flexible TFTs suit applications that do not require high frequency operation, large TFT counts, or extreme miniaturization, where in the order of rising challenge:

- Transistor-based sensor elements (e.g., biosensors, photosensors)
- Logic circuits for simple functions
- Sensor readout and amplification e.g. for wearable and printed systems
- Pixel addressing for sensor matrices
- Flexible and large-area displays, signage, and lighting
- Wireless communication for RFID and NFC applications

Current Status

The current TFT research at VTT focuses on the utilization of high-resolution reverse offset printing (ROP) to pattern high-performance TFTs with channel lengths at the single µm-level on flexible substrates, thus dimensions on par with the TFTs patterned with photolithography. TFTs are currently manufactured at VTT on flexible substrates using a combination of ROP and low-temperature vacuum deposition e.g. atomic layer deposition (ALD) and evaporation. The combination of directly printed, and ROP-patterned vacuum deposited thin films (using VTT's patented ROP-based patterning method) offer a wide materials palette and the ability to tailor the TFT performance depending on the specifications of the application [2]. Both ROP-patterned oxide TFTs and OTFTs are under continuous research at VTT. As an example, VTT has developed ALD-grown ROP-patterned ZnO TFTs that show high performance (>15 cm2/(Vs)) and low voltage operation (5 V) at 150 °C processing temperature [3]. ROP printing plate on 200 mm wafer can produce over 1000 pcs of 5 mm x 5 mm flexible chips, demonstrating the scalability of the process. VTT has proprietary know-how on ROP and in-house processes e.g. for the printing plate and printing blanket fabrication and on resist ink synthesis. Also, conventional printing methods like inkjet or flexography can be utilized if needed. Besides the ROP-based miniaturized TFTs, OTFTs have been developed at VTT since the early 2000s and scaled to R2R manufacturing, which could be ideal for up-scaled fabrication organic electrochemical transistors (OECT) where the limitations in printing linewidth and overlay alignment (typically 50–100 µm) are less critical.

Device Characteristics

Some key performance data:

- Mobility: 5 – 20 cm^2/Vs (oxide TFT), ≤ 1 cm^2/Vs (OTFT)
- ON/OFF ratio: >109 (oxide TFT), >103 (OTFT)
- Operating voltages: 5 V (oxide TFT), <15 V (OTFT)
- OFF-currents: <0.1 pA (oxide TFT)
- Turn-on voltage: ~0 V (oxide TFT)
- Minimum channel and overlap length: ~2.5 – 5 µm (ROP)

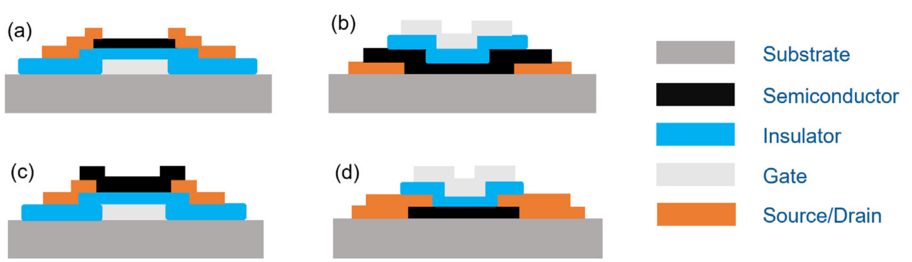

Figure 5.6.1. Different geometries for planar TFTs: (a) bottom gate top contact, (b) top gate bottom contact, (c) bottom gate bottom contact, and (d) top-gate top contact. From ref. [1]

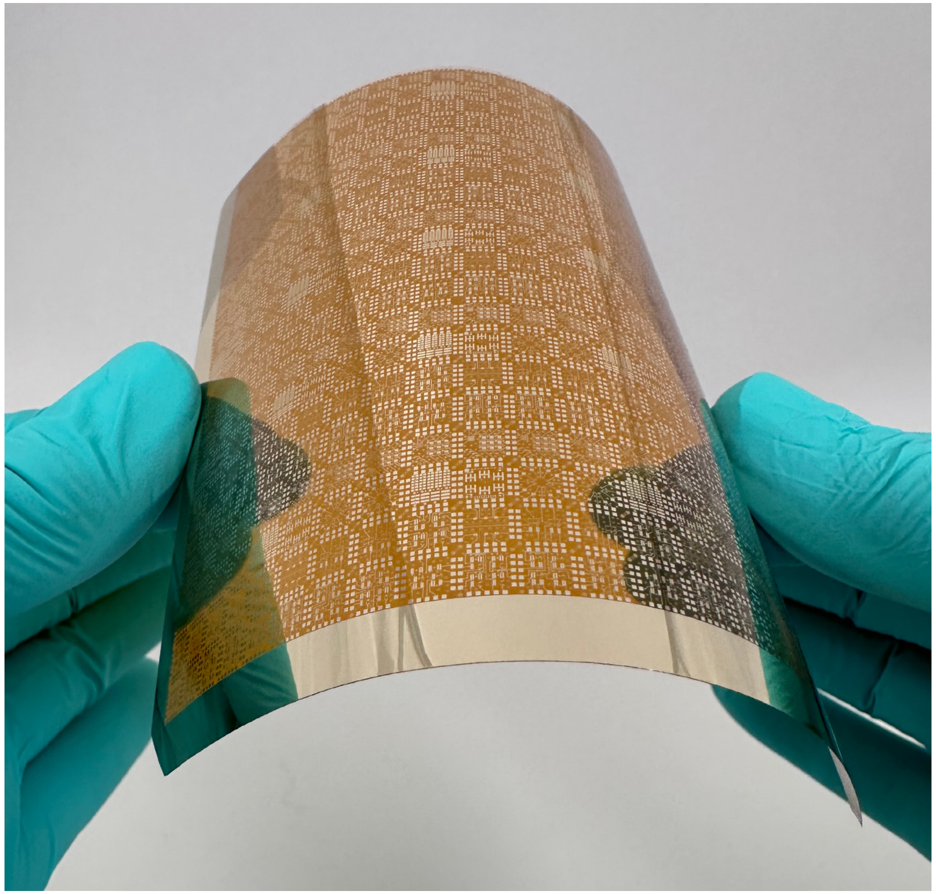

Figure 5.6.2. Flexible oxide TFTs and test circuits patterned by high-resolution ROP at VTT.

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5.7 Printed photovoltaics

Printed photovoltaics are lightweight, flexible solar cells, offering an alternative to traditional silicon-based panels. These modules are especially suited for applications requiring flexibility and autonomy, such as battery charging in consumer electronics or powering indoor sensor networks. Their manufacturing leverages roll-to-roll printing techniques, allowing for large-scale, cost-effective production.

Design and device structure

Two types of photovoltaic technologies can be fabricated using printing methods: organic photovoltaics (OPV)[1], [2] and perovskite photovoltaics (PkPV) [3], [4]. Both share a similar layered architecture, where the active material is positioned between charge transport layers and electrodes. Largest module size can be 28 x 40 cm2 with a geometrical fill factor ca. 40%. Varying series and parallel connections photovoltaics voltage and current can be tailored.

Materials and Manufacturing

Currently, the development of OPV technology is focused on non-fullerene-based active material, that is blended with functional polymer. ZnO and PEDOT are used as charge transporting layers whereas ITO and silver are typical electrode materials.

Perovskite photovoltaics (PkPVs) represent a hybrid PV technology, using organometal halides (OMHs) that combine organic and inorganic materials. The active layer typically uses materials like methylammonium lead iodide ($MAPbI_3$) or lately formamidinium lead iodide (FAPbI3). SnO_2 is commonly used as an electron transport layer on ITO electrodes. On the hole transport side, several materials are available, with spiro-OMeTAD combined with an evaporated gold electrode yielding the highest efficiencies. In contrast, fully printed alternatives typically using carbon as the top electrode tend to show lower performance.

Fabrication methods include spin-coating for high efficiency in small cells, though large-scale, cost-effective manufacturing techniques has been utilised for OPV but for PkPV they are still being developed.

Component Characteristics

Under indoor illumination and conditions, lifespan ranges from 7 to 20 years of printed photovoltaics. However, extrapolations from accelerated aging tests suggest that potential outdoor durability could extend up to 30 years.[5]

Perovskite Photovoltaics (PkPV)

PkPVs have quickly garnered attention for their high efficiency, low weight, and low material costs. Since their introduction in 2009, their lab-scale power conversion efficiencies (PCE) have soared from 3.8% to over 20%, with top results reaching 24.2% nearing those of silicon cells. However, these records are based on small cells, and upscaling remains a challenge.

Structurally, photovoltaics come in two main designs: mesoscopic (optimising charge transport and stability) and planar (simpler and easier to fabricate). Perovskites can also be combined with silicon in tandem cells for better solar spectrum absorption.

Typical photovoltaics have adjustable bandgaps and high open-circuit voltages (1.0–1.9 V). Their lifespans vary: up to 10,000 hours for 12% PCE cells, but only 1,000 hours for those at 20% PCE that is much shorter than silicon solar cells (20–25 years). While full cost comparisons are difficult due to PSCs' lower technology readiness, estimates suggest they could be less than half the manufacturing cost of silicon solar cells once scaled.

- OPV: Flexible, suitable for niche energy harvesting, indoor longevity 7–20 years, rapid and scalable production.
- PkPV: High potential efficiency, manufacturing promises low cost, stability and upscaling are ongoing challenges.

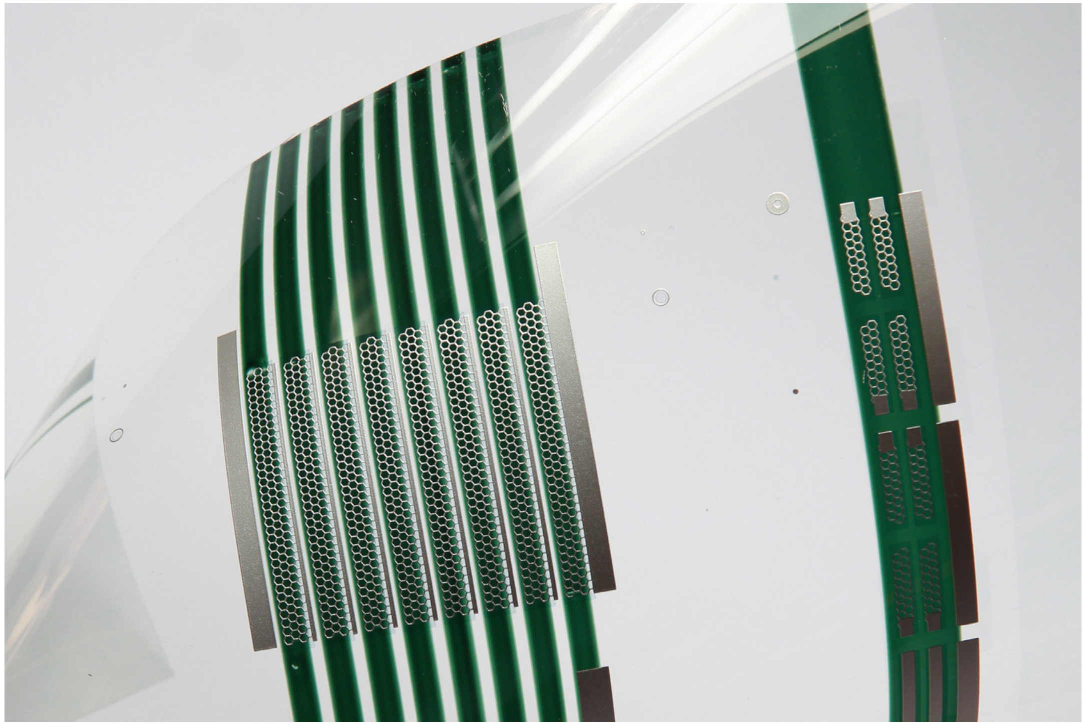

Figure 5.7.1. Fully printed and coated OPV for indoor application

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5.8 Piezoelectric energy harvesting

Piezoelectric energy harvesting is a technique that converts mechanical strain, such as vibrations or movements into electricity using piezoelectric materials. This effect occurs when an electric charge accumulates in substances like crystals, ceramics, polymers, or biological matter upon mechanical stress. Conversely, applying an electrical field to these materials induces mechanical deformation.

These devices are valued for their high energy conversion efficiency and ease of integration, making them prominent in low-power sensor systems and self-powered microsystems. Piezoelectric materials are also widely used in actuators.

Device Structure

Piezoelectric energy harvesters typically consist of a piezoelectric material sandwiched between two electrodes. While this is the basic design, more complex structures are sometimes employed to optimize performance.

Materials and Manufacturing

Common piezoelectric materials include aluminum nitride (AlN), zinc oxide (ZnO), barium titanate (BaTiO3), gallium phosphate (GaPO4), polyvinylidene fluoride-trifuoroethylene (PVDF-TrFE), and advanced ceramics such as PZT, PMN-PT, and PZN-PT. Thin-film materials like AlN and ZnO are preferred for micro-scale applications. Silver is a typical electrode metal.

Production methods such as gravure, flexography, offset, and screen printing are compatible with roll-to-roll manufacturing, enabling large-area applications. Fully inkjet-printed devices have also been demonstrated. The standard process involves printing and drying electrodes, depositing the piezoelectric material, and poling with a high voltage.

Component Characteristics

Piezoelectric harvesters operate mainly in two modes (d31 and d33) depending on polarization and stress directions. In d31-mode, the electric field is perpendicular to the applied stress whereas in d33-mode it is parallel.

Performance is measured by power density (power output per volume) and normalized power density (which considers input excitation). Another widely used parameter for efficiency is defined as output power energy over input mechanical energy. The best reported power densities for mesoscale devices range between 10–25 mW/cm^3, with optimal working frequencies from 2 Hz to 900 Hz.

In summary, piezoelectric energy harvesting offers a compact, efficient route to capture ambient mechanical energy and convert it to electrical power, with versatile applications in modern electronics and sensor networks.

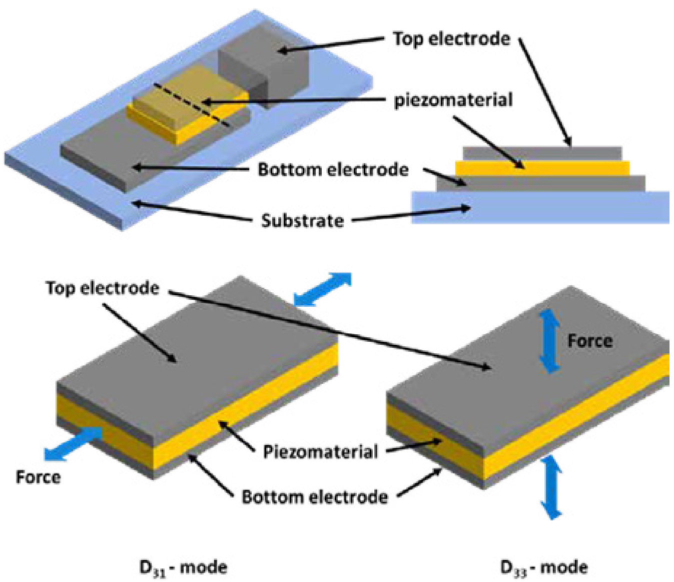

Figure 5.5.8. Schematic presentation of piezoelectric energy harvesting component

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5.9 Printed Batteries

Efficient energy storage is a primary technological challenge of this century, driven by the need for digitalization and electrification in mobile and grid-free applications. Batteries convert chemical energy into electrical energy via redox reactions. While batteries are categorized as primary (disposable) or secondary (rechargeable), the focus of printed technology is largely on secondary batteries. Printed variants offer a competitive alternative to conventional fabrication by improving material efficiency, process controllability, and allowing integration into devices of arbitrary shape.

Basic Principles

Batteries convert chemical energy into electrical energy through redox reactions. There are two main types: primary batteries (disposable) and secondary batteries (rechargeable). Printed batteries can serve as alternatives for both categories, depending on their chemistry. In this chapter, we focus on secondary printed batteries.

Structure and Architecture

A printed battery typically consists of three key components arranged on sandwich structure:

- Anode (negative electrode): Often made from lithium or zinc, it donates electrons during discharge.
- Cathode (positive electrode): Materials like lithium cobalt oxide or manganese oxide accept electrons.
- Separator/Electrolyte: Provides ionic contact and prevents electrical short circuits between anode and cathode.

Regardless of structure, encapsulation is essential to protect the battery from water and oxygen to prevent against environmental degradation.

Materials and Processing

The most common printed battery chemistries are lithium-ion (Li-ion), zinc-ion, and sodium-ion (Na-ion):

- Li-ion: Uses cathodes like NiMnCo, $LiFePO_4$, or $LiCoO_2$, and anodes made of graphite, hard carbon, or lithium titanate (LTO).
- Zn-ion: Uses Zinc-manganese dioxide or Prussian blue analog cathodes with metallic Zinc anodes.
- Na-ion: Utilizes layered transition metal oxides or Prussian white/blue cathodes with hard carbon anodes.

These active materials are often mixed with a binder, specifically Polyvinylidene fluoride (PVDF), to ensure mechanical stability. They are connected via metallic current collectors made of aluminium, copper, or stainless steel.

A battery is categorized as "printed" if at least one layer is fabricated via printing. While current collectors and electrolytes are rarely printed, active layers (requiring tens of micrometers in thickness) are well-suited for screen printing and spray printing. Also dispensing, ink-jet, and flexo-printing has been used.

Performance and Characteristics

The theoretical capacity of a battery depends on the active material's properties. For instance:

- Zinc-based batteries: 820 mAh/g
- Lithium-based batteries: 3860 mAh/g (metallic litium)
- Na-based batteries: 1166 mAh/g (metallic sodium)
- Typical operating voltages: 1 –1.8 V (Zn), 3.0–4.2 V (Li) and 2.0 -4.1 V (Na)

Real energy densities are typically only a fraction of theoretical value. Practical energy density values are 30-100 Wh/kg for Zn-ion, 150-280 Wh/kg for Li-ion and 90-160 Wh/kg for Na-ion chemistries.

While increasing the volume of the active electrode layer can increase capacity, doing so may limit ion mass transfer and reduce overall performance. The morphology (e.g., porosity) of the electrodes also significantly impacts the battery's efficiency.

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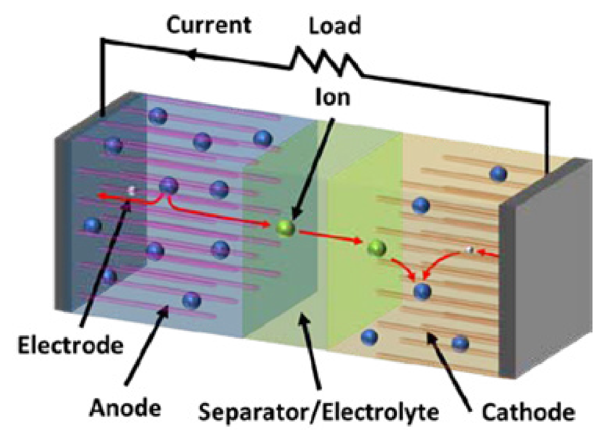

Figure 5.9.1. Battery operating principle

Figure 5.9.2. Pouch cell battery

5.10 Printed Supercapacitors

Printed supercapacitors are advanced electrochemical energy storage devices known for their high power density that is about ten times greater than that of traditional Li-ion batteries. They can be rapidly charged in just seconds and boast an exceptionally long lifespan, often exceeding one million charge cycles, compared to the 500–3,000 cycles typical for batteries. However, they store less energy (roughly 10% of Li-ion batteries) and are best suited for applications where quick power bursts are required.

Advantages of Printed Supercapacitors

- Low manufacturing costs and scalable production
- Supports multi-layer designs
- Utilizes inexpensive, environmentally friendly raw materials
- Flat, flexible, and bendable form factors (including free-form shapes)
- Integration into roll-to-roll (R2R) manufacturing and various product types
- Applicable for both small and large-scale uses
- Enables structural electronics and in-mould integration

Main Applications

- Printed supercapacitors are commonly used where short-term, high-power output is essential, such as:
- Energy management for IoT and autonomous sensor networks
- RFID tags and smart packaging
- Wearables and flexible electronics
- Structural electronics
- Hybrid systems in vehicles (combined with engines, batteries, or fuel cells)
- Building-integrated energy storage

Component Structure

A supercapacitor consists of printed electrodes and an electrolyte. When voltage is applied, ions and electrons move, creating an electric field at the electrode-electrolyte interface. Energy is stored much like in a traditional capacitor, but with a nanometre-scale separation and a large interfacial area, thanks to materials like activated carbon. The electrolyte can be organic, aqueous (like saltwater), or an ionic liquid. Electrodes are typically printed on paper (with barrier layers) or plastics.

