Organic and Printed Electronics

Dr. Danick Briand – EPFL
Prof. Vivek Subramanian – EPFL

Lecture content

1. Practical aspects of the course

– Lecturers
– Objectives
– Schedule & Content
– Evaluation

2. Introduction to Organic and Printed Electronics (OPE)

– Why flexible and printed electronics
– What is printing
– Challenges and opportunities
– Status, trends and applications

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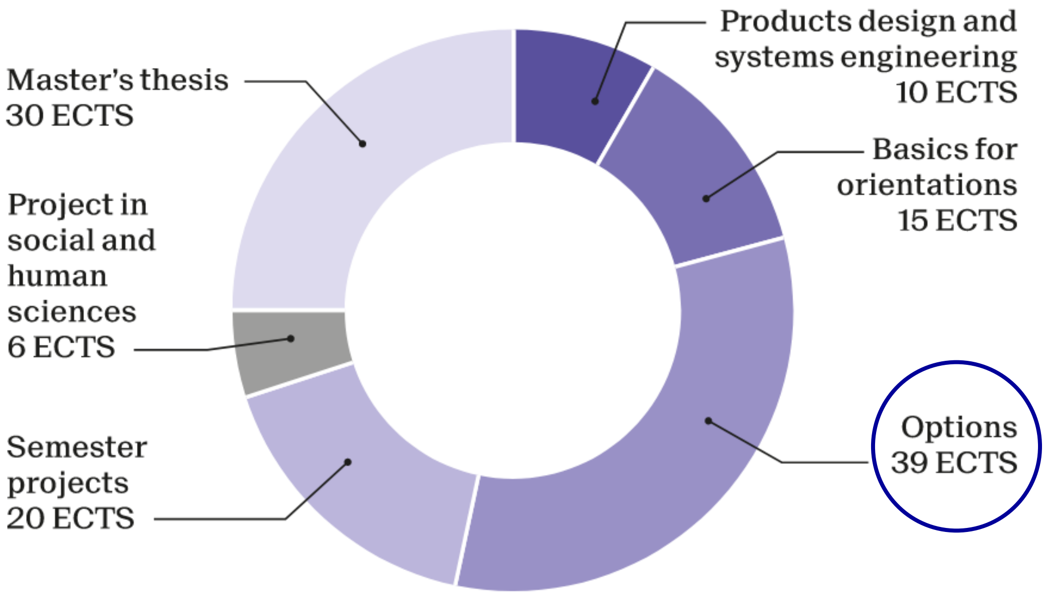
Position of the course in the Master program

- **Optional course in Microengineering**



- 2 h / week on Thursday 10:15 – 12:00
- Number of ECTS: 2
- Oral examination

Course content

This course…

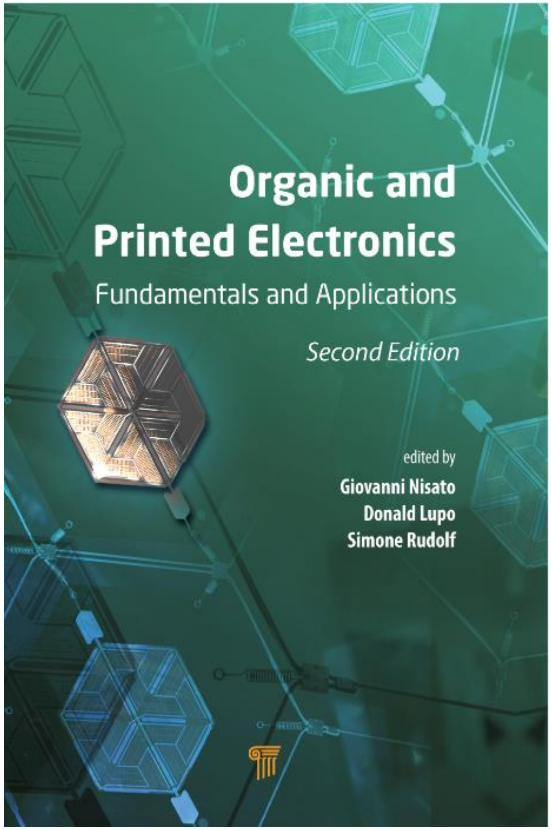
- addresses the implementation of organic and printed electronics technologies using large area manufacturing techniques.
- provides knowledge on materials, fabrication processes, devices, systems, and applications.
- covers fundamentals, core technologies, manufacturing, and applications
- reviews the state of the art and current status on commercialization.

