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Printed Electronics - Electronics Everywhere

Presented by Jari Keskinen, Staff Scientist

Slides by Prof. Matti Mäntysalo, Prof. Donald Lupo and Jari Keskinen

Tampere University

Finland

Physics seminar 3 Oct 2019

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Laboratory for Future Electronics

https://research.tuni.fi/lfe/

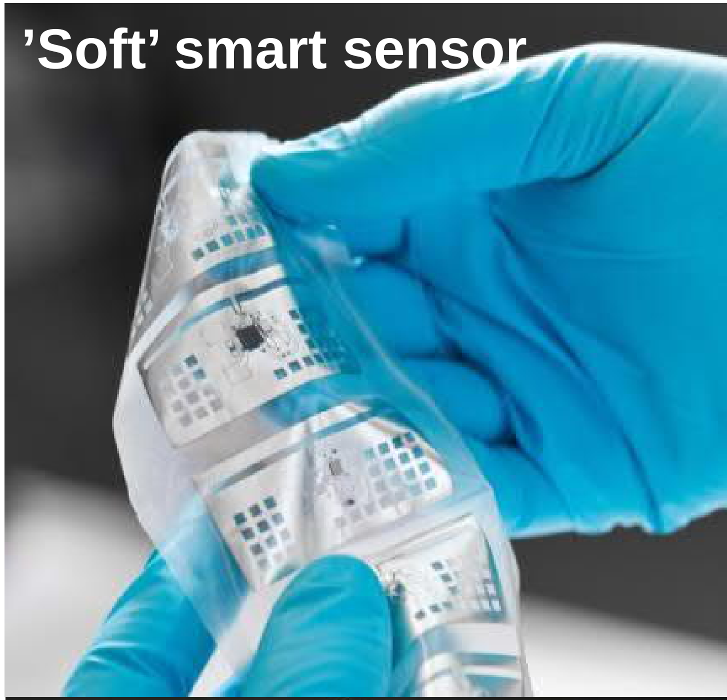
We perform research in novel materials, architectures and processes.

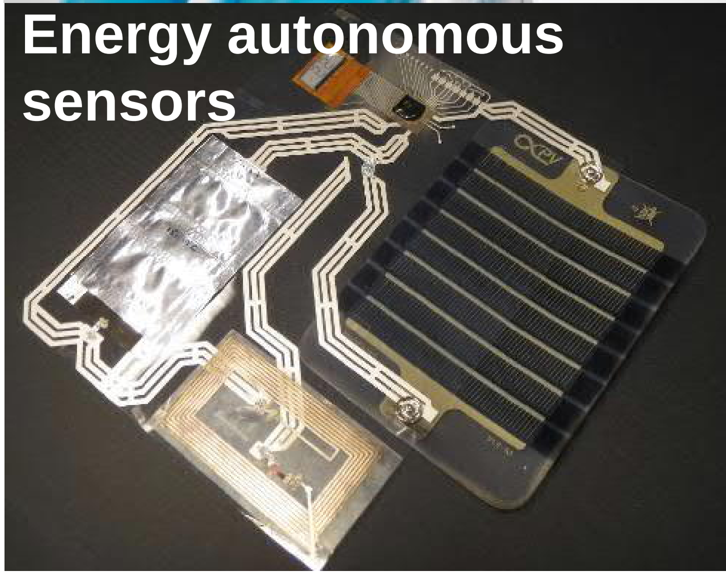
We digitalize physical objects

The focus is on Internet-of-Everything for **ambient intelligence** and **healthcare** application.

Research themes:

- Flexible/bendable/stretchable electronics
- **Integration of printed and conventional electronics (hybrid systems)**
- Energy storage and harvesting
- Printed thin-film circuits and systems





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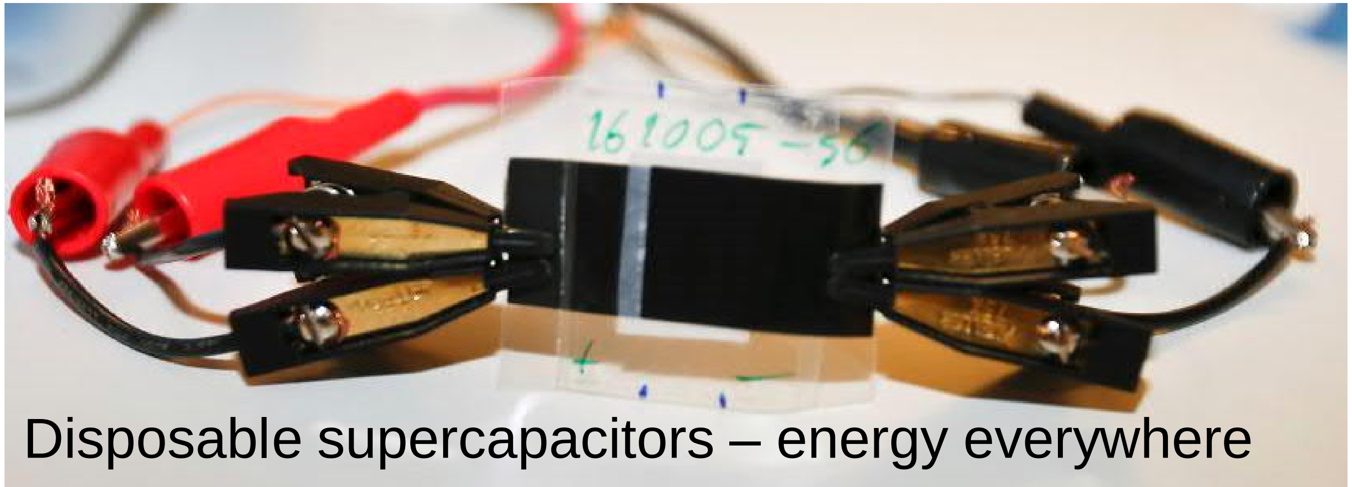

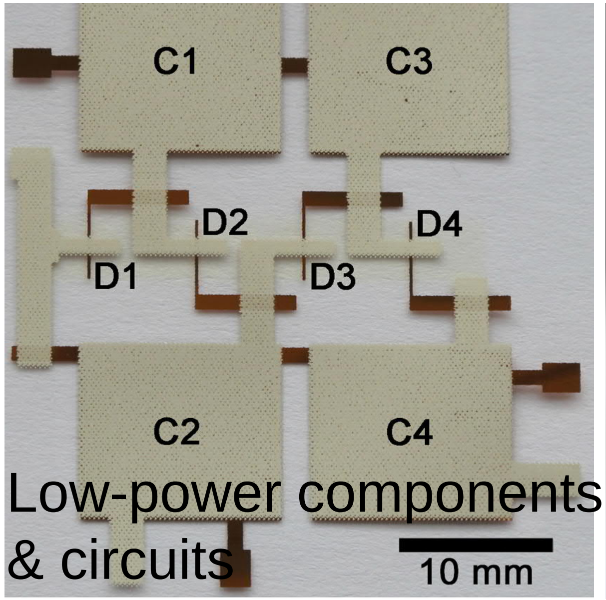

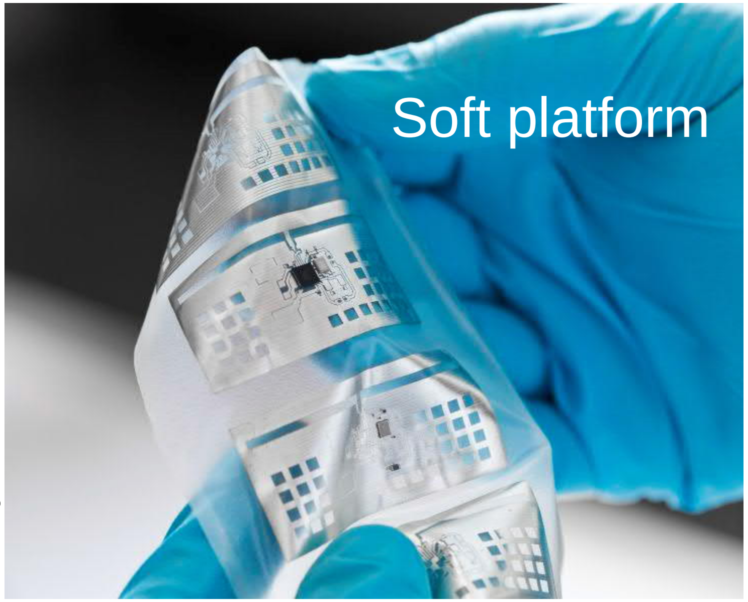

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Content

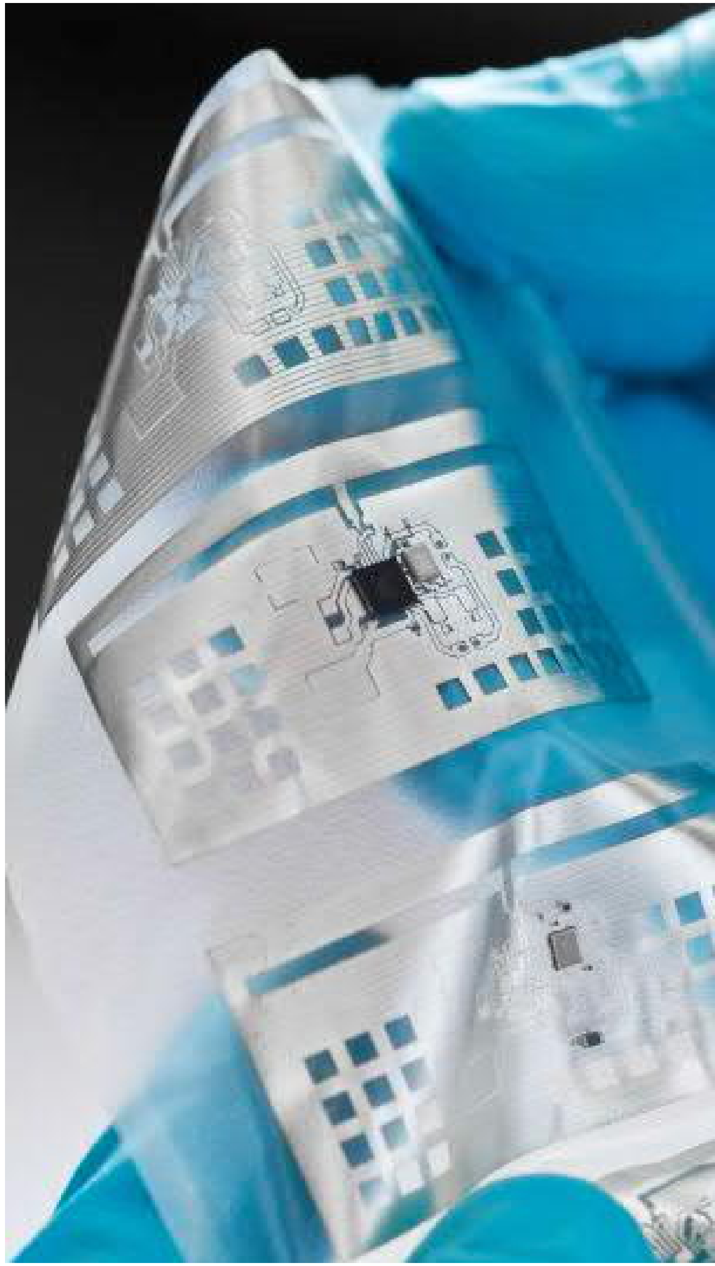
Printed Electronics
- **What is printed electronics (PE)?**
- **Why printing?**

Printing methods

Materials

Examples
- **Electronics packaging**
- **Energy storage**

Projects at LFE



Printed electronics

- *“Printed electronics is a set of printing methods used to create electrically functional devices.”*

Screen

T-shirt

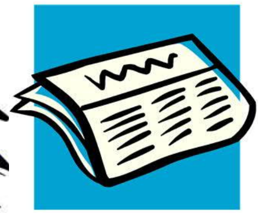
Flexography

Packaging

Gravure

Magazine

Offset



Newspaper

Inkjet

Home printer

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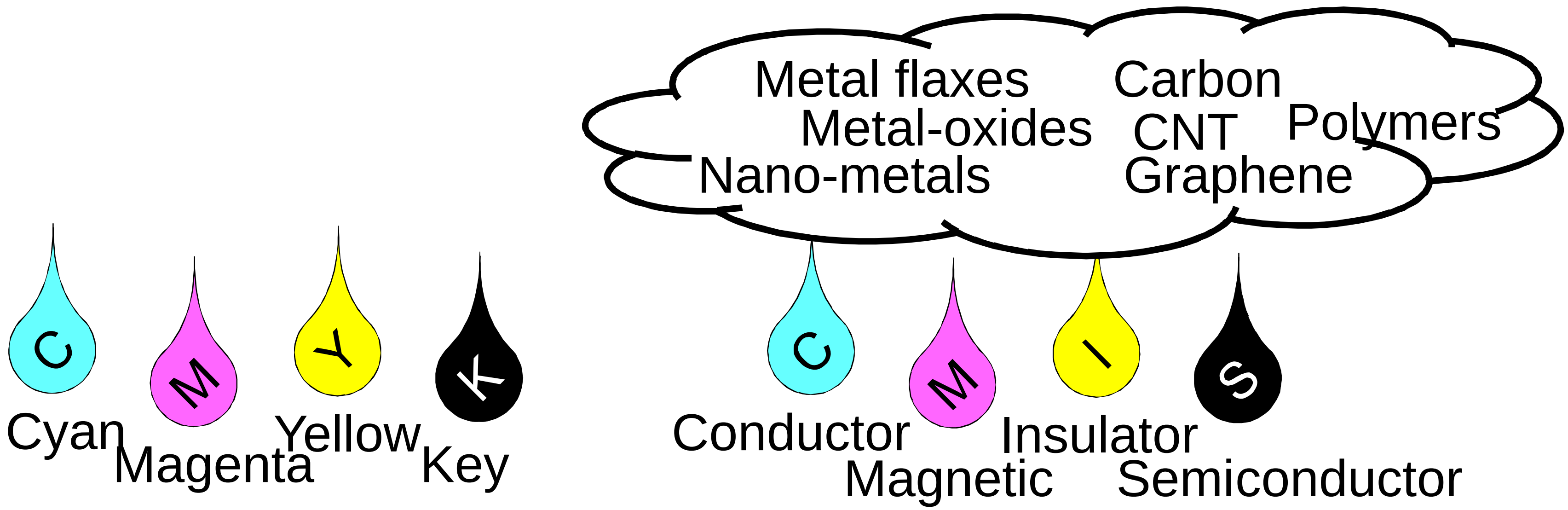
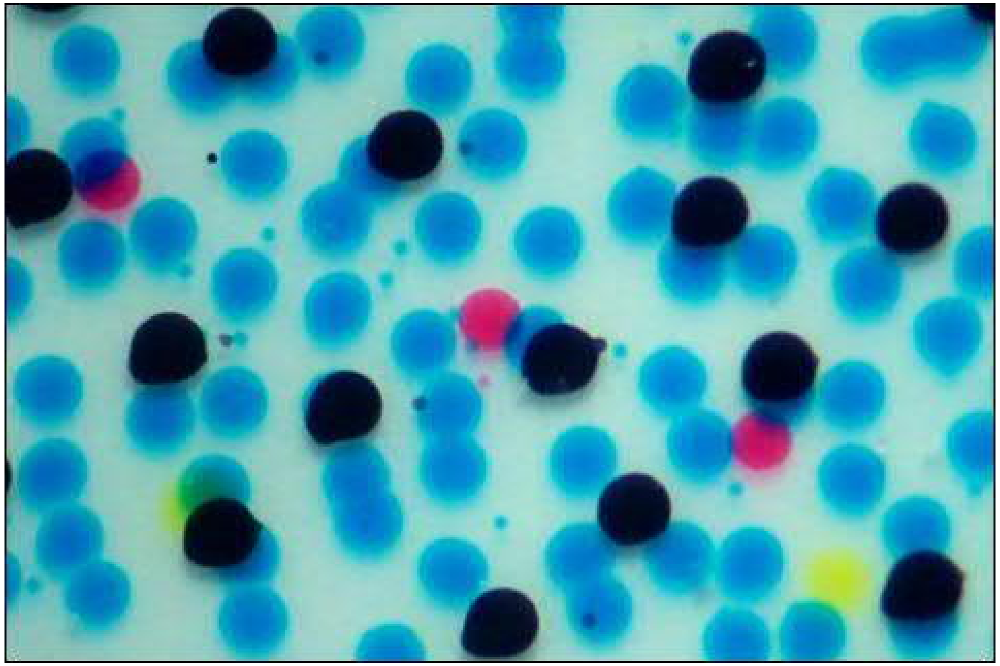
Printed electronics

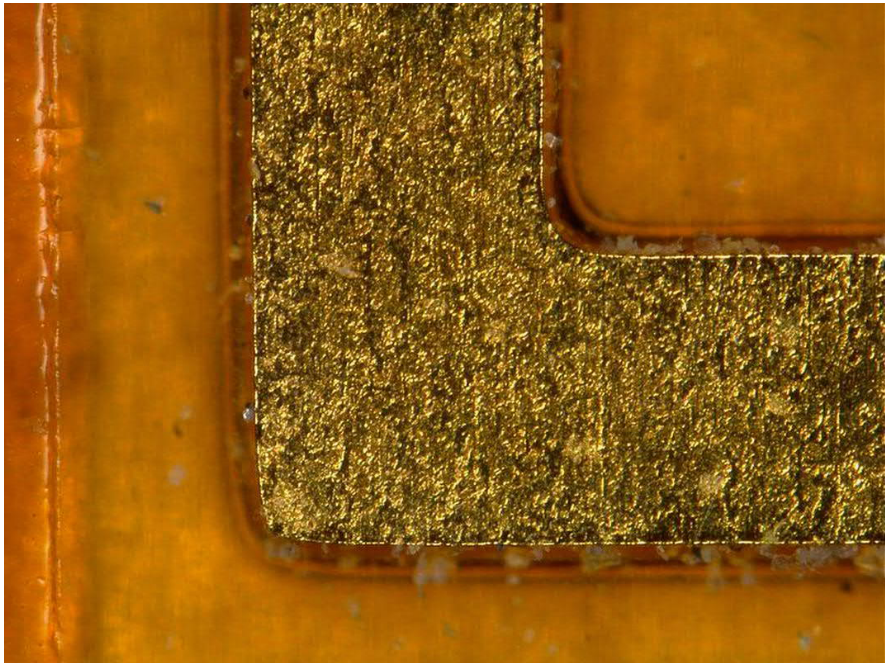
• *"Instead of printing graphic arts inks, families of electrically functional electronic or optical inks are used to print active or passive devices, such as thin film transistors or resistors."*



Inkjet printed image



Inkjet printed conductor



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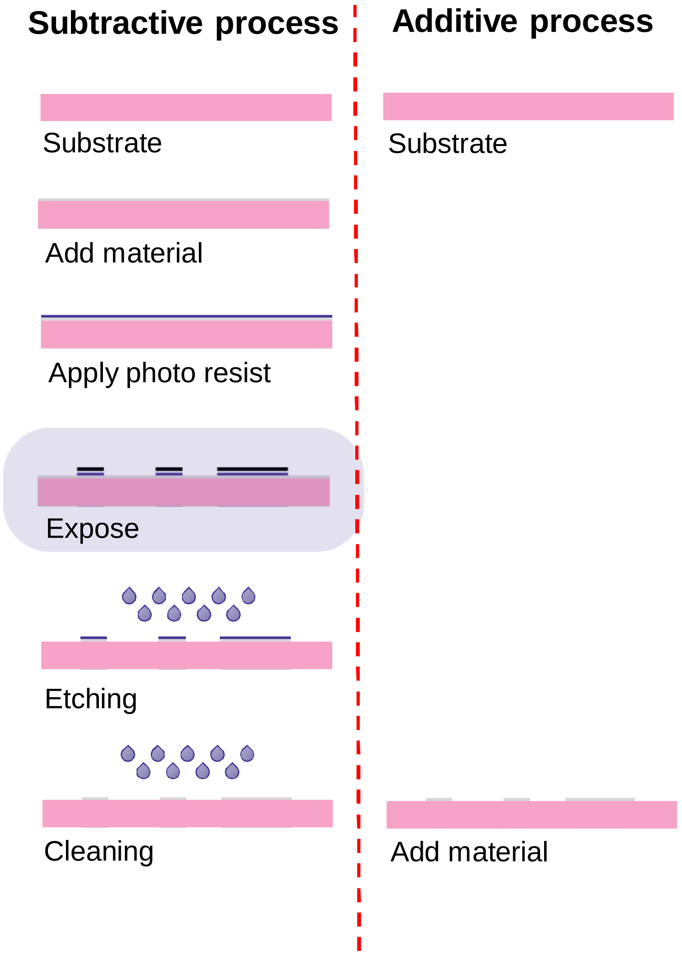
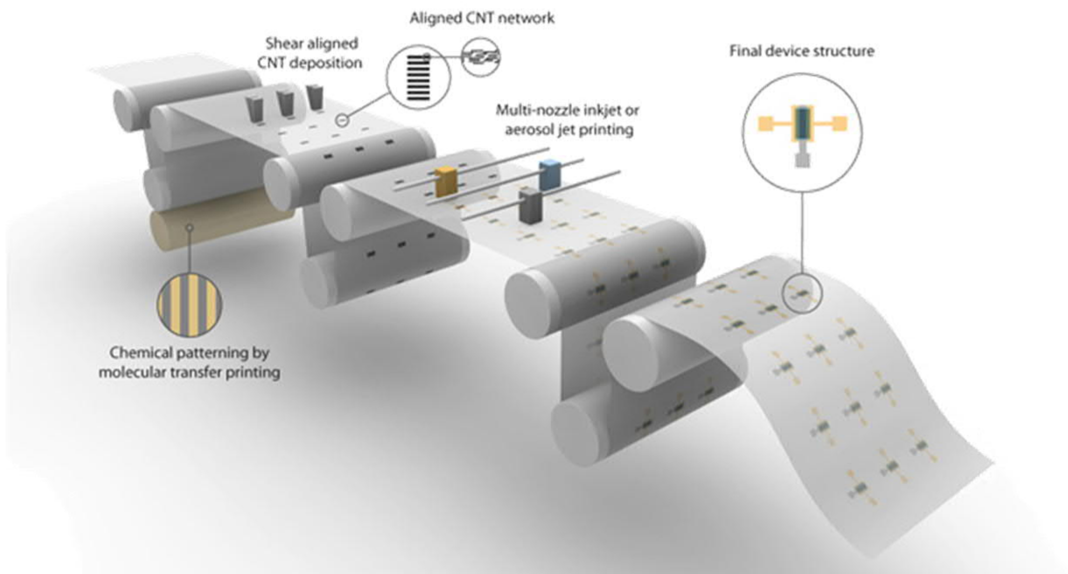
Printed electronics



- Additive => *less material waste*
- No etching => less harsh chemicals
- Less process steps => *energy efficient*



Printed Electronics Processing Concept (Grant Illustration)
From Dr. C. Daniel Frisbie at the University of Minnesota.

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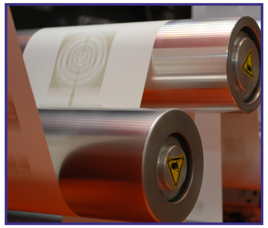
Large Area Printing & Patterning Techniques

High volume printing processes

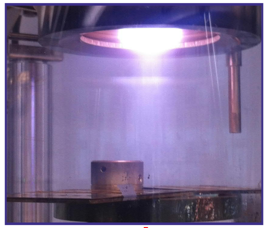


- **Gravure**
- **Flexography**
- **Offset**
- Lithography

Digital patterning processes

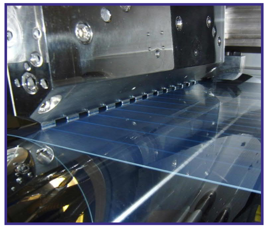
- **Inkjet printing**
- Aerosol jet printing
- **Laser** transfer & **machining**
- **Micro-plasma printing**
- **Syringe deposition**
- Xerography

Further patterning & deposition processes



- **Vapor phase deposition**
- Soft & large area lithography
- Nano-imprint lithography
- Pad printing
- **Wetting/dewetting**
- Hot stamping

Solution coating processes



- Slot-die coating
- **Wire bar coating**
- Curtain coating

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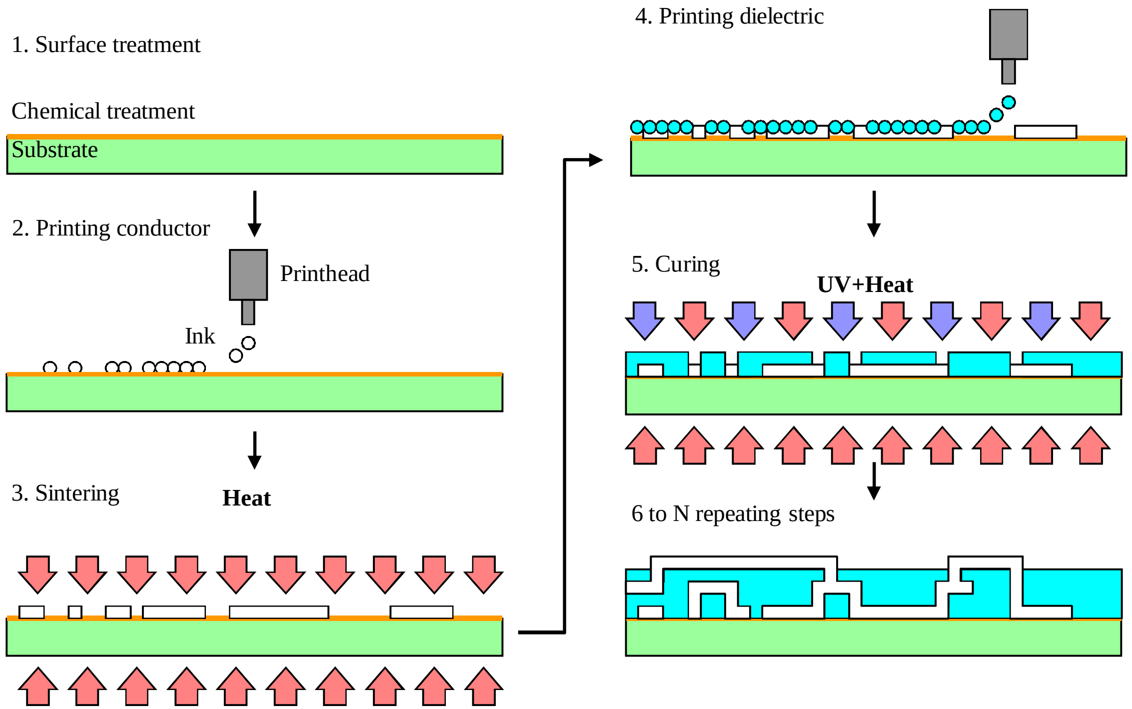
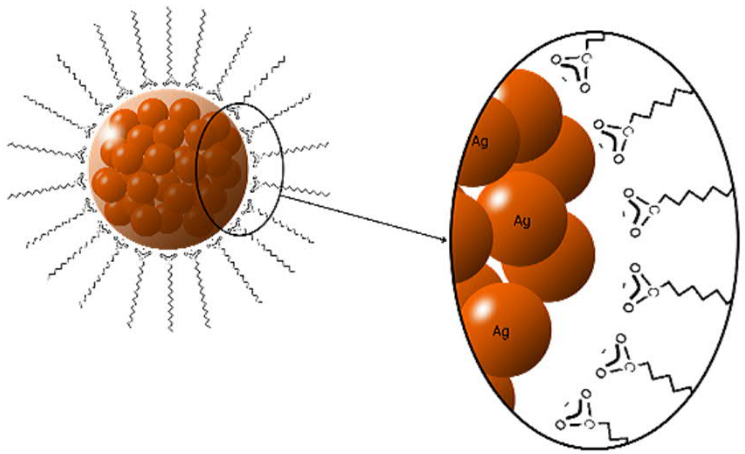
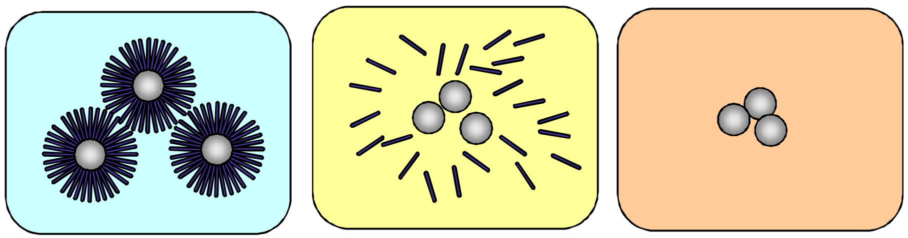
Example: inkjetted PWB





Heating vaporizes the dispersion agent.