Performance Characteristics

- Capacitance: About 0.1 F/cm² with 100 µm electrode thickness
- Self-discharge rates on par with commercial supercapacitors
- Excellent flexibility demonstrated in demanding bending tests
- Non-toxic material options provide an environmental edge over conventional batteries
- Roll-to-roll production has been validated for industrial scaling (e.g., VTT's Printocent pilot line)
- Recent advances include energy-autonomous systems where printed supercapacitors are paired with energy-harvesting organic photovoltaics, further expanding their integration into next-generation electronic devices.

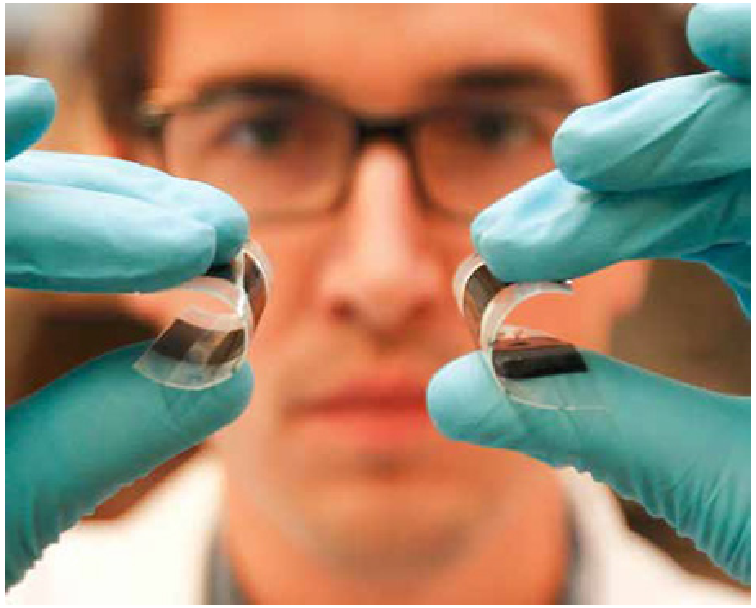

Figure 5.10.1. Printed flexible supercapacitors

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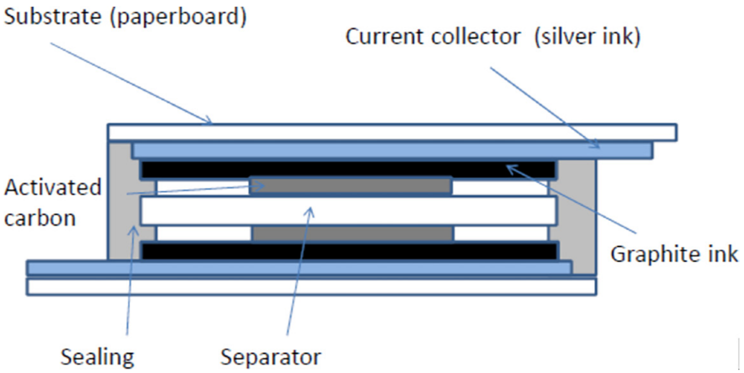

Figure 5.10.2. schematic presentation of a supercapacitor component structure

5.11 Printed capacitive temperature sensors

Printed capacitive temperature sensors represent a modern approach to temperature measurement, offering unique advantages such as large-area sensing, mechanical durability, and low production costs. Unlike traditional sensors, these printed versions can be easily integrated onto various surfaces like plastics, paper, or fabrics enabling applications in wearables, embedded systems, and smart packaging.

At their core, printed capacitive sensors often use a parallel plate structure. The working principle relies on the change in permittivity of a dielectric layer placed between two printed metallic electrodes (typically silver or copper). This change in permittivity with temperature causes the sensor's capacitance to vary, which can be measured directly or read remotely when the sensor is paired with an antenna coil. The remote reading method uses inductive coupling, converting temperature-induced changes in capacitance into shifts in resonance frequency. This approach allows for non-destructive temperature monitoring, even through barriers, with a typical measurement accuracy of about 1–2 °C.

Fabrication of these sensors is highly compatible with established printing techniques, especially screen printing. Multiple printed layers of dielectric material ensure uniformity and avoid defects like pinholes. The choice of polymer or dielectric directly affects the sensor's sensitivity and temperature response—capacitance changes of 20–30% are commonly achieved with commercial materials, and the response can be tailored to be linear or nonlinear depending on the application.

Ultimately, the performance and characteristics of printed capacitive temperature sensors hinge on the careful selection and processing of both the electrode and dielectric materials. These sensors can be custom-designed in terms of size, geometry, and sensitivity, making them a flexible solution for a wide array of modern temperature-sensing needs.

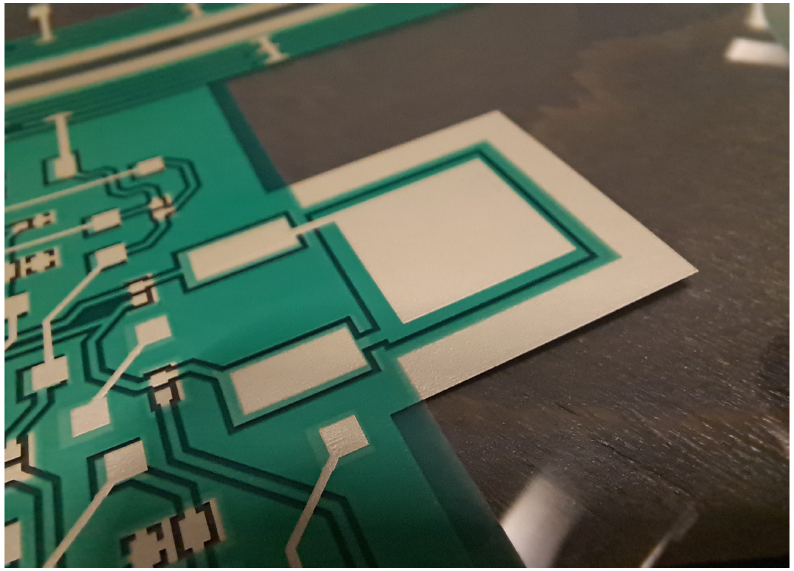

Figure 5.11.1.printed capacitive temperature sensor

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5.12 Printed resistive temperature sensors

Printed resistive temperature sensors are an innovative alternative to traditional sensors, offering notable benefits such as low manufacturing costs, flexibility, ease of mass production, with competitive accuracy. These sensors can be fabricated on diverse substrates such as plastics, paper, and fabric using scalable techniques like screen printing.

How Printed Resistive Sensors Work

At the core of these sensors is a material whose electrical resistance changes significantly with temperature; this property is measured by the temperature coefficient of resistance (TCR). The TCR quantifies how much resistance varies per degree Celsius, making it a crucial parameter for characterizing and designing temperature sensors.

A typical sensor structure includes:

- A temperature-sensitive material (the resistor element)
- Printed conductive electrodes, often made with silver ink

Sensor performance depends heavily on the choice of material, which determines sensitivity and baseline resistance. Most designs offer a linear response within standard temperature ranges, although performance may decline at temperatures below room level. Sensors can be tailored by adjusting shape and size, typically resulting in room temperature resistances from 10 kΩ to several MΩ. A protective dielectric layer is often added to shield the sensor from moisture and prevent physical contact, preserving performance and longevity.

Key Advantages and Applications

Printed temperature sensors excel where light weight, flexibility, and cost savings are priorities. They are especially suited to logistics (e.g., monitoring perishable goods), aviation and automotive industries, healthcare (including disposable sensors), measuring temperature gradients across large surfaces. Affordability makes them ideal for single-use contexts and widespread deployment.

Performance Highlights

Selecting appropriate materials enables a linear and sensitive temperature response, with commercially available inks achieving TCR values around 0.005/°C, and specialty inks reaching up to 0.05/°C. Sensor resistance at a given temperature can be calculated using standard formulas, and typical circuits involve integrating the sensor into a voltage divider setup with amplification.

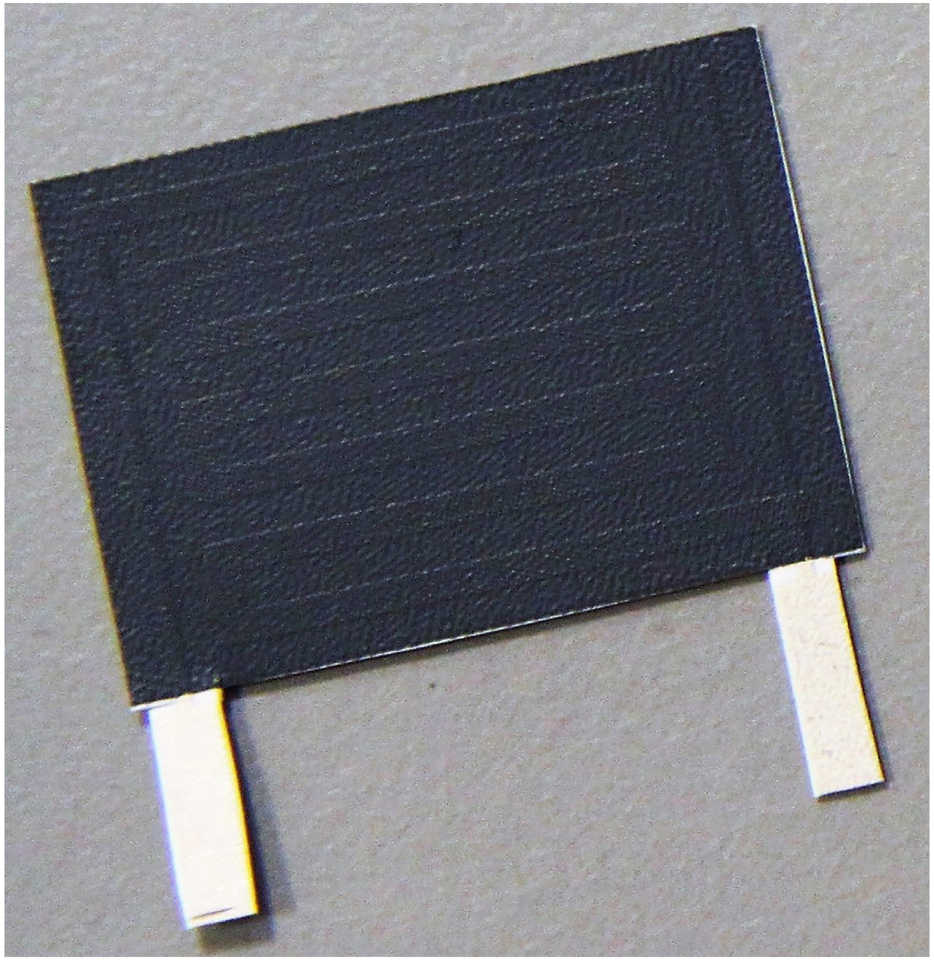

Figure 5.11.1. Screen printed temperature sensor

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5.13 Relative humidity sensors

Printed relative humidity (RH) sensors present a cost-effective and versatile alternative to traditional sensors, owing to their compatibility with various substrates like flexible plastics and paper. Their disposable nature makes them ideal for long-term monitoring applications, such as embedding in building materials to track moisture over time.

These sensors typically consist of simple capacitor structures—either as parallel plate, mesh, or interdigital designs. The core sensing principle relies on the significant difference in relative permittivity between water and air or polymers. As humidity increases, more water is absorbed into the sensor's polymer layer, raising the capacitance and allowing for accurate moisture detection.

Design choices play a crucial role in sensor performance. The structure, geometry, and materials must be carefully selected. Interdigital (IDE) designs, for example, offer low hysteresis but require more space to achieve the same capacitance as mesh or parallel plate designs. Analytical models and electromagnetic simulations help optimize these parameters, such as line width, spacing, and the number of mesh openings or fingers, for specific applications. If remote monitoring is required, the resonance frequency of the sensor circuit can be adjusted by tweaking the capacitor and inductor properties to match the desired frequency range.

One significant advantage of printed RH sensors is their seamless integration with remote reading technology like RFID. By incorporating the sensor into an LC resonator circuit, any increase in moisture content within the monitored structure produces a detectable shift in resonance frequency. This feature broadens the range of practical applications, from building maintenance to smart infrastructure.

In summary, printed humidity sensors are lightweight, flexible, and suited for integration into a variety of environments, offering real-time, cost-effective moisture monitoring with the added benefit of potential remote data collection.

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5.14 Capacitive touch and proximity sensors

Capacitive sensors are widely used to detect touch or the proximity of objects, such as human fingers on touch screens or as replacements for mechanical pushbuttons. They offer simple, durable designs with no moving parts, relying on projected capacitive technology for accurate sensing

Basic Operation

A capacitive sensor works by measuring changes in capacitance when a nearby object, like a hand, alters the electric field around a sensor electrode. The sensor's chip detects this shift, typically by monitoring the RC time constant or changes in current consumption. Power use is low—generally in the milliwatt range.

Electrode Design

Larger electrodes increase sensing distance, but are limited by the sensor chip's capacity. For example, the Analog Devices AD7147 can handle up to 20 pF (or 40 pF with compensation). Electrode capacitance (CP) is estimated using standard formulas for a square plate, while the capacitance added by a human hand (CH) depends on hand or electrode area. Human body capacitance (CB) ranges from 100–300 pF, and is modeled as 100 pF in series with a 1.5 kΩ resistor.

Measurement Methods

Two main approaches exist:

- Self-capacitance: Measures at a single electrode, with both excitation and detection performed at the same point.
- Mutual capacitance: Measures between two electrodes, with excitation at one and measurement at the other.

Multiple electrodes allow tracking the direction and position of nearby objects for advanced interaction.

Printed Electrodes and Materials

Printed technologies allow large, flexible electrode surfaces in posters, textiles, and smart environments. Silver, copper, and conductive polymers (such as PEDOT) are common choices for electrode inks. Transparent solutions use materials like indium tin oxide or fine metal meshes. Printed wiring resistance affects performance: for example, 30 kΩ resistance halves the signal, while tens of ohms cause negligible loss.

Active Shielding

Active shielding reduces noise and stray capacitance by driving the same signal to a shield as to the electrode, eliminating unwanted interference. This can be implemented as a surrounding plane or coaxial cable, improving sensor precision. Insulating layers between electrode and shield further help, but may be hard to achieve in printed structures.

Sensor Chips and Applications

Major manufacturers include ST Microelectronics, Analog Devices, Silicon Labs, Microchip, and Cypress. Innovative uses include integrating capacitive sensors into plastic objects via in-mould labelling (IML), with automotive industries leading the way through companies like TactoTek and PolyIC.

In summary, capacitive touch and proximity sensors offer robust, flexible solutions for detecting human interaction, with printed electronics enabling new forms and applications in smart environments and user interfaces.

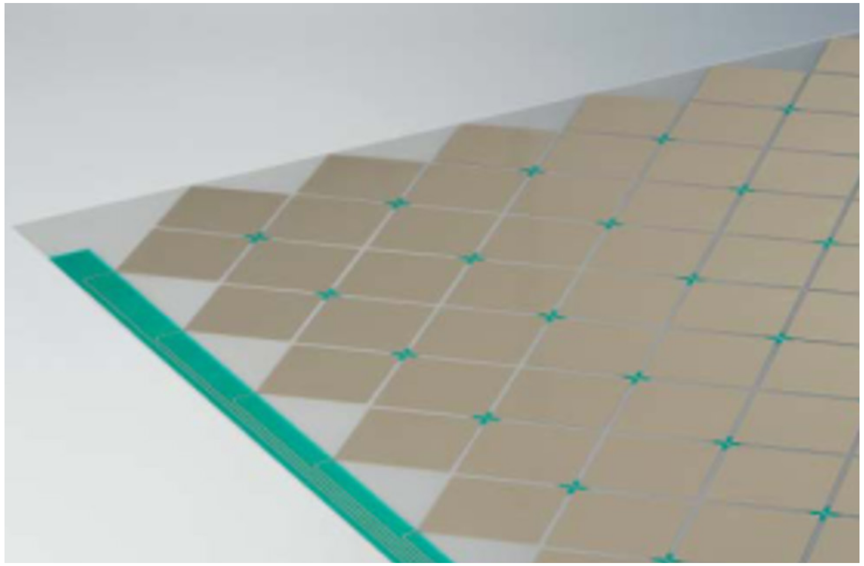

Figure 5.14.1. Large area capacitive proximity sensor

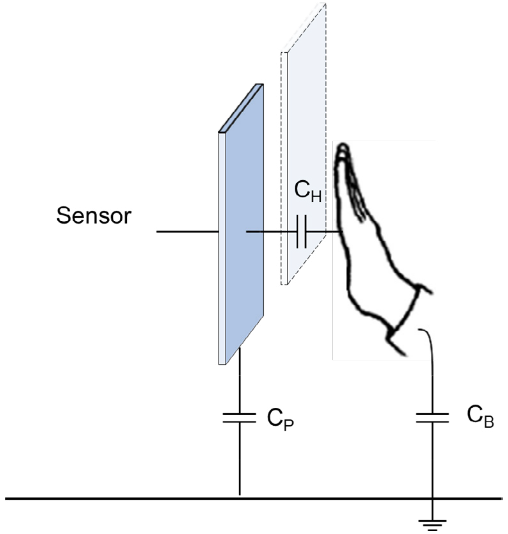

Figure 5.14.2. Operating principle of capacitive touch sensor

5.15 Resistive touch sensors

Touch screen technology is increasingly present in various fields, spanning consumer electronics, commercial products, and industrial equipment. Among the diverse types—resistive, capacitive, infrared, optical, and acoustic wave—resistive touch screens remain the most widely used due to their affordability, while projected capacitive models follow closely behind.

Printed Resistive Touch Screens

VTT is pioneering flexible, printable resistive touch sensors suitable for large areas. These touch sensors comprise two patterned resistive layers (commonly ITO-coated PET) separated by an insulating spacer with air gaps. When pressure is applied using a finger or stylus, the layers make contact, allowing electrical current to pass through the point of touch, and a controller circuit determines the exact location.

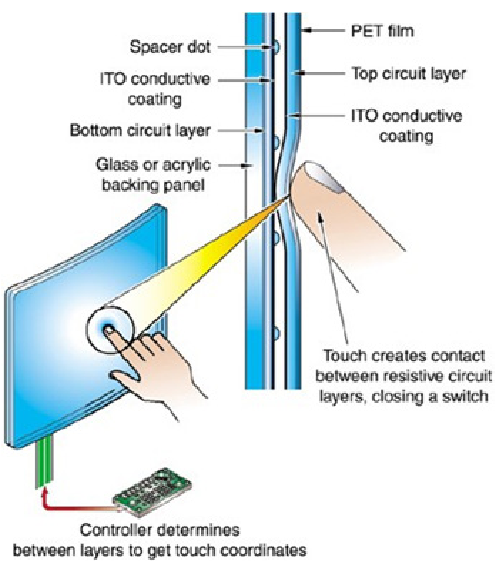

Figure 5.15.1. operating principle of a touch screen

Manufacturing Process

The production begins with roll-to-roll patterning of ITO-PET foils using paste etching. This is succeeded by rotary screen printing of conductive silver paste for wiring and a dielectric paste for the insulating spacer. Each layer is cured via hot-air dryers, and final steps involve cutting and laminating the foils with appropriate adhesives.

Key Features and Benefits

- Thin, lightweight, and flexible construction
- Support for standard communication protocols such as NFC, RFID, ZigBee, and WLAN
- Easy integration with printed graphics and textured surfaces for enhanced user experience
- Hybrid compatibility with various sensing and communication technologies

Figure 5.15.2. Resistive touch screens

Resistive touch screens offer an attractive solution for modern devices, combining cost-effectiveness with adaptability, making them a preferred choice across many applications.

5.16 Piezoresistive sensors

Basic description

Printed piezoresistive sensors offer several advantages over traditional sensors. Advantages are for example low manufacturing costs, mass production scalability, thinness, flexibility and customizability to different shapes and sizes. Printed sensors are easily fabricated on a variety of substrates e.g. plastics, paper or even fabric using screen printing or any other mass-manufacturing method. Cons of printed vs. other piezoresistive sensor technologies is that the sensitivity may vary over time.