Course content

- Based on the content of the book :

  “Organic and Printed Electronics: Fundamentals and Applications”

  – Fundamentals
  – Manufacturing
  – Devices
  – Integration and encapsulation
  – Systems
  – Innovation Management
  – Circularity and sustainability
  – Market perspectives and roadmap
  – Some exercises

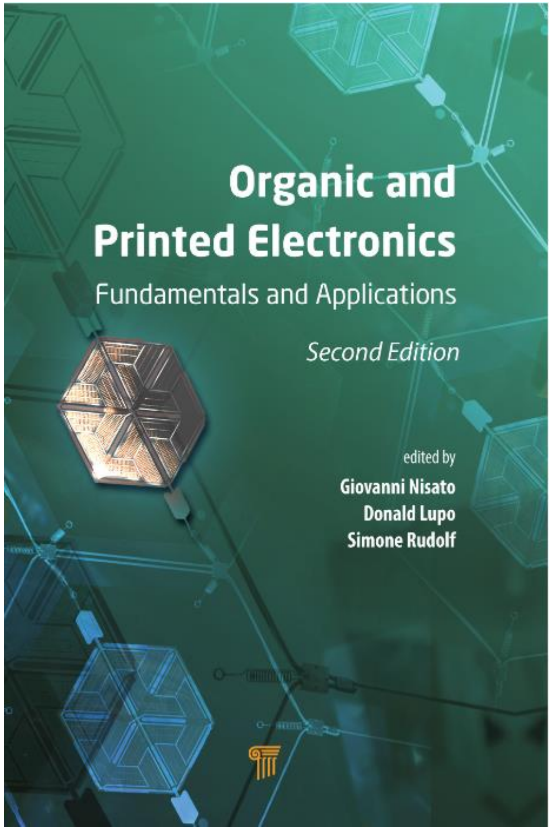


- **E-book 2nd edition 2024 available at the EPFL library**

Book content

- 1 . General Introduction
- 2. Introduction to Organic Semiconductor Physics
- 3. Printing and Processing Techniques
- 4. Characterization Techniques
- 5. Organic Thin Fim Transistors
- 6. Organic LEDs
- 7. Organic and Perovskite PV
- 8. Power Storage
- 9. Printed Sensors
- 10 Encapsulation of OPE
- 11 Hybrid Integration of OPE
- 12. Smart Textiles
- 13. Circular Economy and Environmental
- 14 Innovation Management
- 15 Roadmapping
- 16. Hands-On Experiments

Overview of the book chapters and structure.



Course format and support

- Courses will be mainly given as PPT presentations in class
- Lecture notes are available in PDF format on the moodle prior to each course
- We recommend to read the corresponding chapter in the Reference book
- Links to some pre-recorded lectures will be available on the moodle

  Videos are a support and do not replace the course in class

  !Watch out: course content varies from year to year !
- Quiz will be happen in class to support knowledge acquisition (not graded)

OPE course content and schedule

Dates	Lectures	Lecturers
20.02	**Introduction**	D. Briand
27.02	**Physics of printing I**	V. Subramanian
06.03	**Physics of printing II**	V. Subramanian
13.03	**Materials for large area electronics**	V. Subramanian
20.03	**Thin film transistors fundamentals**	V. Subramanian
27.03	**Thin film transistors devices & Circuits**	V. Subramanian
03.04	**Organic light emitting diodes**	V. Subramanian
10.04	**Solar cells**	V. Subramanian
17.04	**Flexible and printed sensors**	D. Briand
01.05	**Energy storage & Encapsulation**	D. Briand
08.05	**Integration & Smart Systems**	D. Briand
15.05	**Sustainable electronics**	D. Briand
22.05	**Case study**	D. Briand

