Paper Electronics

Paper as Substrate for Printed Electronics and Sensors

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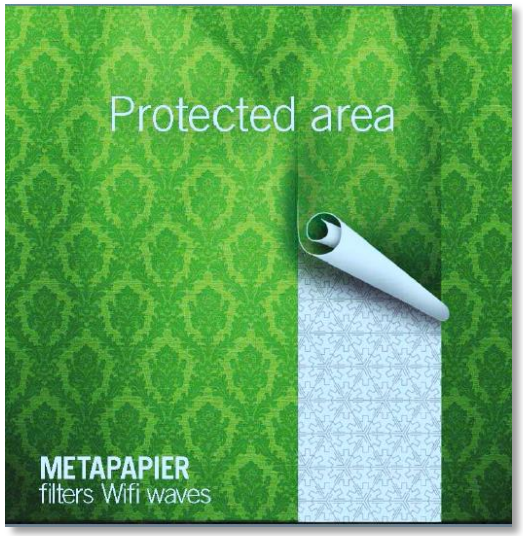
COST is supported by the EU Framework Programme Horizon 2020

Printed Electronics has Created Hype (and Unreasonable Expectations…)

Paper Electronics = Disposable Printed Electronics on/in Paper with Commercial Potential



Electro-magnetic blocking,
De Barros et al.

Incontinence detection, Sensible Solutions Sweden AB

Self-cooking soup packaging
Fulton Innovation

Patient adherence tracking
Pharma DDSi, StoraEnso

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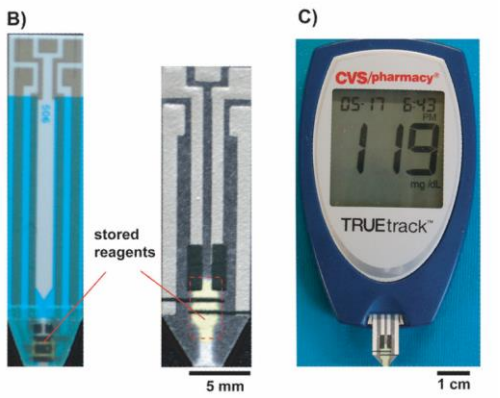
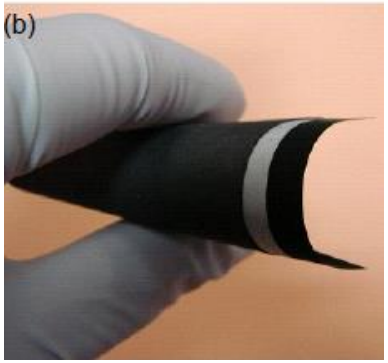
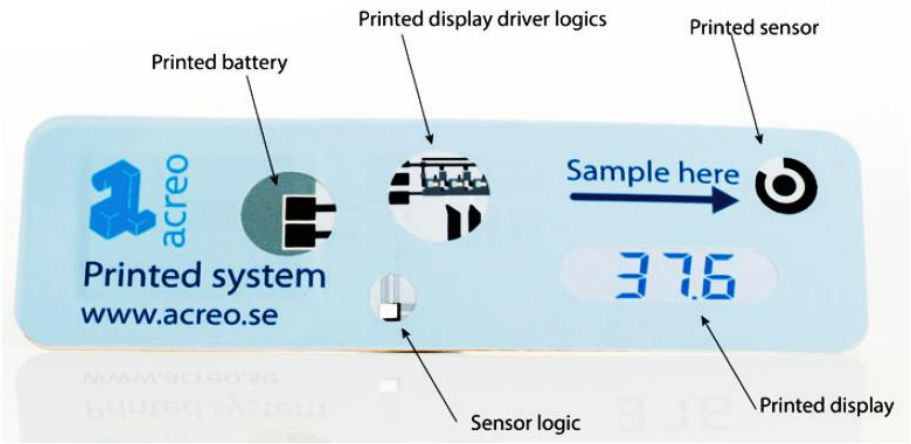
Product Concepts Based on Electrochemistry



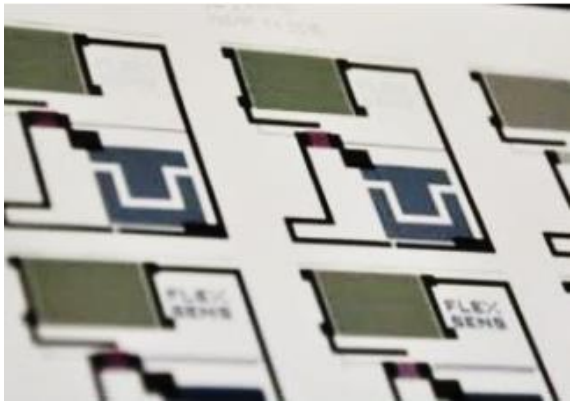
"Zero-Cost Diagnostics"
G.M. Whitesides



Li-ion paper-batteries,
Jabbour et al.



Printed bio-sensing platform, Acreo



Gas sensor on paper,
Peltonen et al., FunMat/FlexSens

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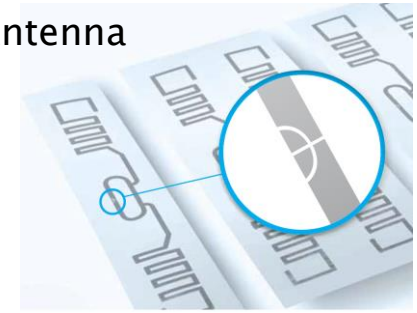
Hybrid Products

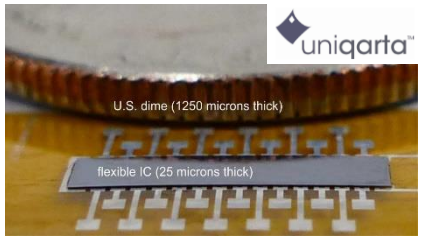
- Combine, e.g. silicon-based RFID-chips with printed antenna:
  - Contactless smartcards and tickets
  - Product tracing and copy protection

Confidex

Walki® Pantenna



Ultra thin chips



Printable LEDs

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Laser-enabled advanced packaging (LEAP)

Advantages of Using Paper as Substrate for Printed Electronics

- Low cost and large existing product base
- Biodegradability, compostability, ease of disposal → one-time use, "throw-away electronics"*
- Mechanical properties: stiffness, foldability
- Adjustable printability of functional materials
- High temperature tolerance → inexpensive infrared sintering
- Transparency by using nanopaper (=nanocellulosic films)
- Biocompatibility beneficial for biological applications