Particles are stabilized by dispersion agent.

Particles are sintering together.

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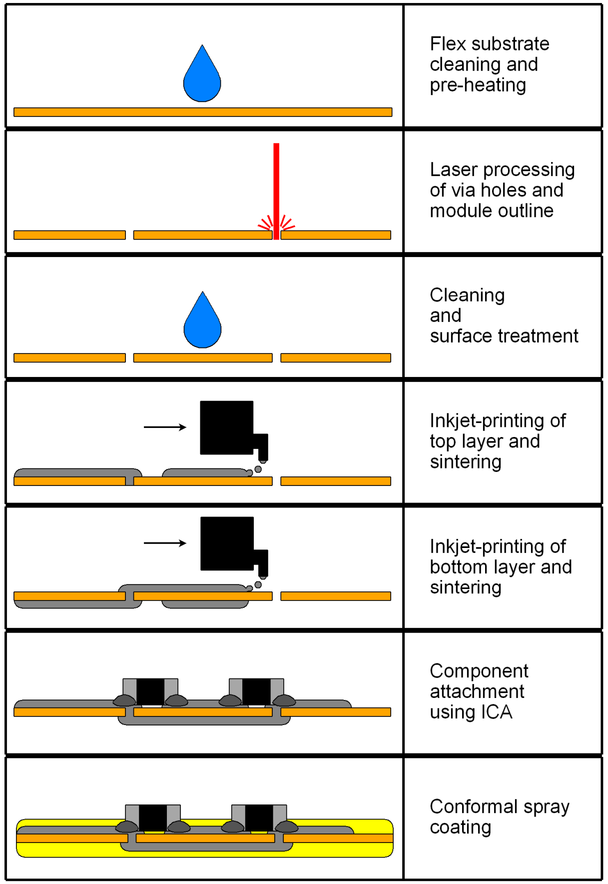
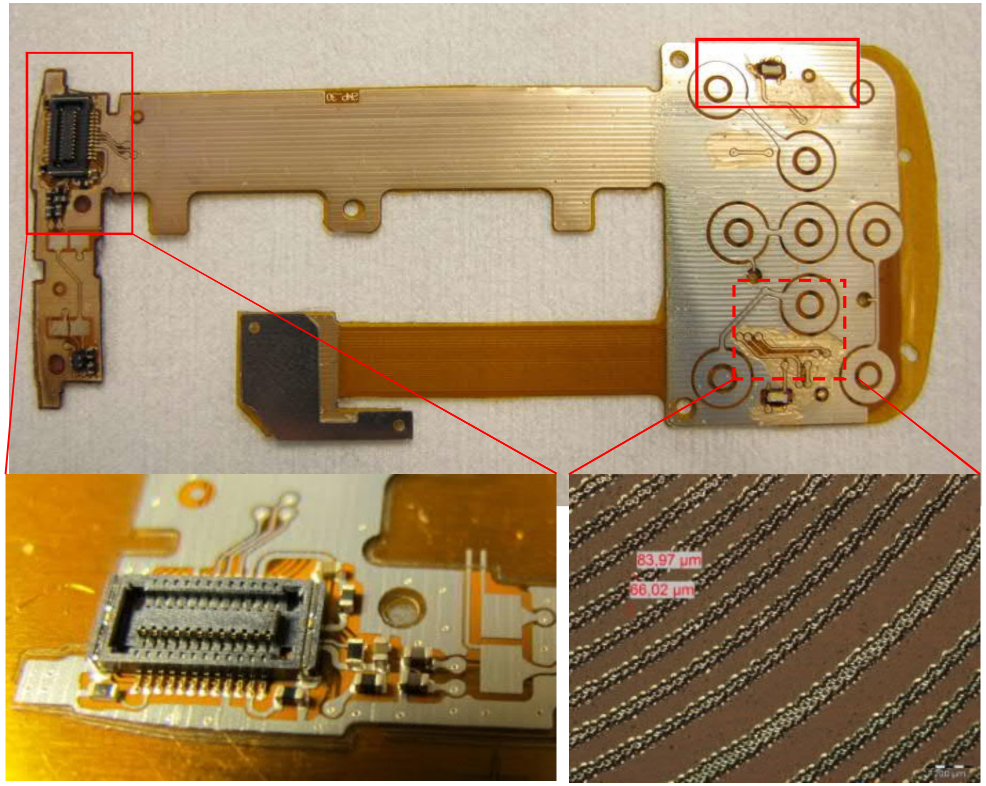
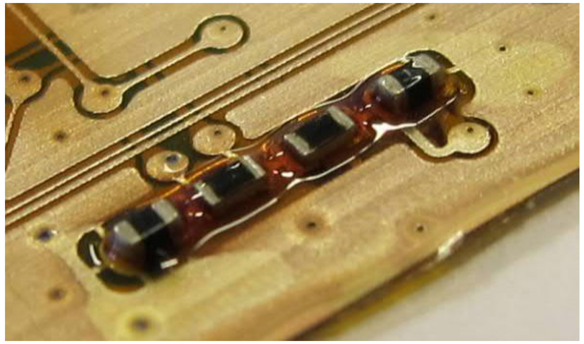
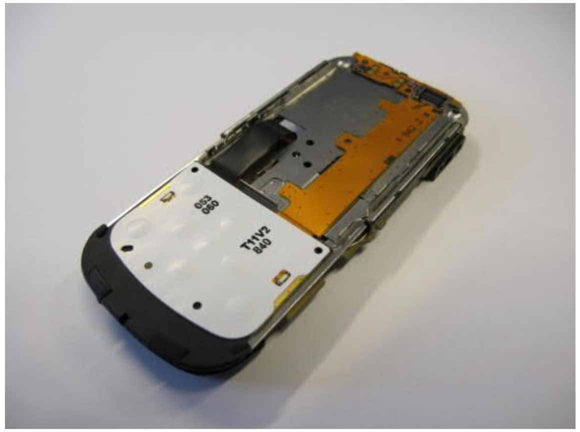
Example: inkjetted PWB







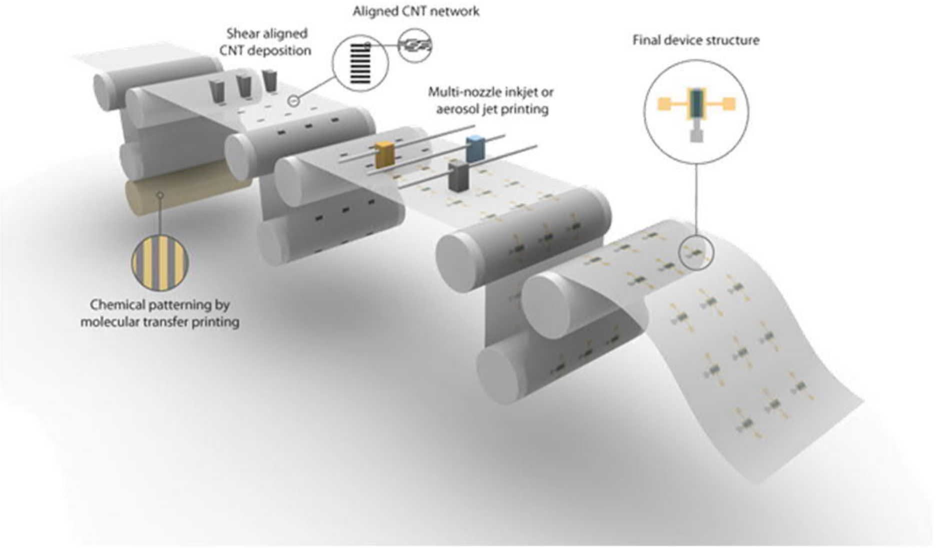


S. Koskinen, et al., Trans. on CPMT , Vol. 3, Issue 9, pp. 1604 – 1610.

Printed electronics – Why?

LOW-COST?

- Fast processing
- Large area
- Added functionality



Printed Electronics Processing Concept (Grant Illustration)
From Dr. C. Daniel Frisbie at the University of Minnesota.

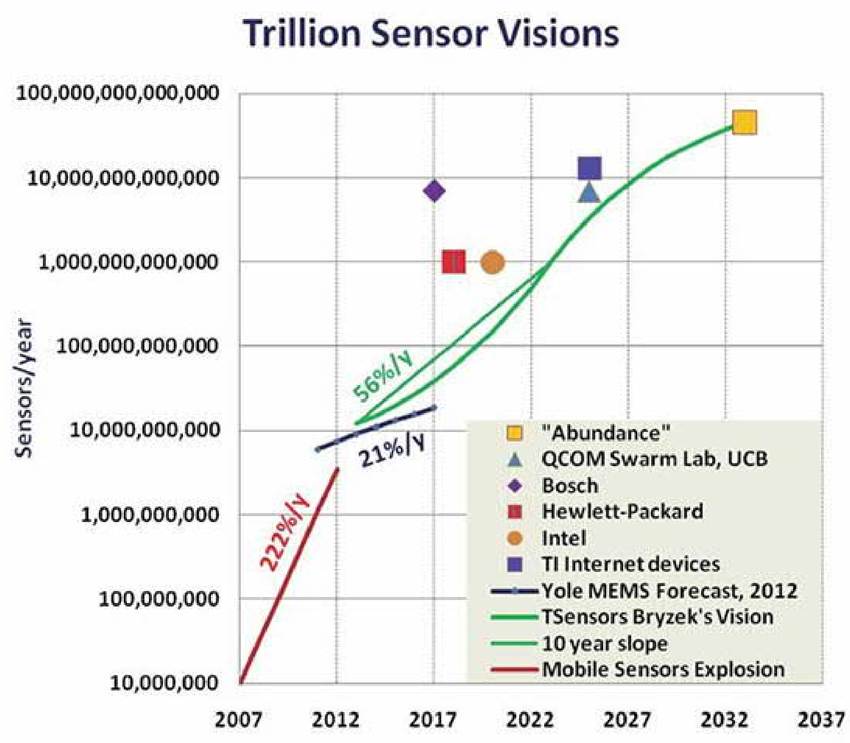
Trillion sensor vision

Billions (and potentially trillions) of MCUs are needed every year.

World's annual manufacturing rate of MCUs is around tens of billion pieces.

Paradigm shift in manufacturing is needed

Source: Thin Film Electronics



Source: FuturistSpeakers.com

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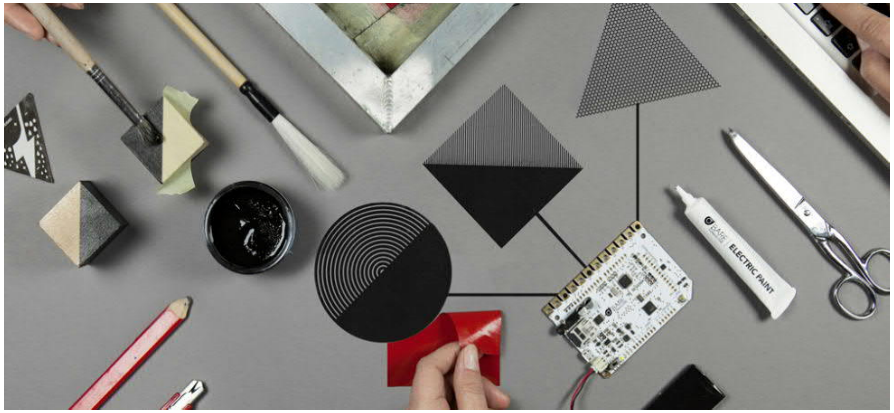
For inspiration

- Matt Johnson, bare conductive
- https://www.youtube.com/watch?v=R0xH0_qaqVw



- Dr. Kate Stone, Novalia
- https://www.youtube.com/watch?v=7H7RkIzNCJs
- https://www.youtube.com/watch?v=xyS06-ryDJA

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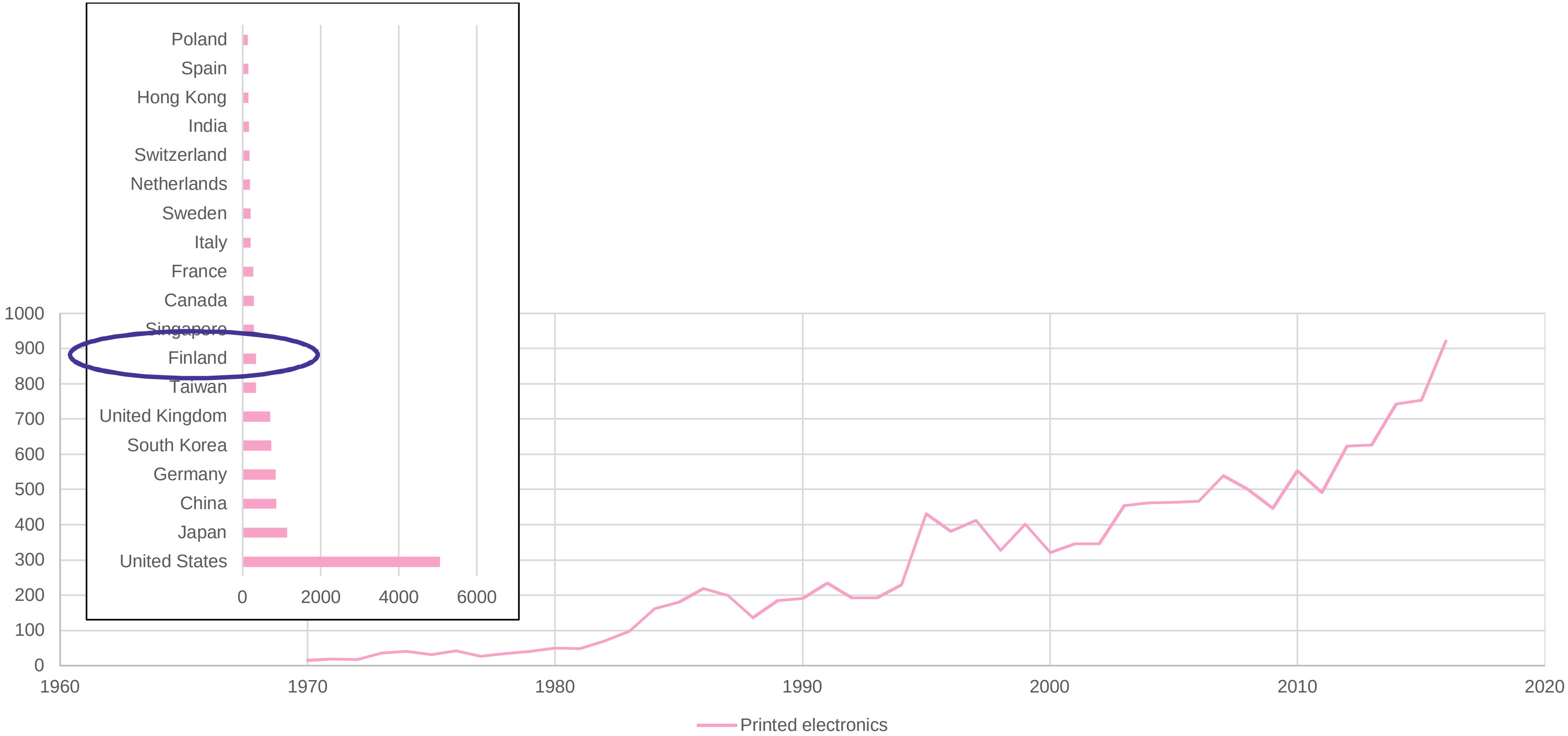
Scopus number of publications: (title, abstract, key word)



Important industry sectors

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Printing methods

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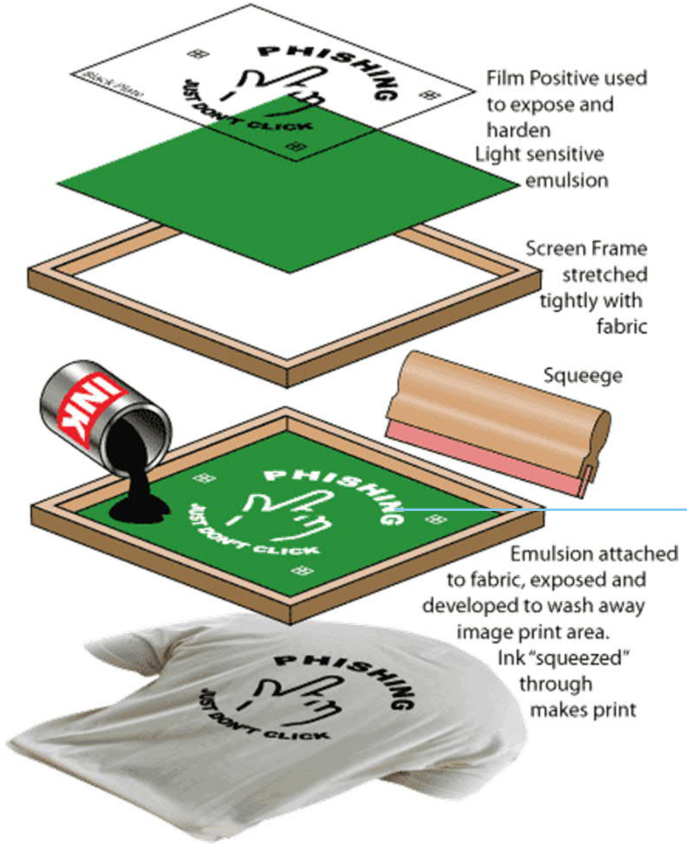
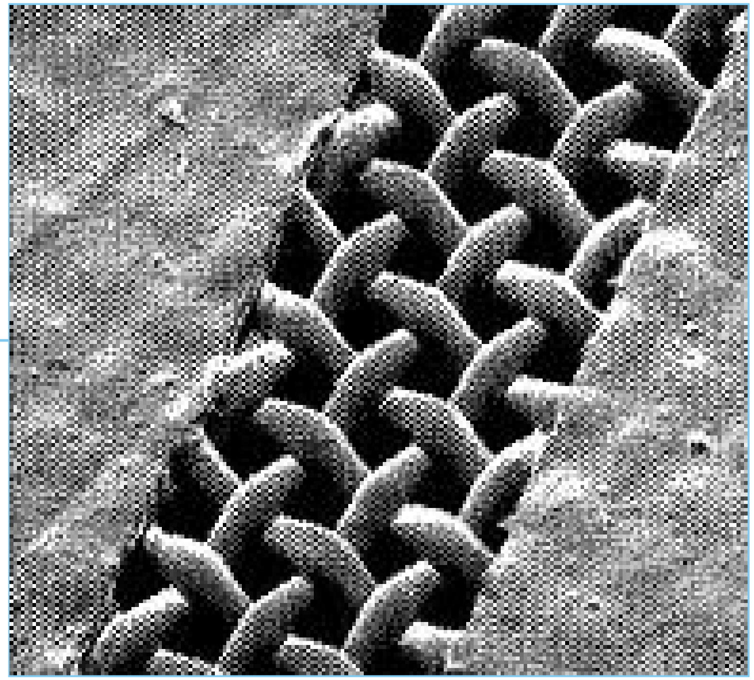
Screen printing (silkkipaino)





http://www.photoshop911.com/tutorials/screen_print_seps/index.html

Screen printing – process

Most common printing method in electronics manufacturing.

Printed conductors and dielectric for LTCC/HTCC

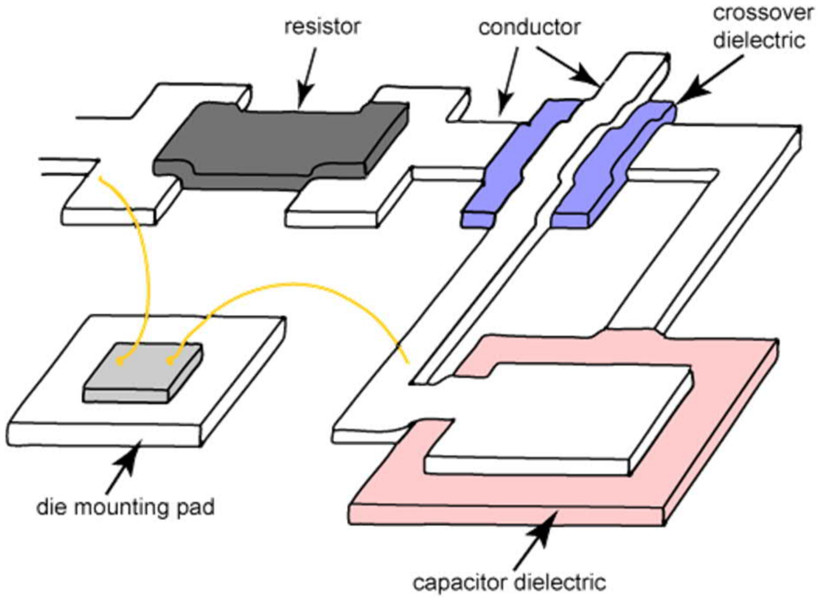
- **Embedded passives, hybrid circuits, solar panels, antennas**

Bumps, solder paste printing etc.

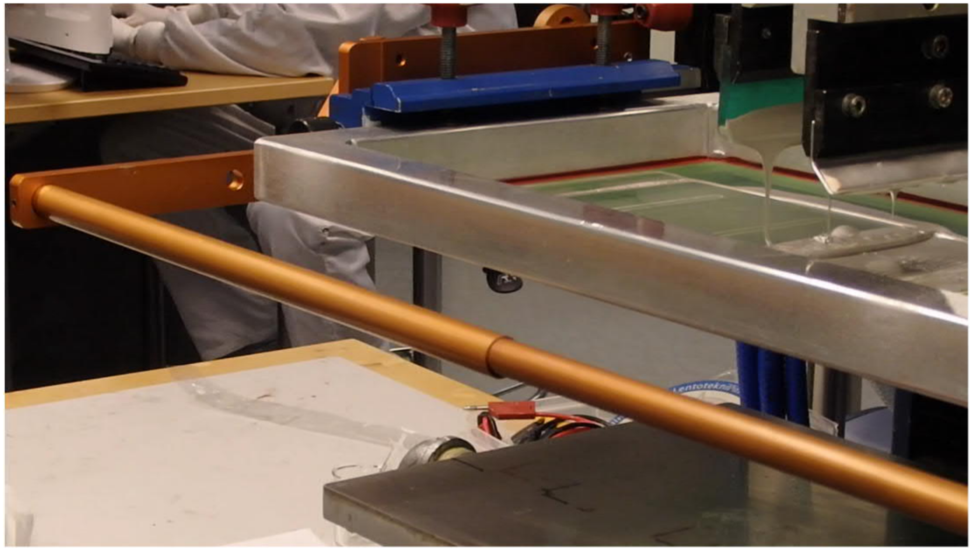
Printing of non-electric structures

- **Adhesives, Solder mask, Thermal conductors, Markings**

Hybrid circuit



http://www.ami.ac.uk



Screen print - ink design

Sufficient viscosity (0,05-5 Pas)

- **helps the ink to remain suspended above a fine mesh prior to being compressed through the screen**
- **allows ink to retain the shape imposed by the stencil**

Thick layers

- **high conductance**
- **slow drying**

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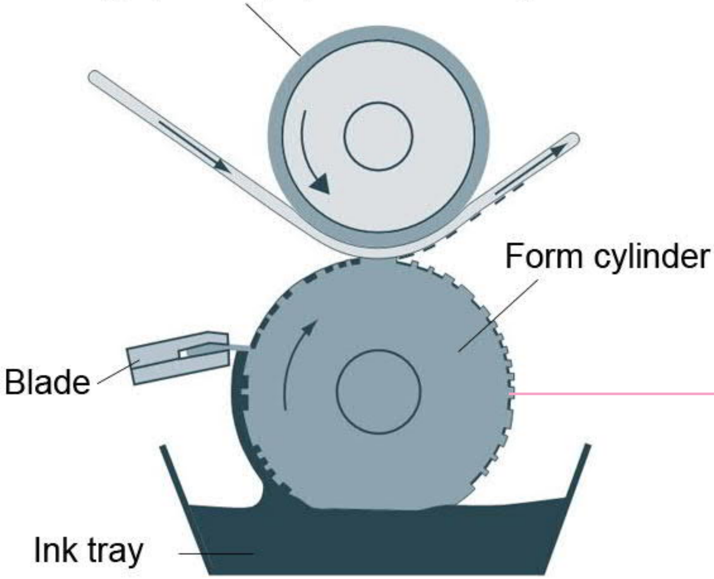
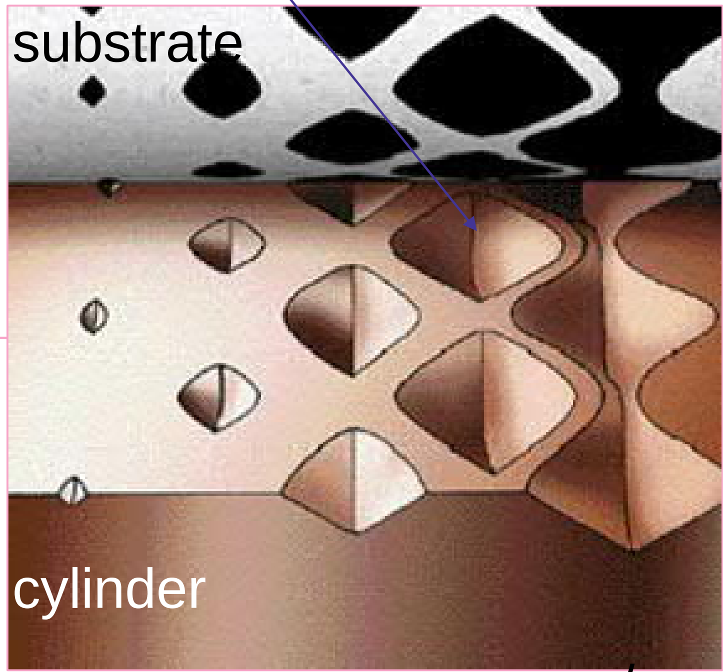
Gravure printing (syväpaino)

25-30µm depth
200-300 cells/inch



http://www.automation.siemens.com



http://www.era.eu.org/

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Gravure ink design

Relatively low viscosity (0,05-0,2 Pas)

- **ink needs to fill the cells of the gravure cylinder**

Low surface tension

- **wetting of cells**

Low shear viscosity

- **flow into and out of the cells and on to the substrate**

Small gap between the doctor blade and unpatterned parts of the cylinder

- **small particles in the ink can cause degradation of the cylinder or doctor blade**
- **the ink is required to withstand high shear forces**