Piezoresistive sensors are manufactured using material(s) whose electrical resistivity changes when mechanical deformation is applied to the material. Usually, the behaviour of the sensor as a function of force is linear, however there are differences in linearity, hysteresis, drift and temperature sensitivity properties of the component. Many piezoresistive (pressure sensitive) materials have weak reproducibility, creep and lack of elasticity [1] so it is important to choose the best materials for printed sensor.

Component structure and design

Typical piezoresistive sensor consist of silver electrodes and pressure sensitive resistive material printed on thin, flexible PET or PI film, as shown in Figure 5.16.1. Flexible substrates provide mechanical support and enable flexibility. Electrodes on both sides of the pressure sensitive material define the sensing area of the sensor.

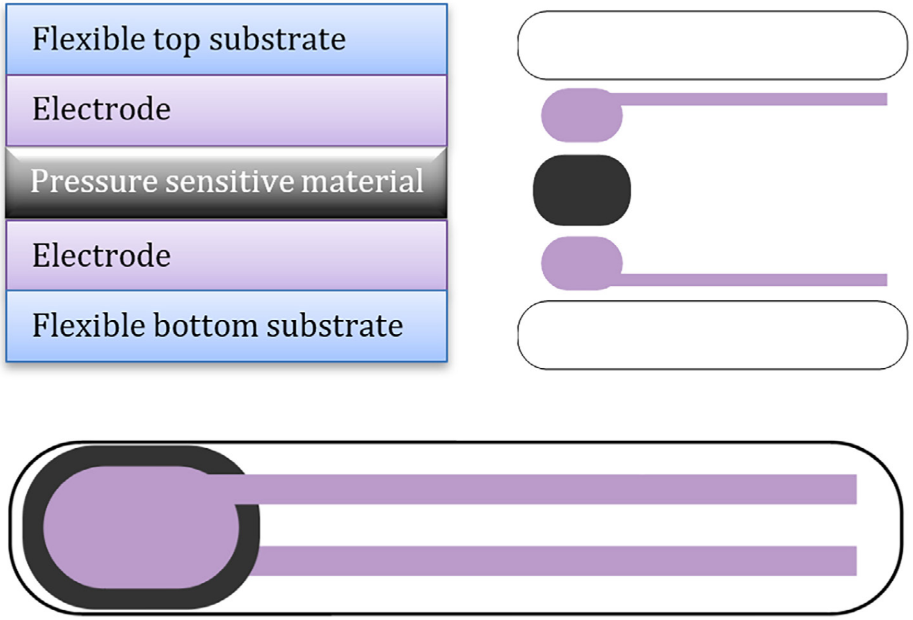

Figure 5.16.1. Printed piezoresistive sensor structure

The sensors can be designed for different geometries and sizes to fit the specific need. Usually component size is a few cm2 with active sensing area <10 mm. The electrical resistance change factor due to mechanical deformation (strain) is called the Gauge Factor (GF) [2]. GF is one of the main parameters used to characterize piezoresistive sensors. GF values are usually from 8–14 with screen printed polymer thick film sensors [3]. Usually, no-load resistance of the sensors is in the range of kΩ to MΩ.

Applications

Printed piezoresistive sensors are manufactured in a variety of shapes and sizes to be able to meet a wide range of design requirements. For that reason, sensors are easy to integrate into different devices. Sensors are suitable for applications where absolute force measurement is needed as well as in sensing applications such as occupancy detection, threshold monitoring, on/off detection or as switches in human interface devices. Printed sensors are not as accurate as traditional strain gauges/load cells, so they are not suitable for high precision force measurements.

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5.17 Potassium sensor

Introduction

Portable diagnostic devices can provide number of advantages by enabling rapid and accurate diagnosis of health and disease. Ideally new sensor concepts could emerge as promising alternatives for continuous monitoring of health and contribute development toward personalized diagnostics and therapy. Ion-selective electrodes (ISEs) belong to a group of diagnostic devices which are easy to use because of simple equipment and rapid response, but the most conventional of them are suitable only for laboratory settings. The key desirable characteristics for newly developed sensors are simplicity, low cost, stability, high sensitivity, and the ability to provide rapid test results thus conforming to the idea of being portable, decentralized, innovative, and cost-effective diagnostic tools.

K^+ ions in bodily fluids like serum, plasma and urine are an important clinical marker for chronic kidney diseases. In healthy adult population, the level of K+ in plasma is in the range of 3.3-4.9 mM. This range is quite narrow, and even small changes in serum K^+ levels can predict adverse health outcomes. In kidney diseases, the plasma K^+ concentrations can be lower (in severe hypokalemia < 2.5 mM), or higher (in severe hyperkalemia > 7.0 mM) than the healthy range. Both are associated with severe health ailments such as heart rate irregularity, muscle dysfunction, and sudden death. By timely informing of variations in K^+ concentrations, portable point-of care devices could improve safety and effectiveness of medical treatments and are particularly beneficial for home dialysis patients.

Principle and design of solid contact ISE sensors for K^+

The overall sensing principle of an ISE relies on measured electrical potential, which is dependent on the activity of the ion to be determined. K^+ ISE sensors comprise an ion-specific membrane (PVC matrix with K^+ ionophore) cast over a conductive polymer (PEDOT:PSS) as a solid contact layer on a printed carbon working electrode (WE) (Figure 1).1 By coordinative binding, the K^+ ionophore is capable of discriminating between potentially interfering cations such as Na^+, the closest interferant for K^+ assays. A measurable open circuit potential (OCP) is generated between the WE and reference electrode (RE) as a result of transfer of K^+ ions across the ISM membrane and ion-to electron transduction in solid contact layer.

VTT's ROKO line was employed to fabricate electrode structures for the ISE sensors by sequential roll-to-roll rotary screen printing of a series of inks onto a polyethylene terephthalate substrate. The printed layers included 1) silver interconnects, 2) carbon WE and counter electrode (CE), 3) Ag/AgCl RE, and 4) insulator to cover the interconnects and define the electrochemical cell region, altogether forming a three electrode sensor configuration as shown in Figure 5.17.1. PEDOT:PSS layer was deposited onto the WE by galvanostatic electropolymerization to minimize the OCP measurement drift. Ag/AgCl electrode covered by polyvinyl butyral (PVB) saturated with Cl- served as a reference electrode (RE).[2] measurements.

Characteristics of the K^+ ISE sensor

Calibration plots were generated from solutions of KCl in phosphate buffered saline (PBS, 0.1 M, pH 7.4) to assess the performance of the developed sensor. OCP values were determined by potentiometric measurements performed using a benchtop potentiostat. Successful quantification of K^+ in buffer solution was confirmed by a linear increase in OCP signal in response to rising K^+ concentration. The measured concentration range was 1-20 mM K+ corresponding to the relevant range in physiological samples like urine, plasma and serum.

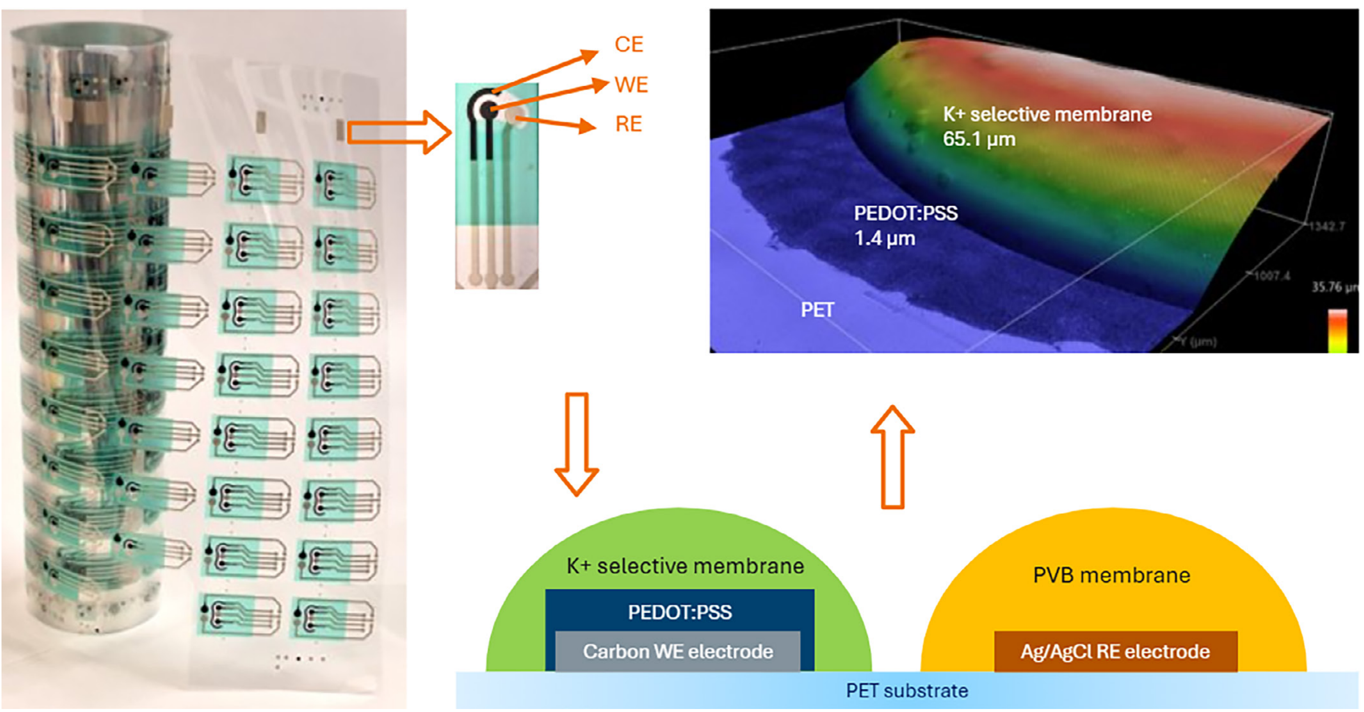

Figure 5.17.1. Roll-to-roll screen-printed electrodes on which K+ selective and PVB membranes were prepared by drop casting. A 3D profilometer image reveals the topography of the working electrode structure.

Future outlook for ISE sensors

New technological innovations have been suggested and implemented with proven efficacy to improve the stability, sensitivity and reproducibility of the all-solid ISE sensors. However, despite the fast technological progress, further development is required to circumvent limitations of these sensors. Optimized function of ISE sensors is ubiquitously needed in the context of flexible wearable sensors to detect electrolyte imbalances and dehydration combined with physical sensors and health trackers. [3] Moreover, transformation of healthcare systems from conventional hospital environment to remote settings and home healthcare promotes pursuing of new sensor concepts. Some critical improvements needed to improve ISE sensor functionality are as follows.

- Water layer effect: When water penetrates to the interface between the conductive polymer (e.g., PEDOT:PSS) and ion-selective membrane layers causing drift of measurement potential and disturbing the long-term usage of ISE sensors e.g. during physical activities. Selection of hydrophobic materials as constituents of ISM and solid contact might reduce the formation of water layer. Essentially, ISE sensors with minimal drift are of interest in search of calibration free assay formats.

- 3D printing of ISEs sensors: 3D printing could enable different designs and materials as compared to planar production of ISEs. 3D printing could offer a possibility for fully printed sensor assembly including ion-selective matrices not only electrode structures.

- Mass-scale production methods: Offering an opportunity for providing miniaturized, affordable and reproducible sensors with improved performance due to high throughput as well as uniform and repeatable fabrication methods. Scalable methods such as rotary screen-printing, large area electrochemical processing, [4] automated dispensing, and roll-to-roll imprinting [5] could accelerate routes for commercialization.

- Continuous operation: To realize longer term ISE measurements, for instance as needed for on-body monitoring, flexible and biocompatible materials are needed for integration of fluid guiding microfluidics. To sustain stable and reliable monitoring of the ISE sensors during long-term activities, replenishing sample volume in the detection area during measurement is required.

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5.18 Visual Indicators, Tests, and Codes

VTT has built extensive expertise in developing visual indicators and tests using functional inks. These solutions leverage chemical and biochemical reactions, printed onto paper or plastic via methods like inkjet, flexography, and screen printing. The result is a range of smart indicators for detecting oxygen, humidity, temperature, sulphur compounds, aldehydes, and even biological substances, using both custom and commercial inks.

How Printed Indicators Work

The principle is simple yet powerful: a target analyte reacts with a specially formulated ink, creating a visible colour change on test strips or indicators. VTT's patented fluid guiding structures allow precise control of liquid flow, enabling advanced, paper-based lateral flow tests. Printed functional inks have also led to the development of dynamic QR codes, which help track products, collect environmental data, and enable unique item-level identification—key aspects for the Internet of Things (IoT).

Key Application Areas

- Product Monitoring: Low-cost printed indicators monitor product quality throughout distribution, detecting changes like spoilage or package leakage. Dynamic QR codes also offer authentication and temperature sensing.
- Health & Well-Being: Paper-based biochemical assays visually detect substances like morphine and hemoglobin, while disposable colour tests assess volatile compounds in breath.
- Water Quality Control: A mass-producible, disposable device can identify common cyanobacteria toxins such as microcystins and nodularins, suitable for both consumers and authorities. Other indicators detect harmful phenolic substances in water.

Status and Readiness

Many visual indicators for product monitoring have reached pre-commercial pilot stages, with real-world trials completed. Technology readiness levels (TRL) for these chemical-based concepts generally range from 6 to 7, though this varies by the specific environmental parameter detected. Health and environmental test strips have also been tested with real samples, achieving TRLs between 4 and 7.

In summary, VTT's printed visual indicators and dynamic codes represent practical, scalable solutions for monitoring quality, safety, and health, and are already demonstrating their value in diverse real-world settings.

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Figure 5.18.1. Blue-gree algea test

5.19 Microfluidic chip

From Lab Innovation to Commercial Applications

Microfluidic lab-on-a-chip technology is transforming laboratory research, offering streamlined, miniaturized systems for sample analysis across healthcare, diagnostics, and environmental monitoring. These chips require less sample material, deliver faster results, and allow for the integration of multiple laboratory functions on a single platform.

Current Materials & Manufacturing Challenges

Most microfluidic devices today are made from glass, silicon, elastomers, or machined polymers, but these methods are often costly and time-consuming—hindering widespread commercial adoption.

Roll-to-Roll (R2R) Manufacturing Innovation

VTT leads in developing roll-to-roll (R2R) mass production for microfluidic chips using polymer, paper, and adhesive substrates. R2R enables:

- Low-cost, foil-based materials
- Minimal tooling expenses
- Disposable, rapid prototypes
- Functional integration
- Multilayer and multiplexed assay capabilities
- Large-scale patterning

Hybrid integration with silicon or injection-molded components further enhances device affordability and functionality.

Key Features

Microfluidic chips can incorporate:

- Fluidic channels for liquid manipulation
- Biomolecule coatings for analyte detection
- Integrated electronics and optics for sensing

VTT's pilot R2R lines can rapidly produce these features at scale, paving the way for broader market impact.

Applications

VTT's platforms are suited for:

- Point-of-care and point-of-use testing
- Personalized and preventive medicine
- Clinical/veterinary diagnostics
- Environmental and food safety testing
- Industrial process monitoring
- Bioterrorism detection
- Drug discovery

Development & Transition Support

VTT offers flexible mass manufacturing and prototyping services for microfluidic devices. Their process allows use of the same materials and tools for concept testing and final production. VTT also supports organizations transitioning from traditional diagnostic platforms to low-cost alternatives, providing expertise in optical/electrochemical sensing, reader device development, and analytical software solutions.

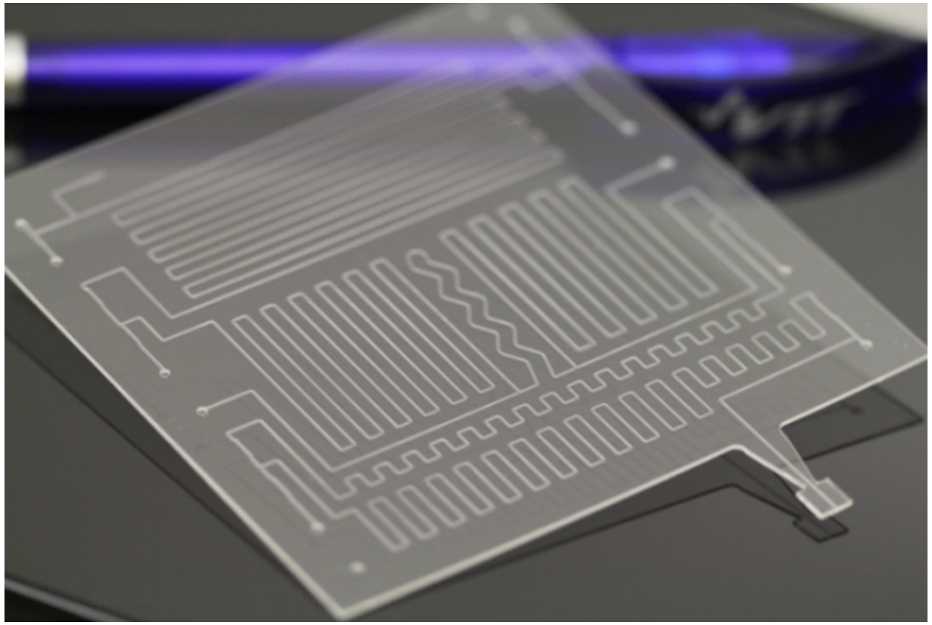

Figure 5.19.1. Microfluidic channels on a plastic substrate

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6

RD CASE EXAMPLES AND PLATFORMS

6.1 Electrochemical Biosensor Platform

Electrochemical biosensors are analytical devices that convert a biomolecule's recognition event into an electrical signal proportional to the concentration of the target analyte. They are among the most commercially successful applications of printed intelligence, best known for disposable glucose test strips.

This R&D case demonstrates the feasibility of producing such biosensors using screen printing. The described platform (Figure 6.1.1), fabricated on PET with silver/silver chloride, carbon, and dielectric inks, forms a robust and adaptable baseline design for various assays and end-use applications. Specificity is determined by the chosen recognition element—typically enzymes, antibodies, or nucleic acids—while the printed structure provides a universal measurement interface.

The case highlights key material choices and design rules, including alternatives for substrates and inks. Thanks to scalable manufacturing, these platforms can be produced as low-cost, disposable test strips suitable for point-of-care or on-site use. Their versatility makes them applicable in medical diagnostics, environmental monitoring, food safety, and defense.

Table 6.1.1. Electrochemical biosensor specifications

Sensor type	Disposable electrochemical biosensor test strip
Sample collection method	Direct drop
Target applications	Blood glucose, lactate etc.
Size	25 mm × 10 mm
Printing method	Flat-bed screen printing, 3 print layers
Substrate	250 µm Polyethylene terephthalate (PET) or 180 µm filter paper
Reference electrode	Silver/silver chloride (60%/40 %) ink
Work/counter electrode	Carbon/graphite ink or mediated carbon graphite
Insulator	Polymer dielectric ink

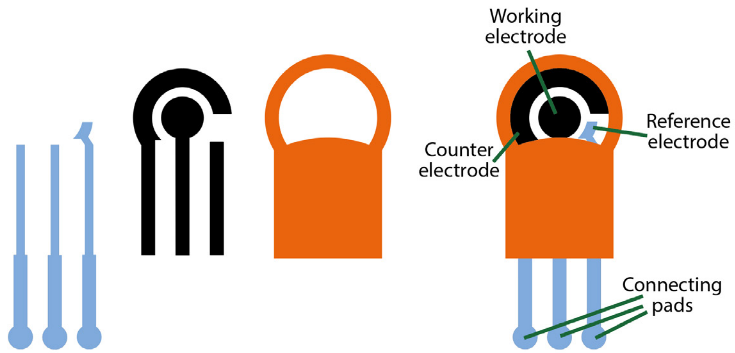

Figure 6.1.1. Layer-by-layer schematic of the screen-printed biosensor platform followed by the complete multilayer configuration.

Platform Characteristics and Design

The biosensor geometry (Figure 6.1.1.) can be adjusted to meet assay requirements. For example, enlarging the working electrode strengthens the signal. However, certain rules must be followed:

- The counter electrode surface must be larger than the working electrode to ensure free current flow, preferably 2,5 times the area of the working electrode.
- Connector pads must match the pitch of the measuring device, usually 2.54 mm.
- The total thickness of the material must fit the measurement connector slot.
- Connectors must be insulated from each other with a dielectric to prevent shortcutting.

The platform described here serves as a universal starting point that can be customized according to assay-specific needs.