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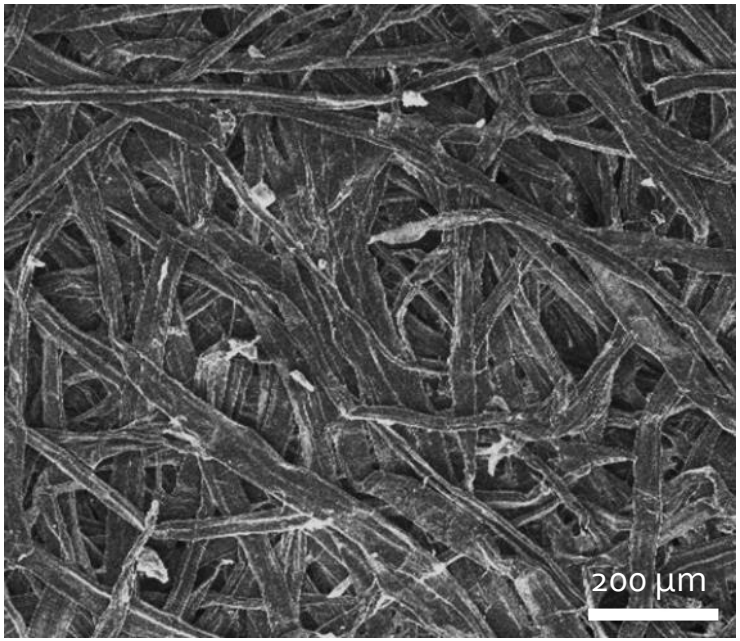
* Aliaga et al., The influence of printed electronics on the recyclability of paper: a case study for smart envelopes in courier and postal services. Waste Management 38:41–48, 2015

Functional Printing on Uncoated Paper

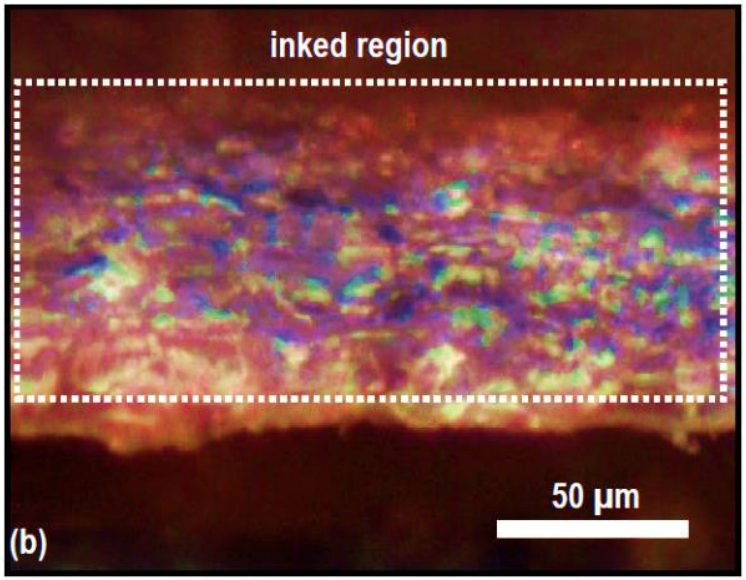


- Poor performance due to:
  - high surface roughness
  - uncontrolled spreading
  - uncontrolled absorption

Inkjetted Particulate Silver Ink

R. Bollström et al., 2013.

Inkjetted PEDOT:PSS-SWCNT Ink



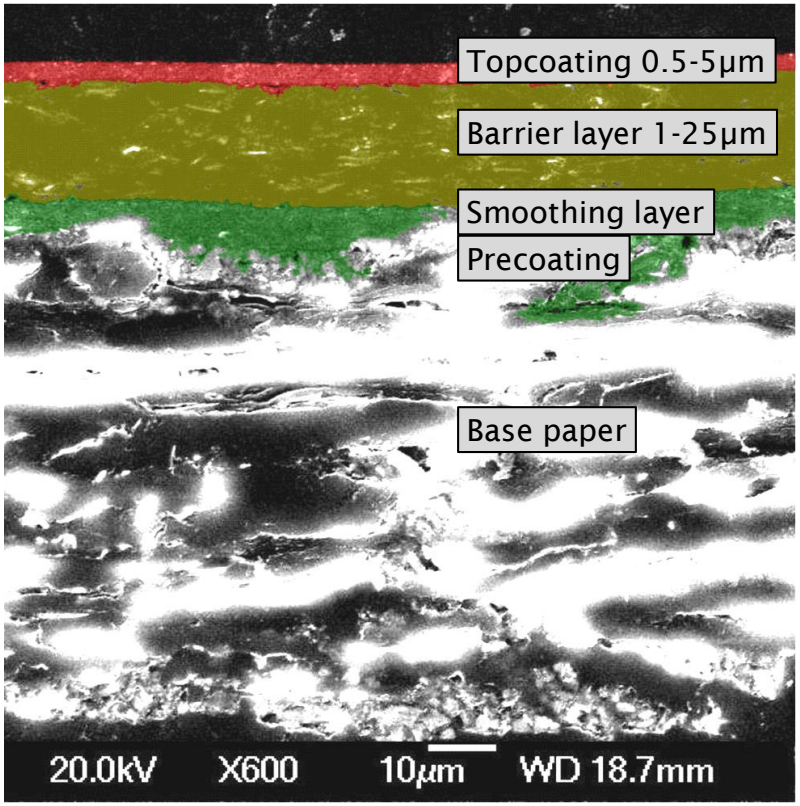
P. Angelo et al. NPPRJ 27(2):486, 2012

Challenges of Using Paper as Substrate for Printed Electronics

- High surface roughness and porosity, large pore size
- Hygroscopicity and poor dimensional stability
- Poor long time heat resistance
- Complex surface chemistry
- Poor barrier properties
- Dusty material not allowed in clean room environment used by printed electronics manufacturers