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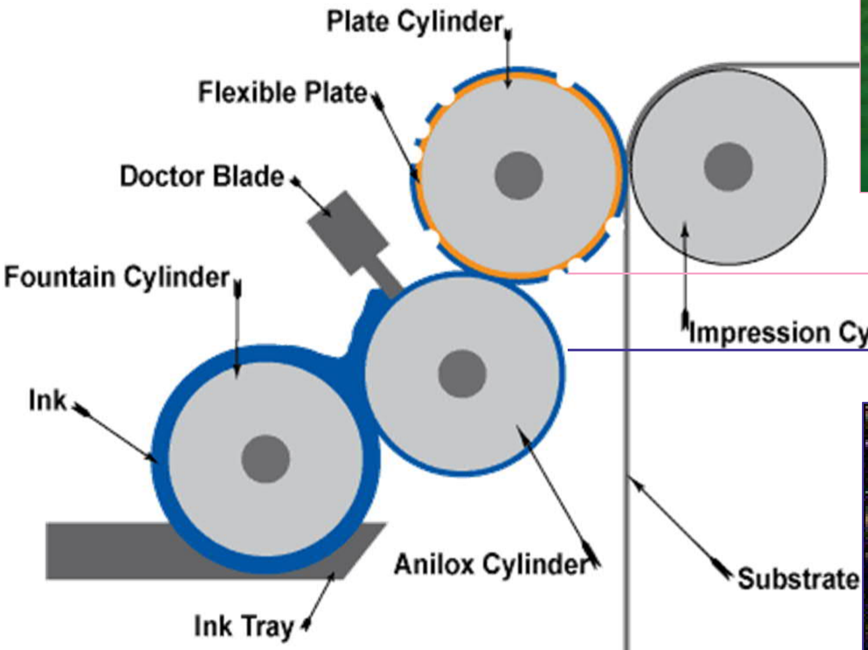
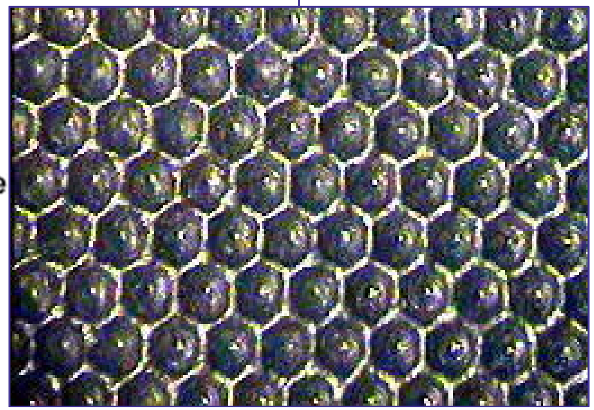
Flexography

wikipedia.com



http://www.americanlabel.com

Anilox is similar to gravure cylinder



tacomarubberstamp.com

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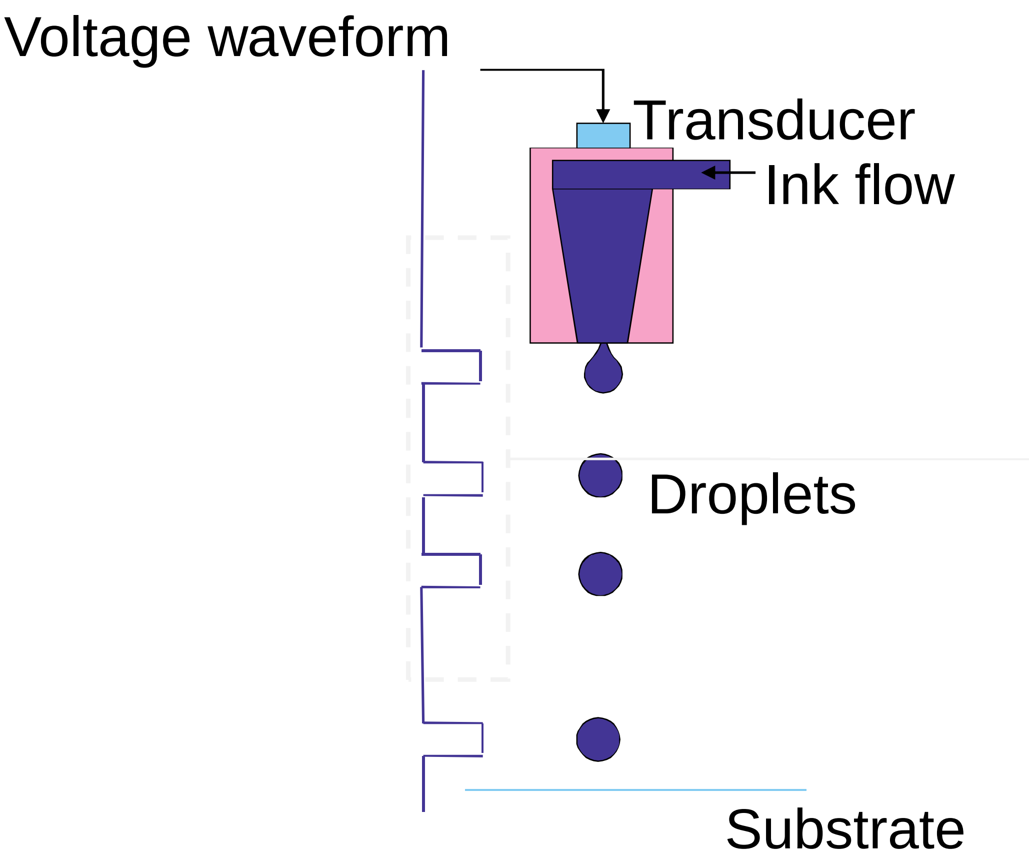
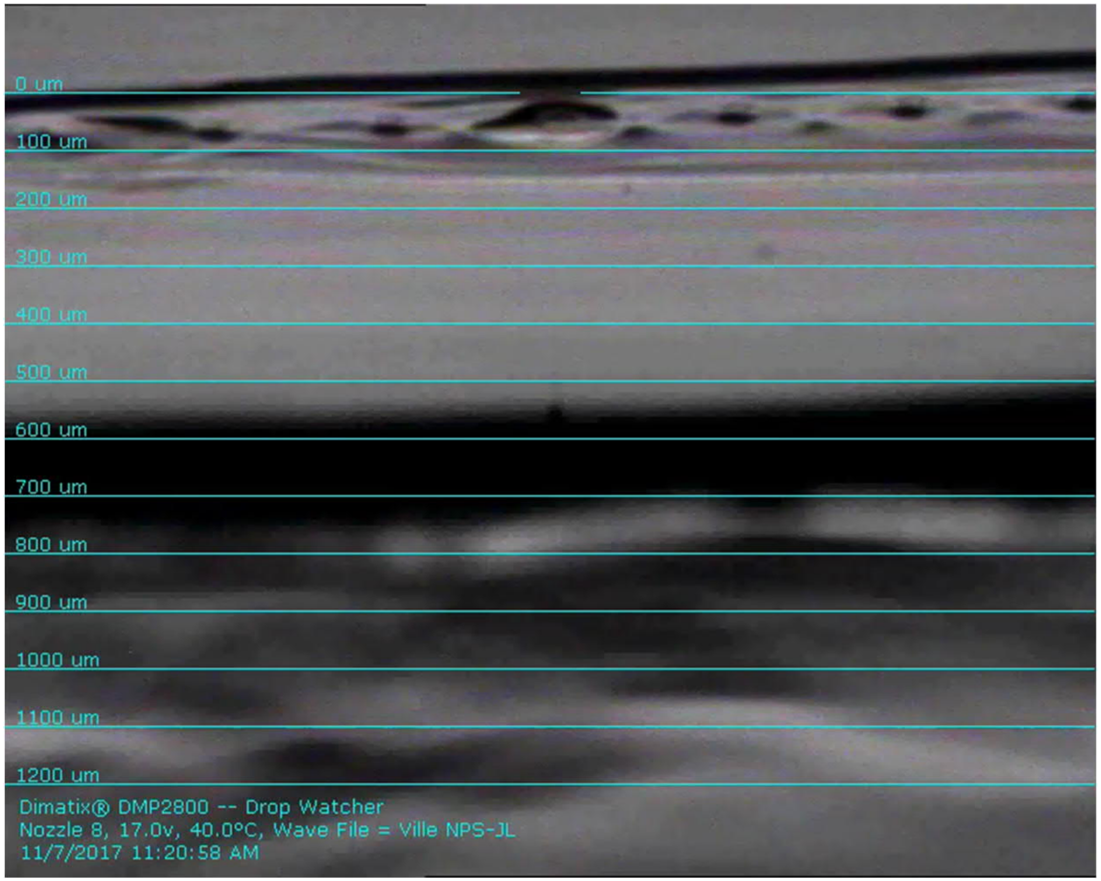
Inkjet (mustesuihku)





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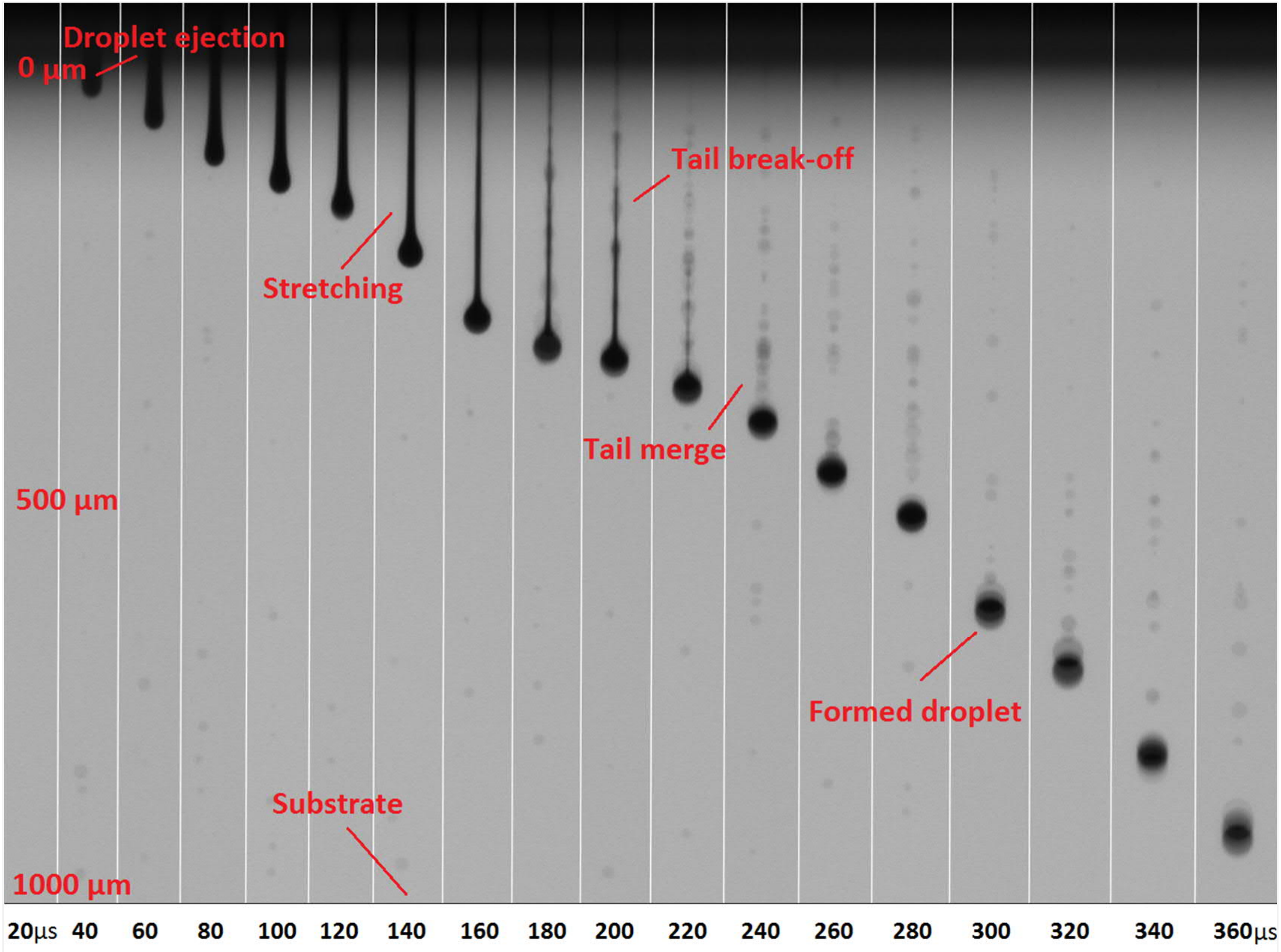

Inkjet – ink design

Viscosity:

- **2-30 cps (depending on equipment, optimum 10-12 cps)**

Surface tension: 28-33 dynes/cm (printing with limited performance up to 60 dynes/cm)

Solid content

- **Usually quite low influences on final performance**

Particle size 1/100 of nozzle diameter (filtering)

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Summary of viscosities

Printing method	Viscosity range [cPa]
inkjet	2-20 cPa
Gravure	50 – 200
Flexo	50 – 500
Screen	50 – 5000
Offset	40,000-100,000

Material	Viscosity [cPa = mPa s]
Water	0.89
Vegetable oil	81
honey	2,000-10,000
Ketchup	50,000–100,000

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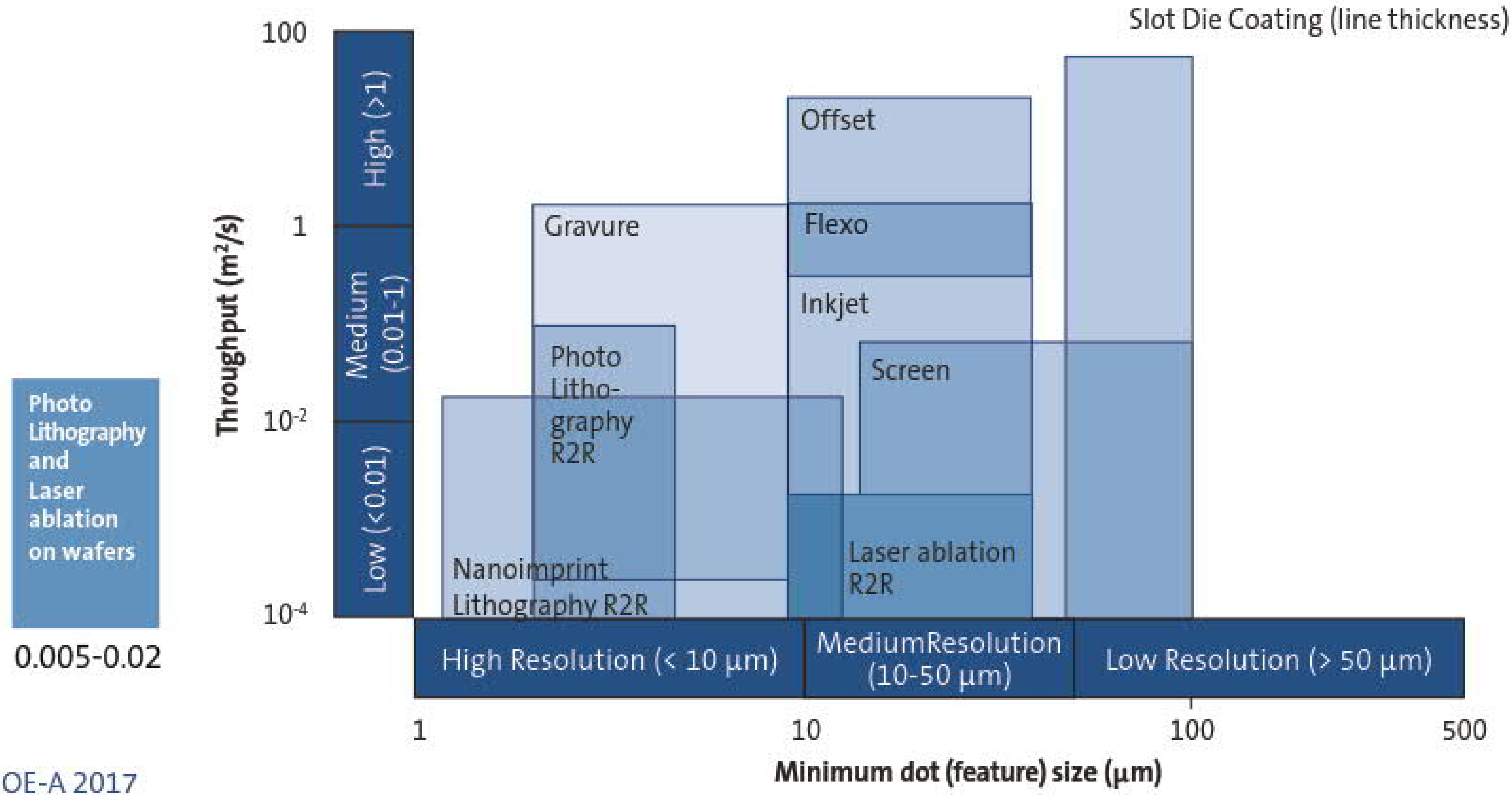

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Summary of methods

	Screen	Gravure	Flexography	Inkjet
Contact printing	Yes	Yes	Yes	No
Low-material consumption	No	No	No	Yes
Film thickness (um)	+ (>10)	- (0.3-2)	- (0.3-2)	- (0.3-2)
Speed (m^2/s)	- (<10)	++ (60)	+ (10)	-- (0.01)
Fine quality (um)	- (>50)	++ (>15)	+ (>40)	+ (>20)
Image	Mesh	Engraved	Raised	Digital

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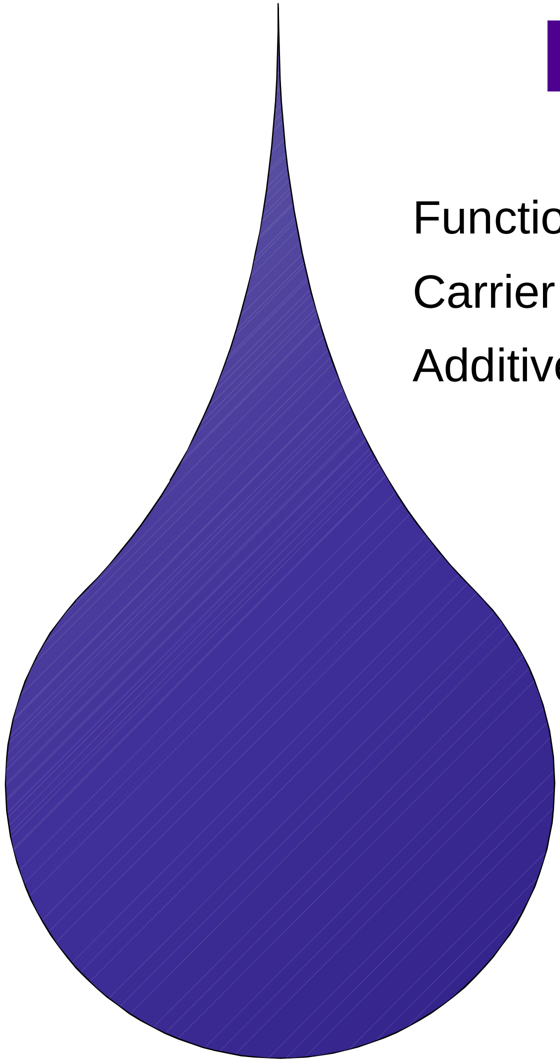
Inks and post processing



Ink

Functional material

Carrier fluid

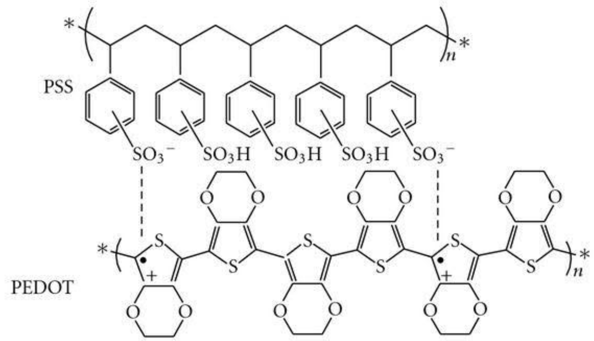
Additives

Liquid	Surface tension (mN/m)
Acetone (2-propanone)	23
Benzaldehyde	38
Ethanol (ethyl alcohol)	22
Methanoic acid (formic acid)	38
Toluene	28
Water	73

Functional materials

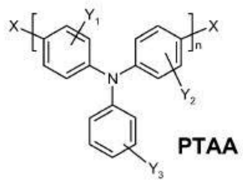
Conductors

- **Metal (Ag, Cu, Au): nano-particles, powders, flakes**
  - Sheet resistance 0.05 Ohm/sq
  - Annealing temperature 120-250C
- **Carbon, CNT, graphene,**
- **Organic conductors (PEDOT:PSS, polyaniline)**
  - Sheet resistance ~1000 Ohm/sq
  - Annealing temperature 60-120C

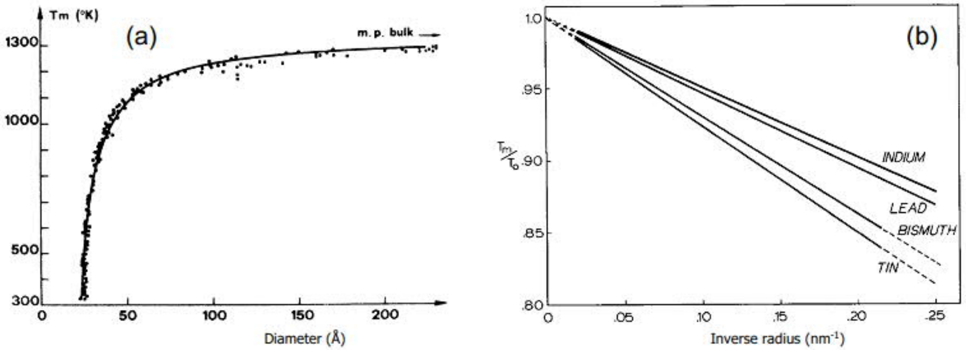


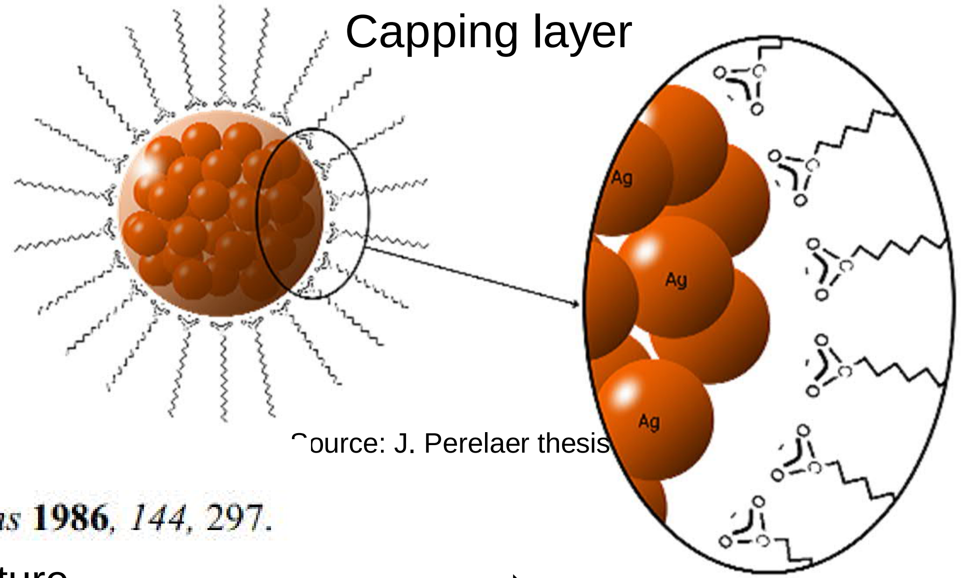
Semiconductors

- **Organic (e.g. Pentacene, polytriarylamine)**
- **Metal oxides (In-Ga-Zn-O)**



Example: Nano-particle

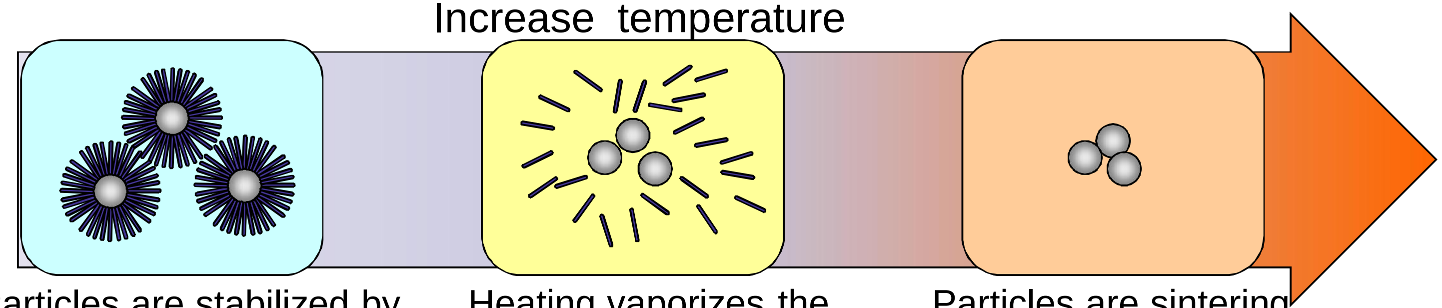




Source: J. Perelaer thesis

a) P. Buffat, J.-P. Borel, *Phys. Rev. A* **1976**, *13*, 2287.

b) G. L. Allen, R. A. Bayles, W. W. Gile, W. A. Jesser, *Thin Solid Films* **1986**, *144*, 297.

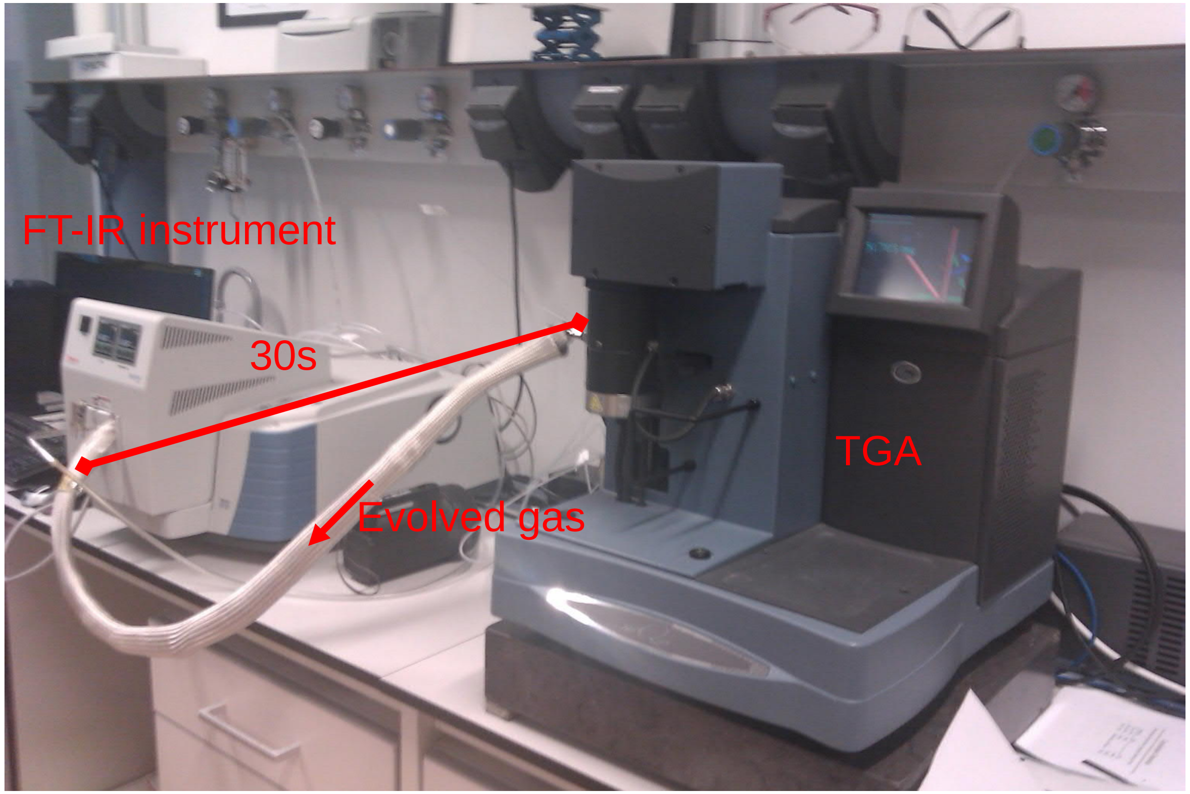


Particles are stabilized by dispersion agent.