Learning outcomes

By the end of the course, you will be able to:

- Identify the advantages, drawbacks, performances, complementarity and uniqueness of large area manufacturing vs. silicon technology
- Integrate the operation principles, architectures and processing of main devices and systems fabricated using printing techniques
- Analyze the challenges of manufacturing products using large area fabrication techniques
- Predict systems integration issues and propose methods for integration and encapsulation of printed devices and systems
- Illustrate applications of functional and intelligent surfaces and smart systems fabricated using large area manufacturing
- Compose examples of processing lines for printed electronics devices/systems

Learning outcomes

By the end of the course, you will be able to:

- Describe for each device the
  - Architecture and operation principle
  - Physics of the organic functional materials
  - Materials and fabrication (printing vs. vacuum processes)
  - Encapsulation
  - Characteristics and performance
  - Maturity: lab level, prototype, commercial products

- Suggest methods to integrate functionalities and components to make systems, fully printed or using hybrid integration

Evaluation

- 100% : Individual oral examination with some time for preparation
- A list of questions will be provided for each lecture to support you in your preparation

References Books

[1] Organic Electronics, Hagen Klauk (Ed.), WILEY-VCH, 2006, 428 p.

[2] Organic Electronics II: More Materials and Applications, Hagen Klauk (Ed.), WILEY-VCH, 2012, 420 p.

[3] Flexible Electronics: Materials and Applications, W. S. Wong, A. Salleo (Eds.), Springer, 2009, 462 p.

[4] Introduction to Printed Electroncis, Katsuaki Suganuma, Springer 2014, 124 p.

[5] Large Area and Flexible Electronics, Mario Caironi & Yong-Young Noh (Eds.), WILEY-VCH, 2015, 592 pp.

[6] Transparent Oxide Electronics: From Materials to Devices, P. Barquinha, R. Martins, L .Pereira, E. Fortunato, John Wiley & Sons Ltd, 2012, 295 p.

[7] **Organic and printed electronics: Fundamentals and Applications, Eds. Giovanni Nisato, Donald Lupo, Simone Ganz, Pan Stanford 2016, 604 p.** ebook available at EPFL.

LESSON 1 – INTRODUCTION

Dr. Danick Briand

Content

- What and Why Printed Electronics
- Challenges, Opportunities, Status and trends
- Examples of and Potential Applications

Printing beyond colors

Color Cyan
Color Magenta
Color Yellow
Color Black

Gloss & Protection

Process Colors

Coating

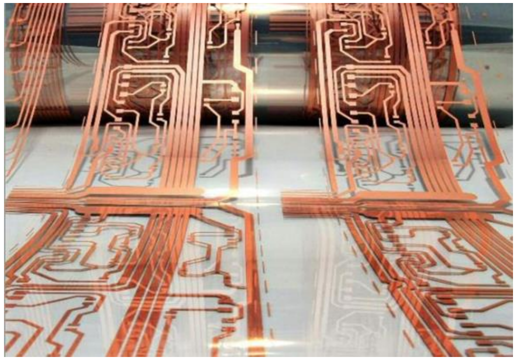
Ca e

- **Large scale production;**
- **High throughput;**
- **Fabrication of “product” on large areas;**
- **“Products” fabricated on flexible, light-weight, ecofriendly substrates…**