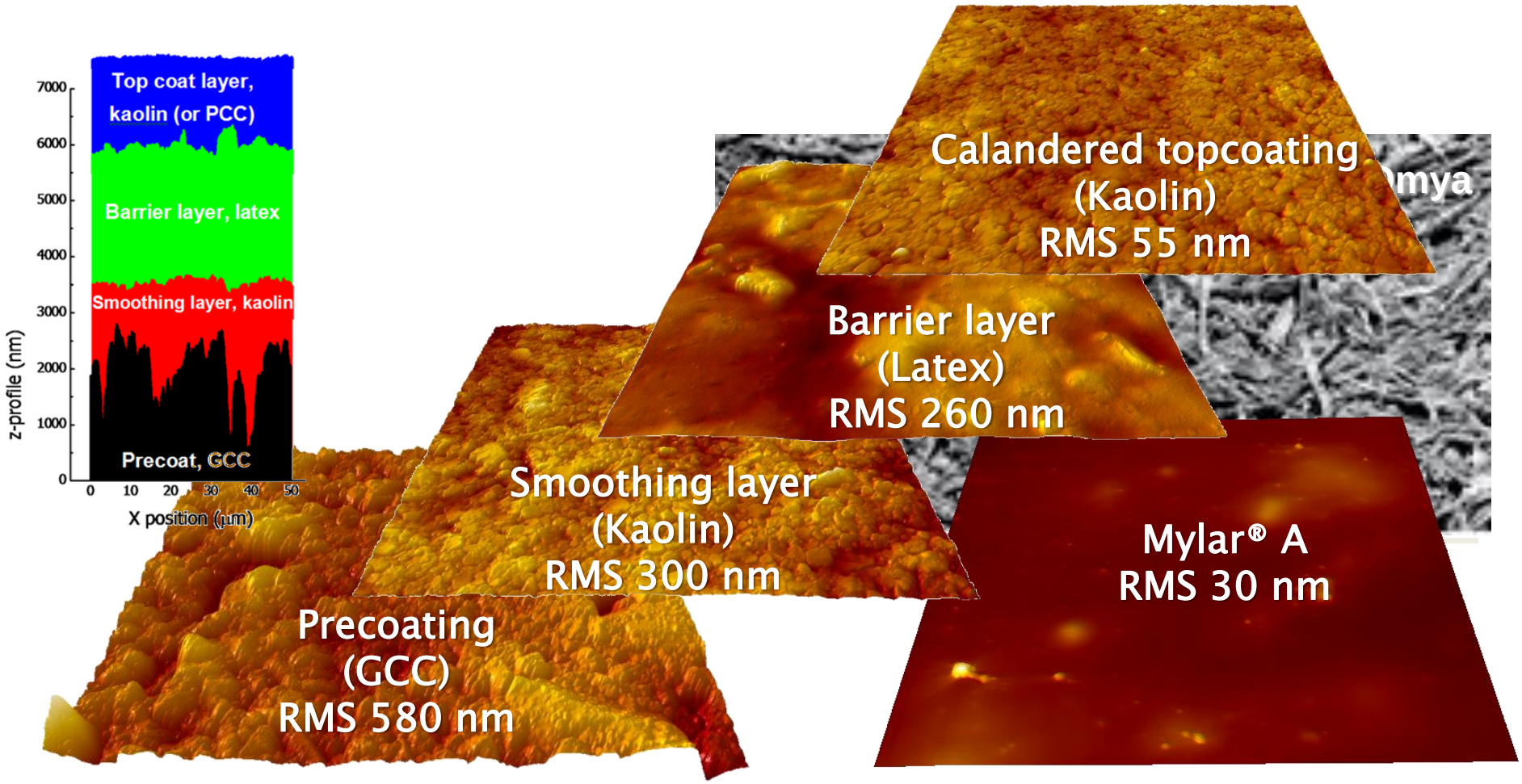
Multilayer Paper-based Substrate for Printed Electronics → Paper Electronics

- A combination of:
  - sufficient **smoothness** (~50nm RMS),
  - solvent **barrier/sealing** properties (DCB, acids, bases etc.),
  - adjustable **printability** for given functional ink through control of surface energy and surface porosity,
  - **thermal performance** allowing for IR sintering
- Roll-to-roll processable, recyclable and compostable



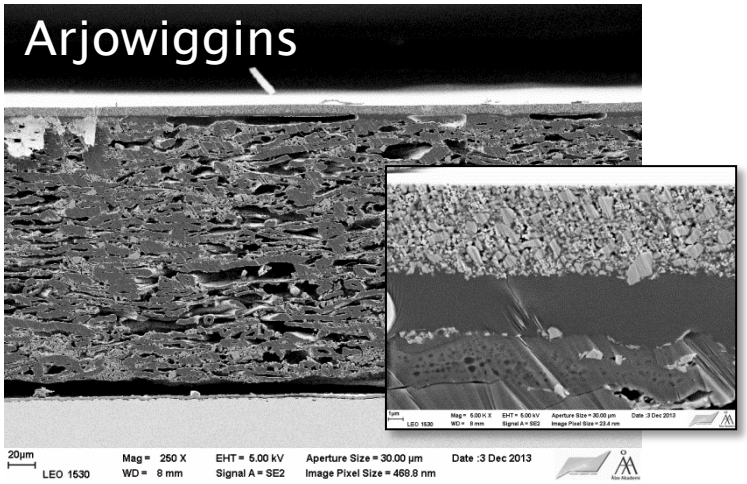
Bollström, R., A. Määttänen, D. Tobjörk, P. Ihalainen, N. Kaihovirta, R. Österbacka, J. Peltonen, and M. Toivakka. "A multilayer coated fiber-based substrate suitable for printed functionality." *Organic Electronics* **10**:1020-1023.
Bollström et al. "Method for creating a substrate for printed or coated functionality, substrate, functional device and its use", EPO Patent EP2392197, Chinese Patent ZL 201080006446.5

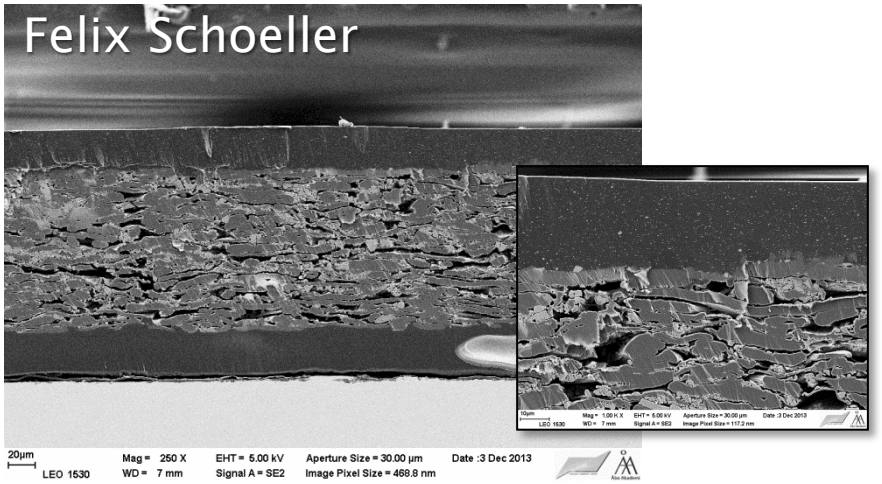
Printed Electronics Requires Surface Smoothness