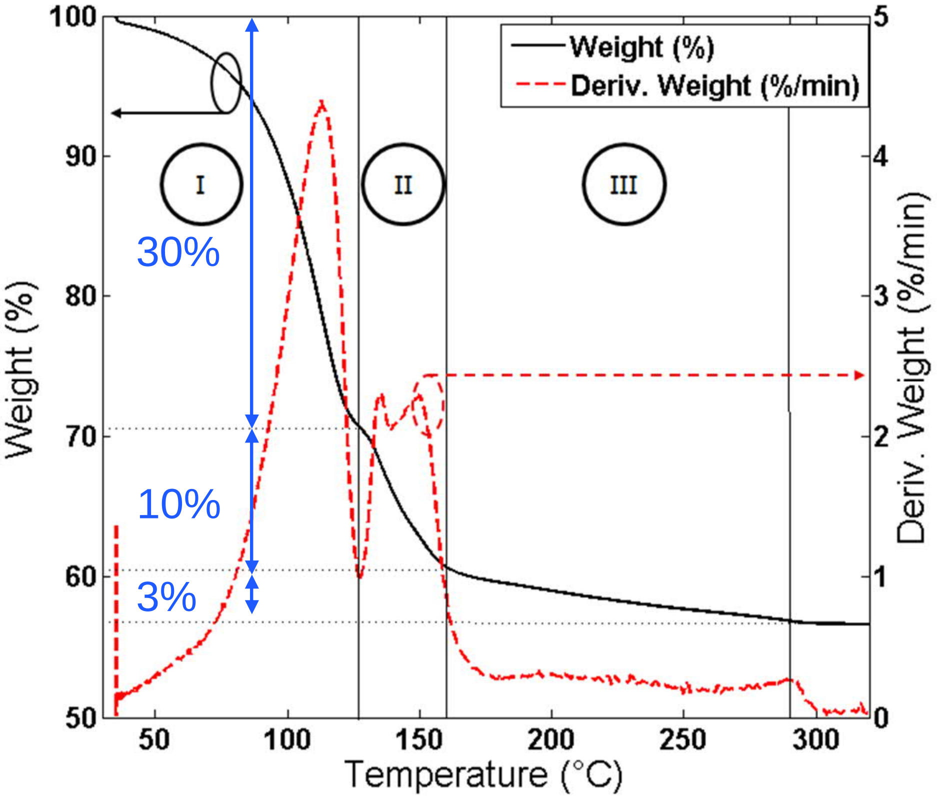
Heating vaporizes the dispersion agent.

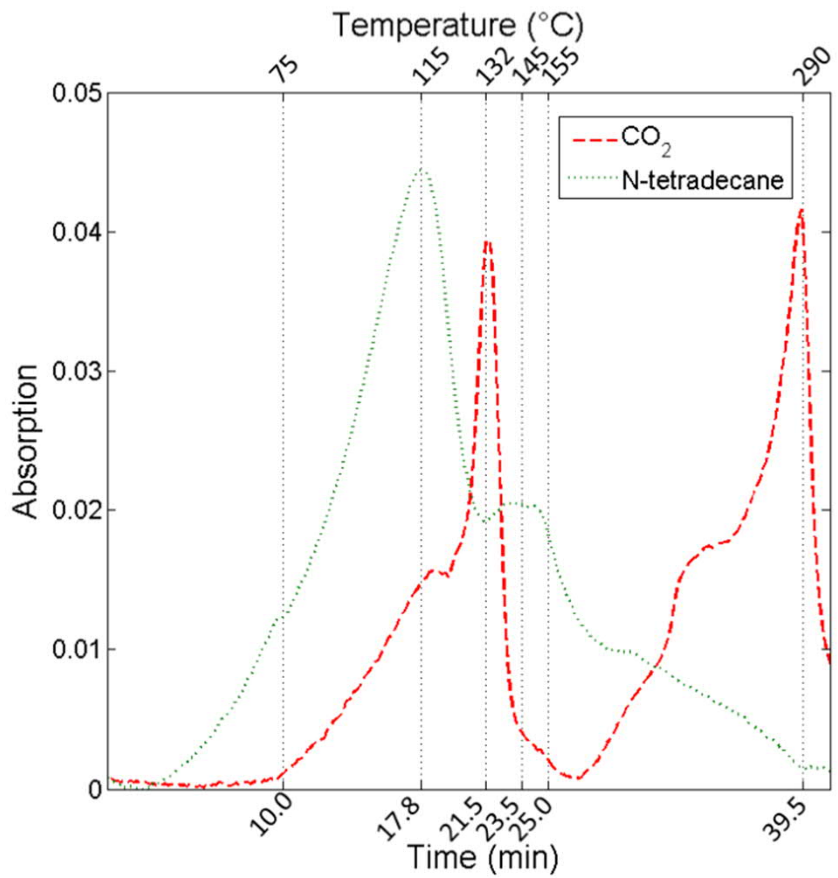
Particles are sintering together.

Optimizing nano-particle annealing temperature



Example of optimizing





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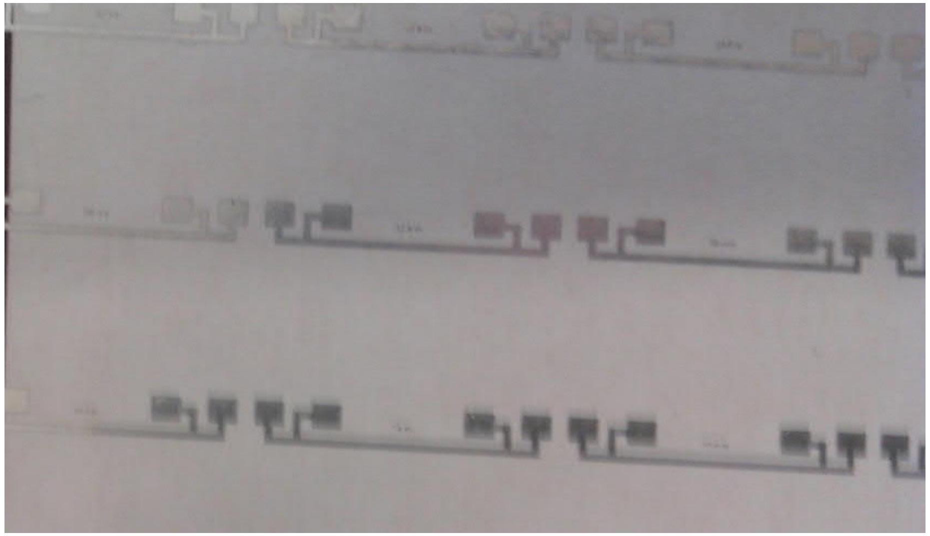
Sheet resistance

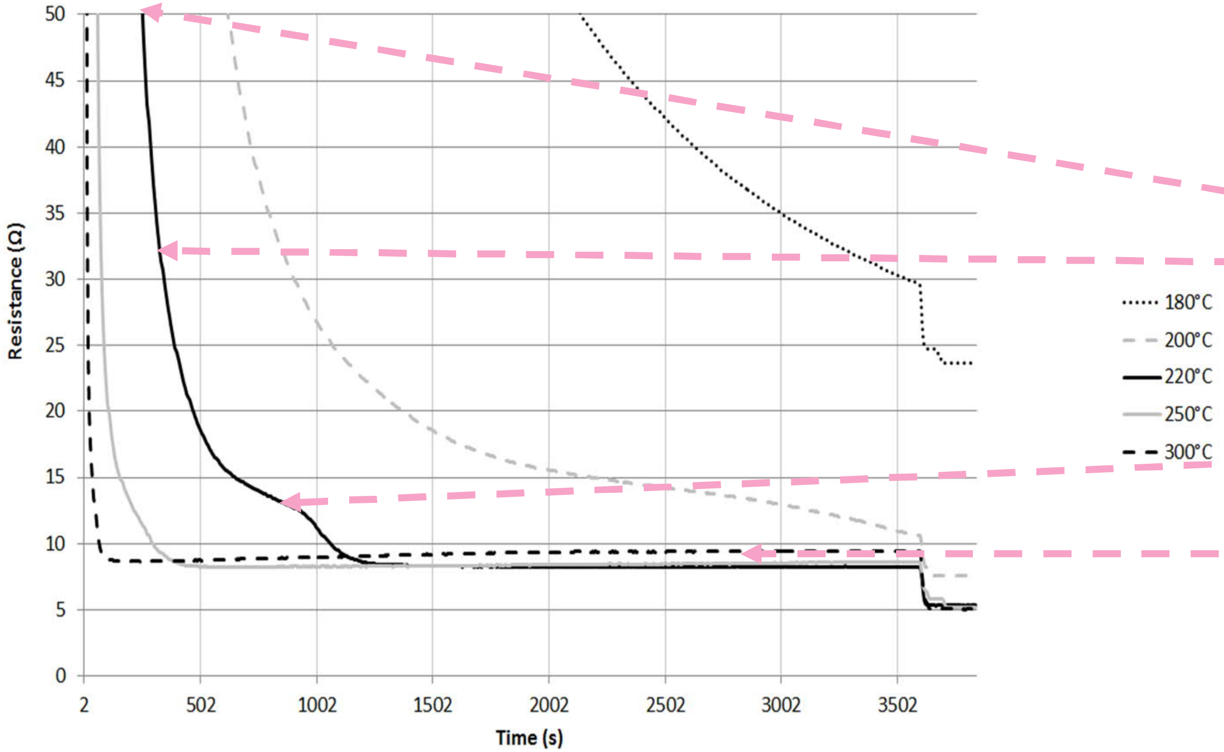
- Lines were printed on paper and sintered for 60 minutes in an oven at a constant temperature

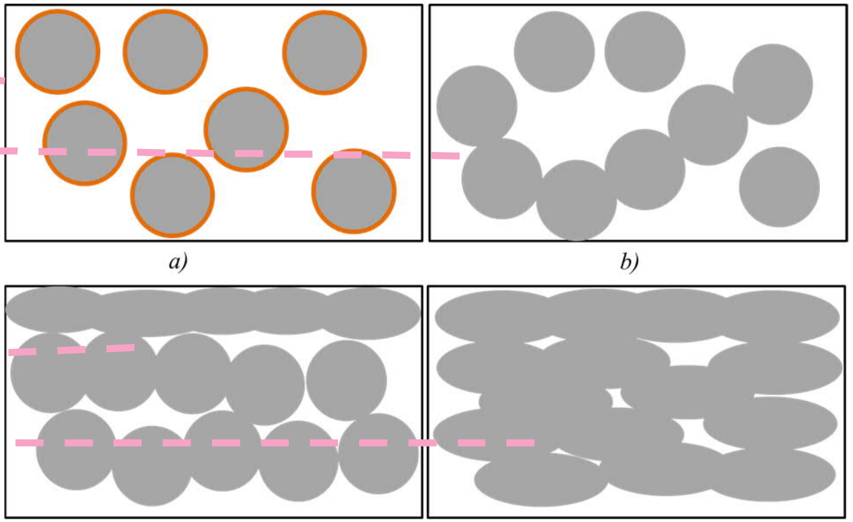
Temperature [°C]	Sheet [mΩ/□]	Resistance
120	66	
150	40	← Stabilized
180	41	



Halonen, 10.1109/TCPMT.2012.2226458

Resistance





a)
b)
c)
d)

Niittynen, doi.org/10.1016/j.tsf.2014.02.001

Alternative post-processing methods

Sintering method	Conductivity	Adhesion	Roll-to-roll compatibility	Temperature
Thermal	+ + +	+ + +	- -	- - -
Laser	+ +	- - -	+ +	-
Plasma	+	- - -	- - -	+ + +
Photonic	+ + +	+ + +	+ + +	-

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Printed hybrid electronics Ag from nano-ink

Band-aid like sensor attached directly on the body

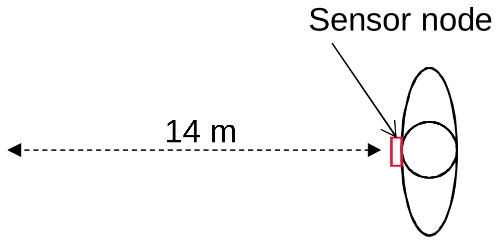
- **14 m reading distance (P_{TX} @ 0 dBm)**

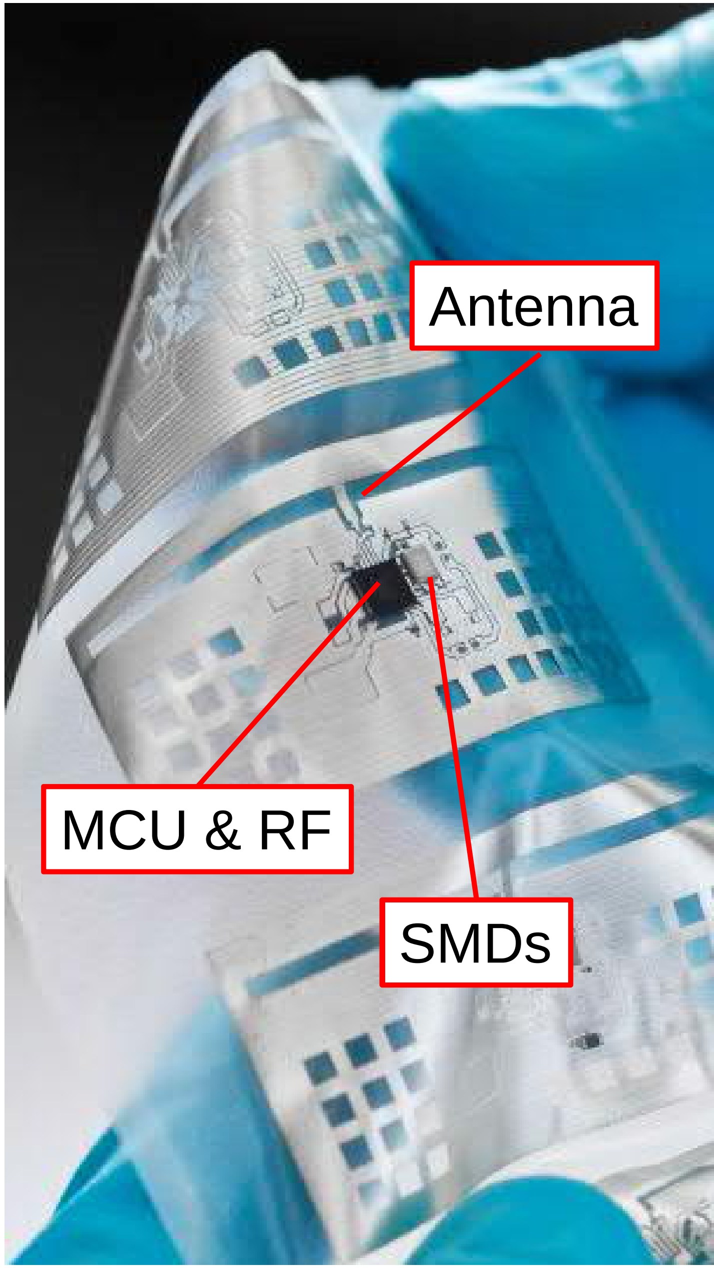
Commercial NRF51822 (SoC) from Nordic Semi (WLCSP package)

- **Bluetooth low-energy**
- **A/D converters**

In addition, there are the

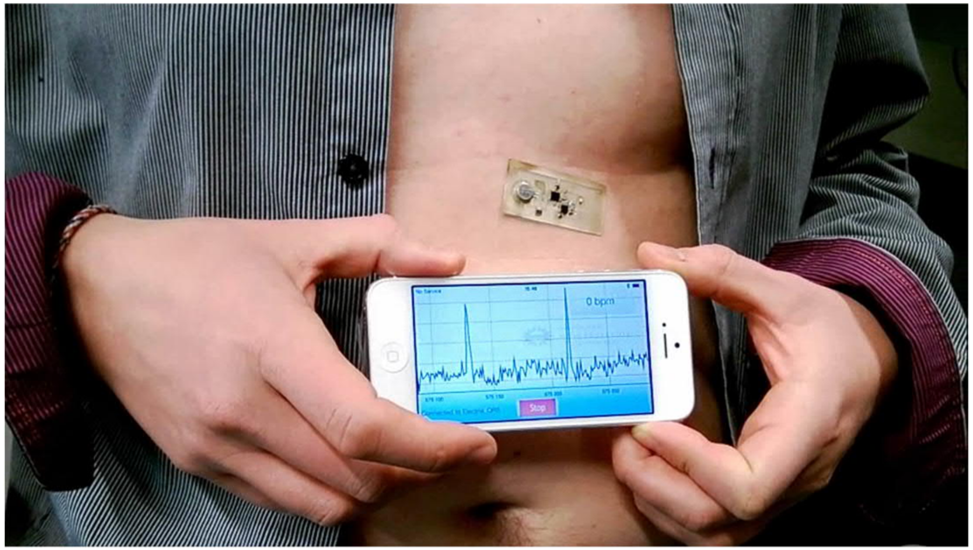
- **Antenna (printed),**
- **amplifier**
- **discrete components and electrodes for measuring the ECG signal.**





Sillanpää, et al.,, ESTC, 2014

Liimatta et al., ECTC, 10.1109/ECTC.2014.6897281



Sheet resistance (stable)	25.8 mΩ/□
Std. deviation (stable)	0.8 mΩ/□
Max. Peak strain	1.50 %
Avg. Peak strain	1.00 %
Std. deviation	0.42 pp

Stretchable conductors needed

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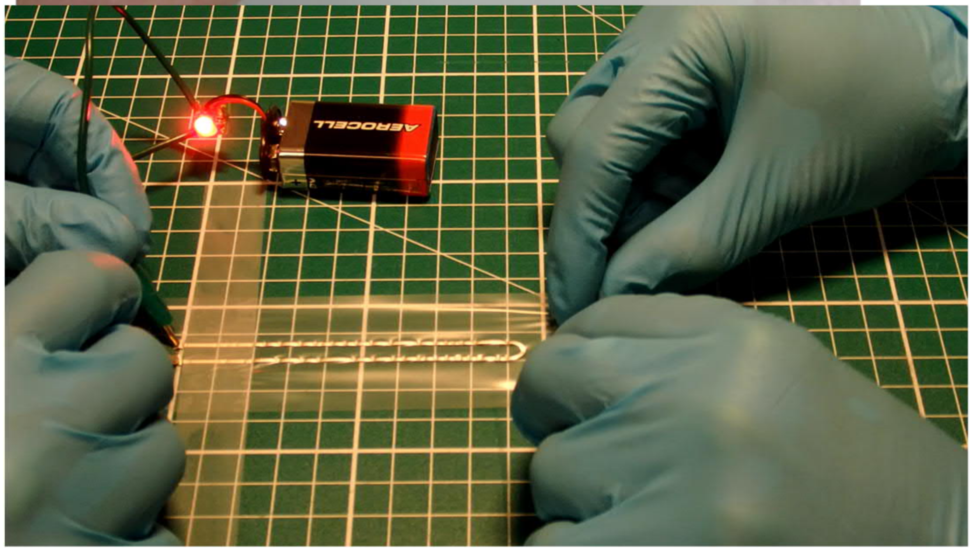

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Screen-Printing Fabrication and Characterization of Stretchable Electronics

Received: 21 December 2015
Accepted: 22 April 2016
Published: 13 May 2016

Jari Suikkola, Toni Björninen, Mahmoud Mosallaei, Timo Kankkunen, Pekka Iso-Ketola, Leena Ukkonen, Jukka Vanhala & Matti Mäntysalo

This article focuses on the fabrication and characterization of stretchable interconnects for wearable electronics applications. Interconnects were screen-printed with a stretchable silver-polymer composite ink on 50-μm thick thermoplastic polyurethane. The initial sheet resistances of the manufactured interconnects were an average of 36.2 mΩ/□, and half the manufactured samples withstood single strains of up to 74%. The strain proportionality of resistance is discussed, and a regression model is introduced. Cycling strain increased resistance. However, the resistances here were almost fully reversible, and this recovery was time-dependent. Normalized resistances to 10%, 15%, and 20% cyclic strains stabilized at 1.3, 1.4, and 1.7. We also tested the validity of our model for radio-frequency applications through characterization of a stretchable radio-frequency identification tag.

Over the past few years, numerous applications of wearable electronics have emerged in the consumer market, applications such as smart watches[1], which extend the functionality and potential of traditional watches, and head-mounted displays[2], which provide augmented reality vision. In addition, wearables are making an impact in the sports industry with wrist-worn activity trackers helping users to measure their physical activities gaining popularity. In the healthcare industry, similar wearables have been studied for unobtrusive monitoring of vital signs, such as blood pressure and electrocardiography (ECG)[3,4]. These applications may well revolutionize the healthcare industry, which is in urgent need to monitor patients remotely[5] to improve the quality of patient life and to promote efficient use of hospital facilities and services. In addition, data shows that diseases can be diagnosed remotely and patients invited for examination based on set alarm limits of various vital signs. In an effort to achieve wireless and battery-free sensors, passive radio-frequency identification (RFID) tags equipped with antennas designed to function as sensing elements have been found a compelling approach[6]. In this area, demonstrations related to stretchable electronics include uni- and bi-axial strain gauge tags[7,8] comprising antennas built from stretchable electro-textiles. Concurrently, RFID-inspired wireless sensing empowered by enhanced ambient energy harvesting capabilities and textile-integration of wearable electronics have emerged as major research themes[9,10]. Concurrently, RFID-inspired wireless sensing empowered by enhanced ambient energy harvesting capabilities and textile-integration of wearable electronics have emerged as major research themes[9,10].

However, wearable electronics applications are facing numerous challenges. One is the unobtrusiveness of the device. A key technology to minimize obtrusiveness is stretchable electronics. In contrast to conventional electronics manufactured on rigid circuit boards, such as silicon, or flexible electronics manufactured on flexible circuit boards, such as polyimide (PI), stretchable electronics are manufactured on ultra-thin elastomer substrates, such as polyurethane (PU) or polydimethylsiloxane (PDMS)[11]. Stretchable electronics can be used, e.g., in applications where their functionality is embedded in human skin[12,13]. In addition, stretchable electronics can be integrated into textiles to add functionality to clothing[14,15]. In skin-affixed and textile-integrated applications, about 15-to−20% strains occur throughout the life cycle of the product[16]. This sets the requirement for strains that stretchable interconnects should be able to withstand.

Conductive traces can be embedded in elastomer substrates in various ways. Conductive patterns have been fabricated, e.g., by etching[17], screen-printing and stencil printing[18], and inkjet printing[19]. Intrinsically stretchable materials, such as polymers (e.g., PEDOT:PSS[20]) and CNT compounds[21], generally permit high elongations but suffer from high resistance, whereas metal interconnects are less resistant yet usually not suitable for high

Tampere University of Technology, Department of Electronics and Communications Engineering, Tampere, Korkeakoulunkatu 3, FI33720, Finland. Correspondence and requests for materials should be addressed to M.M. (email: matti.mantysalo@tut.fi)

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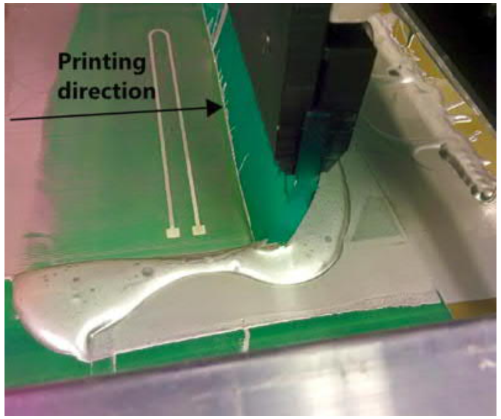
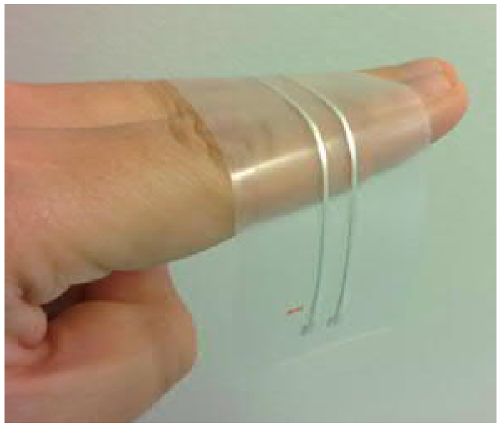
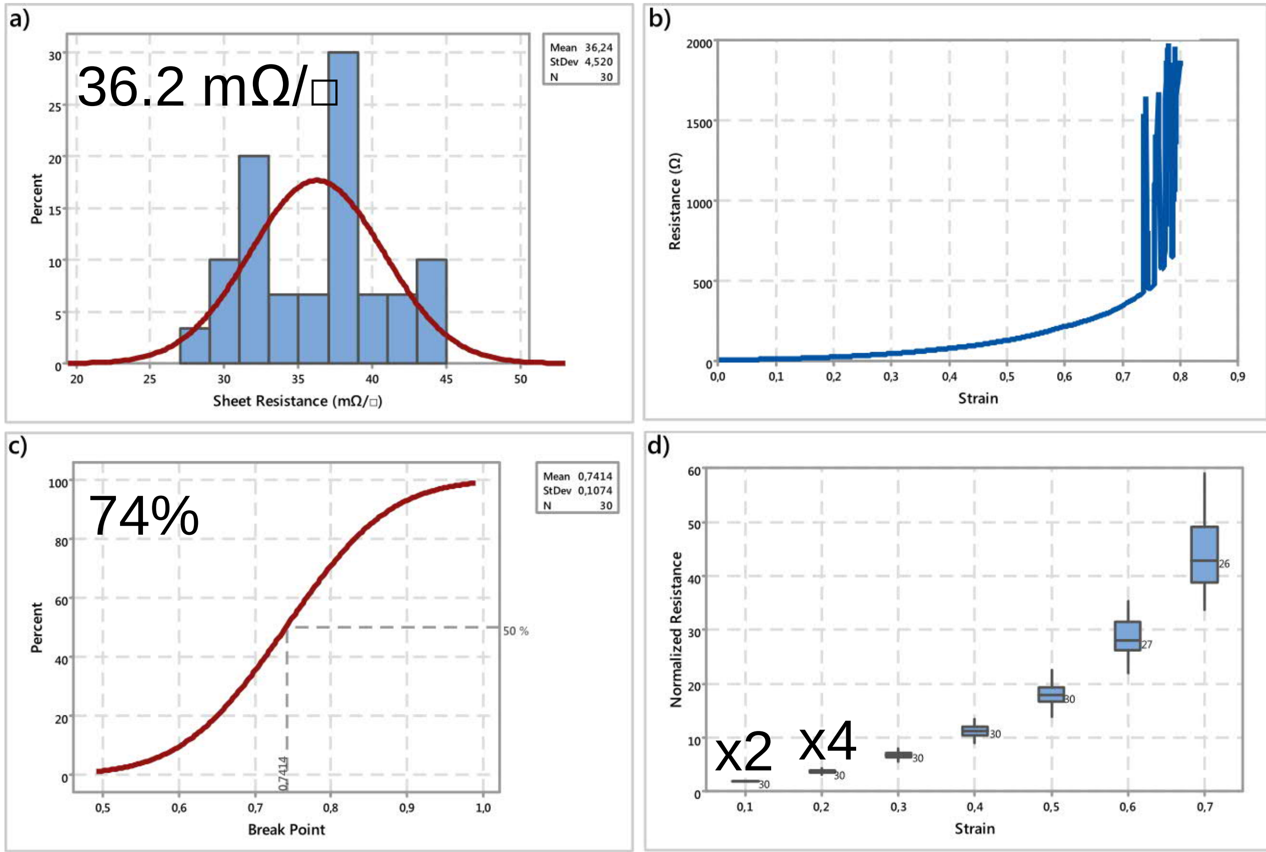
Suikkola, J. et al. Sci. Rep. 6, 25784; DOI: 10.1038/srep25784

Ag-flake

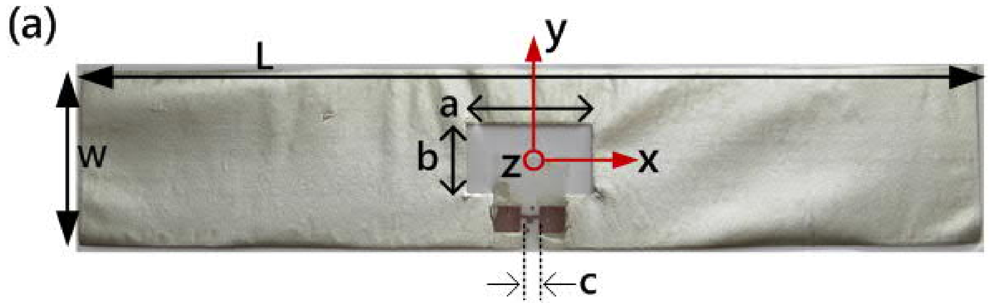






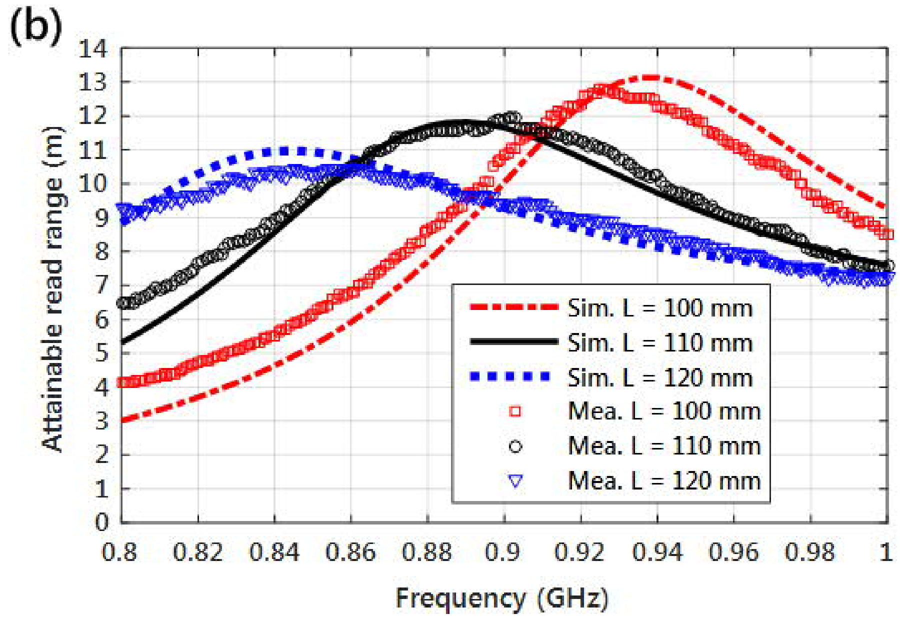
Textile integrated stretchable RFID antenna

$$\frac{R}{R_0} = 64.5269\varepsilon^3 + 24.4836\varepsilon^2 + 5.759\varepsilon + 1$$



Geometrical parameters in millimeters.