Printing Method

Although electrochemical biosensors can be produced using various printing methods such as inkjet, flexographic, or flat-bed screen printing, flat-bed screen printing was selected in this case. It offers scalability from small prototype series to mass production, accurate multilayer alignment, and access to a wide range of commercial inks (for example, from Dupont, Sun Chemical, or Mateprincs).

Substrate Selection

The platform was printed on 250 µm PET (Melinex 339), although 180 µm filter paper (GE Healthcare Whatman 1) was also tested. Substrate choice balances usability and manufacturability. PET, PBT, PC, PI and filter paper (Figure SH) are all realistic options.

- **Usability requirements:** rigid enough for insertion into the measurement device, disposable with household waste.
- **Manufacturability requirements:** low cost, widely available, good adhesion during printing, stability during curing, suitable for cutting and lamination and sufficiently smooth surface.

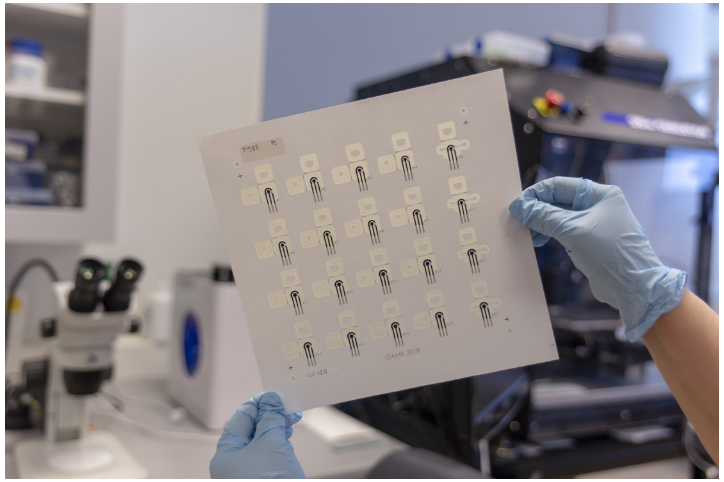

Figure 6.1.2. Electrochemical sensors with microfluidic structures on paper substrate

Printed Layers

The platform (Figure 6.1.3.) is built as a multilayer structure.

- Layer 1 – Conductors & Reference Electrode (RE): Printed with silver/silver chloride ink (Sun Chemical C2130809D5), cured at 80 °C for 10 minutes. This ensures stable reduction potential and good conductivity. Alternatives include silver, platinum, or gold, though cost is higher. RE has to be different material than WE or CE.

- Layer 2 – Working & Counter Electrodes (WE + CE): Printed with electrochemically active carbon ink (Sun Chemical C2030519P4), cured at 80 °C for 10 minutes. Carbon provides the necessary conductivity and chemical inertness at low cost. In some cases, graphite ink containing redox mediators may be used to improve electrochemical performance.

- Layer 3 – Insulator: Printed with dielectric ink (Sun Chemical D2070423P5), cured at 80 °C for 30 minutes. This layer protects the electrodes and insulates them from each other. It can be used to create a physical wall around the working electrode to contain the dispensed bio-recognition material.

Quality Control

Print quality was verified at several levels:

- Visual inspection for layer alignment and surface smoothness
- Conductivity tests of electrodes
- Electrochemical functionality measurements
- Surface roughness evaluation

Figure 6.1.3. Printed electrochemical sensor

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6.2 Wearable Sweat Sensor Platform

Introduction

Sweat rate monitoring is crucial for assessing hydration, diagnosing conditions like hyperhidrosis, and interpreting sweat analyte concentrations. Traditional sweat rate measurement methods are often off-body, require specialized settings, and are not suitable for continuous, real-time monitoring. Most wearable sweat sensors rely on adhesive tapes for skin attachment, which can cause discomfort, skin irritation, and limit integration with commercial wearables. Following work introduces a tape-free, digital wearable sweat rate sensor that uses a 3D-printed sweat collector and a microfluidic channel with embedded electrodes, enabling comfortable, reusable, and accurate sweat rate monitoring during exercise.

Device design

The sensor consists of a soft, concave 3D-printed sweat collector for conformal skin contact and a hard housing for structural support. The collector interfaces with a spiral-shaped microfluidic channel, is fabricated using roll-to-roll screen printing on PET, with embedded silver electrodes for admittance-based sweat rate measurement. The device is attached to the skin using a strap, making it suitable for integration with smartwatch bands or other wearables.

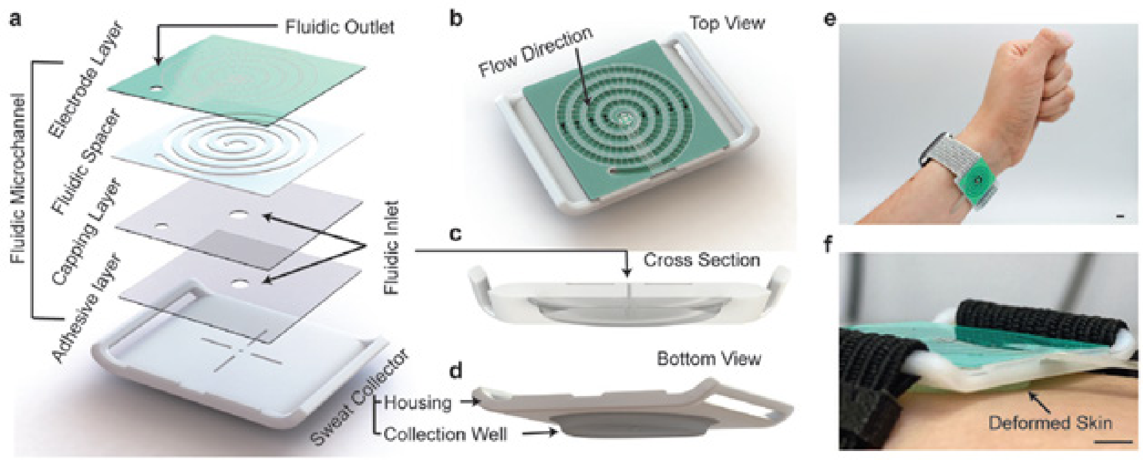

Figure 6.2.1. Tape-free 3D printed wearable sweat rate monitoring device. a) Layer-by-layer stack of the device structure including a top electrode layer with a fluidic outlet, a spacer layer defining the fluidic channel, a hydrophilic capping layer with an inlet, and an adhesive layer for attaching the stack to the sweat collector. b) Top view of the device showing the face-to-face comb-like electrode for admittance measurement. c) A cross-sectional view of the sweat collector showing a common fluidic inlet between the soft sweat collector and the hard housing. d) A bottom view of the skin interfacing sweat collection well. e) An optical image of the device mounted on a custom wristband worn by a subject. f) Minimal but essential skin deformation for conformal wearing of the device on the wrist. Scale bar is 1 cm.

Operation

Sweat accumulates in the collector and enters the microfluidic channel when the hydraulic pressure exceeds the inlet resistance. As sweat progresses through the channel, it bridges comb-like electrodes, causing discrete steps in admittance measured by an LCR meter or custom electronics. The number of electrode gates crossed per unit time is used to calculate sweat rate digitally and in real time.

Collector geometry (curvature, area) was optimized to minimize dead volume and ensure a watertight seal. Furthermore, fluidic channel dimensions were tuned for sensitivity and volume capacity.

Conclusions

The tape-free, digital wearable sweat rate sensor offers a comfortable, reusable, and accurate solution for continuous sweat monitoring during exercise. Its integration potential with commercial wearables and robust performance across subjects and body locations make it a promising tool for personalized hydration and health monitoring. Future work will focus on adding electrochemical analyte sensing and wireless data transmission for broader health applications.

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6.3 Wireless Sensor Platforms

Introduction

VTT has designed multiple flexible and stretchable wireless sensor platforms enabling sensor data acquisition in new applications that are not accessible via conventional rigid solutions.

The VTT flexible Bluetooth platforms target especially wearable applications. The realizations enable the transfer from conventional rigid electronics to flexible and stretchable solutions such as stretchable skin patches. In addition to wearable applications, item level monitoring and communicating packaging are potential application areas for flexible sensor platforms. In this application area we have worked with Near-field Communication (NFC) as the wireless protocol and realised the platform in a form of a smart datalogger label.

The sensor platforms

The VTT StretchNode (Fig. 6.3.1) sensor platform is realized on a stretch- able substrate using roll-to-roll printed silver conductors and pick and place assembly of components. The stretchable realization suits especially well for wearable applications from seamless skin contact to clothing integration. The StretchNode can further be encapsulated with elastomer overmoulding or lamination.

The VTT FlexDot (Fig. 6.3.2) is an ultra-compact skin-patch solution. The device packaging is fully waterproof but also breathable for optimal wear comfort. The FlexDot currently features BLE connectivity and 3-axis accelerometer and gyroscope functionalities and thus enables unobtrusive motion sensing in health and well-being applications.

The VTT FlexPot (Fig. 6.3.3) is an example of the electrochemical sensing platforms. Here, the FlexNode platform was complemented with potentiostat functionality and disposable electrochemical cell (Sweat-Strip) for applications such as sensing of biomarkers in sweat.

The VTT T-tag (Fig. 6.3.4) is an ultra-thin smart datalogger label for item level monitoring purposes in logistics. The T-tag is based on an extremely thin NFC Temperature monitoring IC for logging and communication.

Key features of some of the VTTs wireless platforms are presented below.

StretchNode features

- Roll-to-roll screen printed silver on stretchable TPU
- Automated roll-to-roll component assembly
- (including ACA & ICA dispensing)
- Demonstrator functionality:
- BLE-MCU
- 3-axis accelerometer
- continuous streaming of accelerometer data to mobile device over Bluetooth

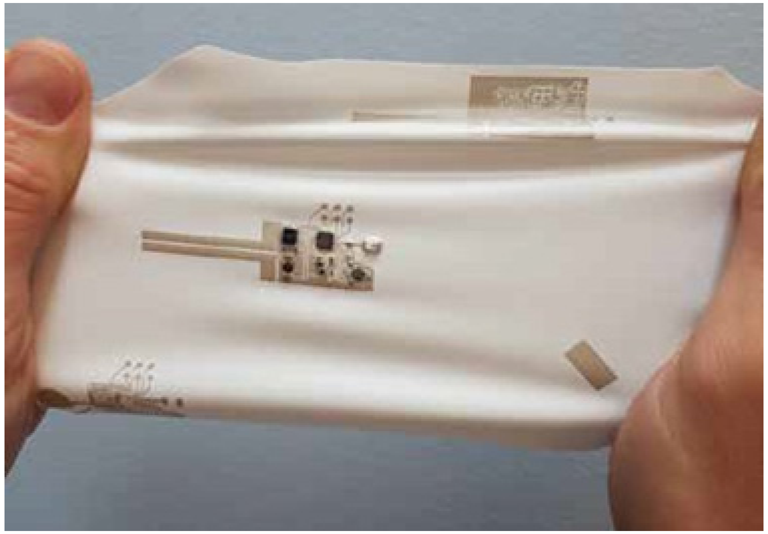

Figure 6.3.1. The VTT StretchNode sensor platform.

Figure 6.3.2. The VTT FlexDot sensor platform.

FlexDot features

- Ultra-compact smart skin patch
- Bluetooth data streaming to mobile devices
- 3-axis accelerometer and gyroscope
- Fully sealed but breathable encapsulation
- Skin-friendly adhesive

FlexPot features

- Platform on flex PCB
- Bluetooth LE wireless connectivity,
- Size 93 mm x 20 mm x 1.5 mm (tallest component apart the battery)
- Potentiostat
- Potential range -400 m. to 400 mV
- Current range nA – µA
- SweatStrip – the disposable strip for sweat collection and analysis
- Printed electrochemical cell
- Printed biomolecules
- Other integrated sensors:
- 3-axis acceleration
- Temperature
- Relative humidity
- Ambient pressure
- 25 mAh rechargeable LiPo battery (thickness 2.5 mm) with several hour battery life with continuous measurement

Figure 6.3.3. The VTT FlexPot - flexible potentiostat platform (left) for electrochemical measurements with disposable electrochemical cell (right).

T-tag features

- Ultra-thin NFC Temperature monitoring IC for logging and communication (h= 40 µm)
- Printed circuit on 50 µm PET or pape.
- Indicator LEDs for logging and threshold temperature indication
- A< 380 x 380 µm2 , h < 200 µm
- Flexible batterie. (2 x 1.5 V, 10 mAh, h ~ 500 µm)
- Theoretical shelf-life in stand-by mode 6 years
- 1 mAh consumed during storage
- Android application as user interface

Figure 6.3.4. The VTT T-tag - temperature logging label.

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A Conformal Wearable Multi-Lead ECG Patch

A Conformal Wearable Multi-Lead ECG Patch: Design for Roll-to-Roll Manufacturing; MH Behfar, E Jansson, KL Väisänen, D Nguyen, T Niemirepo, J Rekilä, M Hietala, T Alajoki; 2023 IEEE Biomedical Circuits and Systems Conference (BioCAS), 2023

A flexible, conformal 6-lead ECG patch has been developed using roll-to-roll printing and converting processes for scalable manufacturing. This hybrid system combines a disposable skin patch with reusable electronics, enabling continuous cardiac monitoring with improved comfort and cost efficiency.

- **Hybrid multi-lead ECG system:** The system integrates a flexible disposable patch with printed lead wires and electrodes, connecting with magnetic snap connectors to a reusable electronics unit that includes processing, Bluetooth communication, and data storage.

- **6-lead measurement capability:** The electronics utilize a biopotential frontend chip configured for two bipolar leads, with the remaining leads derived mathematically, enhancing diagnostic insight beyond single-lead devices.

- **Printed EMI shielding:** The patch incorporates printed electromagnetic interference shields protecting silver lead wires, ensuring high-quality signal acquisition in noisy environments.

- Roll-to-roll fabrication: Patch conductors and shields are printed in multiple registered layers on a stretchable TPU substrate using rotary screen printing, enabling high throughput and scalable production.

- Layer structure and materials: The patch consists of 10 printed layers including silver inks for conductors and electrodes, UV-curable insulators for electrical isolation, and EMI shields, resulting in a total printed thickness of approximately 143 µm.

- Automated integration process: After printing, the patch undergoes automated converting steps including electrode openings, skin adhesive lamination, carrier foil removal, laser cutting for connector vias, and final die cutting, followed by manual attachment of snap connectors and hydrogel electrodes.

- Performance validation: The system was tested on volunteers with clear, high-quality 6-lead ECG recordings demonstrating the device's potential for long-term ambulatory cardiac monitoring with enhanced user comfort.

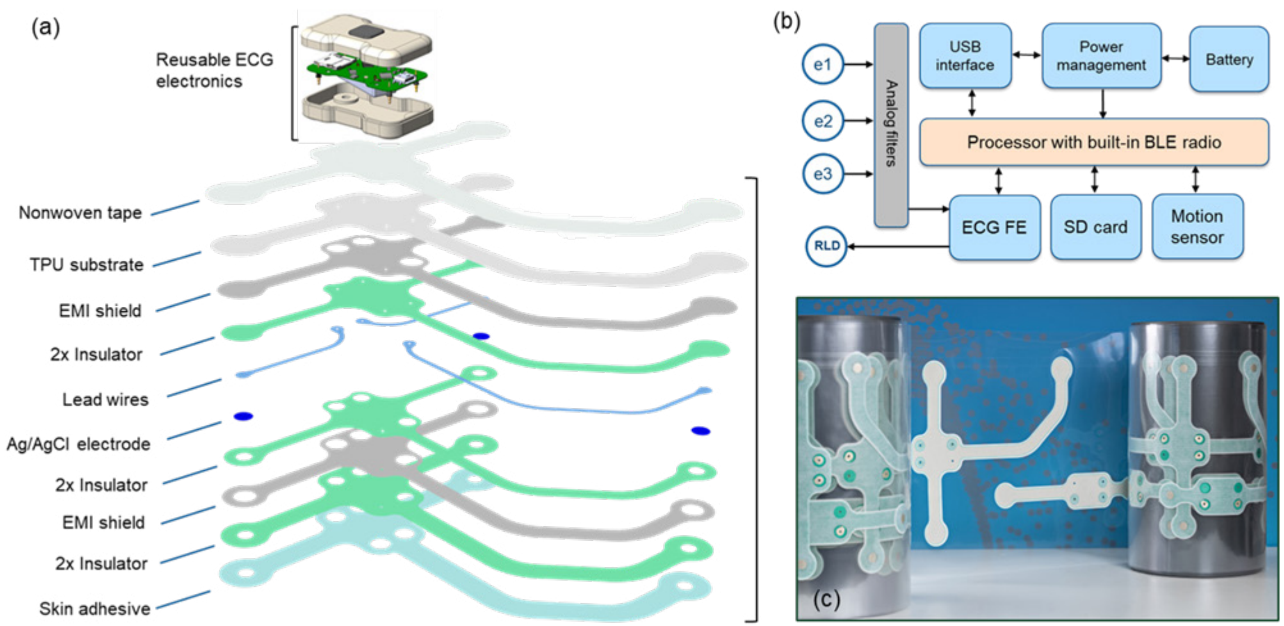

Figure 6.3.5. (a) Layer stack view of the multi-lead ECG skin patch. (b) System diagram of the electronics. (c) Roll-to-roll processed skin patch.

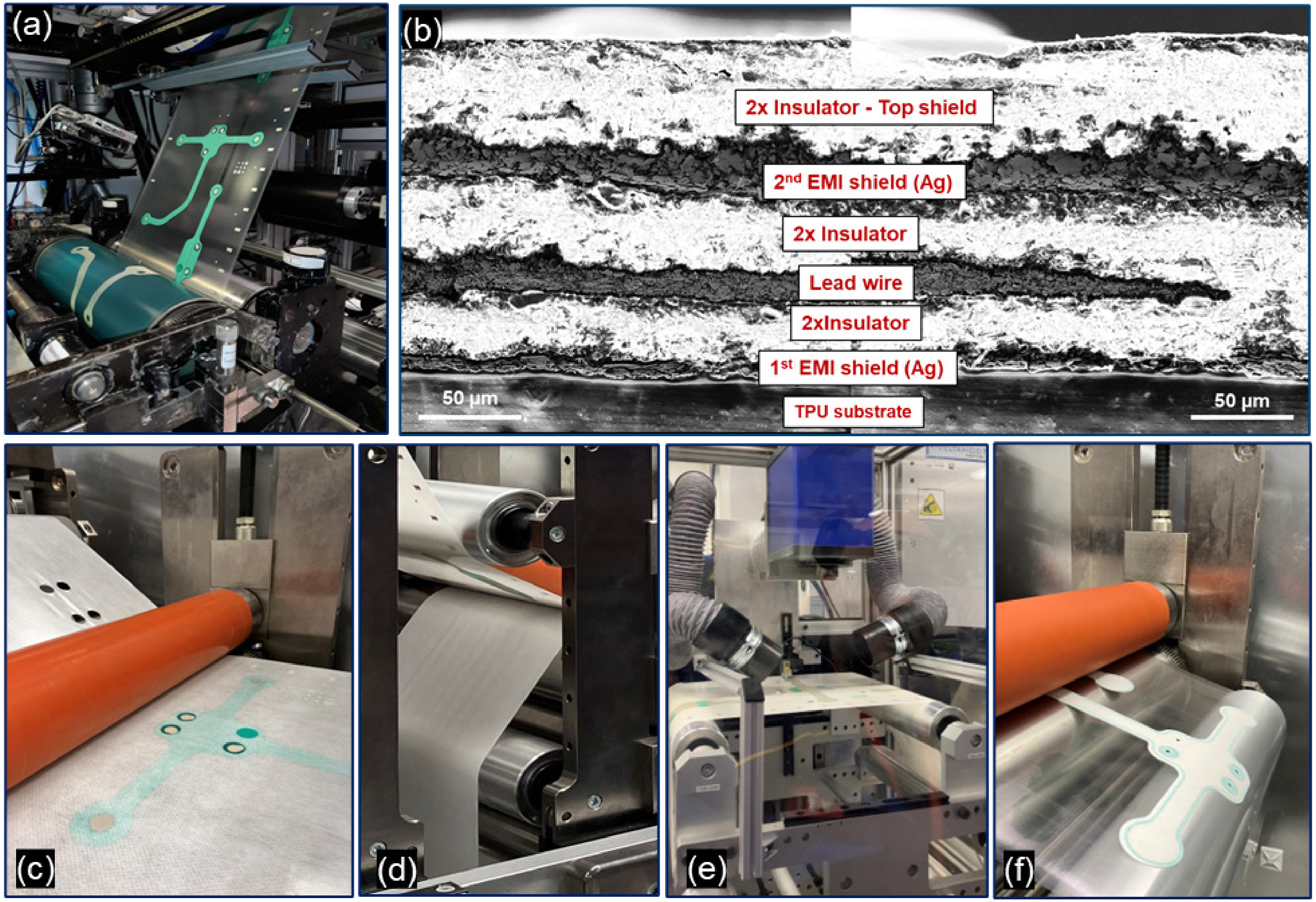

Fig. 6.3.6. (a) Rotary screen printing of the patch conductor and EMI shields onto stretchable TPU substrate. The final physical shield layer was printed with a UV-curable insulator. (b) Cross-sectional SEM images of the printed ECG patch from the middle of the lead wire (left) and near the printed edge of the lead wire (right). The magnification is ×500 and the scale bar is 50 µm. (c) Skin adhesive lamination. (d) Nonwoven tape lamination. (e) R2R laser cutting of the via holes. (f) Kiss cutting the patch outline.