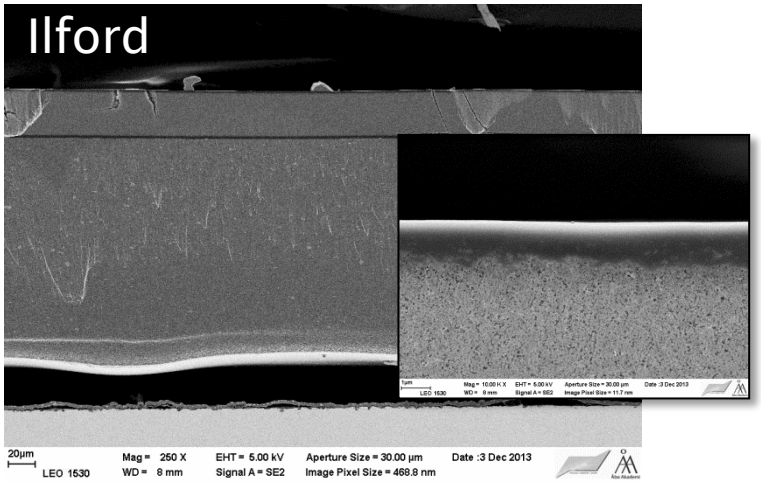


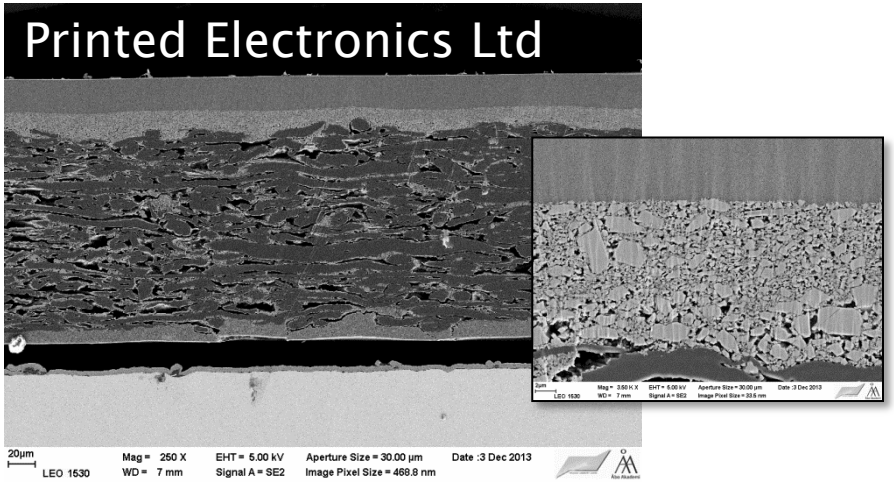
J. Järnström, P. Ihalainen, K. Backfolk, J. Peltonen: **Applied Surface Science 2542:5741**
R. Bollström, A. Määttänen, P. Ihalainen, M. Toivakka, J. Peltonen: **Chinese patent (ZL 201080006446.5), European patent (2392197)**
R. Bollstrom, D. Tobjörk, A. Määttänen, P. Ihalainen, R. Österbacka, J. Peltonen, M. Toivakka,: **Org. Electronics 10:1020**

Commercial Papers for Printed Electronics







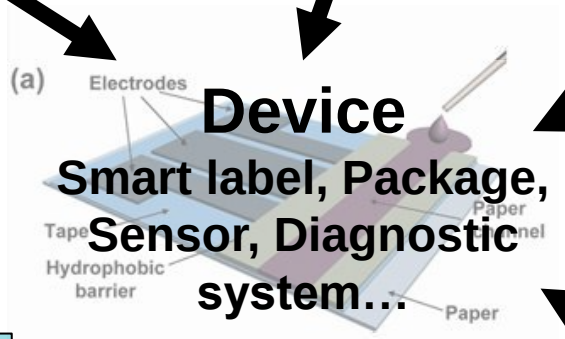


Paper Electronics – from Components to Devices and Products

Sensor component – e.g., chemiresistor, piezoelectrics, accelerometer, touch sensor

Input/Output – e.g., electrochromic inks, color indicators, external interface

Power Supply – e.g., printed battery, supercapacitor, solar cell, fuel cell



Device
Smart label, Package, Sensor, Diagnostic system…

Memory - e.g., WORM, combinations of transistors

Logic component – transistor, e.g., Ion modulating FET

Connectors, Resistors

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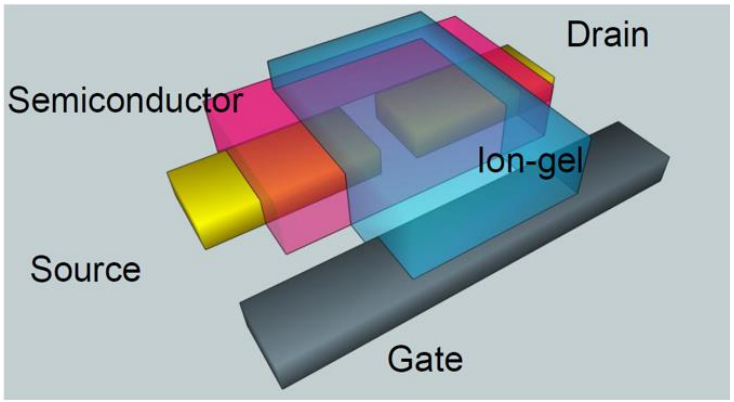
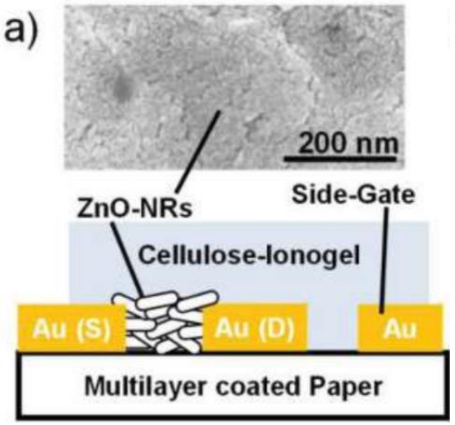
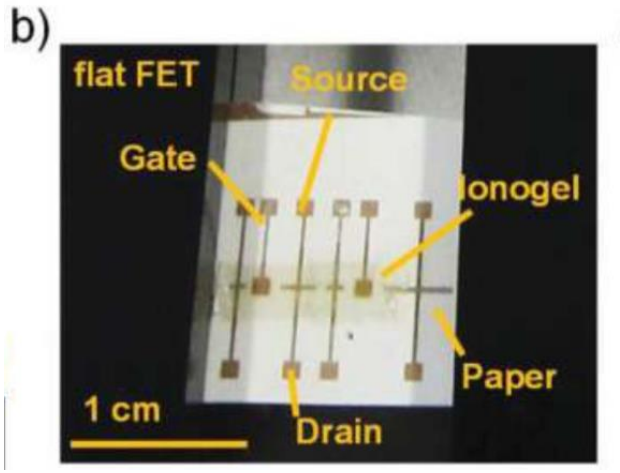
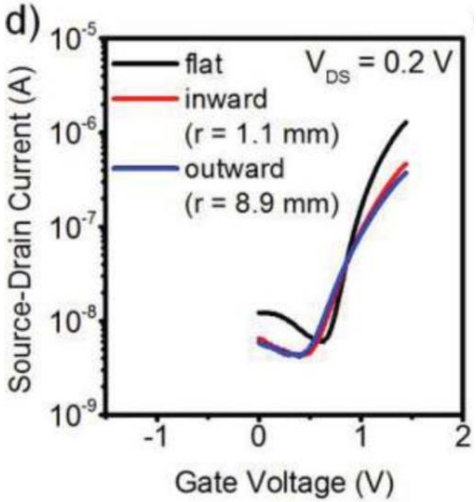
Lateral Electrolyte-gated Field Effect Transistors on Paper