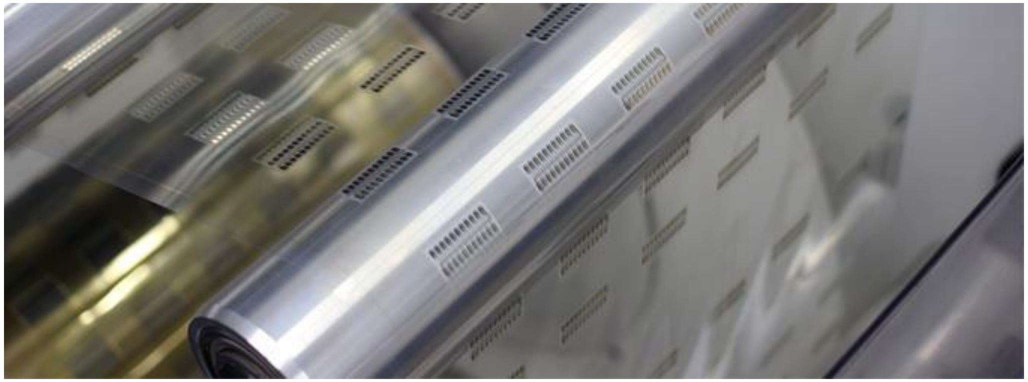
Printing electronic on large and flexible area

The answer is: YES!

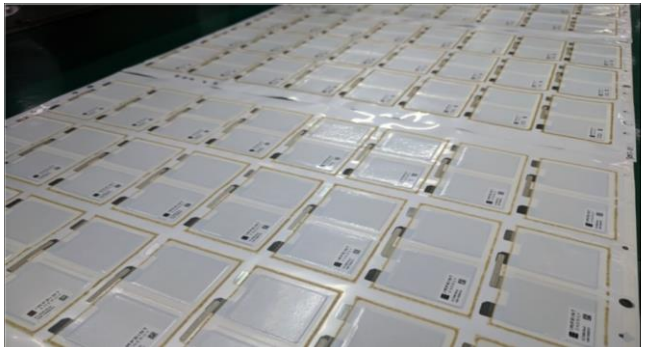
Printing techniques can be successfully employed for the fabrication of electronic devices, on a large variety of substrates:



copper PCB printed on PET
(source: Cavendish Labs Museum, UK)



memories printed on PEN (source: ThinFilm Electronics, Norway)



printed batteries (source: Imprint Energy))

B/W printed display on paper (source: LG))

Printing electronic on large and flexible area

We mentioned the possibility to print on a *large variety of substrates*

PLASTIC, CELLULOSIC FLEXIBLE SUBSTRATES

Why use plastic, flexible substrates?