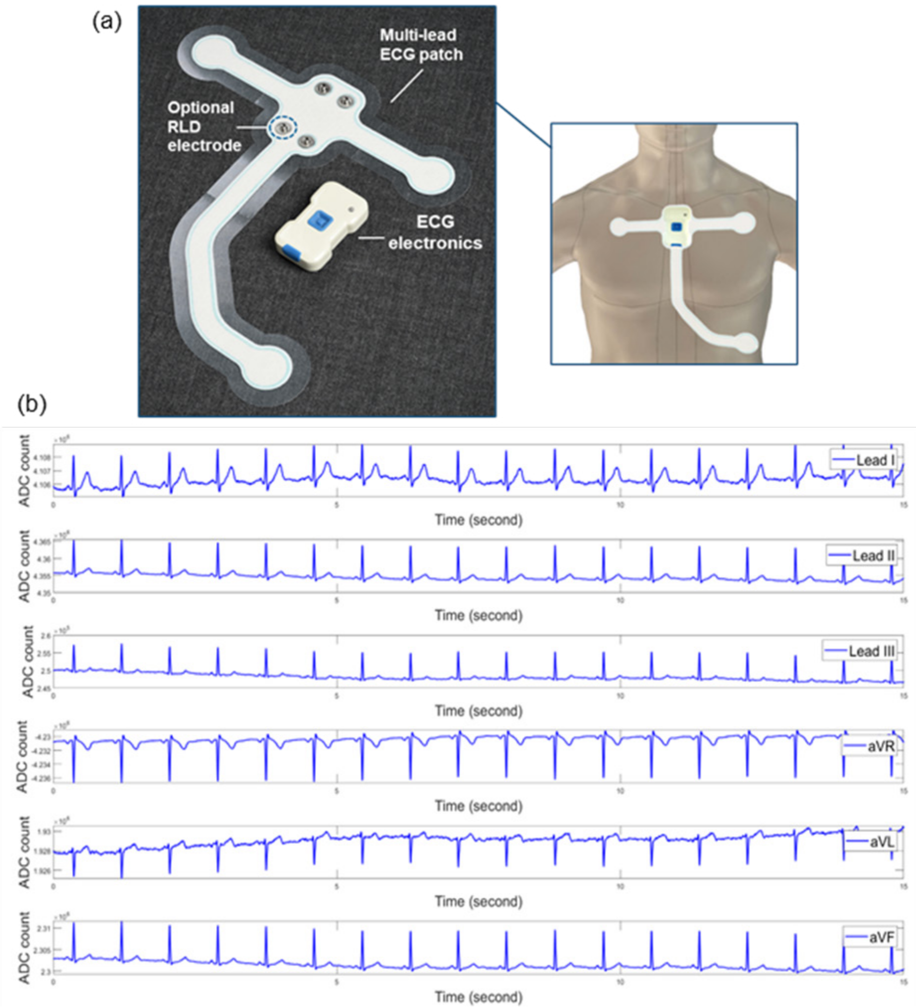

Fig. 6.3.7. (a) Fully integrated multi-lead ECG patch and the enclosed electronics unit. The subset illustrates the patch placement on the volunteer's chest. The use of the RLD electrode is optional. If the RLD amplifier is active, the 4th snap connector serves as the RLD electrode and is interfaced to the skin using the thin-film hydrogel. (b) Sample of 6-lead ECG recording with the developed system.

Fully integrated stretchable ECG patch

Fully integrated stretchable ECG patch demonstrates the feasibility of durable hybrid integration of rigid components on stretchable substrates. Direct assembly of conventional components on stretchable substrate promotes interposer-free sensor configuration. Manufacturing process is scalable and compatible with high-throughput roll-to-roll manufacturing. The ECG patch comprised of printed circuit on thin (100 µm) stretchable thermoplastic polyurethane (TPU), direct integration of microelectronic components such as low-power integrated ECG frontend chip and Bluetooth radio for wireless data streaming, and automatic converting processing with embedded froth foam technology and kiss-cutting method.

System design

- Substrate: Highly elastic, ultra-thin TPU film.
- Electronics: Direct circuit layout printing and component assembly on TPU using a sheet-to-sheet (S2S) process, compatible with roll-to-roll manufacturing.
- Components: Ultra-low-power Bluetooth-enabled MCU (nRF52832, ARM Cortex-M4), single-channel ECG frontend (MAX30003), powered by a 60mAh lithium coin cell (battery life up to 8 days).
- Software: Custom embedded firmware for ultra-low power operation and wireless data streaming to a mobile application.

Fabrication Process

- Printing: Stretchable conductive ink screen-printed on TPU using automated sheet-fed machinery.
- Component Bonding: Passive components bonded with isotropic conductive adhesive (ICA, silver epoxy); active components (MCU, ECG frontend) bonded with anisotropic conductive adhesive (ACA) and thermo-compression.
- Encapsulation: All discrete components encapsulated with UV-curable adhesive to enhance durability and direct strain away from sensitive regions.

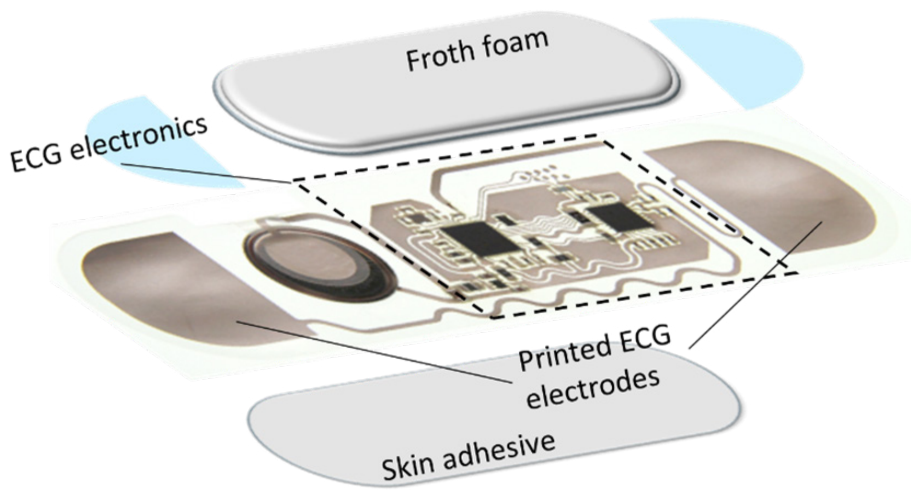

Fig. 6.3.8. Fully integrated stretchable ECG patch structure

Fig. 6.3.9. Fully integrated stretchable ECG patch on skin

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A Conformal Wearable Multi-Lead ECG Patch: Design for Roll-to-Roll Manufacturing, Mohammad H. Behfar*, Elina Jansson, Kaisa-Leena Väisänen, Dung Nguyen, Timo Niemirepo, Jari Rekilä, Mikko Hietala and Teemu Alajoki, 2023 IEEE Biomedical Circuits and Systems Conference (BioCAS). https://doi.org/10.1109/BioCAS58349.2023.10388735

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6.4 Hidden printed intelligence

Hidden or invisible printed electronics refer to electronic circuits and components that are integrated into surfaces or objects in a way that they are not or hardly visible to the naked eye. This technology combines printing techniques with functional inks to create electronics that blend seamlessly into their environment.

R&D case 1: Integration between glass

Glass surfaces are widely used in architectural applications such as windows, walls, and railings in public environments. Due to its transparency, durability, and aesthetic appeal, glass has become an attractive material for integrating printed electronics. This integration opens new possibilities for combining functionality with design, particularly in energy generation and smart surface solutions.

The LIWE Façades project exemplifies this approach by developing an architecturally innovative pilot location featuring graphical solar module façades. The concept incorporated solar modules symbolizing ice crystals through Chinese calligraphy, seamlessly integrated into glass façades. Each façade module measured 3.6 × 1.2 m² and contained 27 printed flexible OPV panels along with LED foil laminated between glass layers.

Structure and Design

Designing building-integrated photovoltaics (BIPV) requires careful consideration of layout, size, and shape specifications for organic photovoltaics (OPVs), as well as structural requirements such as thickness, flexibility, and environmental durability. Traditionally, PV systems have been mounted as separate structures in front of buildings. However, integrating PV directly into façades around windows offers greater design freedom.

Recent case studies highlight opportunities for innovation in BIPV design. Modular structures are essential to allow partial replacement and minimize material waste, especially since OPVs cannot be repaired during their lifetime. While lamination between glass layers enhances durability, it limits maintenance, upgrades, and recycling—posing challenges for circular economy principles.

Materials and Processing

Printed OPVs provide a lightweight, ultra-thin, and flexible solution manufactured using roll-to-roll (R2R) mass-production methods under ambient conditions. These panels weigh approximately 1 kg/m² and can be applied to rooftops or indoor/outdoor façades. Compared to conventional PV technologies and other thin-film solutions like CIGS or DSSC, printed OPVs offer:

Materials and Processing

Printed OPVs provide a lightweight, ultra-thin, and flexible solution manufactured using roll-to-roll (R2R) mass-production methods under ambient conditions. These panels weigh approximately 1 kg/m² and can be applied to rooftops or indoor/outdoor façades. Compared to conventional PV technologies and other thin-film solutions like CIGS or DSSC, printed OPVs offer:

- Design freedom for customized layouts
- Sustainable manufacturing processes
- Potentially very low production costs

Encapsulation between glass is considered the most effective method for extending product lifetime, ensuring durability against environmental stress. However, this approach reduces recyclability and ease of maintenance, requiring a balance between longevity and modularity.

Applications

Beyond energy generation, integrated glass solutions can deliver multifunctional benefits. The FlexInGlass project demonstrated this by laminating flexible LED foils with sensors and IoT connectivity inside glass panels. This innovation enables transparent, lightweight, and robust smart surfaces suitable for public environments such as transportation hubs and shopping centers.

Compared to traditional LED displays, the FlexInGlass concept offers:

- Cost efficiency
- Enhanced durability in harsh conditions
- New possibilities for interactive urban spaces

These advancements combine ecological, aesthetic, and technological value, strengthening customer engagement and satisfaction while paving the way for future smart city applications.

Figure 6.4.1. Glas-integrated photovoltaics

Figure 6.4.2. LED foil integrated into glass (KAISLA DEMO)

Large area flexible lighting element controlled by mobile phone user interface, Keränen, K., Ollila, J., Sarjanoja, E.-M., Yrjänä, S., Huttunen, A., Korkalainen, M. & Makkonen, P., 5 Dec 2016, Electronic System-Integration Technology Conference (ESTC), 2016 6th . IEEE Institute of Electrical and Electronic Engineers, p. 1-5. https://doi.org/10.1109/ESTC.2016.7764709

R&D case 2: Autonomous ski sensor

Introduction

The concept of a smart ski introduces a new era in winter sports by integrating an energy-autonomous sensor system into the ski structure. This system records vibrations during skiing and transmits the data wirelessly, enabling real-time feedback on ski performance. Such insights are valuable for both manufacturers and users, offering opportunities to optimize design and improve skiing techniques.

The Smart2Go project pioneered this innovation by developing the world's first fully roll-to-roll (R2R) printed, miniaturized, flexible, and autonomous energy management and supply platform. The ultra-thin structure of the final demonstrator measures only 1.4 mm in height, ensuring seamless integration without compromising ski performance.

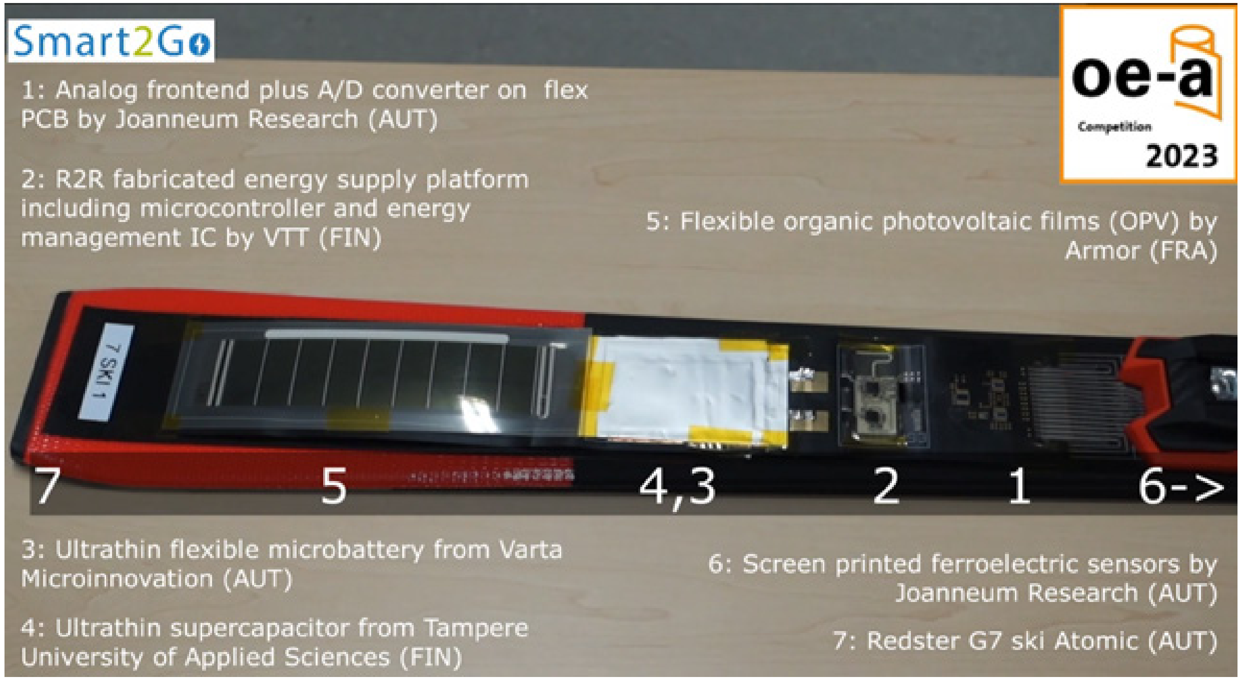

Figure 6.4.3. Smart ski

Structure and Design

The smart ski system is designed to be lightweight, unobtrusive, and fully integrated into the ski body. The sensor platform includes:

- Energy-autonomous architecture for self-sustained operation
- Wireless data transmission for real-time feedback
- Ultra-thin form factor (maximum height: 1.4 mm)

This design enables continuous monitoring of ski vibrations during downhill runs, providing precise data on ski behavior under actual conditions. The modular approach ensures adaptability for different ski models and user requirements.

Materials and Processing

The Smart2Go platform leverages printed electronics to achieve flexibility and miniaturization. Key printed components include:

- Conductive paths for electrical connectivity
- Printed electrodes and interconnections
- Printed piezo elements for vibration sensing
- Printed dielectric/insulator layers
- Printed organic photovoltaics (OPV) for energy harvesting

These elements are manufactured using roll-to-roll (R2R) processes, ensuring scalability and cost efficiency while maintaining high performance in harsh winter conditions.

Applications

The smart ski system serves multiple purposes:

- Performance Optimization: Provides real-time data for hobbyists and professional athletes to refine skiing techniques.
- Customization: Enables ski manufacturers to adapt designs to individual user profiles.
- Energy Efficiency: Operates autonomously without external power sources.
- Enhanced User Experience: Offers insights into skier movements, improving safety and enjoyment.

This technology opens new possibilities for data-driven sports equipment, contributing to smarter training methods and personalized skiing experiences.

Ref: https://oe-a.org/smart-ski

R&D case 3: Assembled platform integration inside acoustic foam

Introduction

Low density, highly porous fibre materials from wood cellulose fibres manufactured by foam forming technique can be efficiently applied in acoustic control (sound absorption) and thermal insulation. The real benefit of these materials lies in the easy recyclability and biodegradability compared to for example polyester fibre waddings, mineral wools etc.

Printed electronics is currently fabricated on PET films due to relatively good thermal and optical properties in relation to bulk avail- ability and costs. PET film in printed and hybrid electronics is made from virgin material i.e. from oil, although, recycled/bio-based PET is already available for some product areas. The substrate and encapsulant materials are the main source of CO2-emissions and, are influencing on waste management/recycling processes. To improve sustainability, performance and consumer acceptance of printed and hybrid electronics, alternative substrate materials are required. Use of alternative substrate materials in printed and hybrid electronics not only support climate actions, resource sufficiency and industrial renewal but also enable exploring materials with better technical properties and improving the user interface experiences.

Nevertheless, added value to novel porous bio-based cellulose fibre structures can be generated by embedding functional printed foils, such as antenna structures or printed LED components.

Interactive cellulose fibre acoustic panel

Today, most commercial acoustics, sound absorber panels are static without any interaction with the environment. VTT has developed an acoustic panel, which contains interactive multifunctional features. The panel is based on porous cellulose fibre technology developed and manufactured at VTT (Figure 6.4.4). In this technology, the porosity can be varied based on the manufacturing parameters, enabling thus changing the sound absorber properties. Interactive features (i.e. printed and hybrid intelligent electronics), such as LED light surface, touch and environmental sensors and IoT connectivity, can be produced on plastic, paper or metal substrate films using roll- to-roll (R2R) processes.

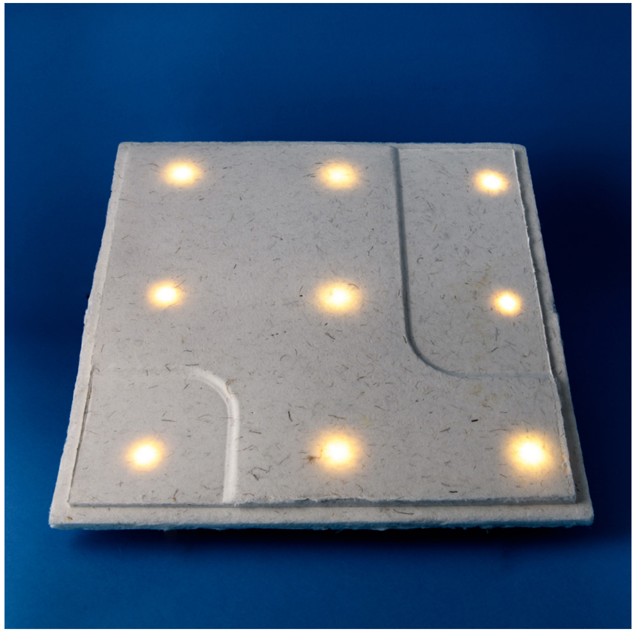

Figure 6.4.4. Cellulose fibre acoustic panel with LED lights.

Materials and Processing

The interactive film is embedded into the cellulose fibre based absorbing material during the foam forming process. Although the manufacturing is a water-based wet process with post-heating and pressure processes, it was found that the interactive film survives complete process flow. Besides the integration of sound absorber material and interactive film, it is essential to understand the effect on sound absorption performance. Based on the simulations of sound absorption, the influence of the position, perforation and thickness of the interactive film on the sound absorption coefficient was established. VTT's scientists were able to prove that sound absorption coefficient of the panel can be increased with the right selection of the panel structure.

VTT developed an interactive acoustic panel based on foam formed porous cellulose fibre materials and embedded RGB-LED display foil shown in Figure 6.4.4. The panel size is 38 cm × 38 cm and weighs 160 grams.

The porous cellulose panels were manufactured in higher volumes in order to realize large size interactive wall panel as shown in Figure6.4.5. Here, totally 90 individual addressable bright LEDs as light indicators were utilized.