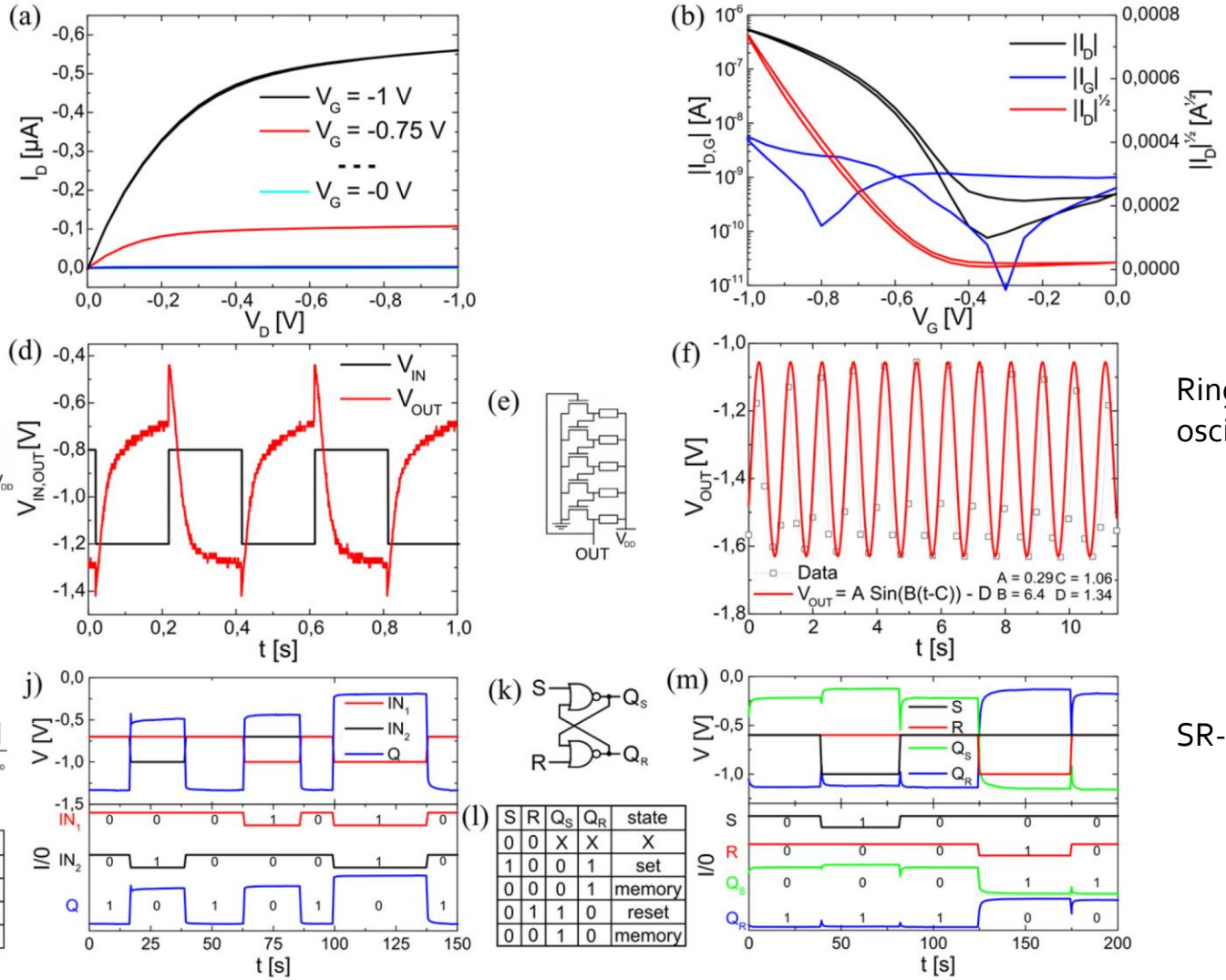




Thiemann S., Sachnov S., Pettersson F., Bollström R., Österbacka R., Wasserscheid P. and Zaumseil J. Cellulose-based Ionogels for Paper Electronics. *Advanced Functional Materials*, **24**(5), 625–634.

Towards Logic Circuits on Paper

CSorb transistor characteristics



IN_1	IN_2	Q
0	0	1
0	1	0
1	0	0
1	1	0

S	R	Q_S	Q_R	state
0	0	X	X	X
1	0	0	1	set
0	0	0	1	memory
0	1	1	0	reset
0	0	1	0	memory