L	W	a	b	c
100	20	14.3	8.125	2



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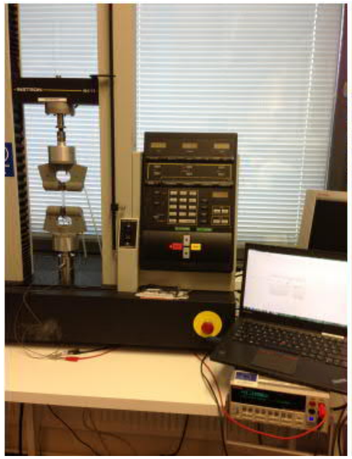
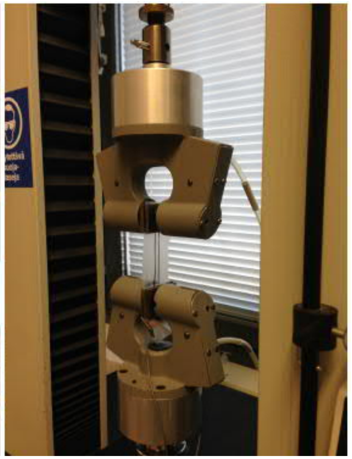
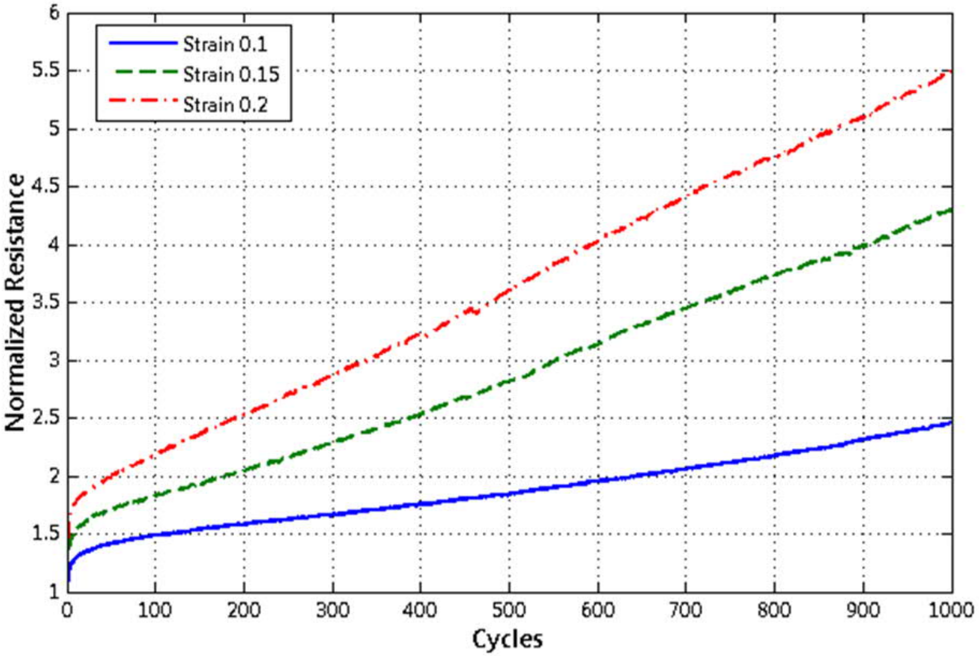
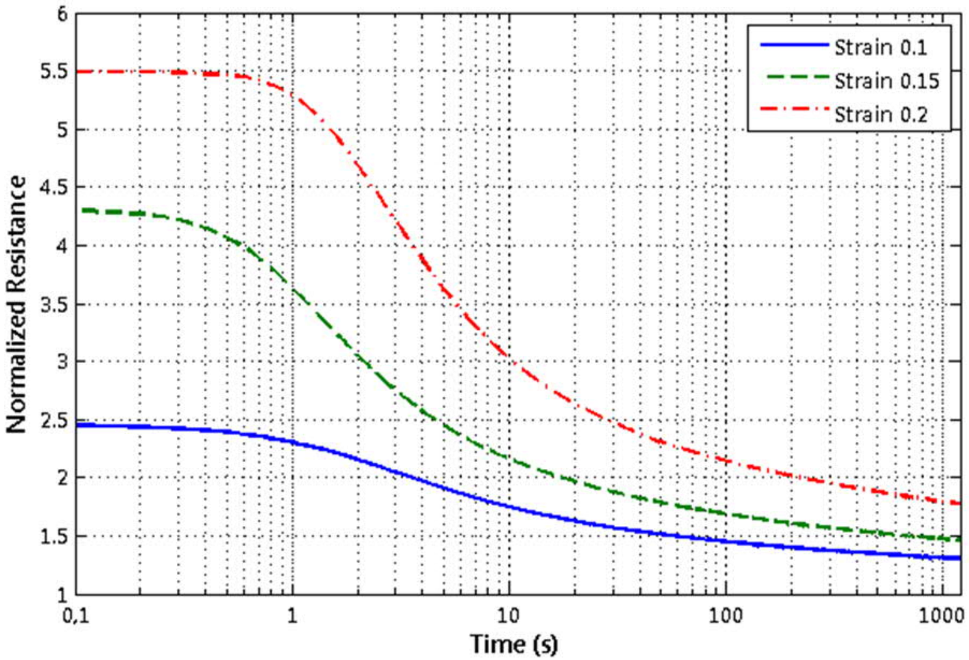
Cyclic strain test









Suikkola, J. et al. Sci. Rep. 6, 25784; DOI: 10.1038/srep25784

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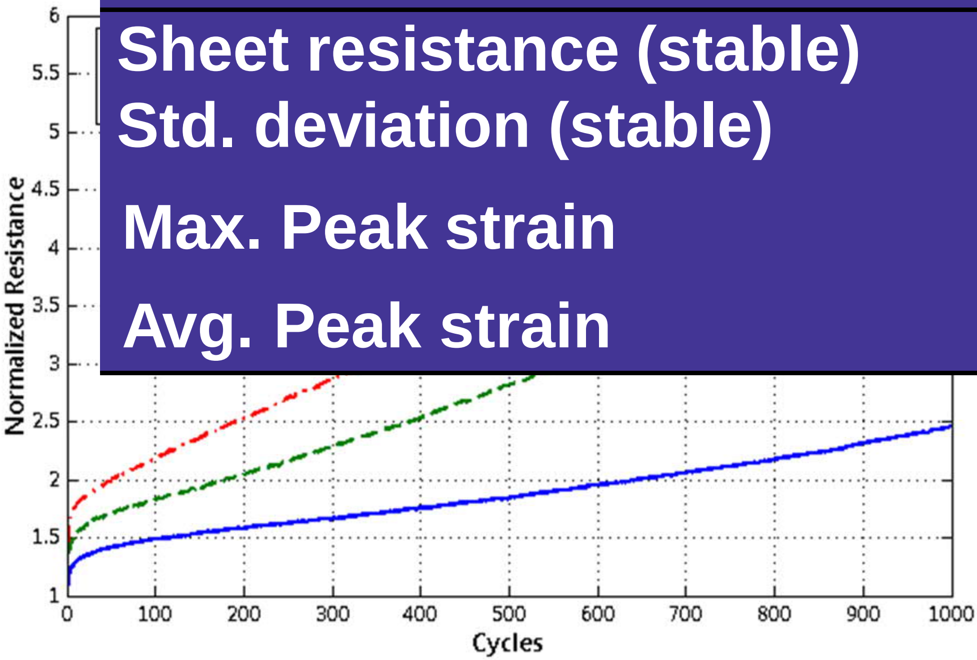
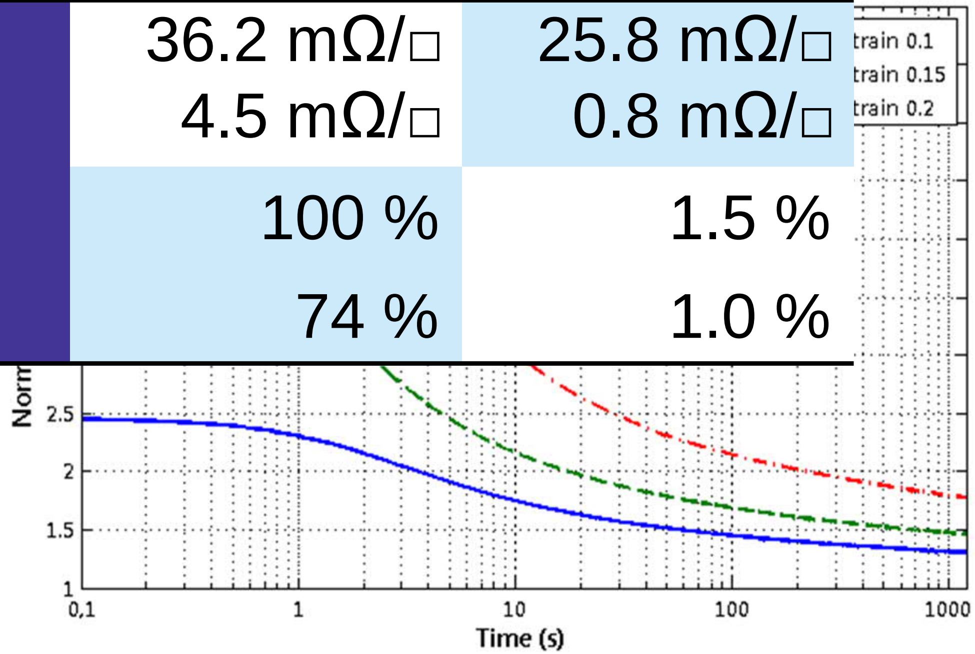
Cyclic strain test

	Ag-flake (screen)	Ag-NP (inkjet)
Sheet resistance (stable)	36.2 mΩ/□	25.8 mΩ/□
Std. deviation (stable)	4.5 mΩ/□	0.8 mΩ/□
Max. Peak strain	100 %	1.5 %
Avg. Peak strain	74 %	1.0 %





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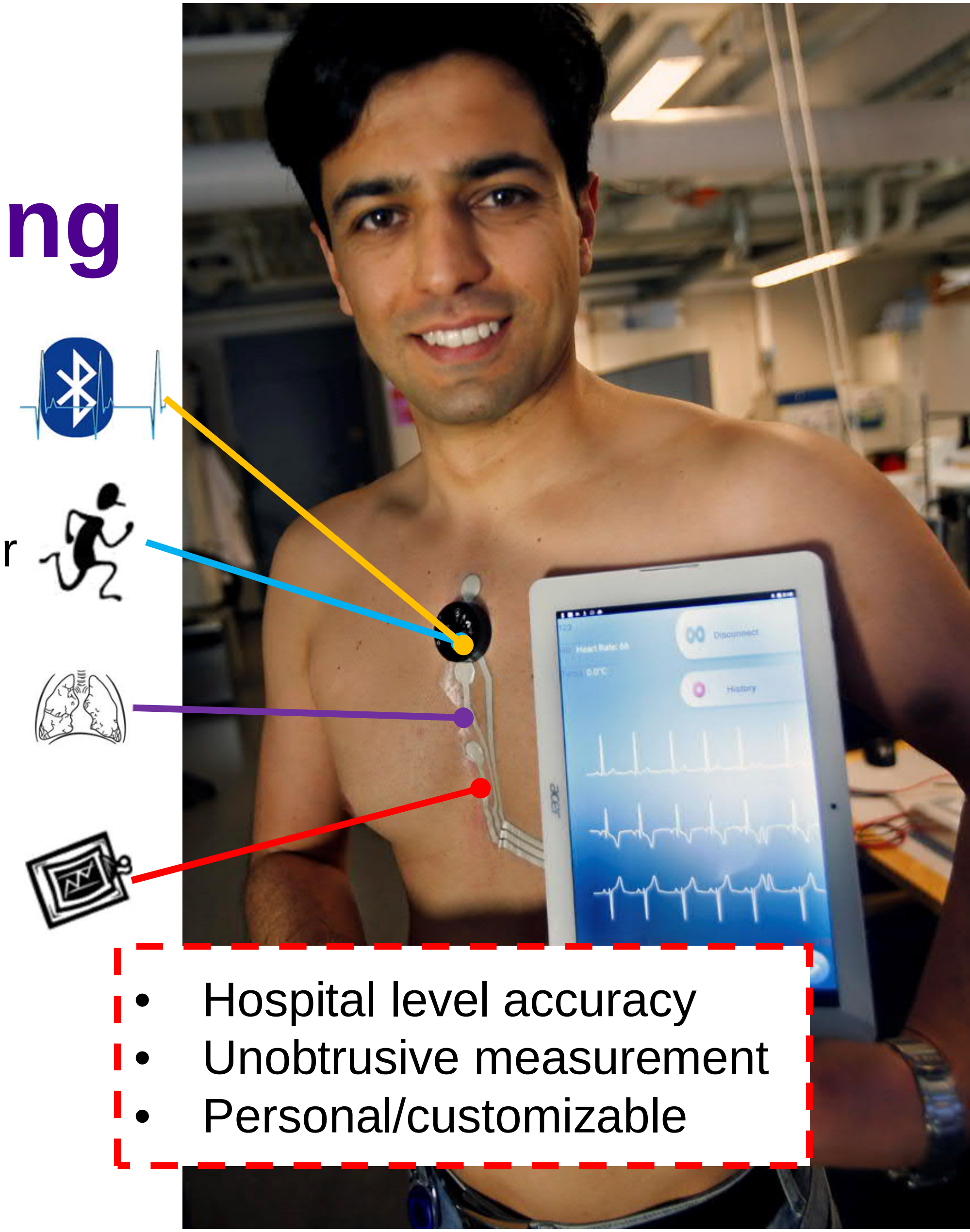
Skin mounted monitoring

System:

- **Mobile App (User interface)**
- **Data collection (small module + bandage)**
  - Holter monitoring and/or on-line data transfer
  - Printed electrodes
- **Analyze software (Cloud)**
  - Cardiac analysis in the cloud.

Sensing:

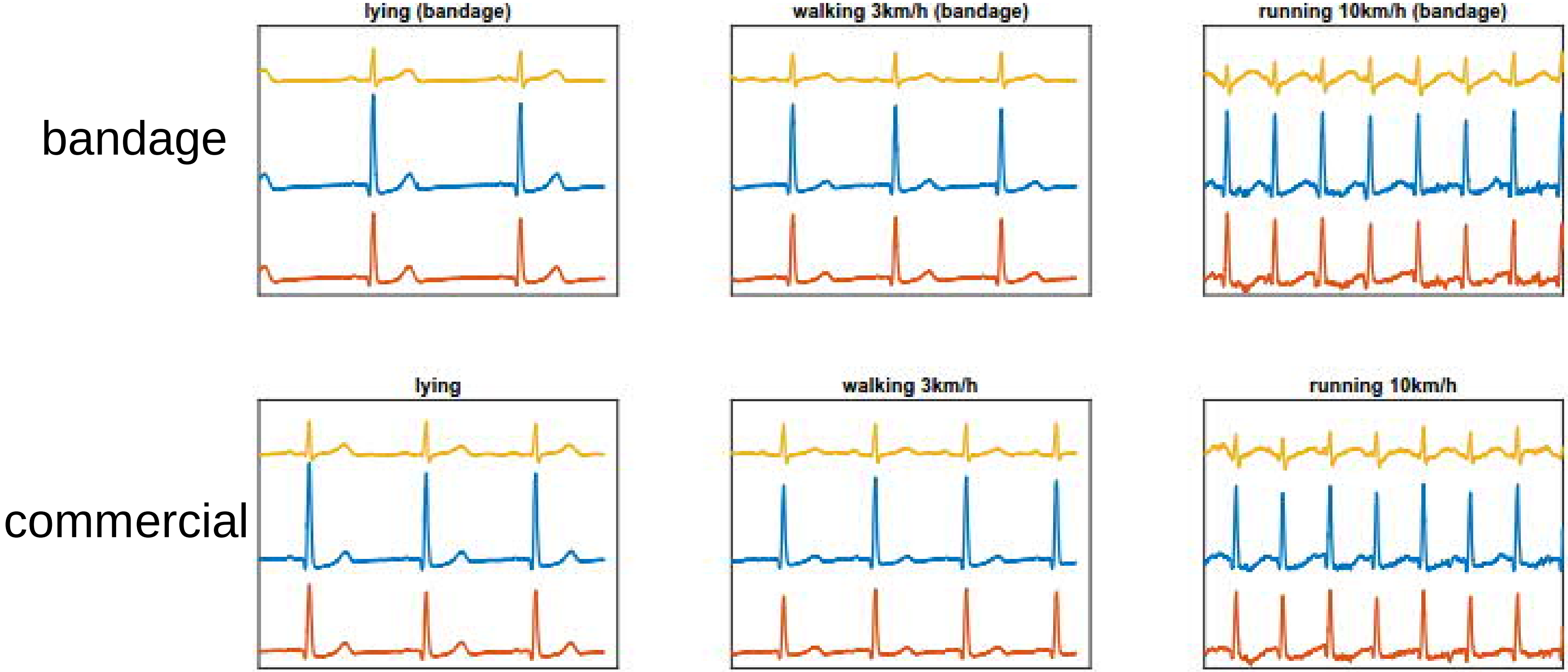
- **ECG (3 lead)**
- **Breathing rate (Impedance pneumography)**
- **Activity (3-axis accelometer + gyro)**



- Hospital level accuracy
- Unobtrusive measurement
- Personal/customizable

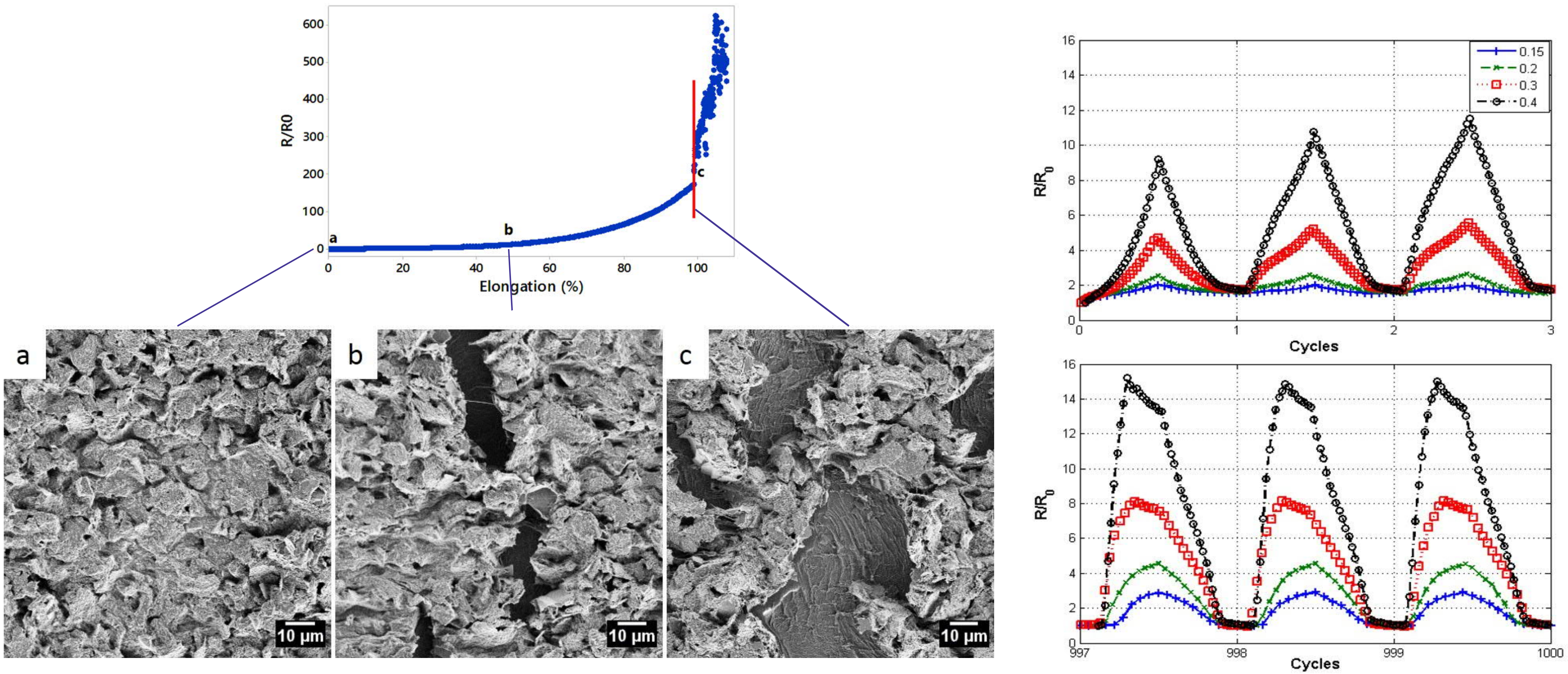
Matti.mantysalo@tut.fi

Printed bandage vs. traditional ECG electrodes



M. Mosallaei, iMaps NordPac, 2017

Screen Printed Stretchable Carbon Interconnects



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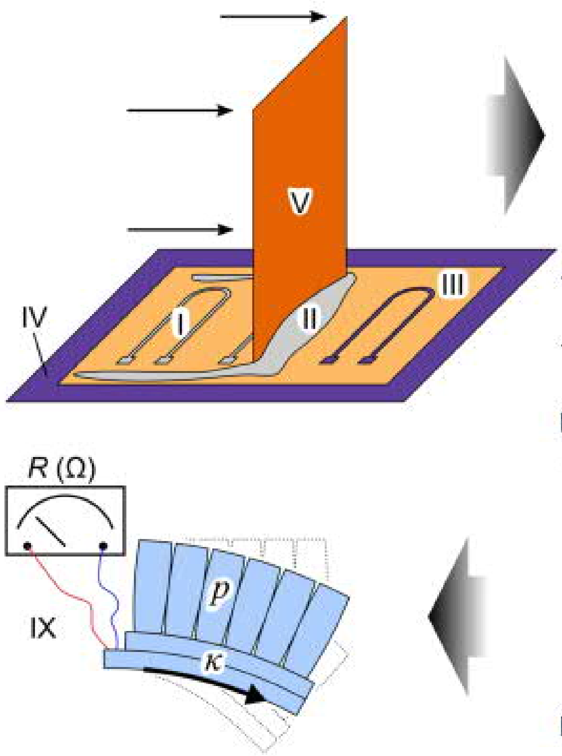
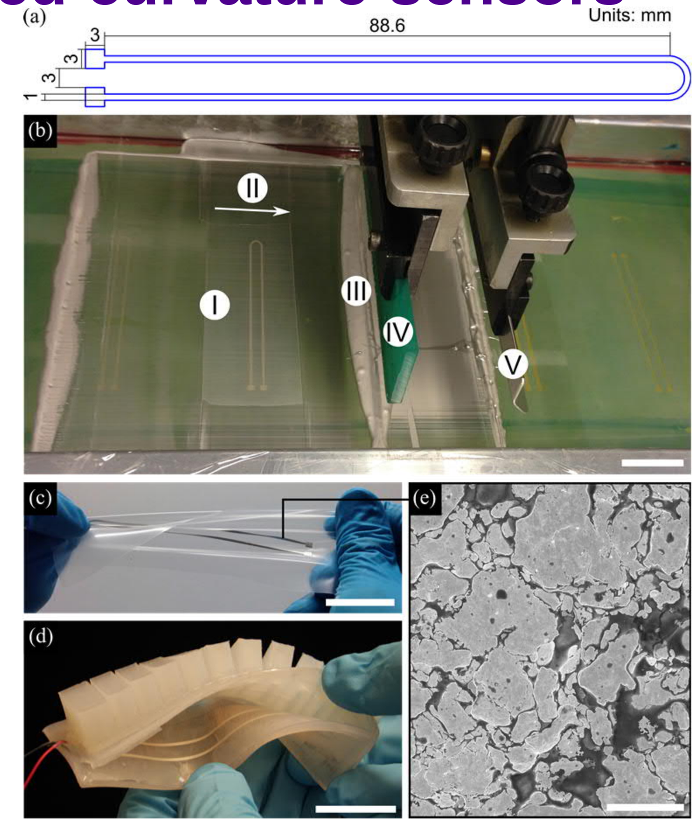
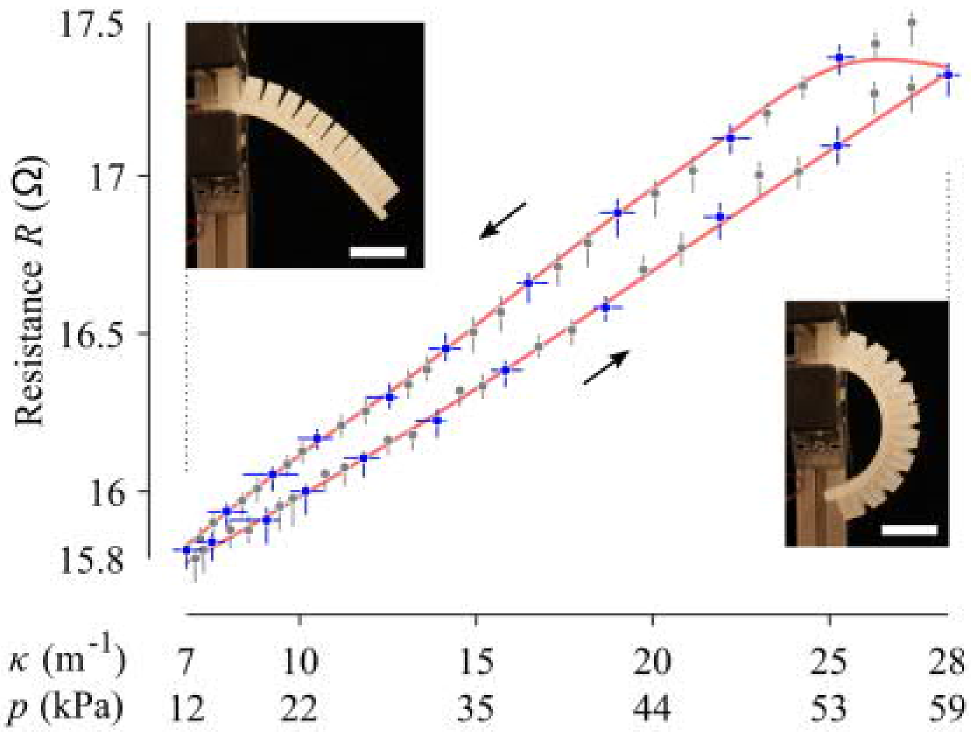
A. Koivikko, IEEE Sensor jounral, **DOI:** 10.1109/JSEN.2017.2765745