The wall panel has overall dimensions of 1.32 m × 1.98 m. In addition, the grid-EYE infrared array sensor was included with the capability of detecting movement of people, which is illustrated by the LED panels.

Figure 6.4.5. Interactive wallpaper demonstrator.

https://www.vttresearch.com/en/news-and-ideas/sustainable-construction-materials

Roll-to-roll printed and assembled large area LED lighting element, Keränen, K., Korhonen, P., Rekilä, J., Tapaninen, O., Happonen, T., Makkonen, P. & Rönkä, K., 2015, In: The International Journal of Advanced Manufacturing Technology. 81, 1-4, p. 529-536. https://doi.org/10.1007/s00170-015-7244-6

R&D case 4: Media surface wall

Introduction

This chapter presents flexible LED lighting foil use-case in intelligent media surface wall. The main advantages of using printed/hybrid LED foils compared to conventional LED stripes are savings in manufacturing and labour costs. Utilization of R2R manufacturing and testing processing enables high throughput for 300 mm wide flexible hybrid electronics production. Conventional flexible electronics solution is based on 20 to 30 mm wide separate polyimide substrate stripes, which are installed separately on the media surface wall system. Typically, six flexible stripes are needed to build up a 300 mm wide LED lighting element system for media surface wall, which means that number of needed connectors can be up to six times more compared to an installation based on a 300 mm wide web. In addition, required work in media surface installation can be up to six times more compared to work in single 300 mm wide LED lighting foil installation.

Structure and design

An example of substrate layout design is shown in Figure 6.4.6. In this example the pitch of digitally controlled SMD RGB(W) LEDs is 50 mm. There are six LEDs in each row and all LEDs are connected in series in digital control bus. In addition, there are six connecting areas for capacitors in each component row on the layout design. Power supply lines are located at the edges of the layout design. Power line width is increased up to 10 mm to decrease line resistance and to ensure proper current feeding capacity to each component row in the 2.5 m long LED foil system. Digitally controlled RGB(W) LEDs operational voltage is limited to 5.5V, which leads to requirement of relatively high total current when high number of LEDs in the foil are controlled to produce white light with high brightness.

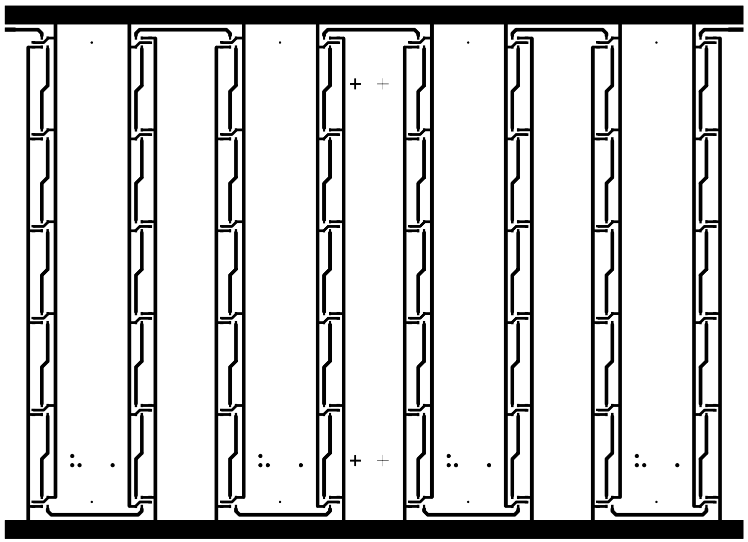

Fig 6.4.6. LED lighting foil layout design example for media surface wall

Materials and processing

Manufacturing stages for printed/hybrid LED foils include:

1. Continuous LED lighting foil substrate layout designed
2. R2R printing of the circuit
3. R2R testing of the printed substrate
4. SMD LEDs and capacitors assembled on substrate. Interconnections performed using Isotropic Conductive Adhesive (ICA) and mechanical bonding using Non-Conductive Adhesive (NCA).

Structure of the LED foil for media surface is based on flexible plastic substrate such as PET. Circuit patterning is done using rotary screen printing with silver ink (e.g. ASAHI 411AW). Assembly of components can be done in the R2R bonding line applying ICA for interconnects and NCA for mechanical bonding.

Applications

LED foil can be applied in various lighting and display applications. The media surface wall in this demo case was used in the elevator car by KONE (Figure 6.4.7). Other possible application areas are very large area displays and lighting elements, vehicle windscreen and window displays and architectural lighting elements in buildings.

https://www.eenewseurope.com/en/interactive-media-foil-integrates-leds-with-haptics/

Figure 6.4.7. Media surface wall in elevator car demo by KONE

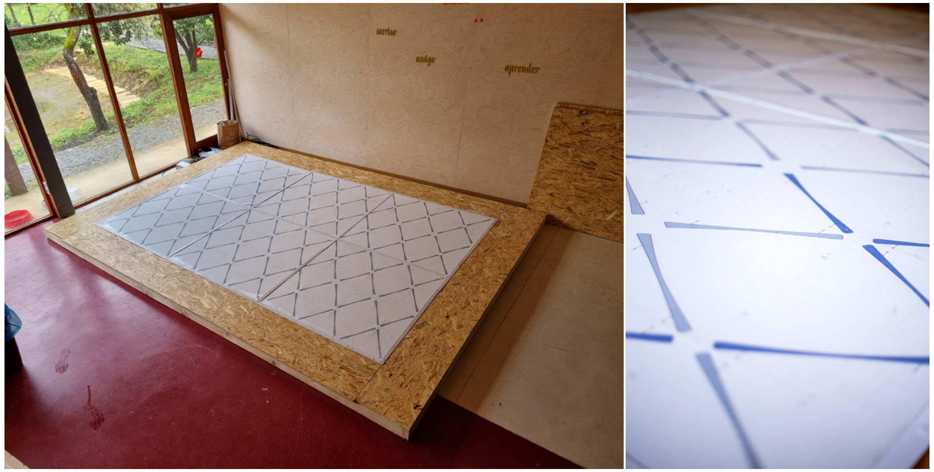

Figure 6.4.8.: High pressure floor laminates with integrated electrochromic display elements for floor patterns.

R&D case 5: Integration into high pressure laminates

Introduction

Within the DecoChrom project VTT extensive innovations went into the development of adaptive gym floor marking, where controllable electrochromic (EC) line markings were embedded into high-pressure laminate (HPL) flooring panels. The aim was to enable switchable sport markings for multipurpose indoor spaces. A pilot installation—integrated with a control system—was planned to allow markings for each sport to be turned on or off individually and then evaluated over several months of real usage.

Structure and design

The design phase involved contributions from multiple partners and focused on optimizing the layout of silver tracks, placement of electrochromic displays (ECDs), accessibility for electronics, and constraints of roll-to-roll (R2R) printing. Specific rules included limiting via placement and keeping interconnections on the rear side.

Several design iterations were created, involving variations in silver thickness and mesh type. A final geometric pattern—formed by repeated triangular units—was selected for the floor. The design also mapped how multiple panels would be assembled into a larger interactable gym floor with options for various floor-game patterns such as hopscotch, maze paths, or four-square layouts.

Materials and processing

Printing:
R2R screenprinting of PEDOT, silver tracks, and vias. Two major printing campaigns were carried out:

- Test 1: Scaleup trial with variations in PEDOT layers and connector types.
- Production 1: Full production run with optimized printing, including additional optical PEDOT layers for improved visual performance.

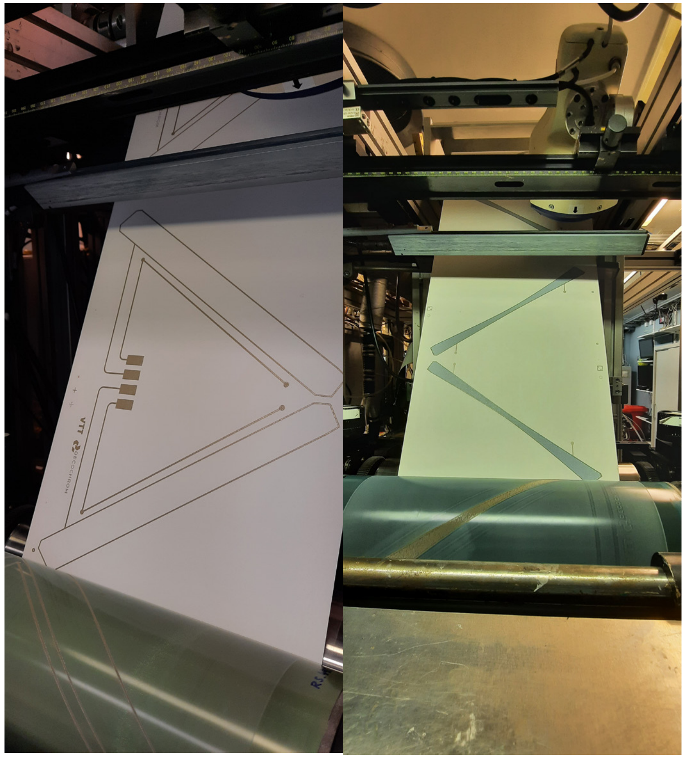

Figure 6.4.9: R2R printing of conductive traces (left) and PEDOT (right) for EC HPL elements.

Impregnation:
Due to high electrolyte cost, impregnation was done manually at Surforma. Both sides of the printed papers were impregnated and dried under ambient conditions.

Pressing:
Prepared layers—including kraft papers, decor layers, printed conductive sheets, and protected flat cables—were assembled and pressed under high temperature and pressure to produce the HPL laminates. Testing of different connector types showed that fully integrated “paper flat cables” yielded the best performance.

Assembly:
Final assembly occurred in Portugal, where laminates were bonded to MDF boards, electronic control components were integrated, wiring was connected to the embedded flat cables, and the system was mounted onto a wooden support structure.

Applications

The prototype uses an Arduino-controlled system with a custom Processing-based interface that allows users to design patterns and send display activation strings. A physical control box provides quick access to three predefined interactive game configurations:

1. Hopscotch
2. Maze game
3. Versatile four-corner playfield

Evaluation with children showed that the dynamic, color-changing markings attracted strong interest—especially the hopscotch pattern. The engaging and transformable floor suggests potential for future interactive playgrounds, educational spaces, sports halls, and adaptable training environments.

7

COMMERCIAL CASE EXAMPLES

PrintoCent

7.1 Illuminated IMSE® Emblem

TACTOTEK

TactoTek's Illuminated IMSE® Emblem demonstrates how brand elements can be transformed into ultra-thin, illuminated features using In-Mold Structural Electronics (IMSE®). The emblem integrates all lighting and structural elements—including optical features, LEDs conductive traces, and mechanical support—into a single molded part typically only 3–5 mm thick. The emblem delivers a uniform, daylight-visible glow while offering low power consumption, simplified construction, and significant design freedom for both exterior and interior automotive applications. Lighting effects can be static, dynamic, RGB, or fully programmable.

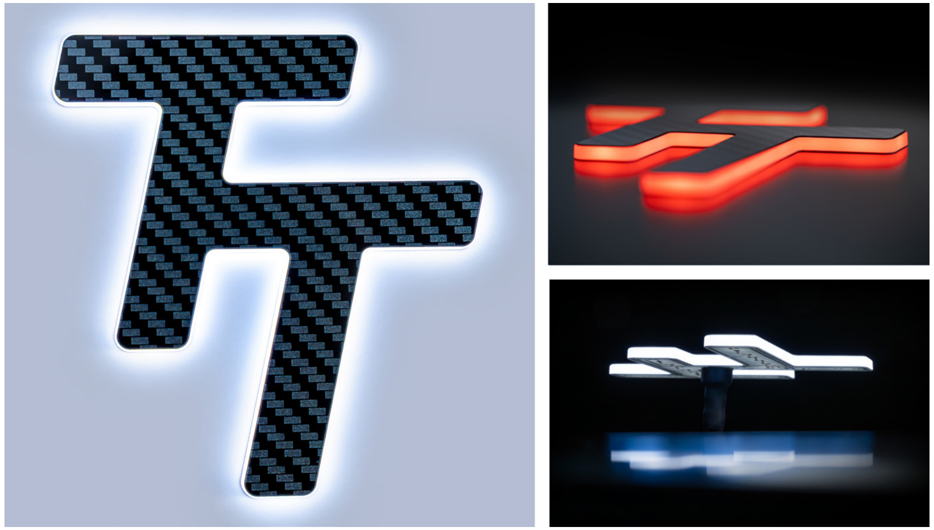

Figure 7.1.1. Illuminated IMSE Emblem
© TactoTek

Integrated Optical and Electronic Architecture

Inside the emblem, low-power surface-mounted LEDs are placed close to the light-emitting surface. The molded IMSE structure guides the light efficiently around the shape. This approach produces smooth, even perimeter illumination while notably improving efficacy (lm/W). Many IMSE emblem concepts meet OEM brightness targets with up to 50% reduced power consumption compared to conventional PCB-and-housing assemblies.

The demonstrator operates at just 1.5 W and delivers strong illumination—5,400 cd/m² in white and 970 cd/m² in red—all within an ultra-thin 3.8 mm structure weighing only 19 g. Despite its minimal profile, the electronics are fully sealed inside the plastic, ensuring reliable performance even under moisture, temperature changes, and vibration.

Thin, Seamless Construction

IMSE technology replaces multi-layer mechanical stacks with a monolithic surface that requires no bezels, light guides, fasteners, or deep cavities. Only a small connector pass-through is needed for installation on the vehicle. The emblem can be assembled with outside-in mounting approach, which simplifies packaging on hoods, grilles, liftgates, side panels, or interior trim, and enables illuminated brand signatures in locations that lack the space for traditional assemblies.

Automotive OEM (Original Equipment Manufacturer) development programs have reported weight reductions of 80–85% compared to existing emblem constructions, along with lower total part count, fewer sub-assemblies, and reduced thermal hardware thanks to higher optical efficiency. Figure 7.1.2. Shows a comparison of the IMSE structure with a similar emblem manufactured using conventional technology:

- **Conventional emblem construction**: Multiple stacked layers—front lens, light guide, LED PCB, backing structure, fasteners, wiring channels. Total weight 245 g.
- **IMSE emblem construction**: A single, molded part that combines surface graphics, optics, electronics, and structure. Typical depth: 3–5 mm with integrated LEDs. Only one connector pass-through required. Part weight 19 g (total weight with fixing features: 40 g).

Scalable Manufacturing

IMSE emblems are built through a standardized, high-volume process chain: conductive ink printing, SMT component placement, film thermoforming, and injection molding. These steps are backed by validated design rules, CAD guidelines, optical and thermal simulation tools, and automotive-grade materials that ensure durable performance in interior and exterior environments.

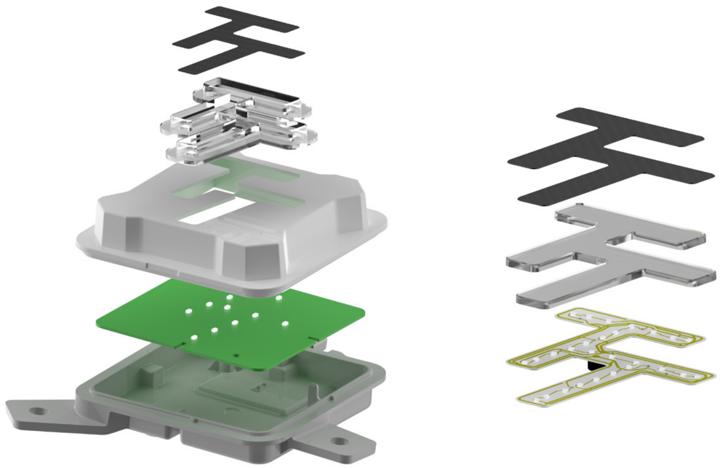

Figure 7.1.2. Comparison of an emblem built with conventional technology (on the left) and IMSE technology (on the right).

https://www.tactotek.com

7.2 Electricity Integrated – Flat and Flexible Solutions for Power and Data

NEW CABLE CORPORATION

Figure 7.2.1. Connectorless shielded flat flexible cable
© New Cable Corporation

Introduction

This section introduces the concept of flat and flexible cable technology—a new way to distribute power and data efficiently within modern electrical and electronic systems. Flat cables offer practical solutions to many long-standing design challenges such as weight reduction, space optimization, and system simplification, while enabling cost savings and sustainable material use in high-volume manufacturing.

New Cable Corporation specializes in the design and development of these advanced cable solutions. As a fabless company, our strength lies in material knowledge, electrical design, and system-level understanding. Our cable concepts can be realized through roll-to-roll (R2R) and sheet-to-sheet (S2S) manufacturing for large-scale production. In high volumes, the technology's material efficiency and lightweight structure create measurable economic and environmental benefits.

Flat and flexible cables are available in both shielded and unshielded configurations, supporting the transmission of data, power, or both in a single, low-profile structure. While the development phase requires careful design work and close consideration of materials and performance, the investment pays off through simplified assembly, reduced system cost, and improved product reliability.

This chapter provides an overview of the main design considerations when applying flat and flexible cables, including connector options, standards, data and power characteristics, thermal performance, materials, and environmental factors. Together, these elements define how electricity can be distributed more intelligently—flat, flexible, and efficient.

Connectors and Connectorless Design

Connectors are a well-known challenge across all types of cabling—whether round, flat, or printed. They often determine the limits of performance, reliability, and ease of assembly. Mechanical wear, contact resistance, and power-handling capacity can all affect system reliability over time. When adapting connectors for flat and flexible cables, these general issues remain, but additional considerations such as surface geometry and contact alignment come into play.

Standard through-hole and surface-mount (SMT) connectors can often be adapted for flat cables, though power capacity and mechanical compatibility are typical constraints. Some connector families originally designed for round cables can be modified for flat geometries, while others with naturally planar contact surfaces are already suitable without major redesign. The connector landscape continues to evolve, and new components optimized for flexible cabling are introduced each year.

An emerging alternative is the connectorless design approach, where the cable itself becomes part of the electrical interface. In this method, the flat cable is directly laminated or bonded onto the target device or structure—such as a structural panel, sensor module, or control board—creating a continuous electrical path without traditional connectors.

Connectorless integration provides several advantages:

- Improved reliability, as there are no solder joints or connector interfaces to loosen, corrode, or oxidize
- Reduced assembly complexity and cost, particularly in automated production
- Enhanced miniaturization, enabling compact and lightweight product designs

In practice, hybrid solutions are often the most effective: some parts of a system use traditional connectors for serviceability, while other sections employ connectorless transitions for integration and reliability. This flexible approach allows designers to balance performance, manufacturability, and maintenance needs according to each application.

Standards, Certifications, and Regulations

Flat and flexible cables can be designed either in compliance with existing industry standards or as custom solutions developed for specific applications. In many cases, the design principles follow the guidelines of the IPC standards, which are widely used in the printed circuit board (PCB) and electronics manufacturing industries. Applying IPC-based design rules ensures traceability, material reliability, and compatibility with established manufacturing and quality systems.

However, the flexibility of flat cable technology also allows for designs beyond traditional standard frameworks. This can be necessary when developing novel interconnect concepts or integrating cables directly into mechanical structures, textiles, or other unconventional substrates. In such cases, performance validation is achieved through application-specific testing rather than predefined cable standards.

Each industry—such as automotive, medical, aerospace, and building technology—has its own set of requirements and regulatory frameworks. These define everything from flammability and insulation strength to biocompatibility, electromagnetic compatibility (EMC), and environmental durability. With the right material selection and design control, flat and flexible cables can fulfill nearly all certification and regulatory needs across these sectors.

Because standards, certifications, and regulations are tightly linked, early collaboration between design, testing, and compliance teams is essential. This approach not only ensures conformity but also speeds up approval processes and helps avoid costly redesigns later in the project lifecycle.