Inverter

Ring-oscillator

NOR-gate

SR-latch

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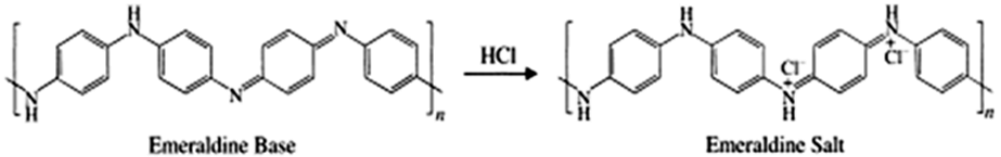
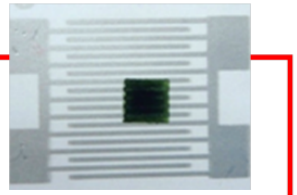
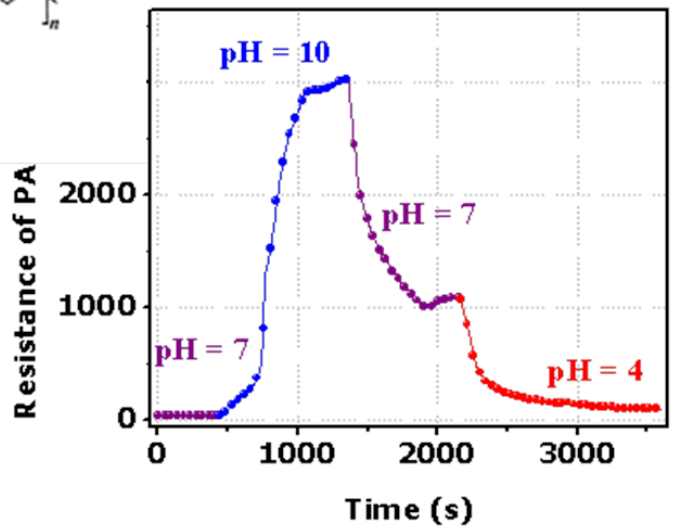
Pettersson, F., *Paper- and Membrane-Based Ion-Modulated Electronics,* 2015, PhD thesis, Åbo Akademi

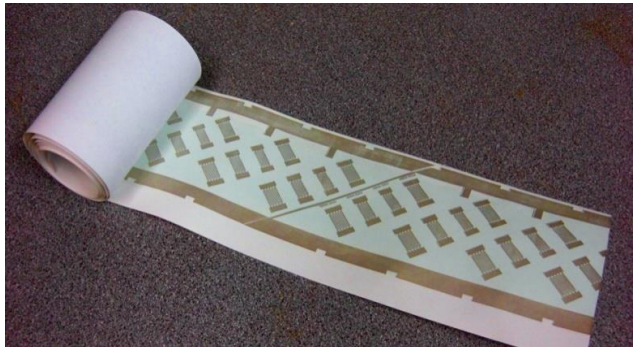
Electronically Readable, Printed pH Sensor on Paper

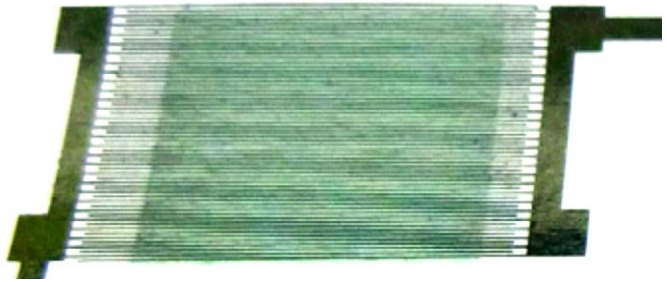


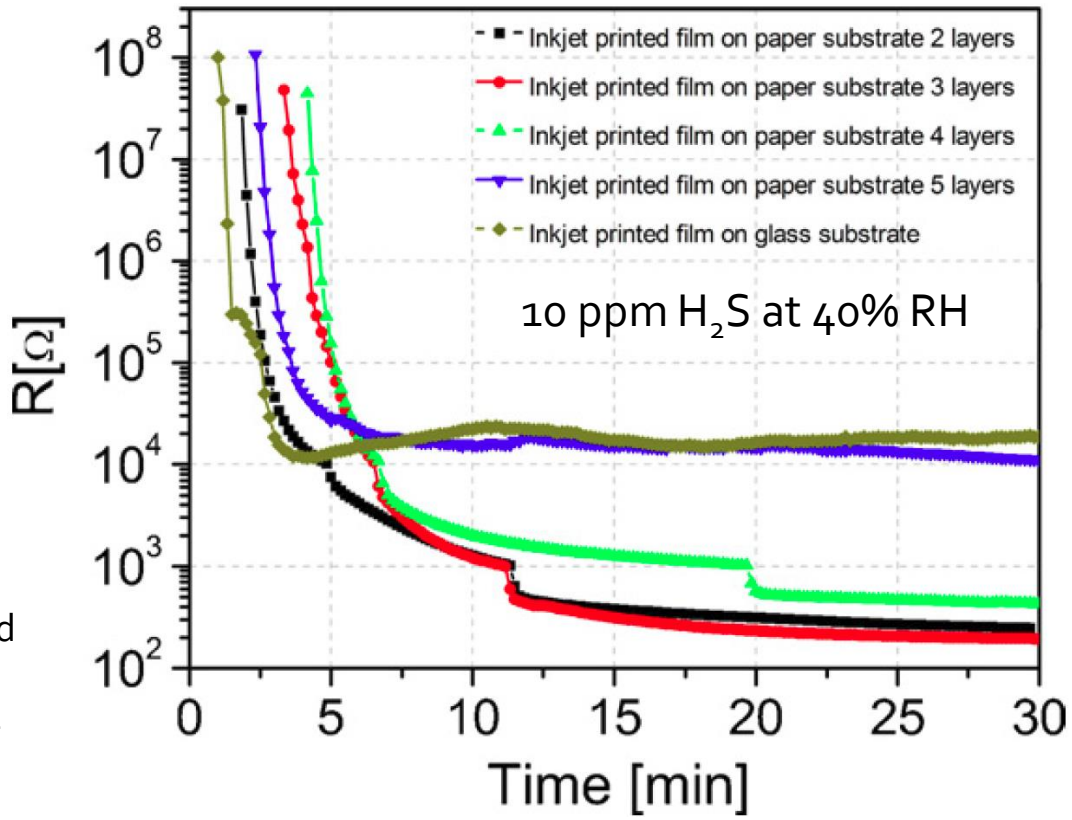




Simple Hydrogen Sulfide Sensor







- Flexography/Inkjet-printed interdigitated electrodes
- Spray-/reverse gravure coated, or inkjet-printed
  - Copper chloride
  - Copper acetate