Soft actuators with screen-printed curvature sensors





A. Koivikko, IEEE Sensor jounral, **DOI:** 10.1109/JSEN.2017.2765745



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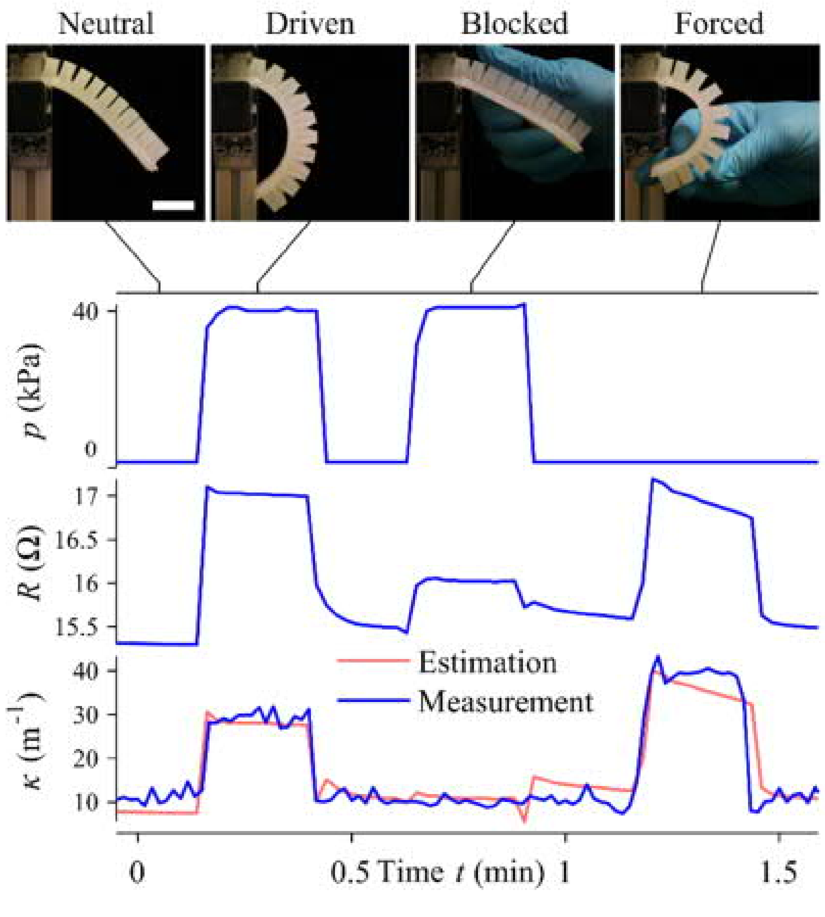

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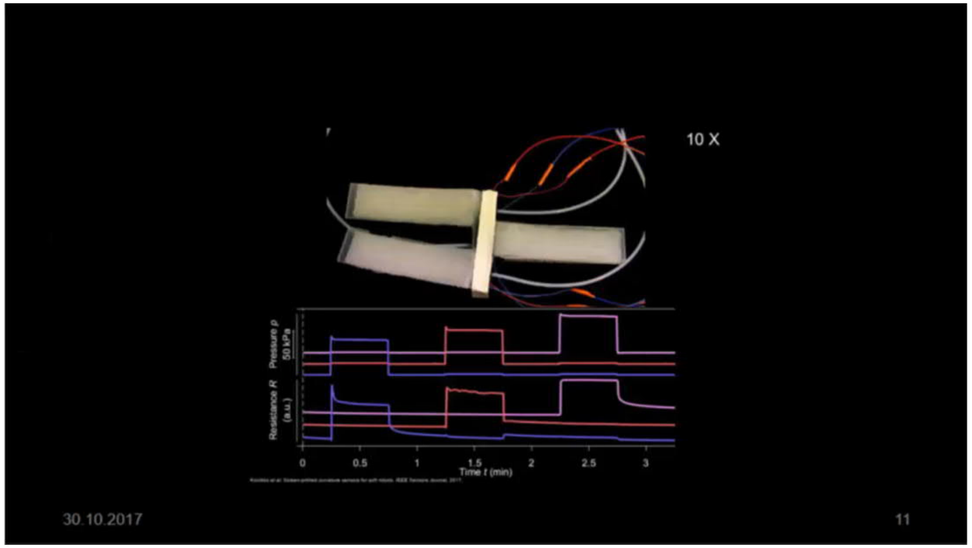
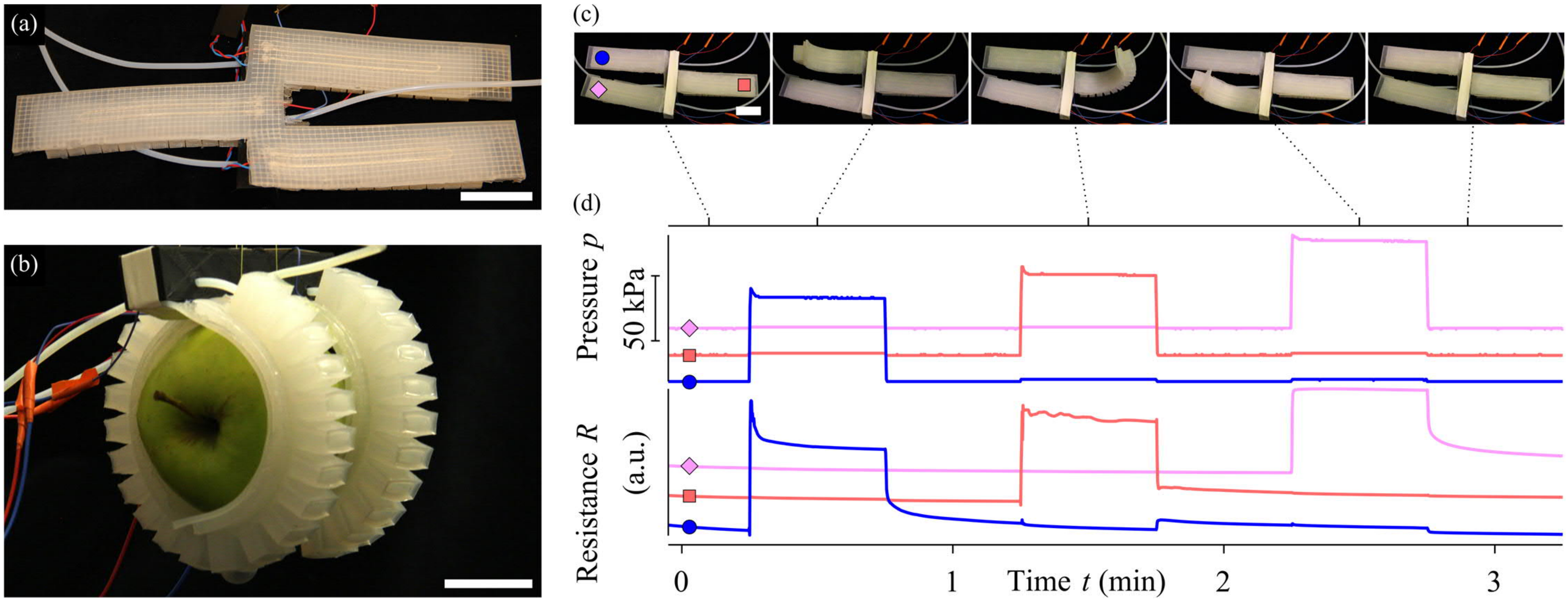


A. Koivikko, IEEE Sensor journal, **DOI:** 10.1109/JSEN.2017.2765745

Soft actuators with screen-printed curvature sensors



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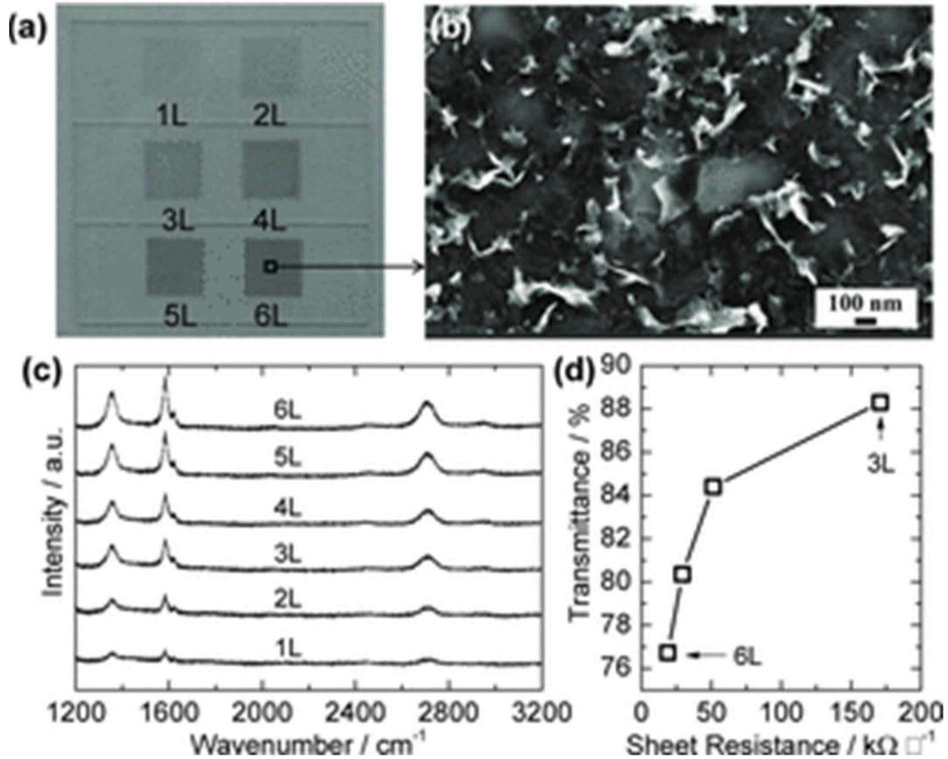
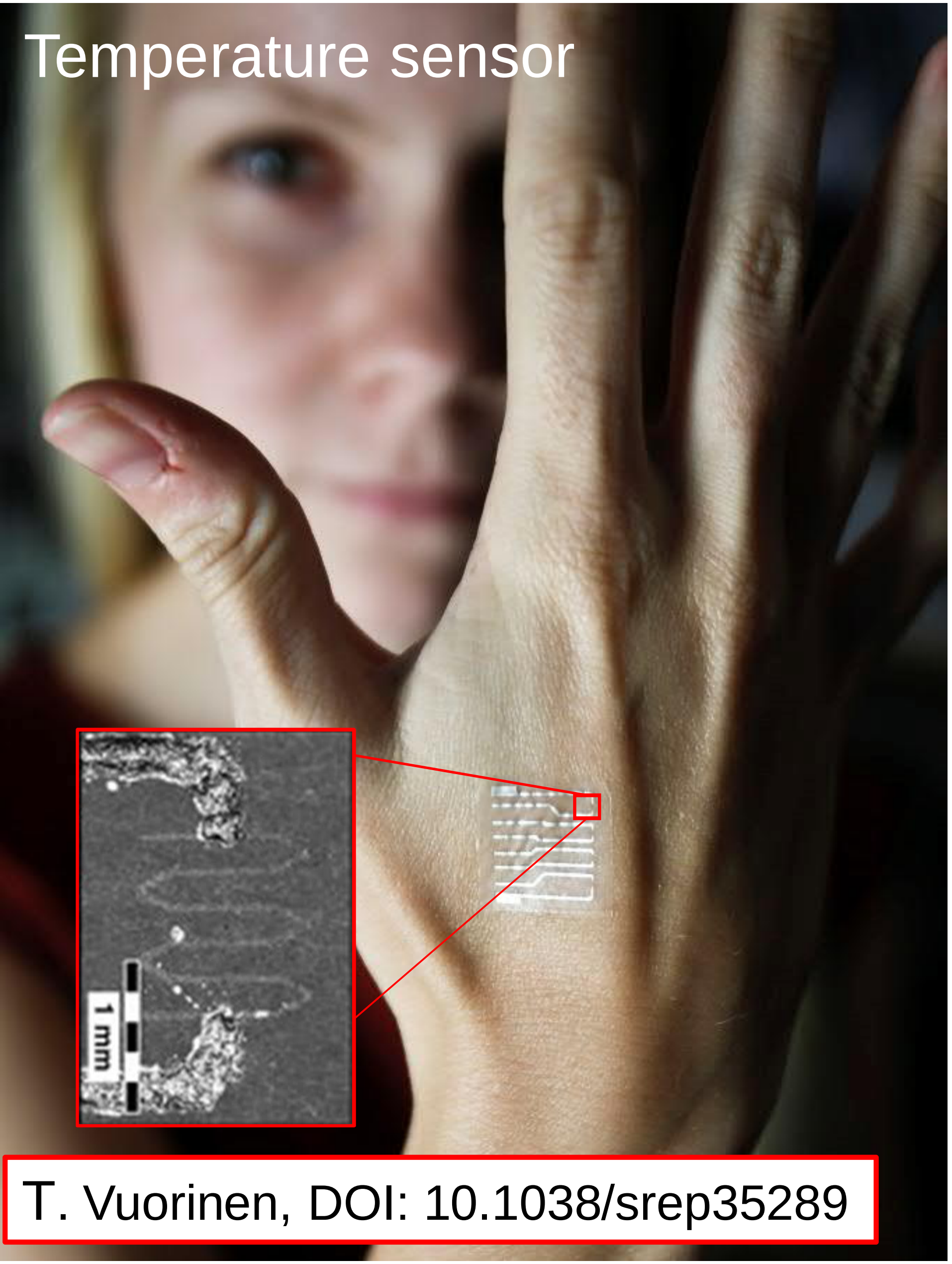
Jiantong Li, 10.1002/adma.201300361

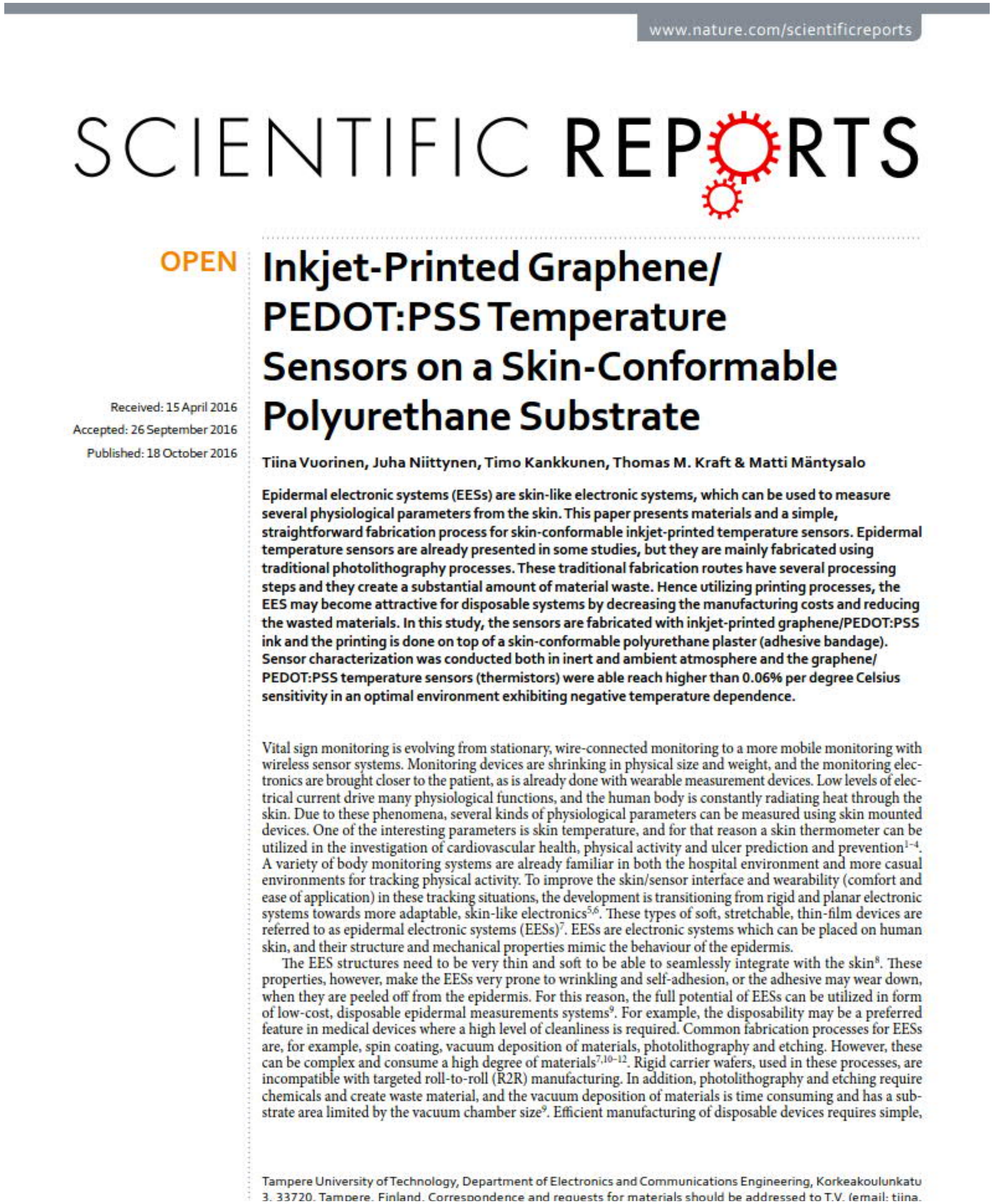
Inkjet printing of Graphene



Temperature sensor



T. Vuorinen, DOI: 10.1038/srep35289



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Received: 15 April 2016
Accepted: 26 September 2016
Published: 18 October 2016

Inkjet-Printed Graphene/PEDOT:PSS Temperature Sensors on a Skin-Conformable Polyurethane Substrate

Tiina Vuorinen, Juha Niittynen, Timo Kankkunen, Thomas M. Kraft & Matti Mäntysalo

Epidermal electronic systems (EESs) are skin-like electronic systems, which can be used to measure several physiological parameters from the skin. This paper presents materials and a simple, straightforward fabrication process for skin-conformable inkjet-printed temperature sensors. Epidermal temperature sensors are already presented in some studies, but they are mainly fabricated using traditional photolithography processes. These traditional fabrication routes have several processing steps and they create a substantial amount of material waste. Hence utilizing printing processes, the EES may become attractive for disposable systems by decreasing the manufacturing costs and reducing the wasted materials. In this study, the sensors are fabricated with inkjet-printed graphene/PEDOT:PSS ink and the printing is done on top of a skin-conformable polyurethane plaster (adhesive bandage). Sensor characterization was conducted both in inert and ambient atmosphere and the graphene/PEDOT:PSS temperature sensors (thermistors) were able reach higher than 0.06% per degree Celsius sensitivity in an optimal environment exhibiting negative temperature dependence.

Vital sign monitoring is evolving from stationary, wire-connected monitoring to a more mobile monitoring with wireless sensor systems. Monitoring devices are shrinking in physical size and weight, and the monitoring electronics are brought closer to the patient, as is already done with wearable measurement devices. Low levels of electrical current drive many physiological functions, and the human body is constantly radiating heat through the skin. Due to these phenomena, several kinds of physiological parameters can be measured using skin mounted devices. One of the interesting parameters is skin temperature, and for that reason a skin thermometer can be utilized in the investigation of cardiovascular health, physical activity and ulcer prediction and prevention[1–4]. A variety of body monitoring systems are already familiar in both the hospital environment and more casual environments for tracking physical activity. To improve the skin/sensor interface and wearability (comfort and ease of application) in these tracking situations, the development is transitioning from rigid and planar electronic systems towards more adaptable, skin-like electronics[5,6]. These types of soft, stretchable, thin-film devices are referred to as epidermal electronic systems (EESs)[7]. EESs are electronic systems which can be placed on human skin, and their structure and mechanical properties mimic the behaviour of the epidermis.

The EES structures need to be very thin and soft to be able to seamlessly integrate with the skin[8]. These properties, however, make the EESs very prone to wrinkling and self-adhesion, or the adhesive may wear down, when they are peeled off from the epidermis. For this reason, the full potential of EESs can be utilized in form of low-cost, disposable epidermal measurements systems[9]. For example, the disposability may be a preferred feature in medical devices where a high level of cleanliness is required. Common fabrication processes for EESs are, for example, spin coating, vacuum deposition of materials, photolithography and etching. However, these can be complex and consume a high degree of materials[7,10–12]. Rigid carrier wafers, used in these processes, are incompatible with targeted roll-to-roll (R2R) manufacturing. In addition, photolithography and etching require chemicals and create waste material, and the vacuum deposition of materials is time consuming and has a substrate area limited by the vacuum chamber size[9]. Efficient manufacturing of disposable devices requires simple,

Tampere University of Technology, Department of Electronics and Communications Engineering, Korkeakoulunkatu 3, 33720, Tampere, Finland. Correspondence and requests for materials should be addressed to T.V. (email: tiina.

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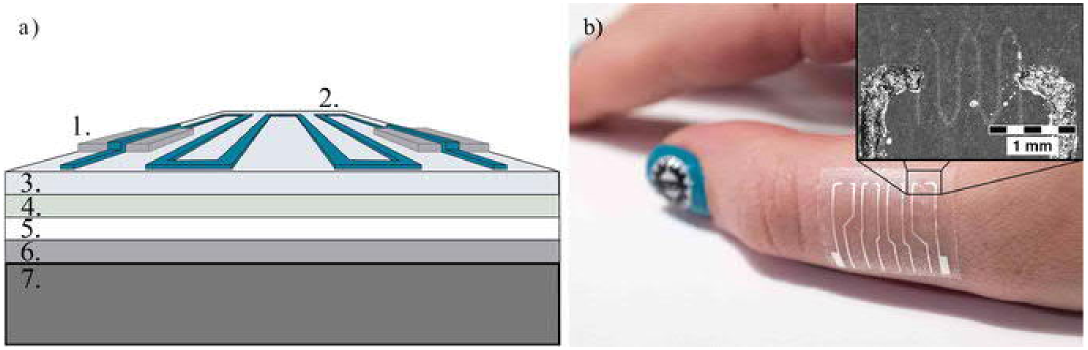
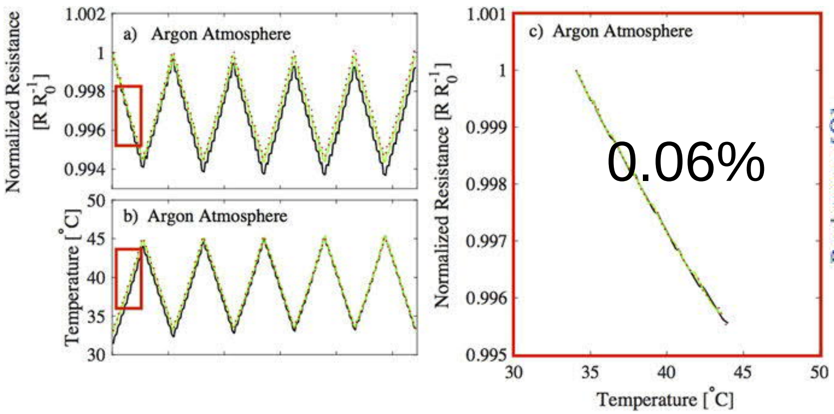
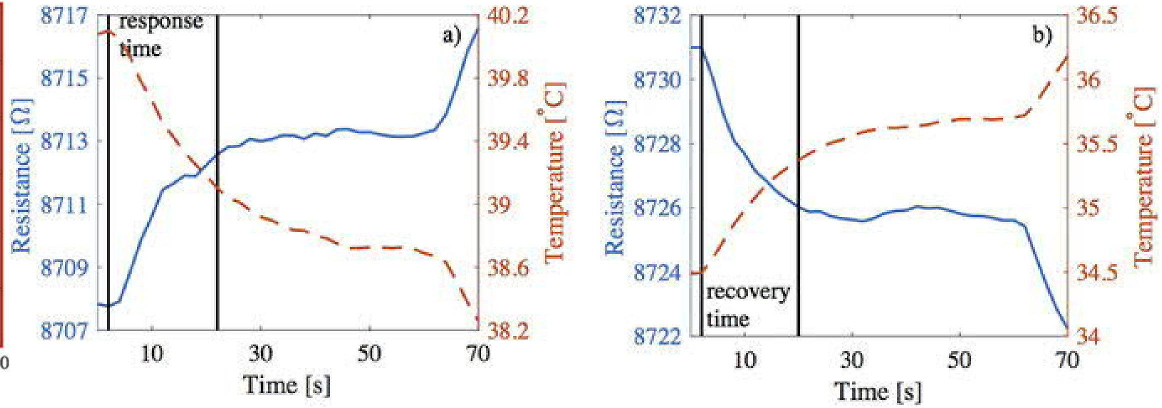
T. Vuorinen, DOI: 10.1038/srep35289

Inkjet-Printed Graphene/PEDOT:PSS Temperature Sensors on a Skin-Conformable Polyurethane Substrate



1. Connect points
2. graphene/PEDOT:PSS temperature
3. PU surface layer,
4. adhesive layer,
5. protective paper,
6. PET film

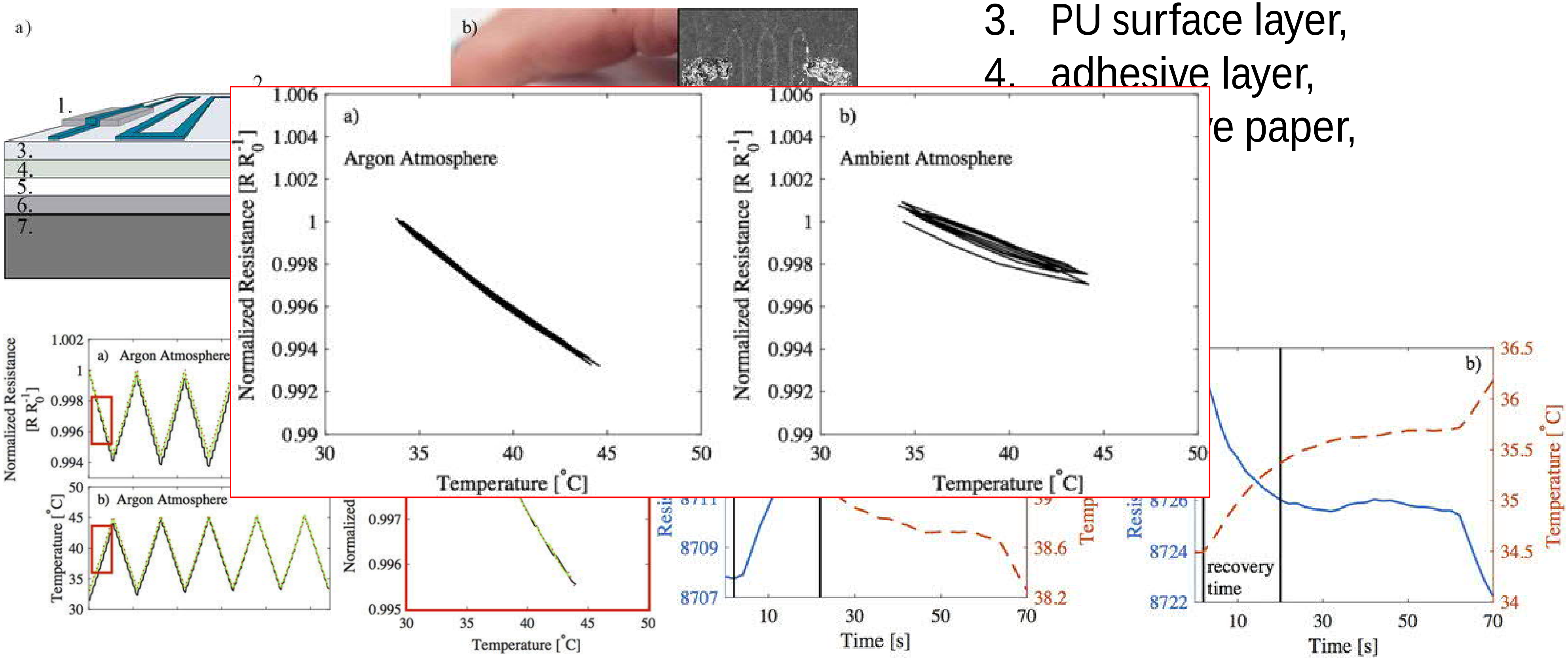




T. Vuorinen, DOI: 10.1038/srep35289

Inkjet-Printed Graphene/PEDOT:PSS Temperature Sensors on a Skin-Conformable Polyurethane Substrate