flexible

source: Plasticlogic

foldable

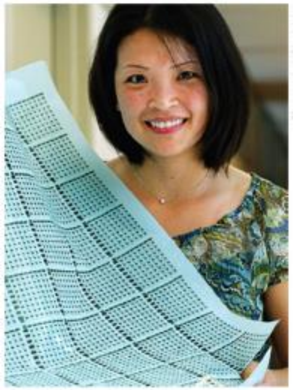
source: Swedish ICT

conformal

source: SEMICONWEST 2012

large area

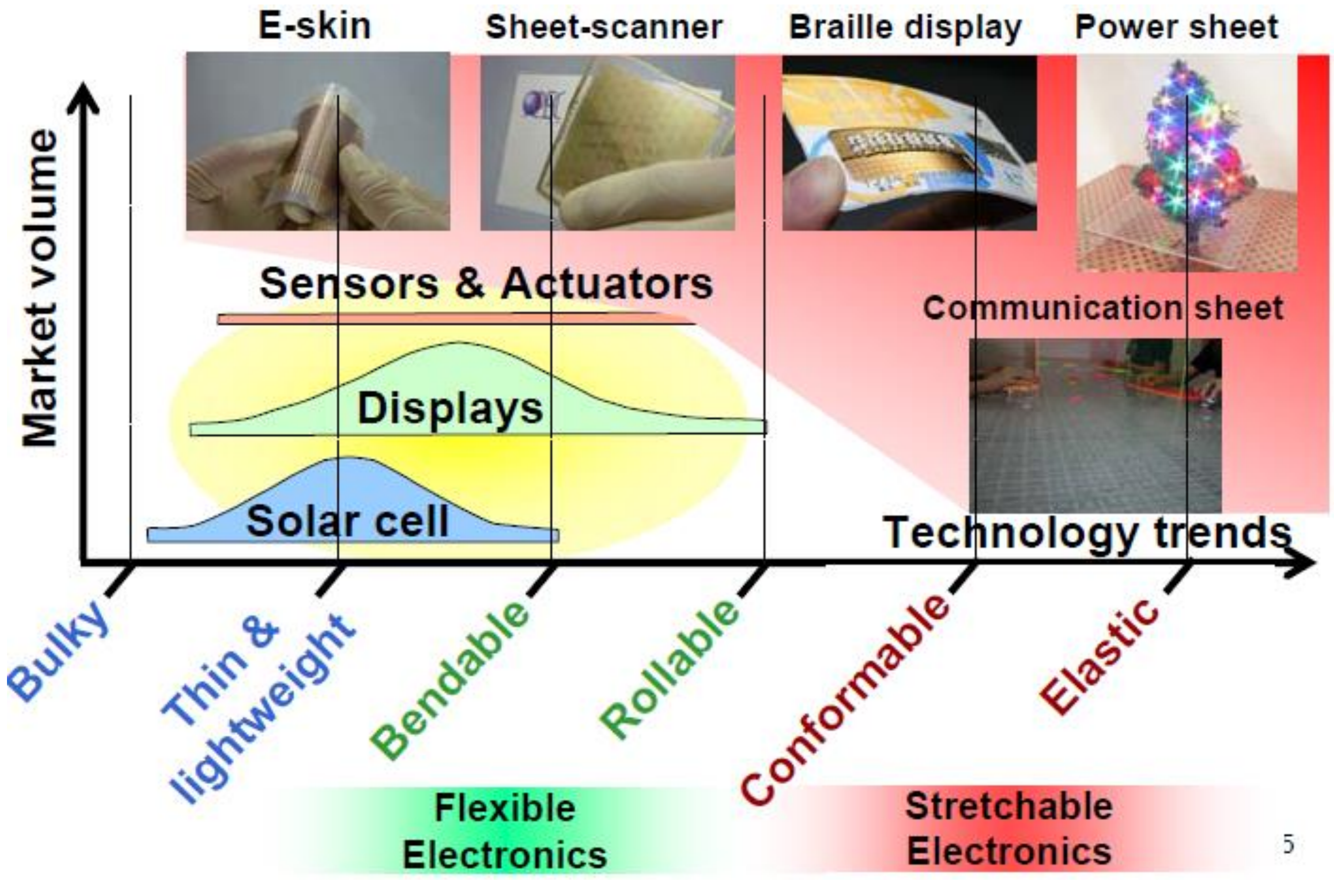
source: Princeton University



lower costs

source: GSA

Technology trends in large area electronics



From T. Someya, Univ. of Tokyo

Printed electronic on large and flexible area