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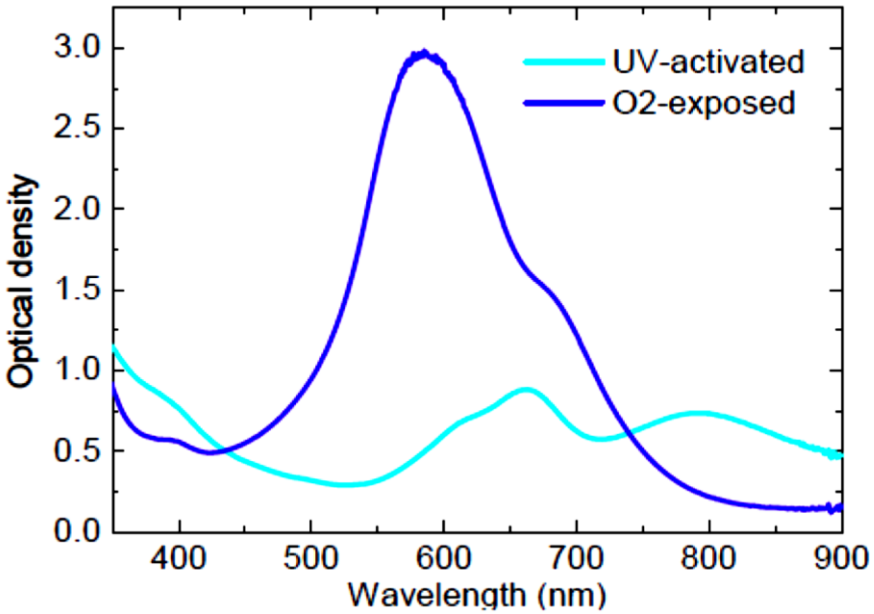
J. Sarfraz, A. Määttänen, P. Ihalainen, M. Keppeler, M. Lindén, J. Peltonen. Printed copper acetate based H2S sensor on paper substrate, *Sensors and Actuators B* **173**:868–873.

Oxygen Sensor

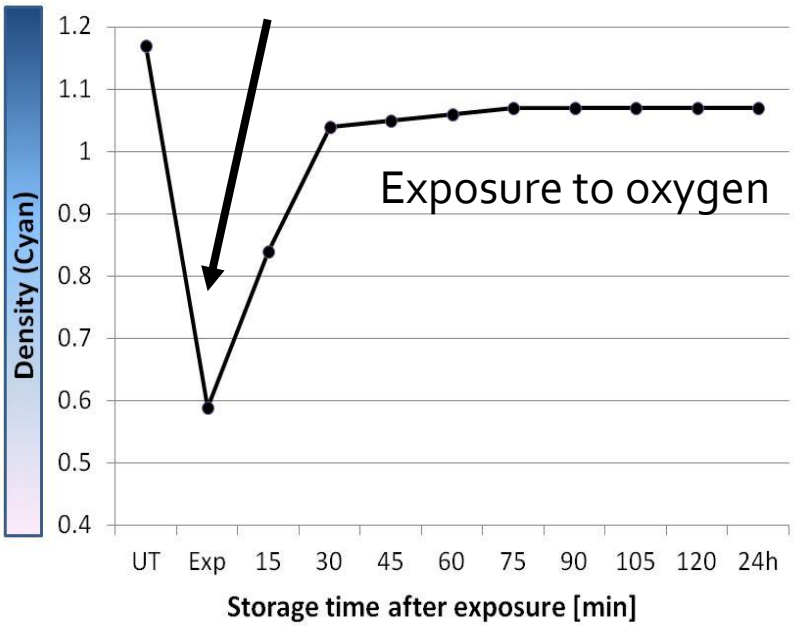
Methylene blue + TiO_2 nanoparticles

Exposure to oxygen

UV-activation



UV-activation



Saarinen J.J., Remonen T., Tobjörk D., Aarnio H., Bollström R., Österbacka R. and Toivakka M. (2016) *Large-scale roll-to-roll patterned oxygen indicators for modified atmosphere packages,* submitted to Packaging Technology & Science.

Adjustable Packaging Line for the Future

- Sensors and indicators for modified atmosphere packaging
  - E.g. for oxygen and hydrogen sulfide

Åbo Akademi University

LAPPEENRANNAN TEKNILLINEN YLIOPISTO

LAHDEN AMMATTIKORKEAKOULU
Lahti University of Applied Sciences

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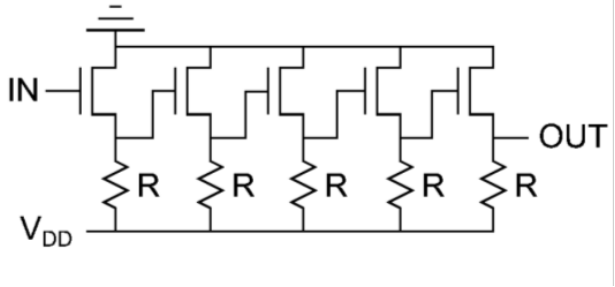
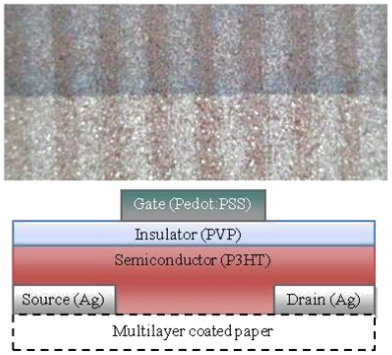
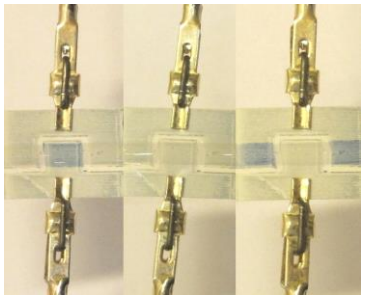
European Union
European Regional Development Fund

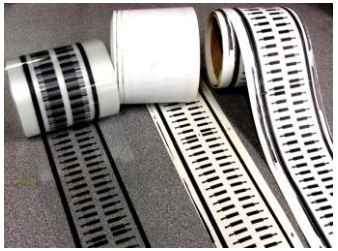
Proof-of-concept Devices on Paper

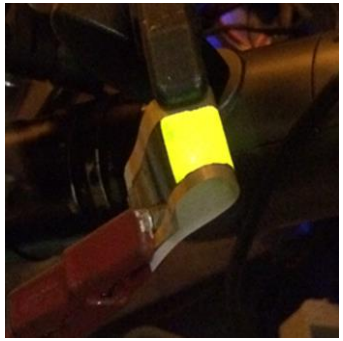
- Transistors
- Ring oscillators
- 1-bit memory
- Electrochromic pixels
- Light-emitting electrochemical cells
- Ion-selective electrodes
- Hydrogen sulfide sensors
- Oxygen sensors
- Printable circuit for gas sensors
- Reaction arrays
- Digital microfluidics