1. Connect points
2. graphene/PEDOT:PSS temperature
3. PU surface layer,
4. adhesive layer,
5. …e paper,



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Drop on Surface

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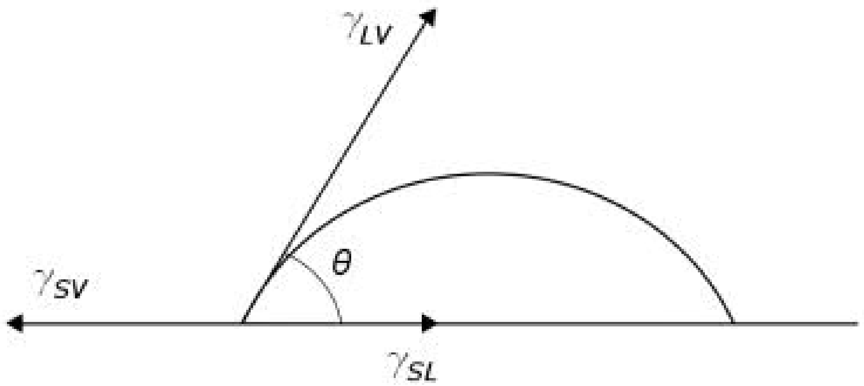
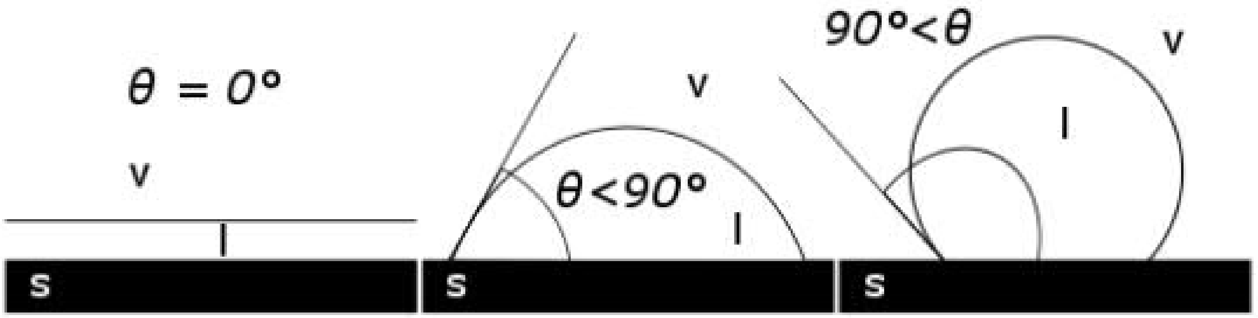
Wetting

$$\cos\theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}}$$

Surface tension of solid, liquid and gas





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Substrate

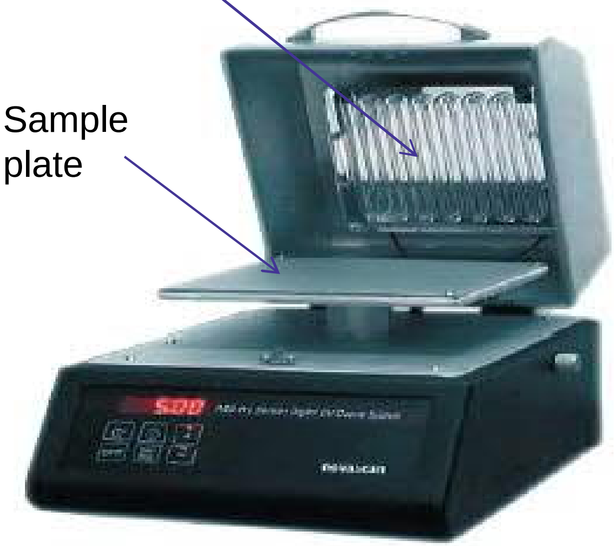
Material	Surface energy (mN/m)
Nylon	67
Polydimethylsiloxane (PDMS)	20
Polyethylene terephthalate (PET)	44
Polyimide (PI)	44
Polypropylene (PP)	30
Polyvinyl chloride (PVC)	40

Surface energy modification

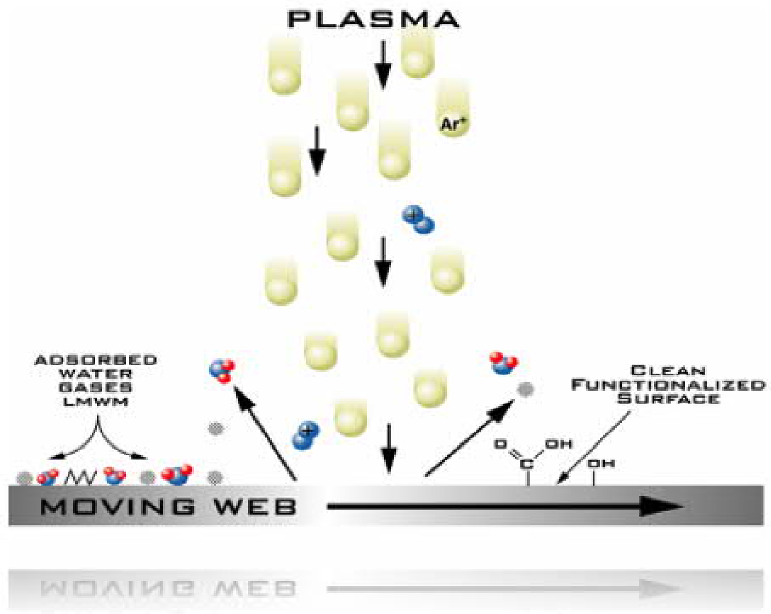
UV-ozone

Low-pressure mercury lamp

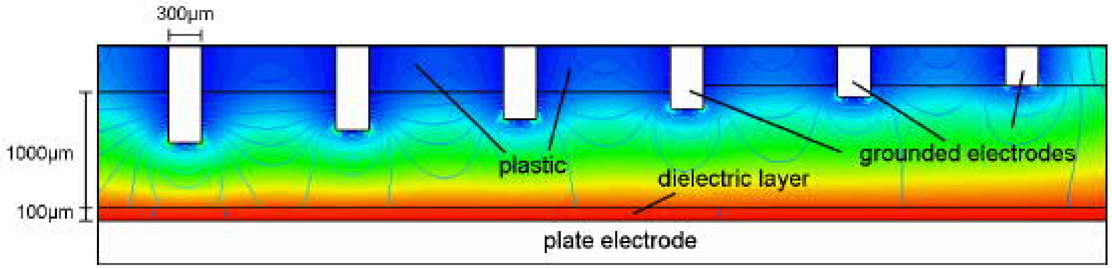
Sample plate

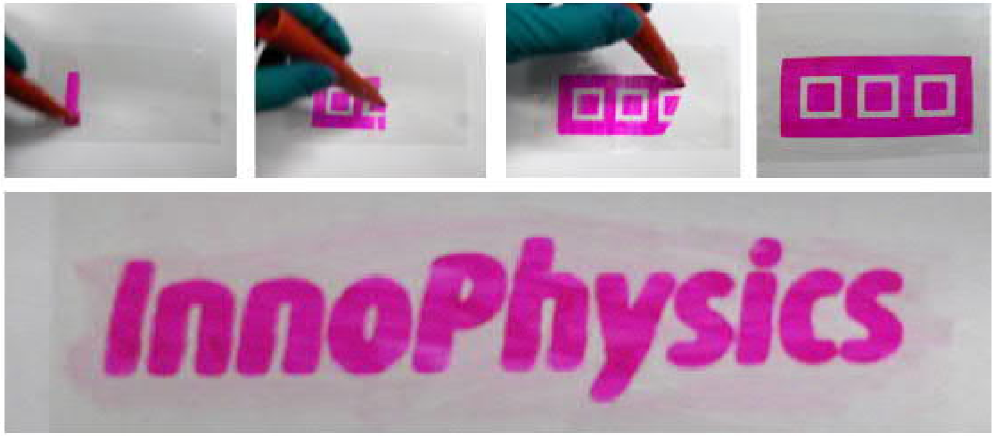


Plasma

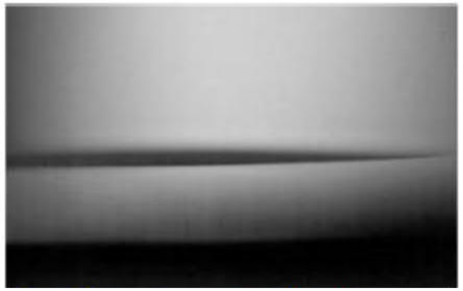


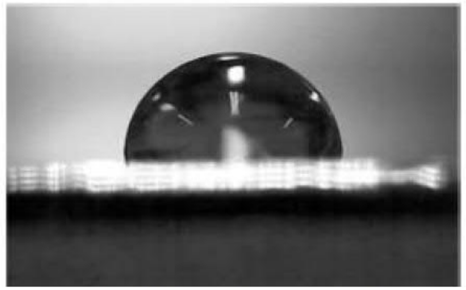
Example: µPlasmaPrint





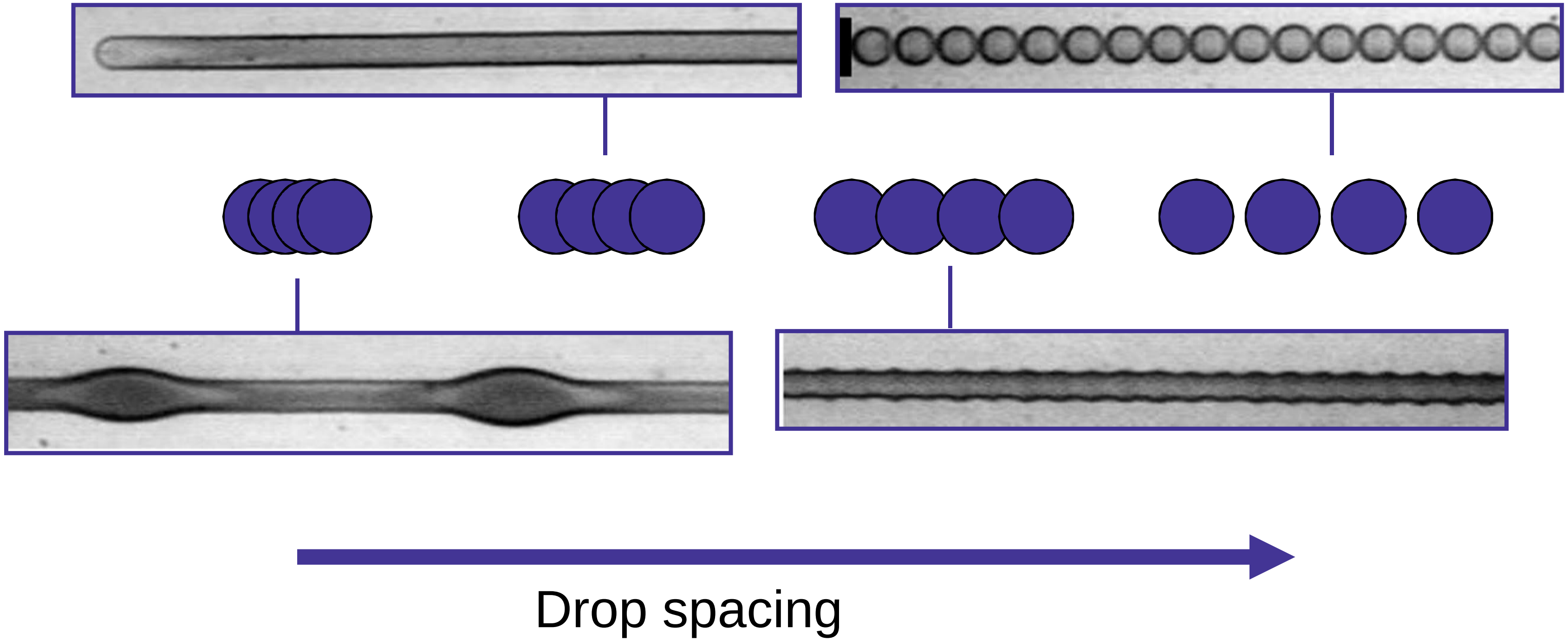
Before plasma treatment





P. Blom, A. Stevens et al., Mask-less Patterning Technology for the Printed Electronics Market, Proceedings of NIP26 and Digital Fabrication, (2010), pp.131-134.

Pattern generation



D. Soltman, “Understanding Inkjet Printed Pattern Generation“, Ph.D. Thesis, University of California, Berkeley, 2011

PE in microelectronics packaging

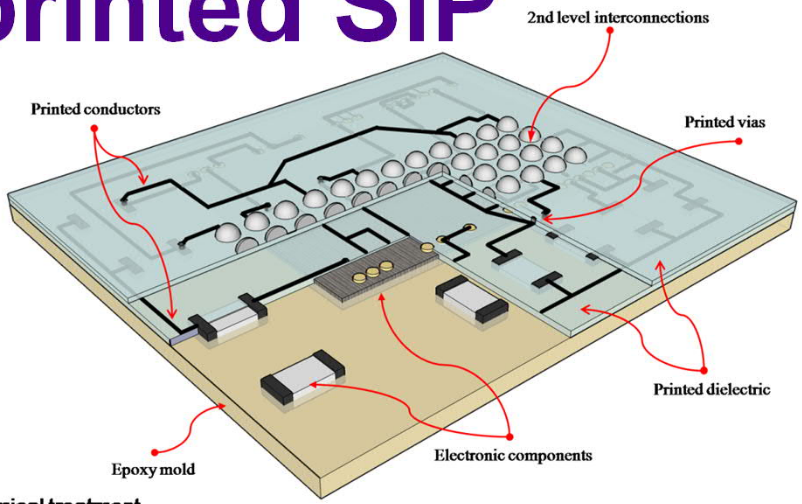
Inkjet printed SiP (System-in-Package)

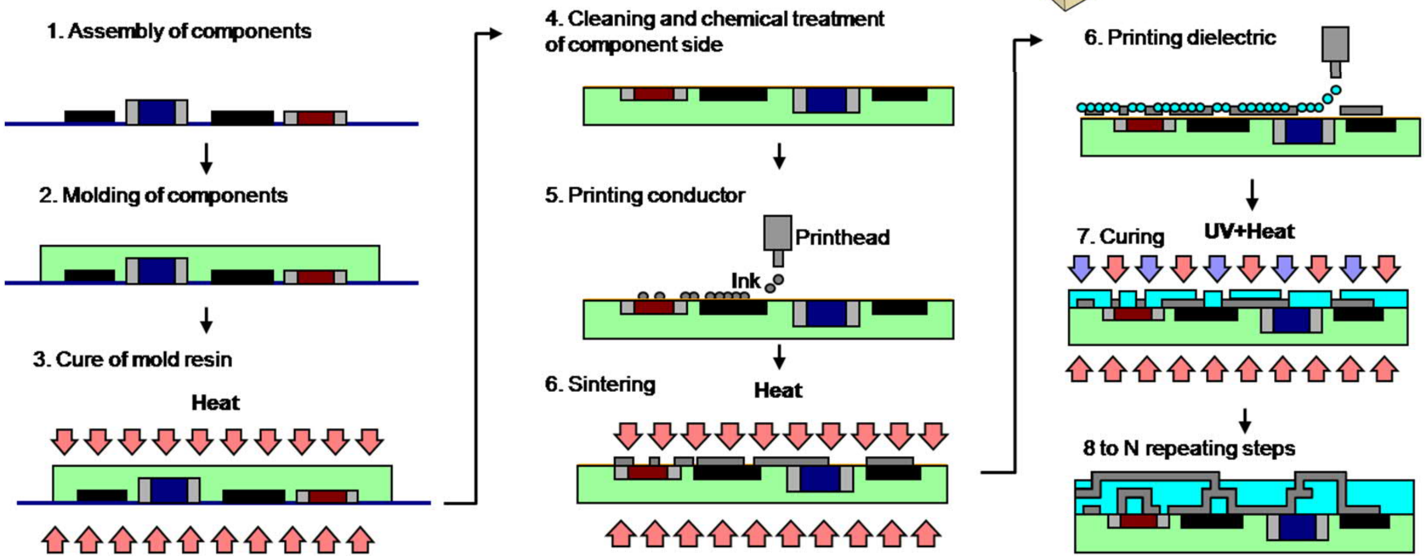
Re-distribution layer

TSV (Through Silicon Via)

Micropillar

Example: Inkjet printed SiP





Pekkanen V., et. al., Utilizing inkjet printing to fabricate electrical interconnections in a system-in-package, DOI: 10.1016/j.mee.2010.04.013

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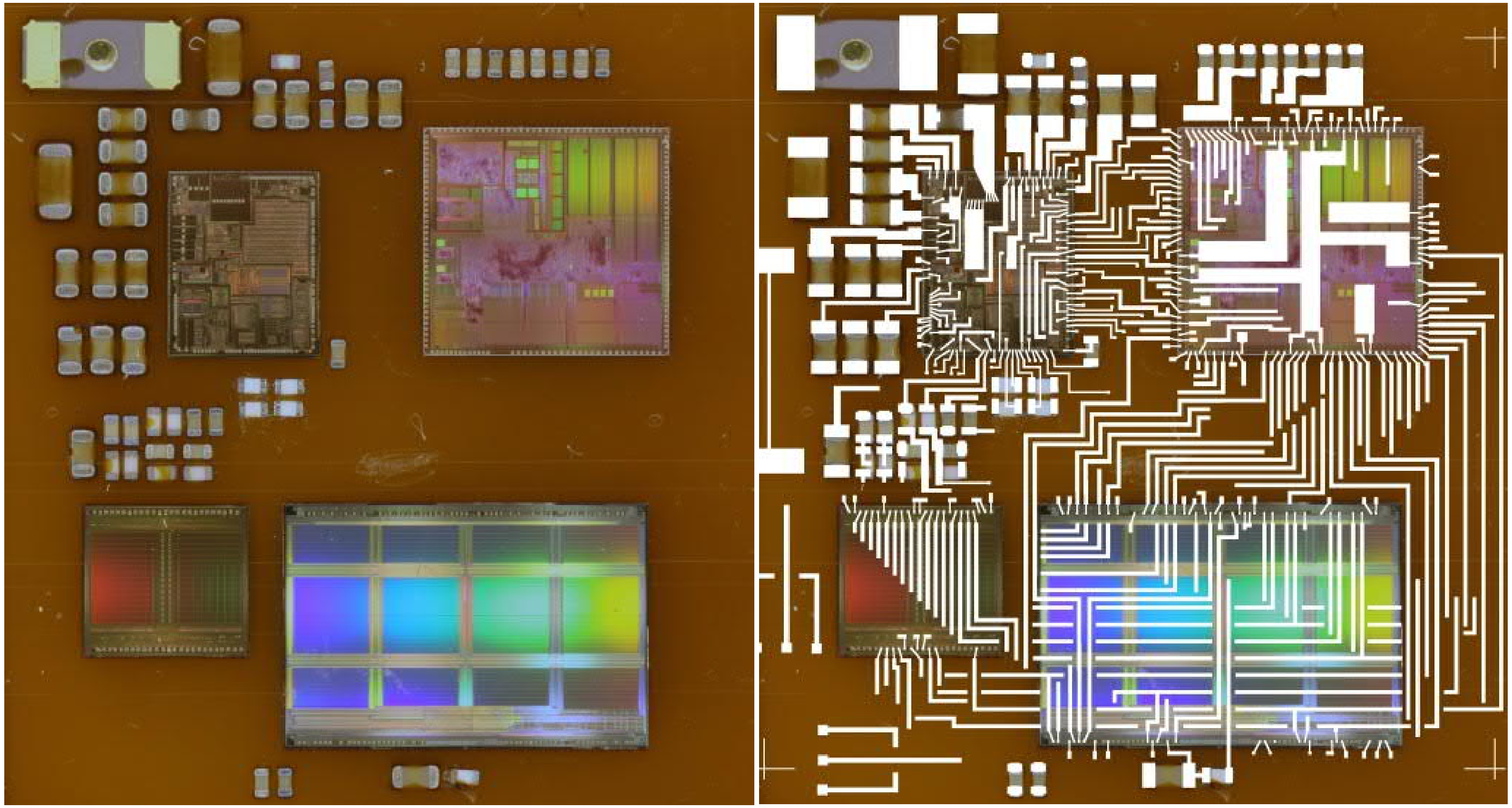
Multiple components



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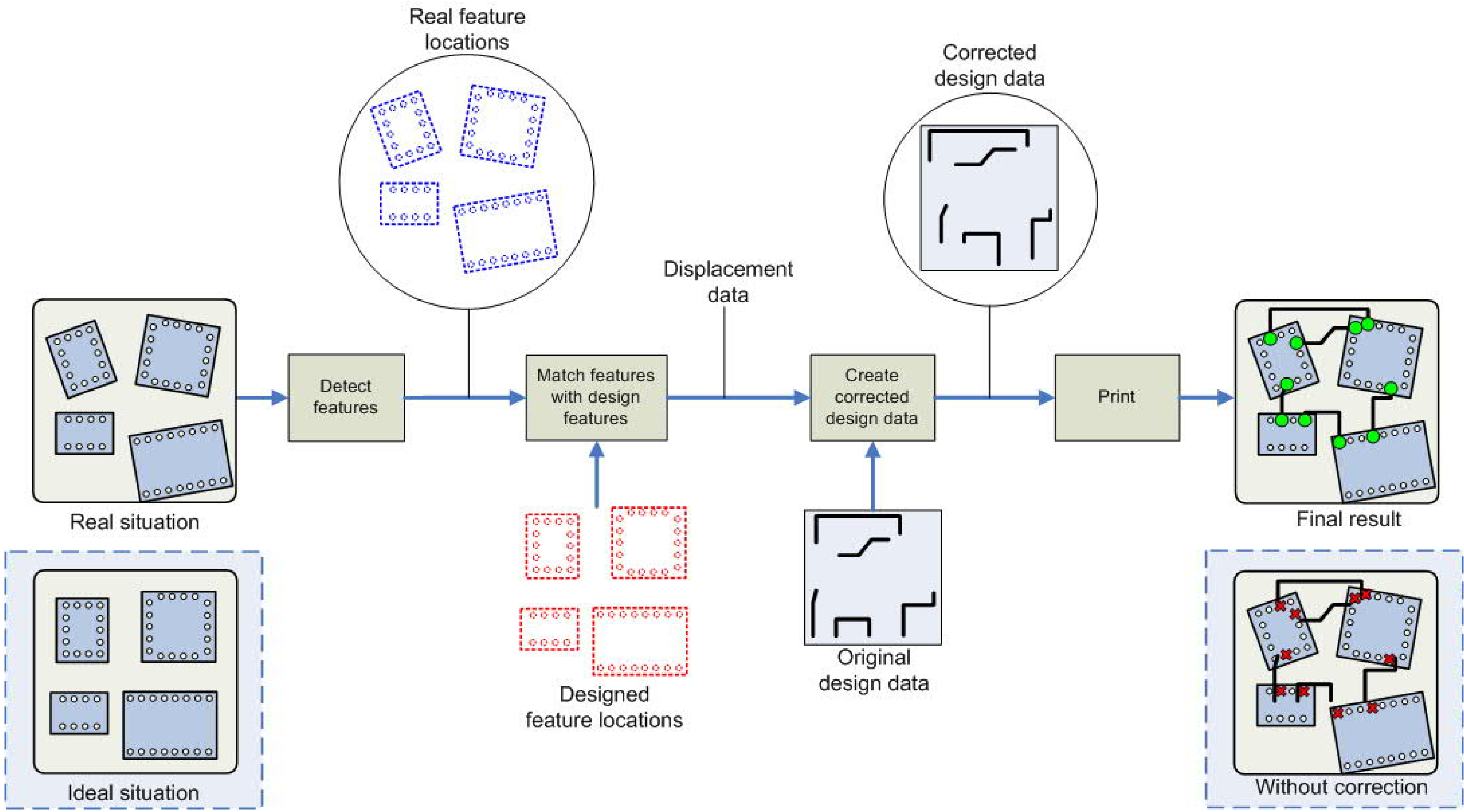


H. Huttunen, et al. ”Object detection for dynamic adaptation of interconnections in inkjet printed electronics.” *IEEE ICIP’08*, USA, 2008, pp. 2364–2367
H. Huttunen, et al. “Dynamic Correction of Interconnections in Printed Electronics Manufacturing”, NIP/DF

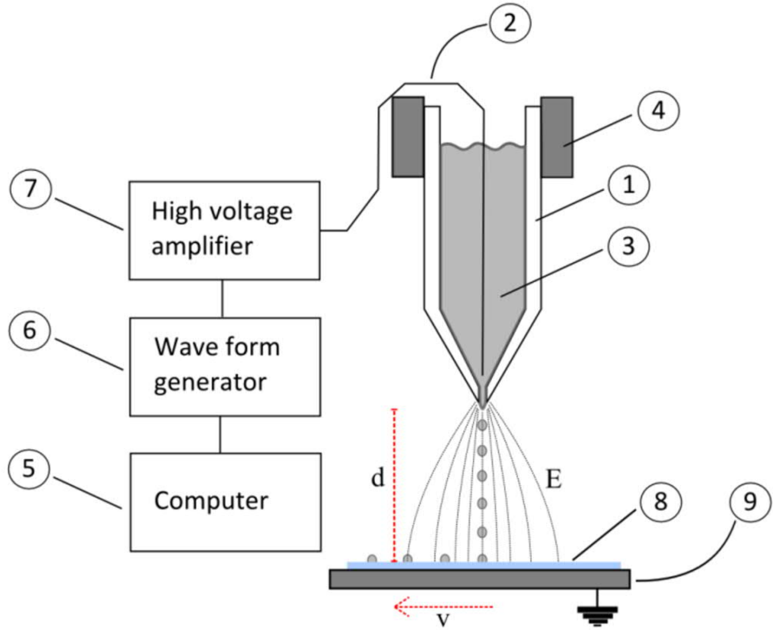
Electrohydrodynamic inkjet (E-jet)

Operation principle:

- **Ink (3) inside hollow glass nozzle (1) is charged via charging electrode (2)**
- **Electric field strength (E) exceeds threshold value → ejection of ink droplet from meniscus**

Benefits:

- **Femtoliter droplet volume → approx. D 1µm**
- **Rapid evaporation of solvent → 3D structures**
- **Wide ink viscosity range: 0.1 mPa*s to 10 Pa*s**
- **Compatible with variety of functional inks (e.g. Ag- and Au-nanoparticle inks, PEDOT:PSS) and dielectrics (e.g. epoxy, SU8, PDMS)**