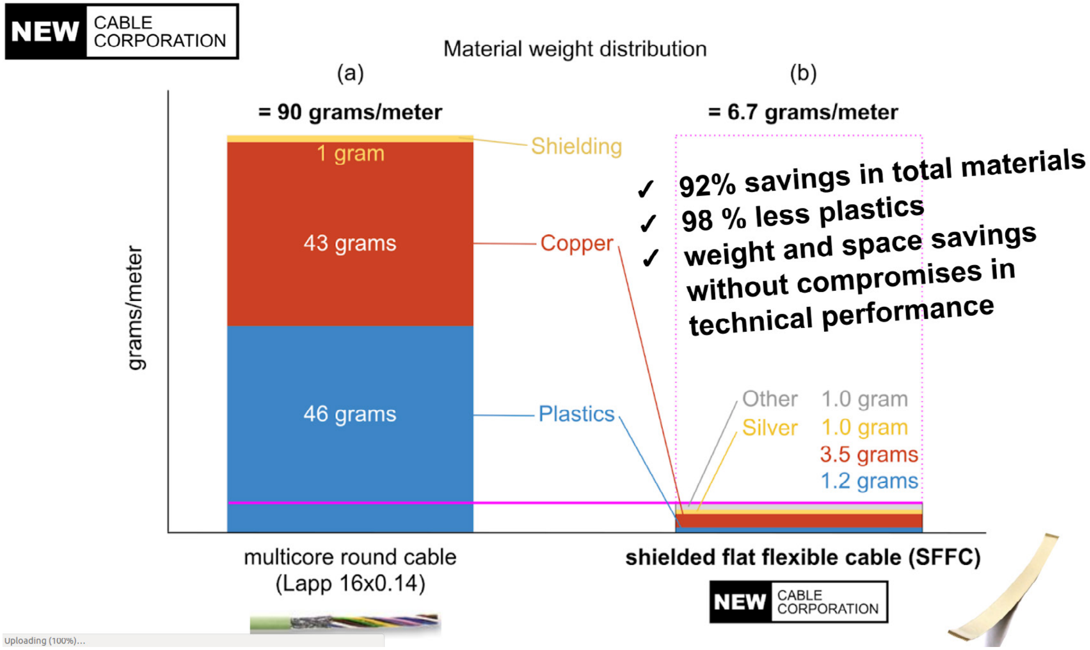

Figure 7.2.2 Mass comparison of multicore round cable and shielded flat flexible cable
© New Cable Corporation

Data and Signal Transmission

Flat and flexible cables enable efficient transmission of data and high-frequency signals across a wide range of applications—from control and sensor systems to radar and wireless front ends. By combining precise geometry control with tailored material properties, the same basic cable platform can serve digital, analog, and RF systems with high reliability and low loss.

When manufactured using copper conductors, flat cables can reliably handle signal frequencies up to 30 GHz in practical applications. For even higher frequencies, waveguide-based designs are under active development, extending the operating range toward 200 GHz. These ultra-high-frequency concepts are particularly interesting for radar, imaging, and advanced communication systems, where flexibility and integration with mechanical structures can bring major advantages in weight, form factor, and cost.

A major strength of the flat cable concept is its built-in impedance control. By adjusting the trace geometry and the dielectric thickness that separates the signal layer from its shielding or ground planes, the impedance can be finely tuned to match the system requirements—whether replicating a twisted-pair, coaxial, or stripline configuration. This allows direct replacement of traditional round cables with predictable and repeatable performance, while maintaining a thin and lightweight profile.

As in most high-speed systems, connectors often define the practical limits of data transmission. Mechanical tolerances, parasitic inductance, and discontinuities can all degrade signal integrity at higher frequencies. To overcome this, New Cable Corporation has developed connectorless interconnect solutions that create a direct transition between the flat cable and the mating circuit. This approach eliminates many sources of reflection and loss, enabling stable and high-speed signal paths without the need for bulky RF connectors.

Together, these features make flat and flexible cables a viable platform for both power and signal distribution, extending from low-frequency control wiring to advanced millimeter-wave data and radar applications.

Power Transmission

Flat and flexible cables are well suited for power distribution, combining electrical performance with mechanical adaptability. Their planar geometry allows efficient current flow while minimizing weight and thickness—ideal for vehicles, buildings, and industrial systems where routing space is limited and current levels are high. In addition to performance advantages, flat cable structures enable significant cost reductions through material savings, simplified assembly, and high-volume manufacturability.

Flat cables can be manufactured using various conductor materials and thicknesses, most commonly copper or aluminum. In practice, there is hardly any electrical limit—only mechanical flexibility defines how thick or wide the conductors can be. Conductors can be built as single-layer or multilayer structures, and by adjusting the layer count, width, and thickness, both high-current and low-voltage applications can be efficiently served.

Design formulas and practical estimation

A practical way to estimate continuous current capacity is to start from the cross-sectional area and an allowable current density:

$$I \approx J_{allow} \times A$$

where

I is the continuous current (A),

A is the conductor cross-section (mm^2) = width × thickness, and

J_{allow} is the allowable current density (A/mm^2), depending on the cooling environment and acceptable temperature rise.

To complement this, designers can use the heatsink relation to account for thermal performance:

$$\Delta T \approx \frac{P_{loss}}{A_{surf} \times h}$$

where

ΔT is the temperature rise (°C),

Ploss = I2R is the power dissipated as heat,

Asurf is the exposed surface area (mm^2), and

h is the convective heat transfer coefficient ($W/m^2 \cdot K$).

By combining these two equations—cross-section sizing for electrical limits and the heatsink relation for thermal balance—designers can estimate current capacity with good practical accuracy.

Heatsink effect — why flat wins

A key advantage of flat conductors is the heatsink effect: heat generated by I^2R losses spreads over a large planar area and can be conducted into the surrounding structure or dissipated to ambient more effectively than in round conductors. In practice this means:

For the same copper cross-section, a flat cable often tolerates a higher continuous current (i.e., higher effective J_{allow}) than a bundled round wire because of superior surface-area-to-volume ratio and better thermal contact with surrounding materials. Flat geometries coupled to good thermal paths lead to much better thermal stability and continuous-current capability.

Example: high-current flat cable

In laboratory testing, New Cable Corporation evaluated a flat power cable constructed from three layers of 200 µm copper, each 50 mm wide, insulated with a 1 kV shrink tube. The cable was 4 meters long and tested under AC load conditions. The results demonstrated that this flat equivalent of AWG00 easily handles 300 A continuous current with moderate temperature rise. At 400 A, the temperature rise stabilized between 40–50 °C above the 20 °C lab ambient, and 500 A operation was achievable for short durations (about one minute). These results confirm the exceptional thermal performance and heatsink efficiency of flat conductor designs compared with traditional round cables of similar cross-section.

Voltage and insulation

Insulation in flat cable constructions is highly adaptable. With the right dielectric spacing and materials, insulation levels up to 10 kV are achievable, while standard designs routinely withstand 1.5 kV tests. The ability to choose between different insulating materials—such as polymer films, laminates, or shrink coatings—provides design flexibility across diverse environments and regulations.

Connectors and transitions

As with data transmission, connectors can limit power performance due to contact resistance and localized heating. Connectorless transitions, where the flat cable is directly bonded or laminated onto the power bus or device structure, eliminate these losses and further improve reliability. In high-current systems, this approach also reduces mechanical stress and thermal hotspots, enabling more stable and maintainable installations.

Materials and Environment

Material selection defines nearly all physical, electrical, and environmental characteristics of flat and flexible cables. The choice of conductor, dielectric, and protective layers determines not only performance but also cost, manufacturability, and long-term reliability in the target environment.

Substrate and dielectric materials

Polyethylene terephthalate (PET) is among the most common and reliable dielectric materials used in flat cables. It provides a good combination of mechanical flexibility, thermal stability, and electrical insulation. PET is also available in numerous grades—recycled, flame-retardant, or high-temperature formulations—making it suitable for both high-volume industrial use and sustainability-driven projects.

Polyimide (PI) offers excellent thermal resistance and is commonly used in high-performance electronics. However, PI tends to absorb moisture, which can cause dielectric degradation or arcing under high voltage or humid conditions. This must be carefully considered when selecting materials for environments with varying humidity levels.

Beyond traditional polymers, almost any plastic or silicone-based material can be adapted for flexible cable construction, depending on the mechanical and chemical requirements. Innovative materials such as stone-based foils and ultra-thin glass laminates expand the design space even further, providing robust yet flexible surfaces with distinctive thermal and dielectric properties.

Conductors and coatings

The main conductor materials are copper and aluminum, both available in a wide range of thicknesses depending on current and flexibility requirements. Copper offers low resistance and excellent mechanical stability, while aluminum provides a lightweight and cost-efficient alternative for high-volume designs.

Surface treatments and coatings can further enhance performance and durability. Options include immersion silver, nickel or tin coatings, and advanced atomic layer deposition (ALD) coatings for precise barrier or surface control. These coatings improve corrosion resistance, solderability, and, in some cases, thermal and electrical efficiency.

Matching materials to environment, cost, and sustainability

Ultimately, the operating environment defines the optimal material combination. Factors such as temperature, humidity, chemical exposure, UV radiation, and mechanical stress influence the lifetime and safety of the product. A design optimized for an industrial robot arm may differ entirely from one intended for a building's embedded power grid or a lightweight aerial platform.

Material selection also drives economic and environmental performance. The flat structure inherently reduces material use, while recyclable or renewable materials, such as PET and aluminum, enhance sustainability. Additionally, energy efficiency improves throughout the product's lifecycle: lower resistive losses reduce heat generation during use, and simplified material layering allows easier separation and recycling at end of life.

Applications and Use Cases

Flat and flexible cable solutions bring measurable advantages across multiple industries. In vehicles, they enable lightweight power and data distribution with optimized routing through narrow spaces, reducing both wiring complexity and total vehicle mass. In buildings, flat cables simplify integration into walls, floors, and facades, offering clean installations with minimal material use and improved serviceability. In medical technology, the same principles support compact, hygienic, and reliable connections for diagnostic and therapeutic devices, where flexibility and space efficiency are critical. Regardless of application, the combination of design adaptability, high data and power capability, and scalable manufacturing—from roll-to-roll to sheet-to-sheet processes—makes flat and flexible cables an efficient and future-proof solution for both technical and economic challenges.

The right balance between performance, cost, and environmental compatibility is the key to successful product design.

Figure 7.2.3 Test of 300 A flat flexible cable

www.newcablecorporation.com

7.3 Movesole Smart Sensing

Force Sensors Enable Smart Industrial Systems

Industrial sensing is shifting from traditional measurement and diagnostic approaches toward predictive operation models. Rather than collecting isolated data points or analyzing combined sensor outputs, modern industrial systems rely on continuous condition monitoring and early-stage detection of performance changes. The goal is to identify trends in operating behavior, anticipate failures, and support pre-scheduled maintenance actions.

This evolution also changes how sensor data is processed. High-performance industrial environments increasingly require analysis at the edge, directly where the data is generated. Processing data locally reduces latency, improves reliability, and ensures that only essential information is forwarded to higher-level systems and decision-making procedures. Force-sensing technologies fit naturally into this new landscape, offering excessive sensitivity to mechanical changes and enabling accurate, real-time assessment needed to predictive maintenance workflows.

Movesole Smart Sensing Technology

Movesole Smart Sensing system is based on a power-free ferroelectret sensor technology, where flexible, permanently charged polymer foams with cellular structures act as highly sensitive detectors. The material generates an electric response to dynamic mechanical forces, enabling precise measurement of pressure and vibration.

A distinctive capability of the Movesole sensor system is its ability to measure forces and vibration directly between two surfaces. This enables installation in locations where conventional sensors cannot operate – such as placing the sensor between an industrial engine and its vibration isolation material – capturing the true mechanical interaction at the interface.

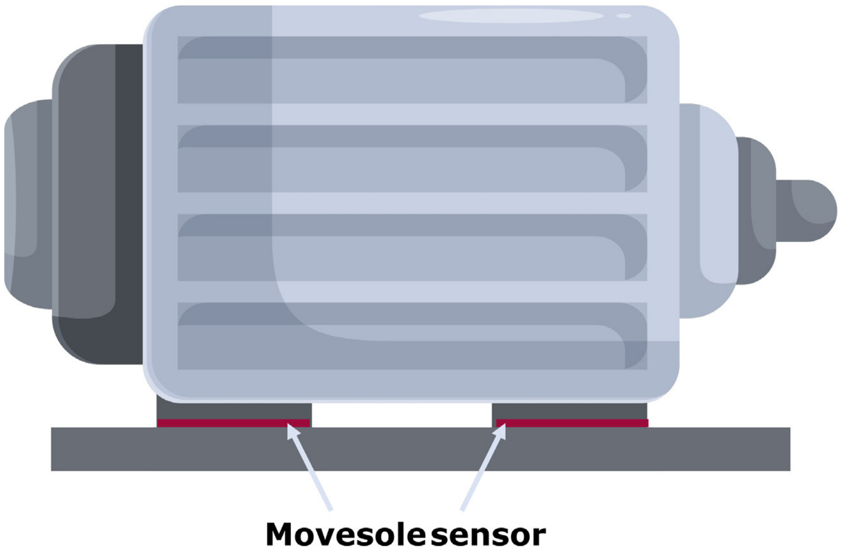

Figure 7.3.1. Movesole sensor system placed between an industrial engine and the underlying surface.

The Movesole sensor system supports a sampling range of 10 – 10 000 Hz, providing high-resolution data on both low-frequence structural changes and high-frequence vibration signals.

Movesole force sensor material – key properties:

- High-performance sensor material
- Ultra-flexible and adaptable to various environments
- Exceptionally durable for long-term industrial use
- Highly sensitive even to small dynamic force changes
- Linear response across the measurement range
- Instant reaction to dynamic load and vibration

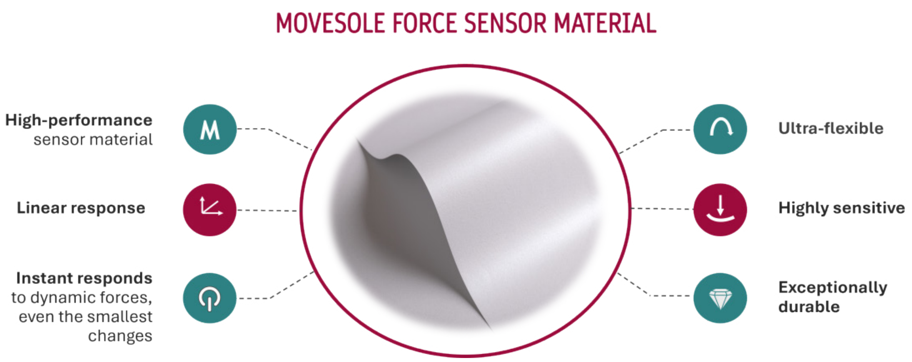

Figure 7.3.2. Movesole force sensor film.
© Movesole Smart Sensing

Use Case for Predictive Maintenance

Local data processing is fully supported: the Movesole sensor system delivers high-quality, extensive raw data that can be analyzed directly at the measurement point. This enables immediate detection of changes in operating behavior and supports predictive maintenance workflows.

By continuously capturing force and vibration signals at the interface between an industrial engine and its surrounding structures, the Movesole sensor system can detect incipient faults such as imbalance, alignment drift, or abnormal load transfer. Subtle variations in amplitude or frequence content can be identified long before they escalate into functional faults.

Local signal processing for feature indentification with Movesole sensor system reduces data volume and emphasizes only the most meaningful condition indicators. By focusing on amplitude trends, frequency-shift signals, or long-term drift patterns directly at the sensing point, the Movesole system can transmit compact, high-value information rather than solely raw data streams. This processed information can then be forwarded for further evaluation.

With this approach, the Movesole sensing system becomes an active part of the industry's maintenance procedures:

- Minimizing unplanned downtime
- Improving operational safety
- Allowing maintenance actions to be executed precisely when needed rather than on fixed intervals

End-to-End Capability for Sensor-Based Prototypes and Products

Movesole offers full-stack development capability for sensor-driven devices – from the company's material innovation to complete system integration.

Building the final solution begins at the core: charging and configuring the proprietary sensor material to achieve the required sensitivity, accuracy, and mechanical performance. From there, sensor structures, electronics, embedded software, software interfaces, and mechanical integration are designed and implemented as a whole solution.

This end-to-end approach enables delivery of functional prototypes and production-ready solutions optimized for real operating environments, ensuring high performance, reliability, and seamless integration into customer systems.

www.movesole.com

The Warming Surfaces Company

7.4 Sustainable warmth for people with Halia® radiant warming technology

Introduction

Halia® radiant warming can transform almost any surface into a smart warming surface. The ultra-thin metal mesh is produced in a high-volume R2R manufacturing process using a series of converting techniques in use within the printed intelligence industry. Because of its thinness and flexibility the structured metal tracks integrate seamlessly into an increasing range of materials, including porous materials like paper or fabrics, which are a challenge to conventional printed heaters. Combined with smart electronics and driving, Halia® warmers are an energy-efficient, and cost-effective way to create comfort and warmth invisibly from surfaces in our living spaces.

With Halia® warming technology, warming can be incorporated into places where previously not possible. The unique benefits Halia digital warming surfaces offer to the user are:

- Comfortable, even, and healthy warmth
- Fast response
- Energy savings and possibility for emission-free warmth
- Thin light weight form factor, with significant materials savings compared to alternative heating technologies
- Seamless product integration

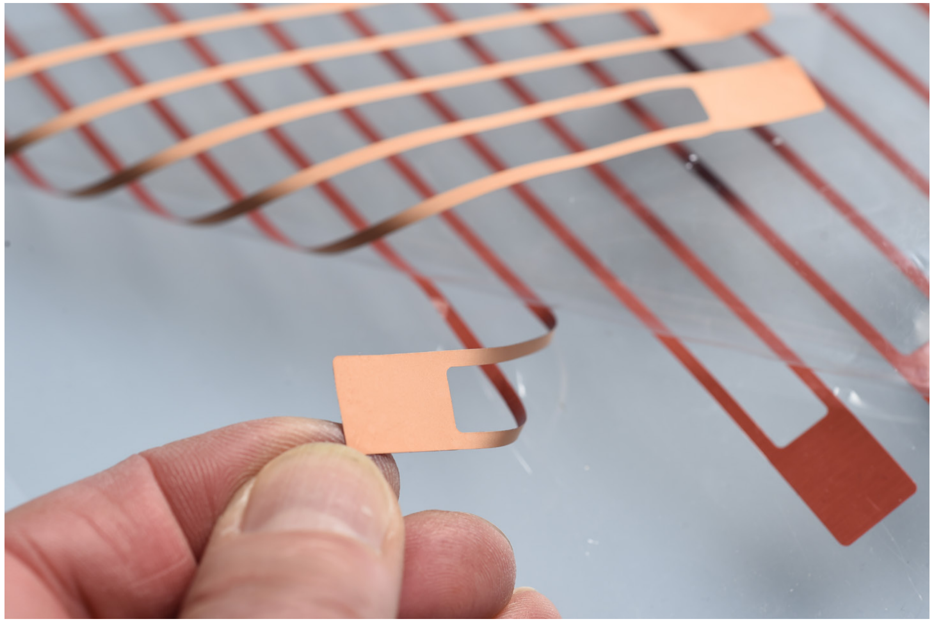

Figure 7.4.1. Ultra-thin, flexible Halia® heating tracks.
© The Warming Surfaces Company

Technology overview - control heating fast like you control lights

The Halia® warming effect is generated by ultra-thin (9-12 micron) resistive metallic tracks, which heat up when electrical power is applied. The bulk grade metal tracks require no plastic carrier films. The ultra-thin plastic free form factor allows them to be embedded into surface materials without adding noticeable weight or changing the appearance of the original material.

Halia® warming is based on radiant and conductive heat. At best Halia warming elements are placed inside the top-surface material. Close to surface the heat response is fast and controlling of heating becomes near real-time and as effortless as controlling lighting. Halia warming surfaces can be further optimized for directional control of the warmth: maximizing heat in the direction where the heat is needed and minimizing leakage of energy to undesired locations.

Halia® technology enables designing warming into products. The heating elements can be applied in standard sizes or designed for specific application cases and controlled according to the end-use specification. The warming surface can be divided into smaller separately controllable ”heat-pixels”. This allows regulating temperatures across the surfaces.

The system uses low voltage (typically ≤ 48V DC), which makes it safe to operate inside different materials and products.

