Introduction to Printed Electronics and Intelligence

Painettavan elektroniikan kurssi – 27.3.2012
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Course information

Lecturer:

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Lectures:
- 27.3. Intro, 10.4 R2R manufacturing, printing etc., 11.4. OLEDs,
  16.4. OPV, 24.4. OFETs
- lab-visits VTT & OY tbd later

Examination:
- 4.5
Recent Printed Electronics and Intelligence Market Data

- Market reports forecast *printed (disposable) electronics* markets to be around 20 bil. USD by 2013 and up to 300 bil. USD by 2025*.
- Frost & Sullivan estimates printed electronics to be on same class in 202X.
  - Twice as Silicon industry today
  - Still in very early market with technology enthusiasts.
  - Not yet able to identify companies who would be dominant players in the market.

- Disposable electronics end use examples:
  - Inexpensive printed RFID tags e.g. for smart packaging
  - E-paper displays sold for point-of-purchase applications
  - New products - “games, gadgets and gizmos” – based on printed and/or organic electronics
  - Materials supplied to disposable electronics with strong demand for inexpensive conductive inks
  - Paper and board substrates for disposable electronics

* Sources: Nanomarkets, IDTechEx, Frost&Sullivan
PE market estimation by IdTechEx

Source: IDTechEx
State of developments

- Media and market research attention on “printing of electronics”, less so on printed high volume applications.
- Several years of R&D, but commercialization in early stages.
- Established companies in various fields are evaluating the impacts and possibilities of these new technologies on their businesses.
- R&D activity and spending is increasing.
  - In particular materials suppliers show increasing activity.
  - Materials suppliers show highest short term revenue potential, as their materials are being tested by application developers.
- First commercial applications in hybrid media, diagnostics and packaging.
- Growing venture capital interest, but still lack of commercial breakthroughs.
Benefits of printing

- Cost-effective processing
  - High-speed fabrication
  - Low material consumption
- Low temperature process
  - Flexible substrates
- Well-established techniques
  - Technology exists
- Direct patterning
  - High form factor
- R2R capable
  - Large area printing
  - Profit

Suited for cost-efficient products - printed electronics
Limiting factors of printing

- enables fabrication of very thin layers, 10 nm – 100 µm, and high throughput
- but lateral resolution is limited to micron scale
Limiting factors of materials

• organic semiconductors are sensitive for moisture and oxygen
  => good barriers needed (WVTR $10^{-6}$ g/m$^2$/day, OTR < $10^{-4}$ cm$^3$/m$^2$/day)
  • typically today values are $10^{-4}$
  • lifetimes thousands of ours
  => Limitations for applications

• mobility of organic semiconductors is low
  • CNTs > 10 000 cm$^2$/V*s
  • Si approx. 1000 cm$^2$/V*s
  • Organic semiconductors <1
  • Values depend on material purity and doping level

• Lifetimes of organic semiconductors
  • state-of-art 1 years
  • rather kHours
Example

- typical top gate transistor

**Cut-off frequency** \( f_0 \leq \frac{V_{GS} \mu}{2\pi L^2} \)

- \( L \) ... critical dimension, channel length
- \( \mu \) ... charge carrier mobility

If \( L=50 \, \mu m \) ja \( \mu=0.1 \) \( (V_{gs}=10V) \) (typical OFET)

\[ \Rightarrow f_0 = 60 \, MHz \]

- Real operating frequency much lower due to parasitic losses
- Currents tens of \( \mu A \)

If \( L=0.1 \, \mu m \) ja \( \mu=1000 \) \( (V_{gs}=10V) \)

\[ \Rightarrow f_0 \text{ in THz region} \]
Printed intelligence

Starting idea

• New technology driven disruptive innovation at the cross sections of the paper and electronics industries:
  • manufacture electronic components utilizing roll-to-roll production techniques – *printed electronics*
  • printing of new functionalities into high volume low cost packaging and printed media applications – *printed functionality*
Printed Intelligence