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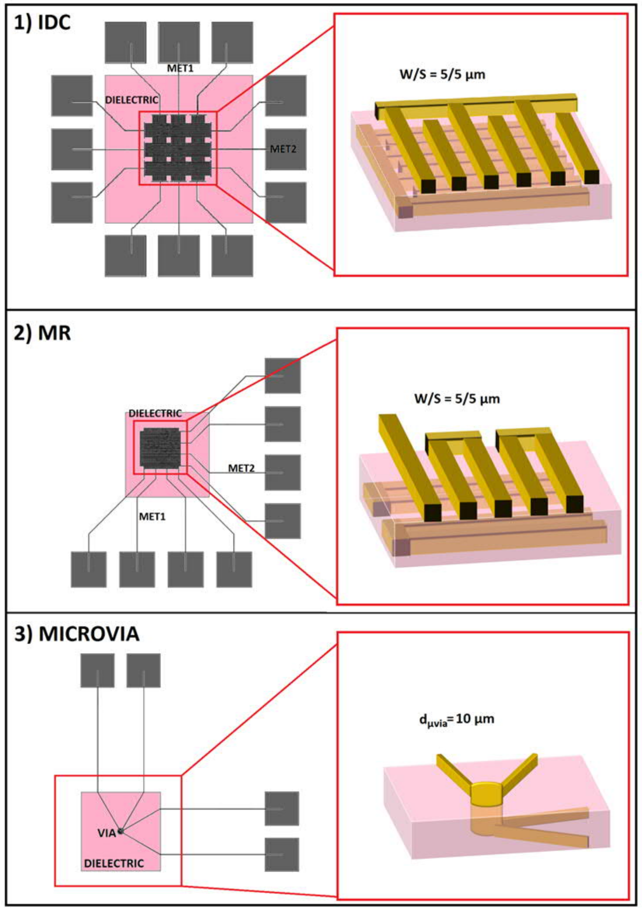
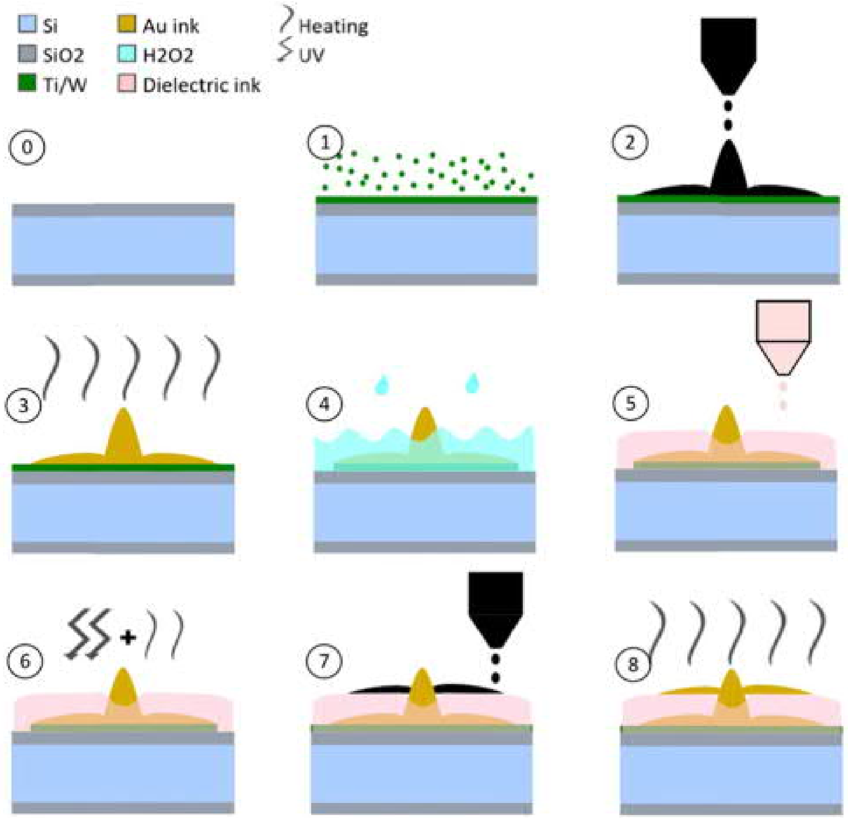
Laurila, DOI: 10.1109/TED.2016.2644728

Re-distribution layer

RDL: SIJ
Insulator: DMP 2831





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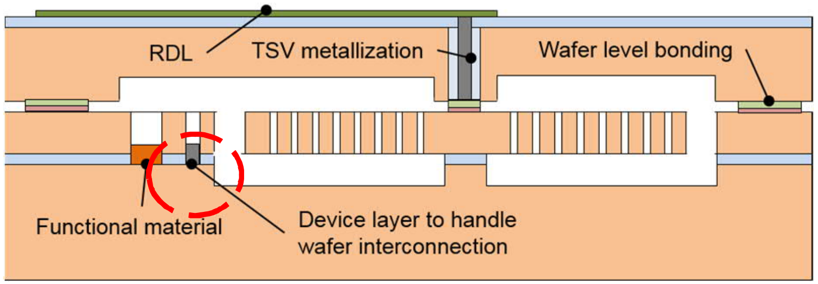
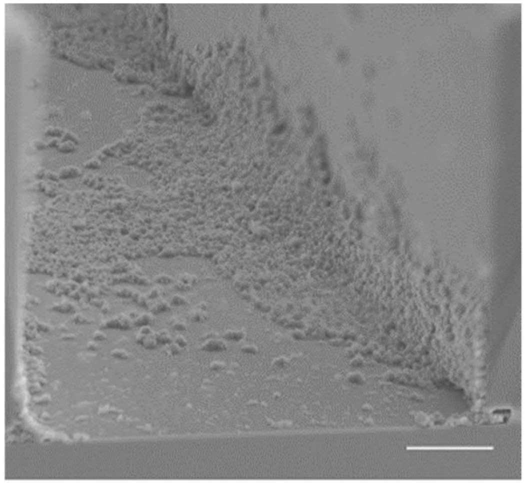
Khorramdel, 10.1109/JEDS.2017.2764498

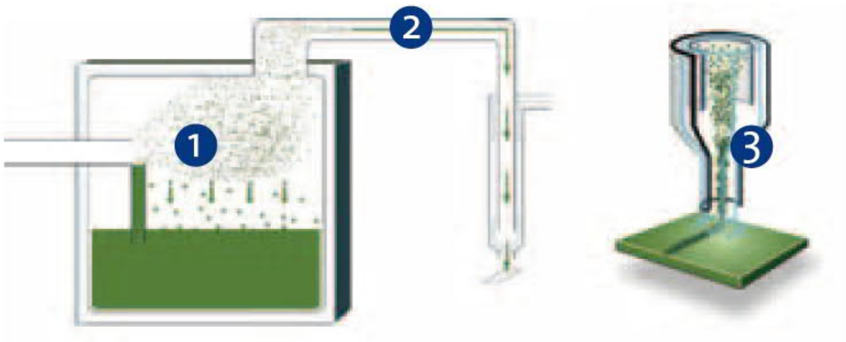
US9969607B2

Device to handle wafer connection





PRINCIPLE



- Aluminum ink (Al-IS1000) from Applied Nanotech, Austin, TX
  - 20.5 g of the original ink was diluted by 16.5 g of pure ethylene glycol
- Aerosol Jet 300 CE with pneumatic atomizer manufactured by Optomec, Albuquerque, NM
- Annealing in oven 800C

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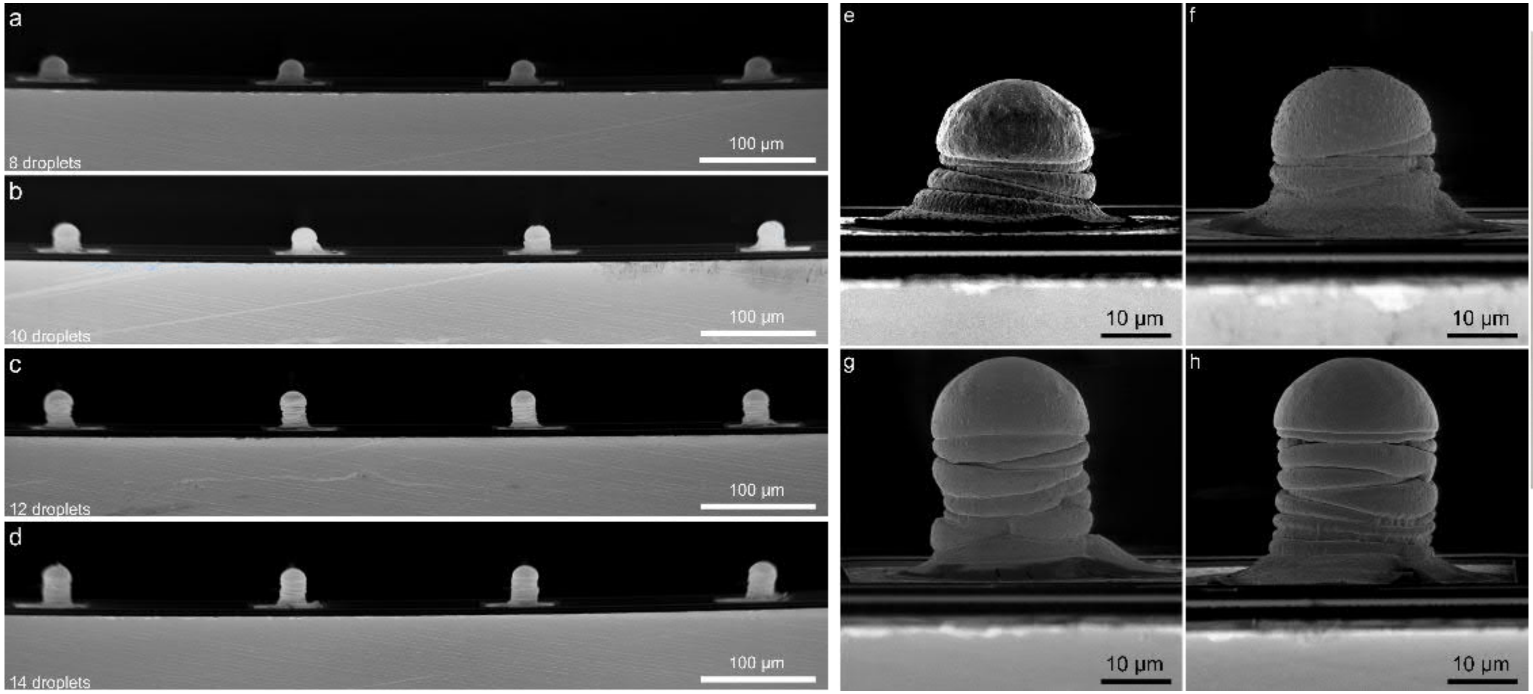
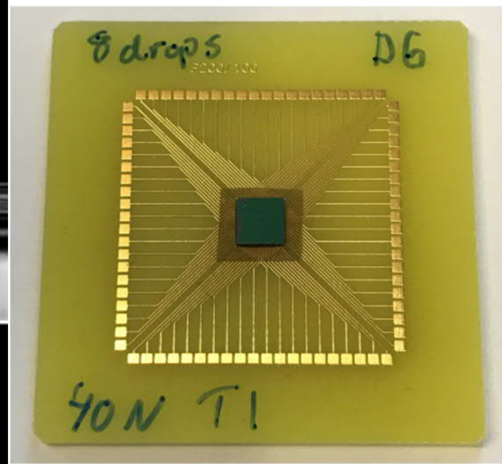
https://doi.org/10.1088/2058-8585/aa9171

Inkjet printed metallic micropillars for flip-chip bonding

B. Khorramdel, T. M. Kraft and M. Mäntysalo

8
10
12
14





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Energy storage

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Clean energy storage by printing methods

- We want to harvest ambient or directed energy (e.g. RF, motion, light)
- Intermediate storage is needed for time when there is no ambient energy source
- Supercapacitor: between a battery and a capacitor
  - Stores more charge than a regular capacitor but more cycles than battery
  - Can in principle be made out of just plastic, carbon, water and salt
  - Compatible with printing and coating processes

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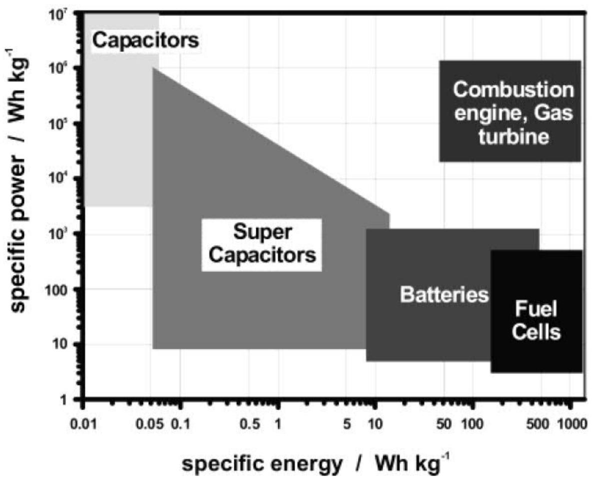
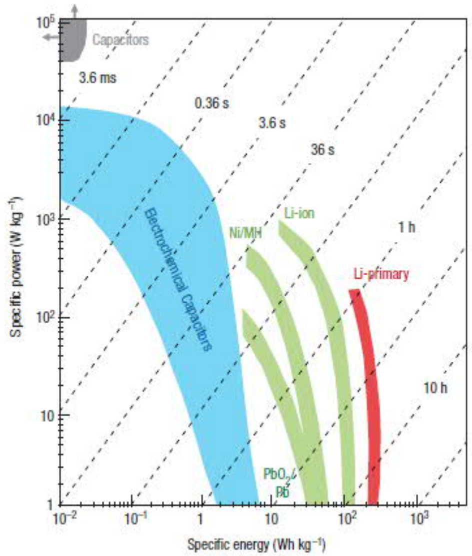
Supercapacitor = Ultracapacitor = Electrochemical double layer capacitor (EDLC)

- High specific power
- High specific energy
- 0.1 - 5000 F (several decades higher than in conventional capacitors)
- Maximum voltage in one cell about 3 V
- E= 1/2 CU^2



[Winter, Brodd, Chem. Rev. 2004, 104, 4245−4269]

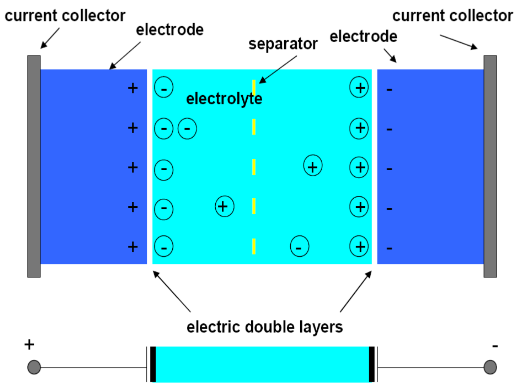


[Simon, Gogotsi, 2008]

Ragone plots

Supercapacitors

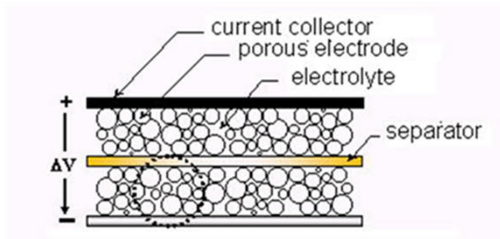
- C= ε A/d
  - A increases when specific area increases, operational principle makes d very small
- Electrostatic principle
  - The capacitor is formed electrochemically between electrolyte and electrode
  - Surface area can be increased using e.g. activated carbon



C1 C2

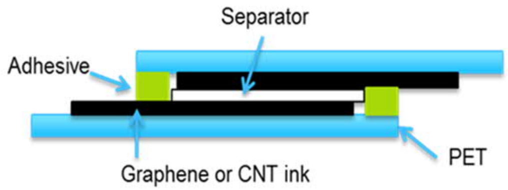
$$\frac{1}{C} = \frac{1}{C1} + \frac{1}{C2}$$

Practical



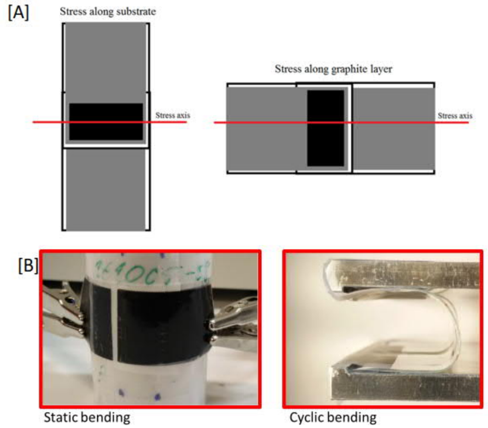
[www.ness.co.kr]

Practical printed



Flexibility of printable supercaps

- Our target are thin, flexible devices for light weight and novel form factors
- Key question was: how flexible are supercaps, with > 100 µm of particulate films?
- Series of supercaps with standard electrode inks (graphite + AC) and variety of sealants
- Static and cyclic bending
- Best designs showed no failure down to 1.25 cm bending radius.



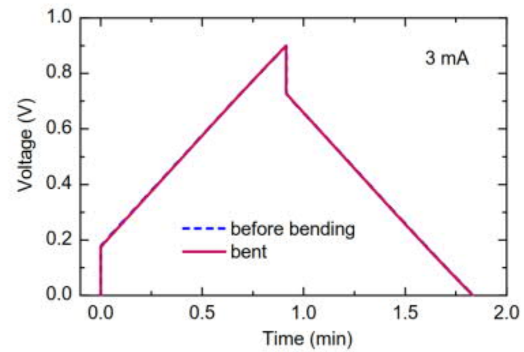


Figure 4: Device charge and discharge cycle measured at a constant 3 mA before and after static bending.

10.1109/NANO.2018.8626290

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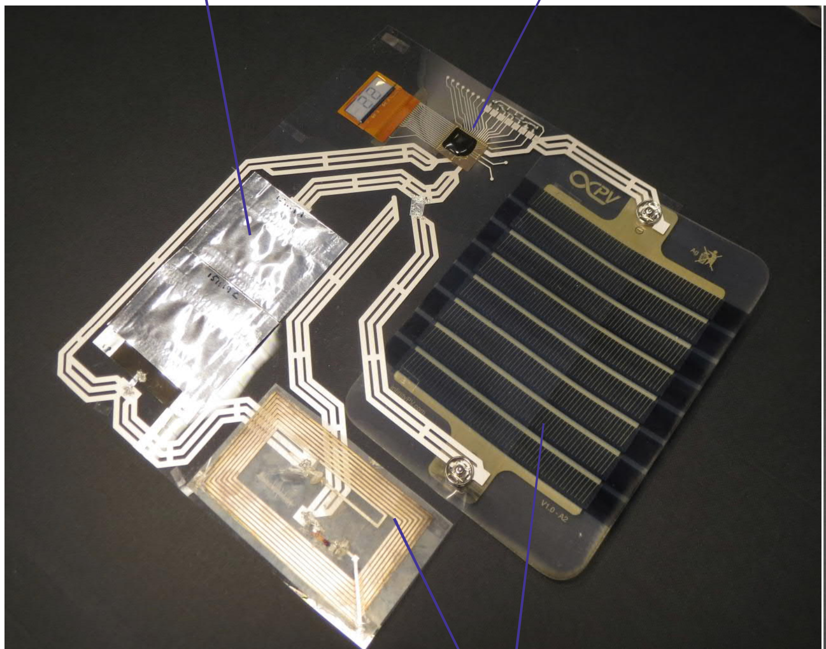
Energy autonomous temperature sensor – smart chocolate box

Energy storage in supercaps

ASIC with power management, T sensor and Eink display driver

E-Ink temperature display



Energy harvesting – OPV module and printed RF (13.56 MHz) harvester

https://www.youtube.com/watch?v=y7I98_3ZK6Y

- Charge supercaps with energy from light or RF, run sensor on stored energy for at least 6 hours
- Participants: TUT, Stora Enso, Aalto Univ., Walki

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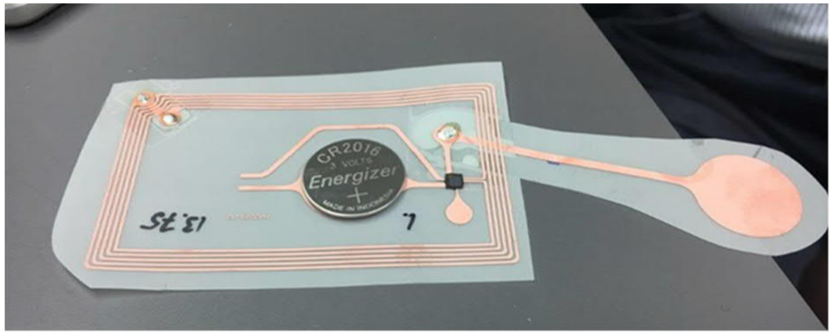
CONFIDEX

Energy autonomous flexible temperature tracker

- Joint demonstrator from LFE and Confidex – demonstrate viable energy autonomous wireless sensor based on commercial product
- Three main components in product: coil NFC read antenna, IC, power source for the IC (Li coin cell)
- Integrated RFID (HF) microchip with built-in temperature sensor
- External communication with the IC over the NFC interface with an NFC enabled smart phone.
- The HF antenna is specially designed and matched for this IC
- IC designed to run on Li battery, requires 2.2-3.3 V

	Confidex T-logger
Variable to be measured	Temperature
Energy available	Light, NFC
Voltage	3 V (or 1.5 V)
Current continuous/pulse	2 µA/100 µA - 28 ms
Application	Food/drink cold chain or transport monitoring



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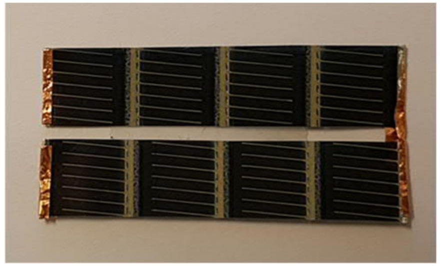
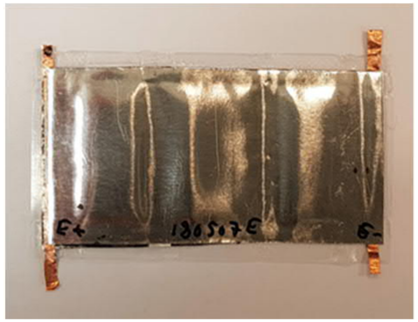
CONFIDEX

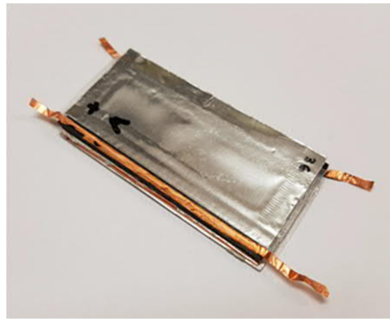
Achieving energy autonomy

- Aim: environmentally friendly alternative to the battery:
    - Commercially available organic photovoltaic cell (OPV) to power a flexible temperature logger.
    - Printed, flexible, series connected supercapacitor module based on graphite, activated carbon, paper, water and table salt



OPV cells manufactured by Infinity PV cut to dimensions defined by the empty space inside the antenna





Supercapacitors with dimensions defined by the empty space inside the antenna, 3 series connected cells
In one package or stacked

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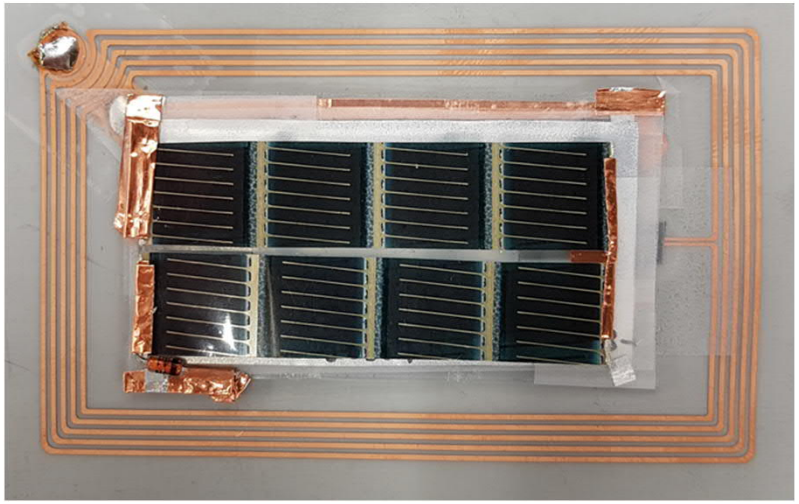
CONFIDEX

T-logger +OPV+ supercapacitor integrated

- Operation of tracker and charging of supercap module in indoor lighting demonstrated at 300 – 1000 lux
- 3.3 V -> 2.2 V, 130 mF corresponds to 0.39 J
- Allows use of the IC for 18 hours in the dark after charging
- Viable for daily light/dark cycles for indefinitely long use
- Free of potentially corrosive or toxic materials – relevant for food/pharma applications
- Poster award at InnoLAE 2019 conference



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Summary

Printed Electronics

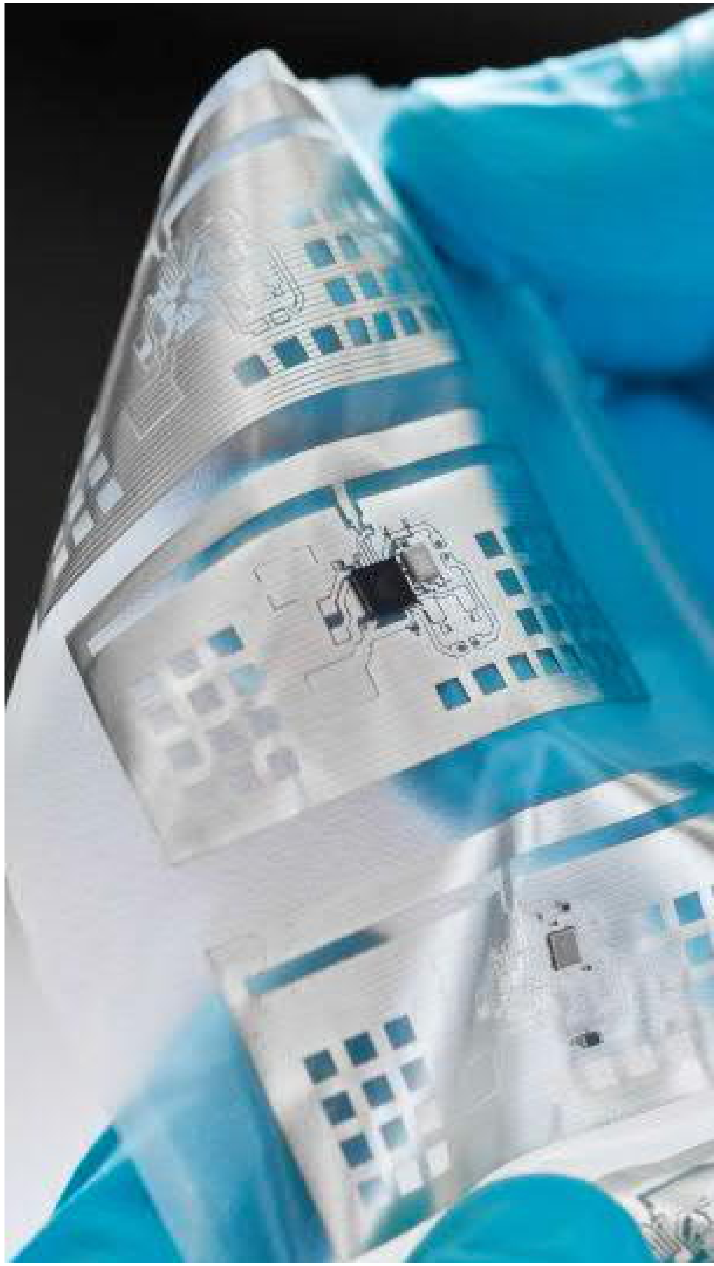
- **What is printed electronics (PE)?**
- **Why printing?**

Printing methods

Materials

Examples

- **Electronics packaging**
- **Energy storage**



Current projects:

- AoF:
  - PII (FIRI), Printed Intelligence Infrastructure, 2019-2021
  - EpiPrint (Research fellow) - Development of epidermal electronics using nano-materials and advanced printing technologies 9/2015-8/2020
  - VBA (project) – Vascular Biomechanics Assessment using printed soft electronics and advanced signal processing 9/2017-8/2021
  - HiFlex (project) – high frequency printed circuitry for wireless communication, 9/2017 – 8/2021
  - LightningSense (project, IoT of future) energy autonomous wireless sensor node powered by indoor light, 9/2018 – 8/2021
- Business Finland:
  - Elastronics (co-innovation), stretchable hybrid electronics for wearables; characterization, modeling, fabrication, reliability, : 9/2018-8/2020
  - PAUL (FidiPro): technology platform to enable a printable, sustainable Internet of Everything, 11/2014 – 10/2019
- EU:
  - Smart2go (H2020): 1/2019- 12/2021 - Smart wearables for sports and safety
  - Charisma (ITN): 2019 – 2023 – Energy autonomous smart sensor label with electrochromic readout
- Other:
  - BioÄly (regional funding), sustainable biodegradable materials 3/2018 – 12/2020,

Recently completed projects:

- Business Finland:
  - Naked Approach, (Strategic opening), Nordic perspective to gadget-free hyperconnected environments, 3/2015-6/2018
  - Towards Digital Paradise, applying NA developed technologies, 1/2017-31/2018
  - VitalSens, VitalSens - Platform Technology for Affordable, Continuous Health Monitoring, Tekes – DBT (India) co-funded project, 9/2014 – 4 / 2018
- Austrian FFS
  - Self-PoSH (Bridge funding, coordinator Joanneum Research) – laterallly patterned piezoelectric sensors and their use for motion harvesting, 1/2017 – 12/2018

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Near future work opportunities for students

- ECOtronics - sustainability throughout electronics and optics lifecycle
  - Business Finland: funding decision received in September

- MEMS devices by printing methods


Thank You for
Your attention!
Questions?