Potentially

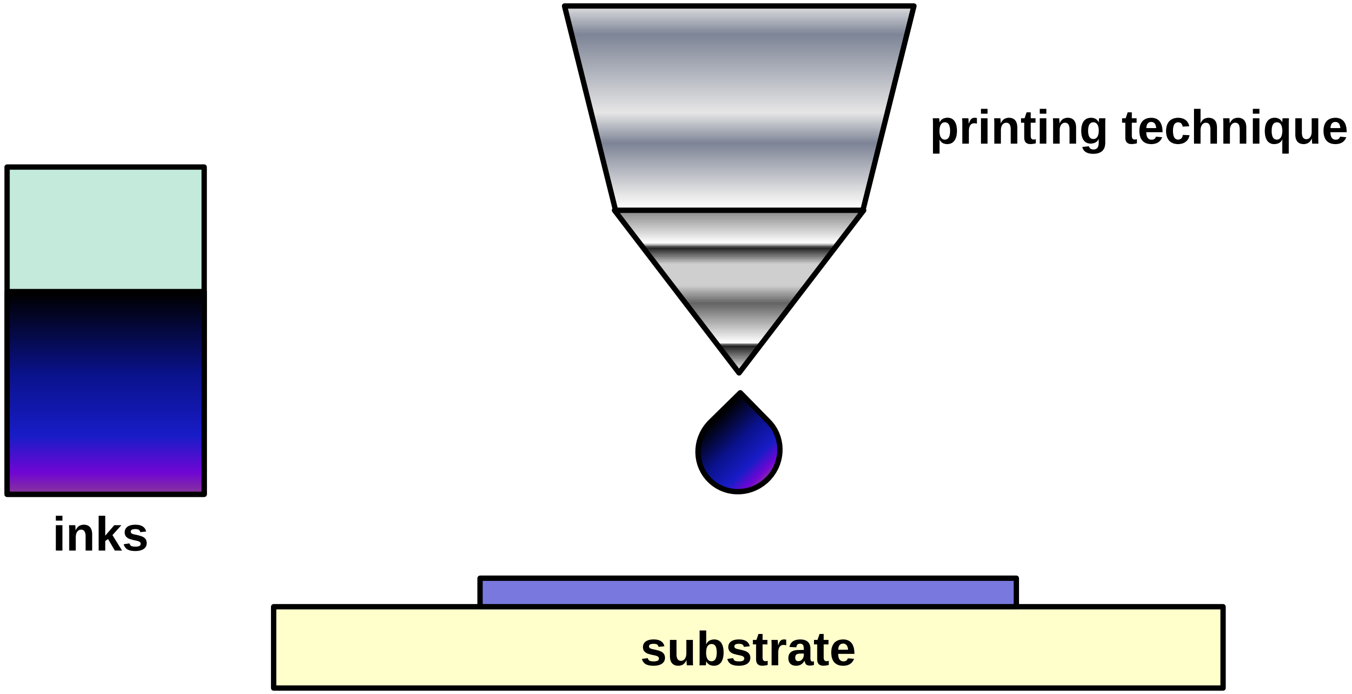
- Low-cost and reduced infrastructure
- Processing on large area (e.g. roll to roll process)
- Custom design / Quick prototyping
- Thin, lightweight, transparency
- Flexible
- Robustness e.g. A soft tactile screen will not break when your phone falls

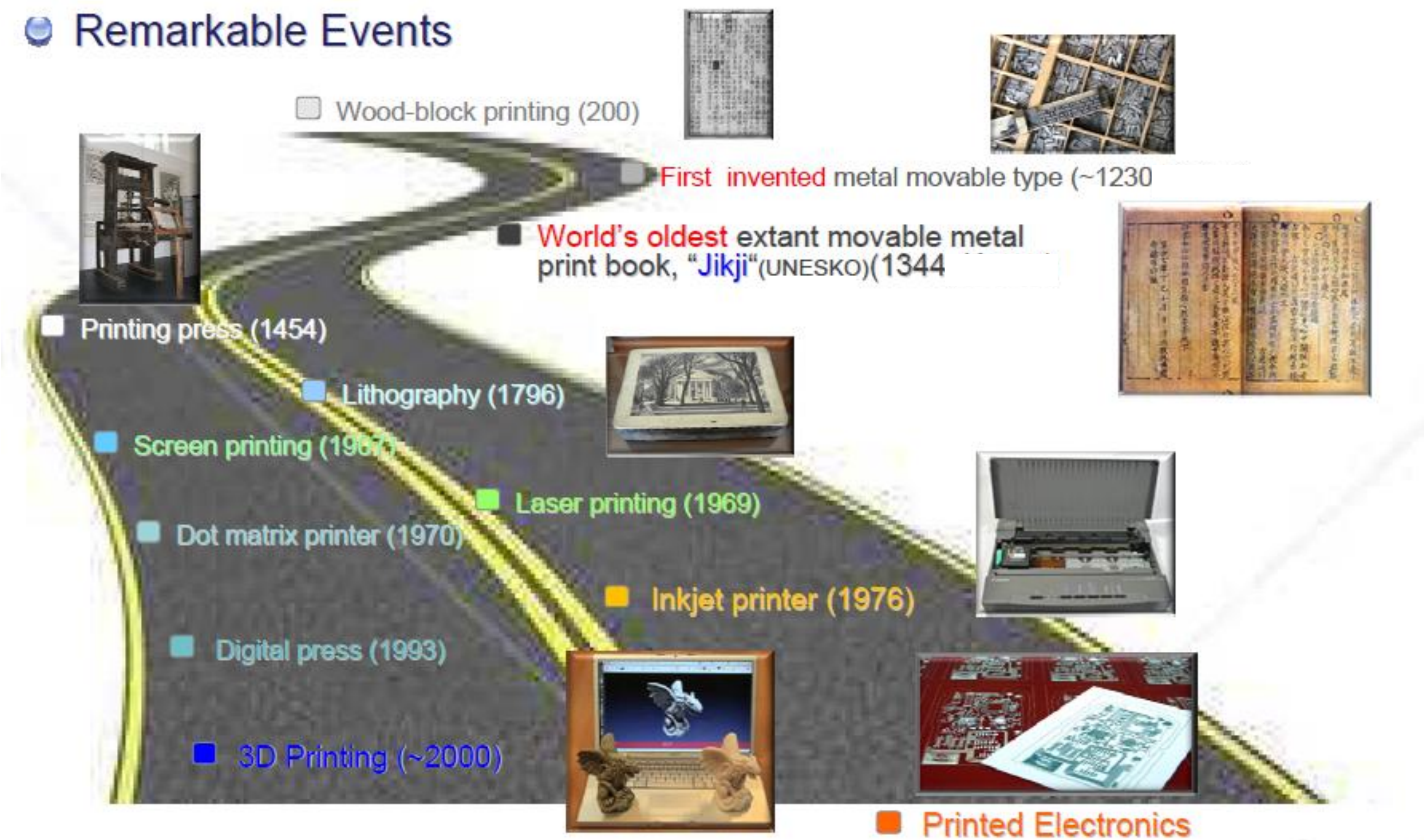
What is printing?