Printed intelligence are *components* and *systems* which:

- extend the functions of printed matter beyond traditional visually interpreted text and graphics
- perform actions as a part of functional products or wider information systems
Printed intelligence
Combines new technologies, applications and markets

- Current status
- Target of developments

Printed intelligence markets

New markets

New applications
Technical challenges

- Fluid processable materials with sufficient printability and electronic characterization
- Printing like mass-manufacturing methods fulfilling demands for individual layers and hence components
- Integration of electronic and functional devices and systems with sufficient performance

<table>
<thead>
<tr>
<th>Generic, enabling technologies</th>
<th>Components, circuits, integration-on-web, systems-on-foil, embedding 'electronics from inks' into products</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>R2R to hybrid processes &amp; production equipment</strong></td>
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<tr>
<td></td>
<td><strong>Materials</strong></td>
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</tbody>
</table>
VTT Printed Intelligence
technology | applications | business

- is a growth oriented strategic VTT initiative
- combines multidisciplinary know-how of VTT: electronics, optics, biotechnology, nanotechnology, chemistry, printing, P&P, process automation
- has a strong established partnership network to research and industry
- strongly orientated towards applications and business

Spearhead research program:
VTT Center for Printed Intelligence
Building the basis for a new technological opening

Commercialization program:
VTT Printed intelligence 1/2010 ->
Successfully introduce technologies from lab to early market trials and commercial adoption
Roll-to-Roll Manufacturing Technologies

- Gravure-, flexo-, and screen-printing
- Coating processes for fiber based substrates
- R2R-hot-embossing for DOE’s and microfluidistics
- Ink-jet printing
- Laser processing
- Lift-off “evaporation + solvent washing”

- Functional ink formulation
- Development of the printing tools
- On-line characterization
- Pilot scale production
Roll-to-Roll Pilot facilities

PICO 2003
- 2 gravure printing units
- R2R hot embossing unit
- Corona and lamination units
- Drying units (air, UV, IR)
- Web width 200 mm
- Max. web velocity 100 m/min
- Installed in clean room (ISO7)

ROKO 2007
- 4 replaceable printing units
  - Direct and reverse gravure, rotary screen, and flexography units
- Corona and lamination units
- Drying units (air, UV, IR)
- Web width 300 mm
- Max. web velocity 10 m/min
- Possibility to print in inert gas

Post treatment
- die cutting
- slitting
- rewinding
New Roll-to-Roll Pilot Factory

Roko

Inert gas machine

Lab2Fab-machine

Post treatment

R2R evaporator
R2R thermal nanoimprinting lithography (hot-embossing)

- Mechanical structures are embossed under pressure and heat on plastic web
- Embossing cylinder
  - Ni-shim
  - Laser or e-beam patterned
- Features sizes
  - Horizontal: ~100 nm at minimum
  - Vertical: <50 nm - 50 µm
R2R laser processing

- Integration of novel laser processing techniques to R2R environment
  - Scanner technology
  - Ultrafast lasers (ps, fs)

- Applications:
  - Ablation
  - Cutting
  - Via drilling
  - Sintering
  - Patterning
  - Lamination

R2R laser processed (4 m/min) Al (12 nm) electrode structures on flexible substrate

VTT’s R2R pilot processing facility with Lumera Rapid picosecond ablation laser.
R2R electrical sintering

- Proof-of-concept demonstration: 100 V at 300 MHz applied to an electrode pattern on a roll
- Silver nanoparticle ink is observed to sinter as the roll is passed over the nanoink coated substrate
- Alternatively, the first R2R stage can do patterning (to minimize ink usage)
Inkjet facilities

Dimatix table top Ink-jets

4-colour industrial ink-jet printer with inline curing

MicroDrop
Example: R2R inkjet and electrical sintering
Web Control, Runnability and On-Line Measurements