Integrating warming into large area surfaces helps realize the benefits of radiant heating not achieved with conventional bulky small area radiators. In large area format radiant heating is more energy efficient and healthier than conventional convection heating, which is based on heating an entire mass of air and thereby indirectly heating people and objects through the air. Further benefits include:

- Ultra-thin & flexible à integrates invisibly into structures and no additional heaters needed
- Space saving → replaces bulky heater units
- Easy integration & installation → no separate bonding films needed, cost savings
- Digital & low voltage → intelligence, energy savings and safety
- No rare-earth metals, only small amounts of recyclable metals → sustainability
- Scalability through high volume manufacturing → availability, cost savings

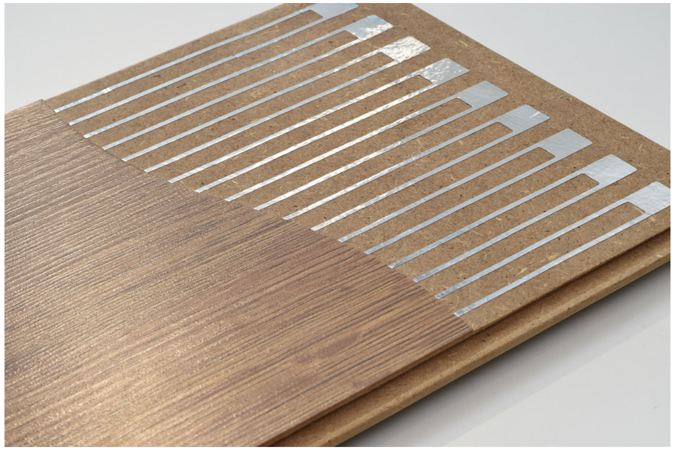

Figure 7.4.2. Halia® warming tracks integrated into top surface of a HPL (high-pressure laminate) structure.
© The Warming Surfaces Company

Manufacturing and materials

Halia® warming tracks are produced using a patented roll-to-roll (R2R) manufacturing process, where thin metallic layers, typically brass, copper or aluminium, are patterned continuously on a flexible substrate. This method is suitable for high-volume, consistent production of the ultra-thin and evenly conducting heating elements. The processing itself uses very little energy as no curing stages are required. The finished tracks can be delivered as sheets or rolls, which are then integrated onto the material of choice. The flexible support material needed in manufacturing is removed and only the metal tracks remain in the final products. The first commercially available material with Halia® warmth is high-pressure laminate (HPL) which is widely used in building and transport vehicle interior, as well as furniture.

Environmental impact and sustainability

The principles of circular economy are applied in the design of Halia® warming; minimal use of materials, minimal energy consumed. The Halia warming technology offers several measurable positive environmental impacts:

- Each application development needs to show a minimum of 20% energy savings, but in some applications, energy savings are more than 80% (e.g. replacing gas heaters in restaurant terraces)
- possibility for zero in-use emissions of heating when renewable energy is used
- using only a small fraction of common metallic materials compared to conventional heaters
- very low energy consumption in manufacturing

The Halia team helps customers grow their carbon handprint, to reduce energy and resource consumption of heating in living spaces. Together with our customers we develop the final products and business to follow circularity. For example, Quatro tables are designed to last long by choosing durable materials for tabletop and leg, the parts can be refurbished,
updated and recycled in the end of life. We offer a subscription model for restaurants.

Figure 7.4.3. R2R production of Halia® heating elements.
© The Warming Surfaces Company

Our core company value is sustainable warmth. We are committed to building a sustainable company in all its forms: well-being, social, environmental, business. We have selected four UN development goals to focus on, we calculate our carbon footprint yearly and we have an environmental program.

Commercial applications – first product Quatro warming table

Halia® warming technology enables a paradigm shift in how we bring warmth to living spaces. It allows essentially an emission-free way to effectively warm people instead of the planet. For architects and designers, there is an entirely new playground to explore heating of living spaces be it in building surfaces, furniture or other interior products. In renovations, Halia® radiant warmers can be retrofitted into the interior surfaces of existing homes and buildings. In new construction, Halia® warming can be integrated into prefabricated building elements for modular construction. There are also numerous other application areas for Halia technology e.g. marine, automotive, industrial, de-icing.

The first commercial product utilizing Halia® warming is Quatro warming tables. The tabletop is made from compact high-pressure laminate (HPL), a strong and durable material commonly used in furniture, public spaces, and outdoor settings, and it is manufactured by HPL laminates and compacts producer Surforma® - a longstanding PrintoCent member - and comes in a range of colors and textures. In Quatro tables, the heating tracks are embedded inside the bottom layers of the tabletop, warming comfortably and evenly the lower parts of the persons sitting at the table. The table includes four independent warming zones connected to a low-voltage control unit. Warmth in each area can be adjusted. The table includes optical sensors that detect when a person is seated and the corresponding warming zone switches on automatically. When the person leaves, the heating turns off again. This helps reduce unnecessary energy use while keeping the table convenient and effortless to operate.

In hospitality business, thermal comfort significantly impacts guest satisfaction and overall experience, and extends the terrace business season. Quatro tables energy efficiently provide cozy pockets of warmth for the individual needs of restaurant customers.

Figure 7.4.4. Quatro terrace table with Halia® warming.
© The Warming Surfaces Company

The Warming Surfaces Company Ltd.

The company behind Halia® warming is The Warming Surfaces Company Ltd. a spin-out company from VTT Technical Research Centre of Finland and its science-based incubator program VTT LaunchPad. The company was established in Oulu, Finland 11/11/2022 and is now a front-runner in large area surface integrated low power heating.

At the time of this text, December 2025, patented Halia® warming technology is certified for use inside HPL and compacts, and for applications in furniture. We offer engineering and design services to companies in the furniture and interior surface materials supply chains, to help apply Halia® warming into their products, and supply Halia warming elements and control units to our licensing customers. Contact us to explore collaboration possibilities on how to bring sustainable warming to your products.

www.warmingsurfaces.com

7.5 Collaboration for Smarter, More Sustainable Neurotechnology: Results from the Sustronics Project

screentec

Introduction

The Sustronics project, funded by the EU and Business Finland, focused on developing more sustainable, high-performance electronics for medical applications. During the project, Screentec and PLUX Biosignals designed, manufactured, and evaluated a new generation of printed EEG electrodes designed to demonstrate that biopotential monitoring can be both clinically reliable and environmentally responsible.

The focus of the project was to compare several Screentec-produced electrode variants, differing in substrate and conductive materials, with the current clinical reference, the Cardinal Health™ Kendall™ hydrogel electrode. The objective was twofold:

1. verify electrical performance against clinical norms, and
2. assess the feasibility of lower-impact, recyclable materials in EEG applications.

Figure 7.5.1. Test sample of 3 Screentec single-lead EEG electrodes
© Screentec

Figure 7.5.2. Cardinal health™ from Kendall™ hydrogel electrodes
© Screentec

Testing followed a structured EEG protocol and included waveform analysis, frequency-domain behavior, usability, adhesion, comfort, and sustainability considerations. All tests were performed by Plux Biosignals with biosignalsplux EEG sensors under controlled laboratory conditions and simultaneous dual recordings with reference electrodes.

Electrode Requirements

The design requirements were defined to ensure that the new EEG electrodes deliver high-quality signal performance, remain easy and comfortable to use, and significantly reduce environmental impact.

Functional Requirements

- Reliable detection of EEG frequency bands (theta, alpha, beta, gamma)
- Stable performance during eyes-open, eyes-closed, and blinking tests
- Low susceptibility to noise, especially 50 Hz mains interference
- Compatibility with biosignalsplux EEG acquisition system

Usability Requirements

- Comfortable placement on skin
- Ease of removal without residue
- Sufficient adhesion for the recording duration
- Packaging that maintains adhesive performance over shelf-life

Sustainability Requirements

- Introduction of bio-based or recyclable substrate materials (e.g., paper)
- Reduced reliance on silver-based conductors
- Potential to lower environmental footprint by ≥30% compared to baseline PET/silver hydrogel electrodes
- Clear visual and material cues supporting “eco-friendly” perception by users

Production and Materials

The project employed established printed electronics processes and carefully selected materials to create flexible, high-performing, and more sustainable EEG electrodes. The combination of screen-printed conductors, optimized substrates, and simplified layer structures supported both technical reliability and eco-friendly design goals.

Printing Method

Screen printing was used due to its suitability for multi-layer structures, flexible substrates, and precise conductor patterning. Material sets were selected to support conductivity, mechanical compliance, and compatibility with sustainable substrate options.

Substrate Selection

Two substrate types were evaluated:

- PET (Conventional): stable, familiar in medical electrodes, good printability.
- Paper (Sustainable): renewable, recyclable, visually “eco-friendly,” and compatible with R2R processing.

Conductive Materials

- Silver ink: high-conductivity baseline conductor.
- Copper-based adhesive: lower-impact alternative enabling recyclable constructions.

Product Structure

While layer stacks varied slightly by variant, typical construction included:

- Substrate
- Conductor layer (silver or copper adhesive)
- Skin-contact interface (hydrogel or conductive adhesive)
- Snap connector
- Protective liner

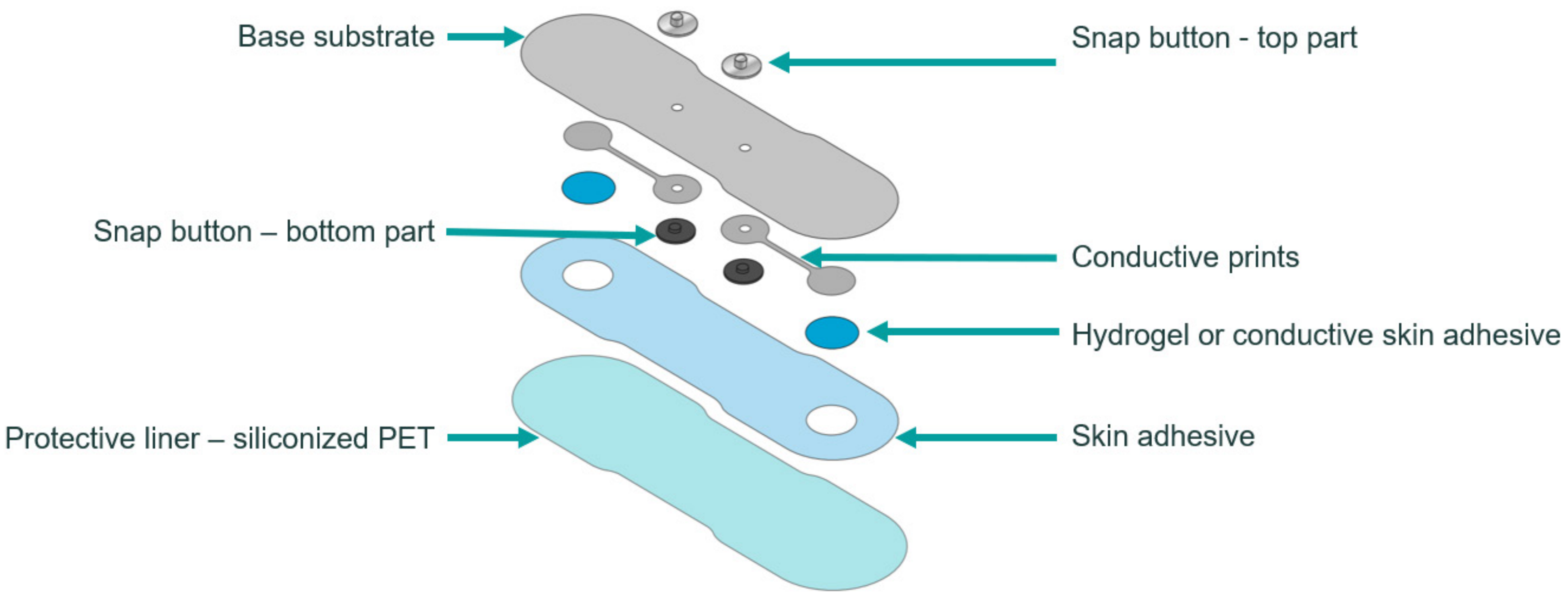

Figure 7.5.3. Typical product structure.

Testing Setup and Protocol

Testing was conducted using a biosignalsplux 8-channel hub together with biosignalsplux EEG sensors, enabling simultaneous acquisition from both reference and prototype electrodes. The evaluation setup included Screentec's single-lead printed EEG electrodes and Cardinal-Health™ Kendall™ hydrogel electrodes (current clinical gold standard). Recordings were performed in a dual-channel configuration with both electrode types placed on the forehead to ensure directly comparable EEG signals under identical physiological conditions.

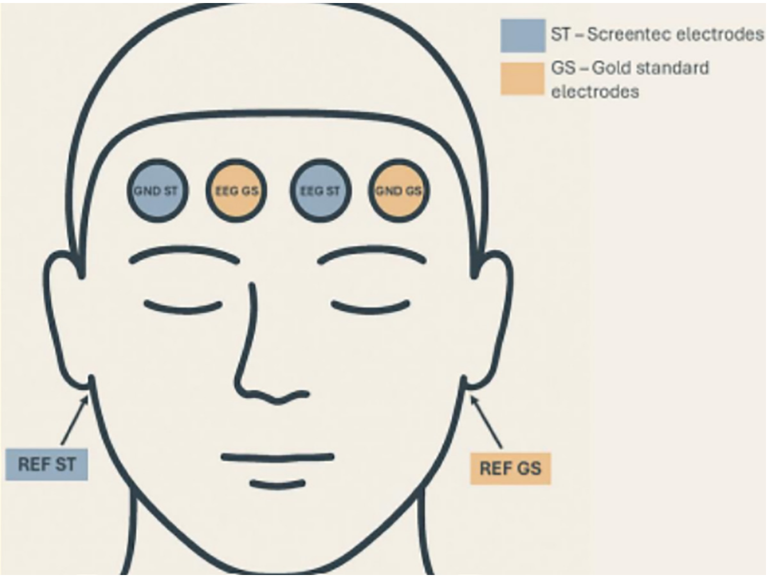

Figure 7.5.4. EEG sensor electrode setup.

Recordings captured three conditions:

- Eyes open (30 s)
- Eyes closed (30 s)
- Eyes blinking (30 s)

Frequency analysis evaluated theta (4–7 Hz), alpha (8–12 Hz), beta (13–30 Hz), and gamma (30–100 Hz) activity. Raw signals were unfiltered for unbiased comparison.

Key Performance Results

Waveform Observations

Across all samples, waveform morphology closely matched the reference electrodes.

- All prototypes captured blink artifacts at identical time points.
- Minor unexpected peaks were observed in variants 1 and 2 during eyes-open periods.
- Variant 3 delivered the most stable morphology across all phases.

Frequency-Domain Results

All prototypes successfully detected alpha waves (8–12 Hz) during eyes-closed conditions, which is a key criterion for EEG reliability.

However, performance varied by variant:

1. (PET + Ag + hydrogel)

- Occasional fixed peaks at 50 Hz indicating possible mains interference
- Higher relative error in alpha and gamma bands (up to ~22%)
- Reliable but less consistent than sustainable variants

2. (PET + Ag + conductive adhesive)

- Highest observed errors in beta and gamma ranges (up to ~26%)
- Similar 50 Hz interference patterns as variant 1.
- Good blink synchronization but less suitable for high-frequency EEG research

3. (Paper + Cu adhesive) - Best Performing Variant

- Lowest and most consistent relative errors (~1–6% across bands)
- Frequency peaks aligned with physiological expectations (e.g., ~10.5 Hz alpha)
- Lowest sensitivity to mains interference
- Signal fidelity on par with hydrogel electrodes - a major milestone for sustainable EEG

Usability and Adhesion Performance

PLUX testers reported that all electrodes were comfortable to wear and could be removed without leaving residue on the skin. Some adhesive weakness was noticed before application, particularly in variants 1 and 2. In contrast, variant 3 offered a clearer “eco-friendly” visual appearance because of its paper-based substrate.

This highlights the need for:
- refined adhesive selection
- improved packaging to preserve adhesion over shelf-life
- mechanical testing under humidity and storage stress

Sustainability Achievements

Material Reduction and Bio-based Content

Variant 3 achieves:
- >50% bio-based materials
- recyclable paper substrate
- copper adhesive replacing silver
- lowest LCA-calculated environmental footprint among tested variants

Environmental Impact Targets

Generation 2 prototypes already demonstrate a clear pathway toward reduced environmental impact. They offer the potential for at least a 30% lower environmental footprint compared to PET-and-silver baselines, achieve meaningful reductions in single-use waste by replacing traditional PET hydrogel pads, and enhance user perception using visibly sustainable material choices.

Summary and Outlook

The results demonstrate that sustainable EEG electrodes can match clinical performance standards when material choices and printing architecture are carefully optimized.

Key conclusions

→ All Screentec prototypes captured essential EEG features, including alpha activity.
→ Paper-based electrodes outperformed PET-based variants across nearly all metrics.
→ Adhesion and packaging require further refinement for long-term stability.
→ The results validate the feasibility of recyclable, bio-based EEG consumables for future medical-grade systems.

Figure 7.5.5. Sustainable wearable electrode by Screentec

Looking ahead, the consortium will advance toward Generation 3, integrating reusable sensor modules, eco-friendly electrode assemblies, and comprehensive Digital Product Passports (DPP) supported by VTT's Life Cycle Assessment (LCA) models.

This case confirms that high-performance neurotechnology and sustainable design are not competing priorities. When engineered together, they provide a viable path toward next-generation medical devices with reduced environmental impact.

www.screentec.com

ABBREVIATIONS

List of keywords and abbreviations

ACA	Anisotropic conductive adhesive
ACF	Anisotropic conductive film
ACP	Anisotropic conductive paste
AI	Artificial intelligence
ALD	Atomic layer deposition
AZO	Aluminum-doped ZnO
BLE	Bluetooth low energy
CAD	Computer aided design
CAM	Computer-Aided Manufacturing
CAP	Cellulose acetate propionate
CBM	Circular business models
CNT	Carbon Nanotubes
CPH	Components per hour
CRM	Critical Raw Materials
CtS	Computer-to-Screen
DK	Design Kits
DPP	Digital Product Passport
ECA	Electrically Conductive Adhesive
ECG	Electrocardiogram
EEG	Electroencephalogram
EDA	Electronic Design Automation
EMI	Electromagnetic Interference
FFC	Flexible Flat Connector
FHE	Flexible Hybrid Electronics
FPC	Flexible Printed Circuits
GF	Gauge factor
IC	Integrated circuit
ICA	Isotropic conductive adhesive
IMD	In-mould-decoration
IMSE®	In-mould structural electronics
IML	In-mould-labeling
IR	Infrared
ITO	Indium tin oxide
IV	Current-voltage
LC	Inductor-Capacitor
LCA	life cycle assessment
LCR	Inductance (L), Capacitance (C), and Resistance (R)
LED	Light emitting diode
LSE	Large Scale Enterprises
MCU	Microcontroller Unit
MD	Machine Direction
MDR	Medical Device Regulation
MIMO	Multiple input, multiple output
MoS2	Molybdenum disulfide
NCA	Non-conductive adhesives
NFC	Near field communication
NP	Nanoparticle

OAMK	Oulu University of Applied Sciences
OLED	Organic light-emitting diodes
OMH	Organometal halides
OMO	Oxide-metal-oxide
OPV	Organic photovoltaic
OSP	Organic Solderability Preservative
OTFT	Organic TFT
PBT	Polybutylene terephthalate
PC	Polycarbonate
PCB	Printed circuit board
PCBA	Printed circuit board assembly
PCE	Power conversion efficiency
PDMS	Polydimethylsiloxane
PEEK	Polyether ether ketone
PEDOT	Poly(3,4-ethylenedioxythiophene)
PEN	Poly(ethylene 2,6-naphthalate)
PET	Polyethylene terephthalate
PFAS	Per- and polyfluoroalkyl substances
PI	Polyimide or printed intelligence
PIC	PrintoCent Industry Cluster
PkPV	Perovskite Photovoltaics
PLA	Polylactic acid
PMN-PT	Lead magnesium niobate-lead titanate
PSC	Perovskite solar cells
PSS	Polystyrene sulfonate
PZN-PT	Lead zinc niobate-lead titanate
PZT	Lead zirconate titanate
R2R	Roll-to-roll
RA	Rolled & Annealed
RFID	Radio frequency identification
RGB	Red, green, blue
RH	Relative humidity
ROP	Reverse-offset-printing
S2S	Sheet-to-sheet
SCRA	Sustainability, cost and risk assessment
SDG	Sustainable development goal
SEM	Scanning electron microscopy
SiP	System-in-Package
SMD	Surface mount device
SME	Small and medium-size enterprises
SMT	Surface mount technology
SnO2	Tin(IV) oxide
spiro-OMeTAD	Hole Transport Material for solid-state Dye Solar Cells
SSbD	Safe and sustainable by design
TCR	Temperature coefficient of resistance
TD	Transverse direction
TFT	Thin-film transistors
TPU	Thermoplastic polyurethane
UO	University of Oulu
UV	Ultraviolet
UXV	Unmanned vehicle
VOC	Volatile Organic Compounds
VTT	Technical Research Centre of Finland
ZnO	Zinc oxide

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