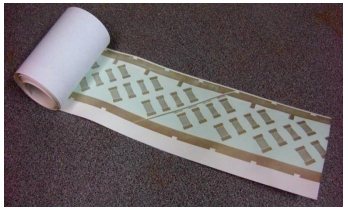


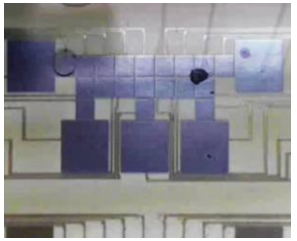




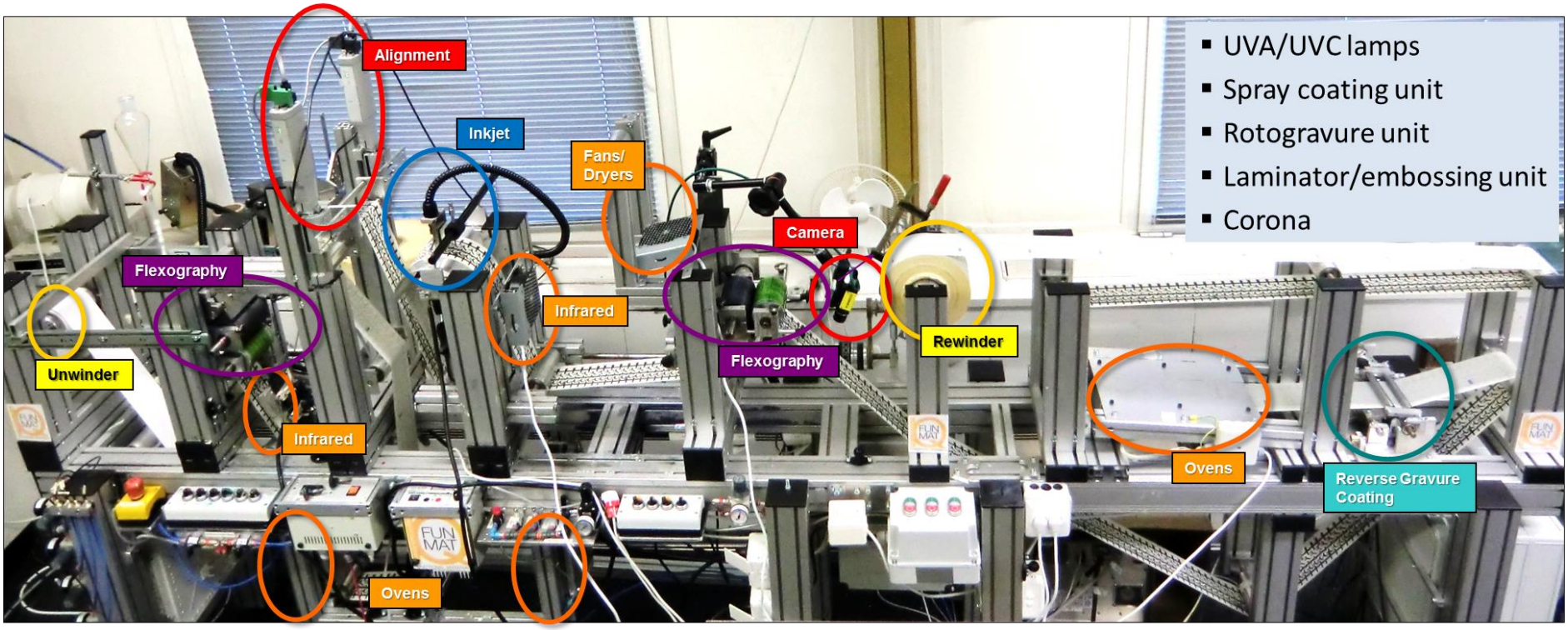








“FunPrinter” - Custom-built Hybrid Printer for Functional Materials



Paper as a Substrate for Printed Electronics and Functionality

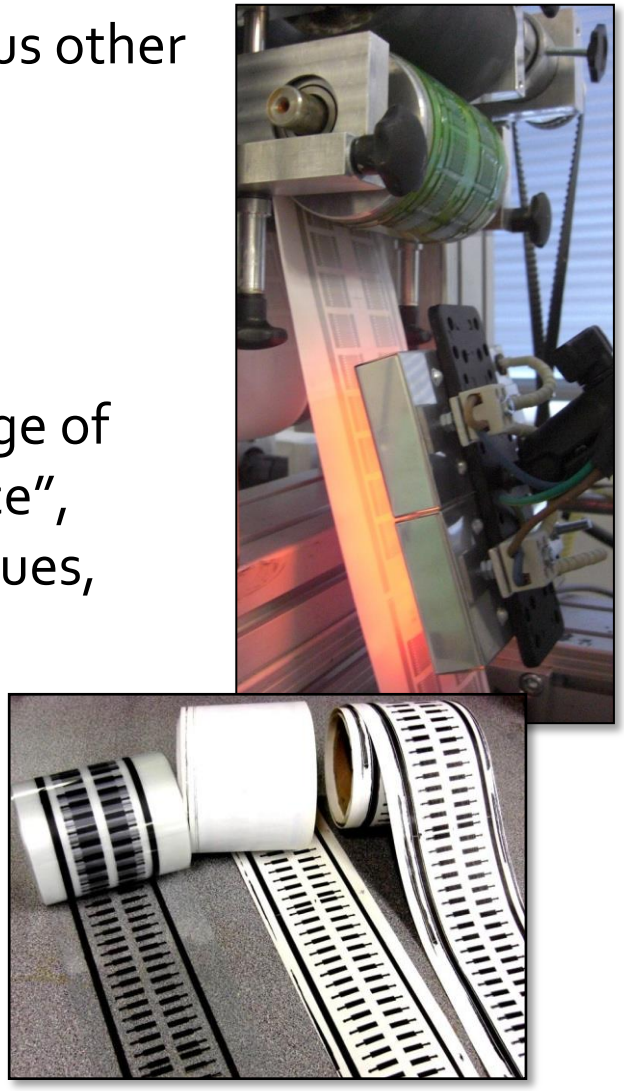
- No universal "Paper for printed electronics" exists (excluding perhaps plastic coated paper)
- Device(s) to be fabricated, i.e. end-use application, determine which paper properties must to be measured and controlled:
  - Barrier properties, surface roughness, surface energy, surface porosity, dimensional stability, thermal resistance…
  - …while maintaining the low cost and recyclability
- Devices often need to be adapted for paper
- Fabrication of complex devices directly in/onto paper challenging in existing converting and printing processes:

  → Separate production of devices/components (on paper/silicon/plastic)

  → Integration in/onto products, e.g., as stickers

Conclusions and Outlook for Paper Electronics

- Printed transistors, simple circuits and numerous other devices as well as sensors can be fabricated on multilayer coated specialty paper
- Hybrid products and simple products based on conductive lines already on market
- Numerous challenges remain, including shortage of profitable business cases and market ”resistance”, expensive materials and processes, scale-up issues, non-existence of suitable hybrid printer facilities (paper not allowed in clean rooms)
- Highest commercialization potential for low-cost “large area” applications and simple sensors



http://www.abo.fi/lpcc

http://www.funmat.fi/

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