Paper Electronics

Paper as Substrate for Printed Electronics and Sensors

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Printed Electronics has Created Hype (and Unreasonable Expectations...)

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

- Electro-magnetic blocking, De Barros et al.
- Self-cooking soup packaging, Fulton Innovation
- Incontinence detection, Sensible Solutions Sweden AB
- Patient adherence tracking, Pharma DDSi, StoraEnso

ActInPak

Martti Toivakka 2016
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
Hybrid Products

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

Confidex

Walki® Pantenna

Powercoat® Alive

Ultra thin chips

Printable LEDs

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

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

Printed Electronics Requires Surface Smoothness

R. Bollström, A. Määttänen, P. Ihalainen, M. Toivakka, J. Peltonen: *Chinese patent (ZL 201080006446.5), European patent (2392197)*
Commercial Papers for Printed Electronics

Arjowiggins

Felix Schoeller

Ilford

Printed Electronics Ltd
Paper Electronics – from Components to Devices and Products

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

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

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

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

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

Connectors, Resistors

Smart label, Package, Sensor, Diagnostic system...
Lateral Electrolyte-gated Field Effect Transistors on Paper

Towards Logic Circuits on Paper

CSorb transistor characteristics

Inverter

NOR-gate

Ring-oscillator

SR-latch

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

10 ppm H$_2$S at 40% RH

Oxygen Sensor
Methylene blue + TiO$_2$ nanoparticles

Adjustable Packaging Line for the Future

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

[Image of fish package with text: "TUNNISTA TUORE KALA, TARKISTA VÄRI."
"Indikaattori muutaa siniseksi kilan päättyessä."
"Revirvoisuuksia 100 g: reuna 5%, josta työntymässä raivea 2%" "omega 3-tilaide: suola 0,5% energiaa 1001 kJ/akahäätomien" "säätö 0%"
"Scan this to verify the freshness, test the color."]

[Logos of Abroad Academy University, Lahti University of Applied Sciences, and 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

- UVA/UVC lamps
- Spray coating unit
- Rotogravure unit
- Laminator/embossing unit
- Corona
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.