- Novel on-line measurement and characterization techniques
- Modeling and simulation of the R2R manufacturing process
- Improving the runnability and productivity of the R2R process

*Long way from table top printers to real R2R production!*
Register accuracy control

- For measurement of interlayer alignment of multilayer printed structures
- For visible, semitransparent or transparent layers
- Spatial resolution < 5µm
- Based on machine vision (pattern matching)
- Industrial camera & pulsed LED illumination
- LabView software
**Printing quality measurement system**

- Extremely high power strobo-system freezes web movement
- Reflectance and uniform backlight illumination with several possible wavelengths to enhance inspection of printed material
- High accuracy camera with selectable magnification lens gives accurate information from the printing quality
- Possible illumination wavelengths:
  - 365, 405, 465, 525, 590, 627, 660 and 735nm
- Simultaneous absorption measurement
Thick film and surface characterization

- Layer thickness
- Surface topography
- Technologies:
  - Camera based
- Tomography
- Chemical mapping
- Technologies:
  - Spectral imaging

3D-camera system image
- Spatial resolution 10 µm x 10 µm
- Depth resolution < 1µm
**Materials; Key Part of the Game**

*Example: Effect of solvents on printing quality*

- To achieve sufficient drying of the print, good adhesion for the fluid and required printing quality
- Surface tension of the fluid must be lower than surface energy of the substrate

Solvent with low boiling point

- Same ink concentration, 70 l/cm, 30 – 45 μm cells
- Printing parameters: 1000 N, 60 m/min

Mixture of solvents with high and low boiling points
Materials; Key Part of the Game

Example: Formulated PEDOT:PSS ink for anodes

PEDOT:PSS dispersion

Modified ink

+ surfactant
+ wetting agent
+ organic solvent

40-nm thick modified PEDOT:PSS print on ITO-PET
Example: ink modification

- PEDOT & P3HT:PCBM
- Printing cylinder parameters (cell depth, mesh, ink volume etc.)
- Printing parameters (Printing speed, nip pressure, doctoring angle etc.)
- Ink formulation (solvent mixtures, additives, ratio, total concentration etc.)
Application examples: optical codes

R2R hot embossed OROM element on a product package.

Printed machine readable variable codes.

UPCODE™ smart code, linking hybridmedia. www.upcode.fi
Application examples: electrical codes

Printed barcode sensor to detect $\text{H}_2\text{S}$ that is released in spoilage of poultry

Nicanti authentification solutions

www.nicanti.com
Application examples: OLEDs

Gravure printed large area OLED with an active area of 30 x 100 mm² on glass

R2R pilot scale all printed 2 color OLED powered via NFC link.

OLED temperature indicators on product packages
Application example: Organic solar cells

Gravure printed OSCs on flexible ITO-PET substrate
- Gravure printed PEDOT (air processing)
- Gravure printed P3HT:PCBM (air processing)
- Evaporated cathode
- All R2R process during 2011

\[
\begin{align*}
\text{Cathode (Ca/Ag)} & \quad - \\
\text{P3HT:PCBM (150 nm)} & \\
\text{PEDOT:PSS (30 nm)} & \\
\text{ITO} & \\
\text{PET/PEN} & \\
\text{Voc} & = 0.61 \, V \\
\text{Isc} & = 5.41 \, mA/cm^2 \\
\text{FF} & = 0.52 \\
\eta & = 2.82 \% \, (AM1.5 \, reference) \\
\text{Life time} & > 1300 \, hours
\end{align*}
\]
From laboratory scale cells to printed modules and integrated systems

**Lab scale small area gravure printed cell**
- Gravure printed HTL PEDOT:PSS
- Gravure printed active polymer blend P3HT:PCBM
- Evaporated cathode Ca/Ag

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCE</td>
<td>3.1%</td>
</tr>
<tr>
<td>Voc</td>
<td>0.6 V</td>
</tr>
<tr>
<td>Isc</td>
<td>10.2 mA/cm²</td>
</tr>
<tr>
<td>FF</td>
<td>0.54</td>
</tr>
<tr>
<td>A</td>
<td>18 mm²</td>
</tr>
</tbody>
</table>