The most important fabrication method used to realise functional devices on large area substrate is printing.

A set of techniques used to transfer a specific pattern on the surface of a substrate by means of inks. *(Adapted from "Encyclopædia Britannica")*

Elements of a printing process:




Remarkable Events
Wood-block printing (200)
First invented metal movable type (~1230
World's oldest extant movable metal print book, "Jikji"(UNESKO)(1344
Printing press (1454)
Lithography (1796)
Screen printing (1907)
Laser printing (1969)
Dot matrix printer (1970)
Inkjet printer (1976)
Digital press (1993)
3D Printing (~2000)
Printed Electronics

From printing color to printing electronics

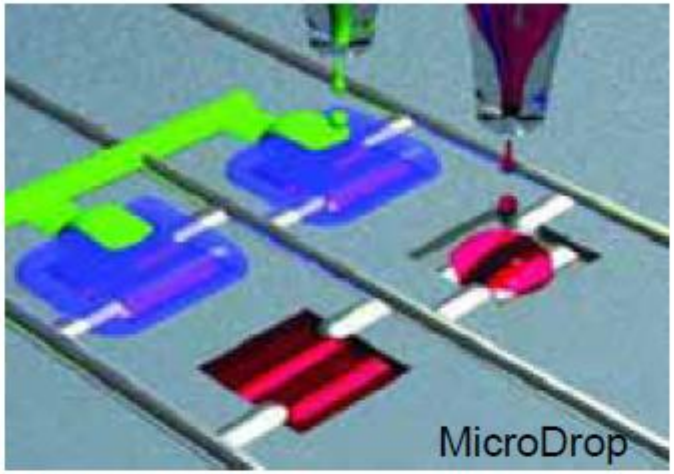
Important enablers

- **Soluble organic electronics materials**
- **Nanomaterials particles in suspension**
- **Stable polymeric substrates**