**Sheet printed module (8 cells in series)**
- Patterned ITO-PET
- Gravure printed PEDOT
- Gravure printed P3HT:PCBM
- Evaporated cathode Ca/Ag

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCE</td>
<td>2.9%</td>
</tr>
<tr>
<td>Voc</td>
<td>4.9</td>
</tr>
<tr>
<td>Isc</td>
<td>19.3 mA</td>
</tr>
<tr>
<td>FF</td>
<td>0.47</td>
</tr>
<tr>
<td>A</td>
<td>15 cm²</td>
</tr>
</tbody>
</table>

**Integrated system OPV+battery+circuit**
- 4 printed organic solar modules:
  - PCE 2.3%, 15.5cm², Voc 4.6V, Isc 1.1mA/cm²
- Printed rechargeable Li battery:
  - 36 mAh @ 36 cm²
- Thinned control transistor chip
- 30 μm thick flip chip bonded
- Rotary screen printed backplane

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PriMeBits Electric Memory Card

- Questionnaires, marketing games, customer feedback, ...
- Memory by VTT based on electrical sintering
- Circuitry and assembly on paperboard by Stora Enso
- Battery by Enfucell
- Readout with a contact reader or using a Nicanti reader
Game demo based on printed non-touching 3D user interface
Printed Hybrid Systems
Flexible and printed electronics- Plastic Integration

Printed Hybrid Systems are *components* and *systems* which:
- Combine printed intelligence and non-printed components and sub-systems in order to optimise both performance and cost
- Integrate several manufacturing processes

Key Technologies:
- *Multi-layer polymer foil hybrid systems:*
  - Flexible electronics
  - Printing technologies and materials
  - Multi-layer lamination
  - Chip bonding & embedding
- *Assembled foil over-moulding:* In-Mould-Labelling • Injection moulding

Key Drivers & Benefits:
- Low cost packaging, integration and 3D system miniaturization with polymers, high through-put manufacturing and simpler value chain
- Enhanced functionality embedding, convergence and freedom of design (electrical, mechanical, optical, sensing, actuation, power …)
- Flexible, light, thin, large-area and low-cost conformal integration
Assembled Film Over Moulding – Process Flow

- VTT has two R2R pilot manufacturing lines
  - Rotary screen, gravure, hot embossing, flexography and lamination units as well as UV, hot air and IR curing

- Assembly of bare chips into foils
  - VTT has ICA, ACA and NCA technologies with stud bumping

- Foil is preformed into 3D shape
  - High-pressure forming
  - Multi-layer lamination

Plastic foil

Printing of active and passive layers

Discrete electronic components assembly

Lamination / Shaping of the foil

Assembly of the foil into the mould

Injection moulding material

Over-moulding

3D polymer product

- Embedding of bare chips in over-moulding process

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Flexible printed energy device: biofuel cell

- Manufacturing in printing or paper converting processes
- Recyclable and manufactured from sustainable materials
  - enzymatic cathode combined to Zn anode
  - enzymatic anode under development
- Size and shape can be tailored
- Power output in the range of $10^{-5}\text{Wcm}^{-2}$ / 0.7 - 0.8 V for single cell (can be connected in series)
### Printable RH indicators for fibre based packages

**Examples of the indicator performance at different humidities**

<table>
<thead>
<tr>
<th></th>
<th>RH 24.7%</th>
<th>RH 51.4%</th>
<th>RH 79.6%</th>
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<tr>
<td>0 h</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
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<tr>
<td>3.5 h</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
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<tr>
<td>20 h</td>
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<td><img src="image8.png" alt="Image" /></td>
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<td>7 d</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
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**EU Sustainpack -project:**
Innovation and Sustainable Development in the Fibre Based Packaging Value Chain

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Examples from Public Research Projects

**Low cost disposable biosensor platform**

R2R manuf. Optical components and detection using fluor. labeled antibodies

**Integrated all-polymer structure**

Hot-embossed microfluidics

Inkjetted fluorescence immunoassay in a μ-fluidic channel
Printable Biocompatible and bioactive materials

- Printable optimised matrix materials for immobilisation of antibodies or chimeric avidins on biosensor surfaces
- Generic printable bioactive surface materials to be integrated on sensor chips

Structure of a sol-gel matrix

Improve stability of proteins, during processing and storage

Improve lifetime of immobilised proteins

Improve resistance to environmental effect

Stability of anti NT-proANP doped in the sol-gel
BioAct – Bioactive paper and fiber products

Printed biomolecules:

Objective to develop and demonstrate bioactive paper or fiber based products produced on large areas using mass-manufacturing methods such as printing, coating or fiber suspension modification.

Products provide features in which biomolecules react specifically with target molecules producing:

- readable signals (visually, electronically or by other means), or
- other actions (such as restraining microbial growth)

Research partners: VTT, Åbo Akademi, Helsinki University of Technology, University of Lapland. Funding by Tekes – Finnish Funding Agency for Technology and Innovation, VTT and eight industrial partners.

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Clean Card® PRO–Orion Diagnostica Oy

Clean Card® PRO is a new-generation hygiene test for monitoring the effectiveness of cleaning of surfaces which come into contact with food. The test detects protein residues, the presence of which indicates inadequate cleaning.

Features:
- simple procedure: moisten - wipe – interpret
- colour change indicates an unclean surface
- result in only 30 seconds
- facilitates immediate corrective action
- no special training required
- no expensive equipment needed

VTT has helped several customer companies to develop new products based on VTT’s expertise on Printed Intelligence. For example, Orion Diagnostica Oy and VTT jointly transferred old swabs and reagent bottles based hygiene monitoring system to a new-generation, fast and easy to use integrated test device, which can e.g. help to focus the use of dip slide testing in a cost efficient way.

Finnish Chemical Industry Association Innovation Prize 2010 for Orion D and VTT
Optical barcode reading with mobile phones is expanding the way consumers access and use digital content and services.

- RFID (NFC) and other electrical reading technologies making inroads into mobile phones and other mobile devices. Initial applications in supply chain and anti-counterfeiting applications. Aim toward consumer applications.

- Printed intelligence is expanding the application space of both optical and electrical solutions through enhanced performance of printed matter:
  - Printed matter to carry metadata (e.g. digital content, indicators, biosensors)
  - Reading devices will activate functions within the printed item.
In sum: printed intelligence industry today

- Increasing interest in end user markets
  - not yet a priority -

- Need to identify value creation opportunities

- Strong efforts continue in technology research

- Still early stages in proving products
Trends in printed intelligence speeding up developments toward product

- Increasing interest in end user markets - not yet a priority -
- Need to identify value creation opportunities
- More product introductions to market
- Proof of cash in-flow
- Products utilizing existing capabilities
- More research beyond components
- Strong efforts in technology
- High yet realistic expectation setting
Printed intelligence technology timelines
“technology ready in-lab”

Components, circuits, integration-on-web, systems-on-foil, embedding 'electronics from inks' into products

R2R processes & production equipment

Materials

2007
Examples of recent product launches by Finnish companies
- UPM pakkausvahti
- UPCode
- Hygicult
- Nicanti

2008 - 2012
- Simple component production (e.g. antenna, UI boards)
- Hybrid products with printed circuit
  - Antennae, large area sensors
  - Commercially applicable especially when large area required
- Interactive packaging
- Organic light emitting displays, solar cells and RFID in limited performance applications

2013 - 2017
- Printed active matrix displays
- Autonomous systems containing power source, logic, display
- Embedded power sources (printed fuel cells, solar cells)
VTT creates business from technology