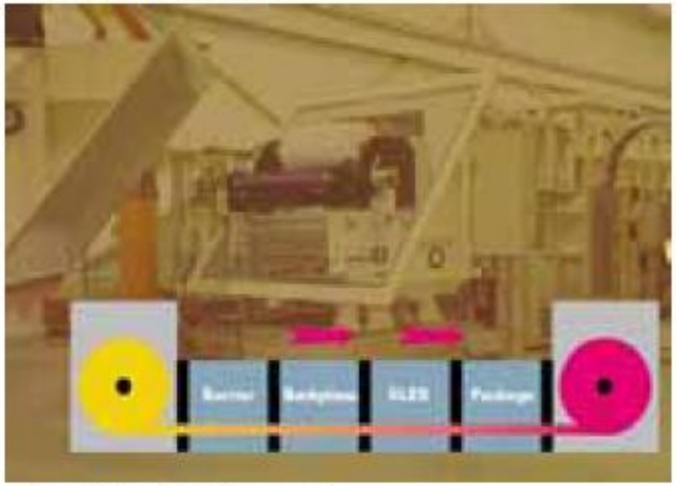
Soluble Semiconductors

New ways of processing

Printing and sintering at low temperature



Inkjet printing



Roll to Roll coating

From Holst Center

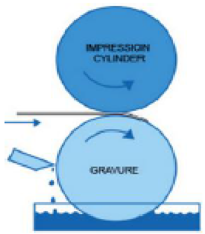
- **Printing**
  - It is a reproduction technique. It is used to apply information or functions to a substrate or directly on product
  - Two families:
    - Conventional printing processe (permanent printing plate)
    - Digital printing process (inkjet as example)

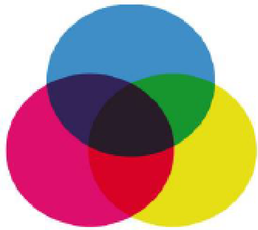
- **Benefits of printing**
  - Low cost manufacturing
  - High speed fabrication (meters / s or min)
  - Low temperature process (< 100-200°C)
  - Flexible substrates
  - Established technology
  - Additive manufacturing

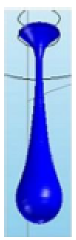
VTT, Finland

Printing process steps: Ink, printing and drying

Material Deposition







INK : suspension or solution

↓

Deposition / Printing

↓

drying
expel liquid necessary for printing

↓

functionality formed

printing & drying

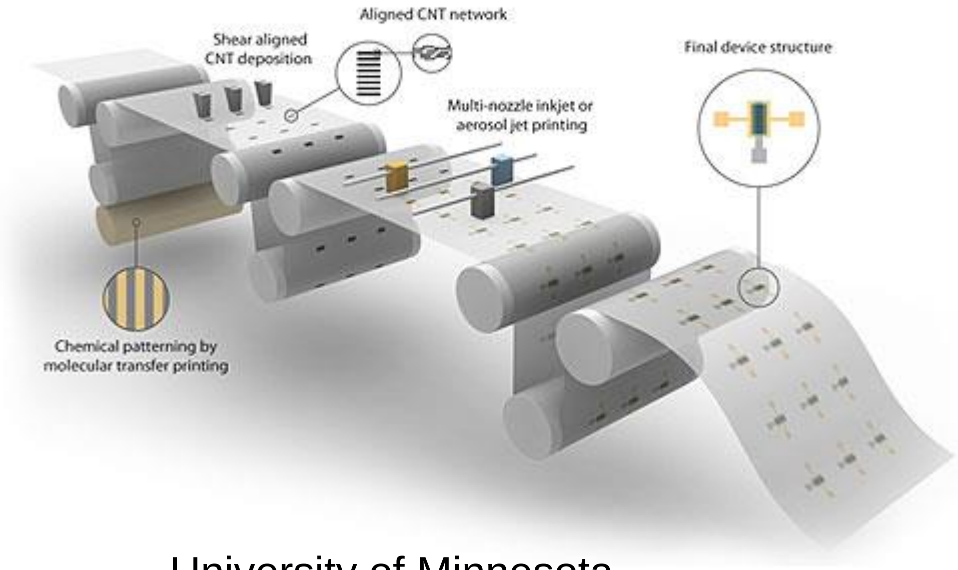
wet

dry

Two main substrate formats and manufacturing approaches

- Sheet to sheet
- Roll to Roll (for high volume)

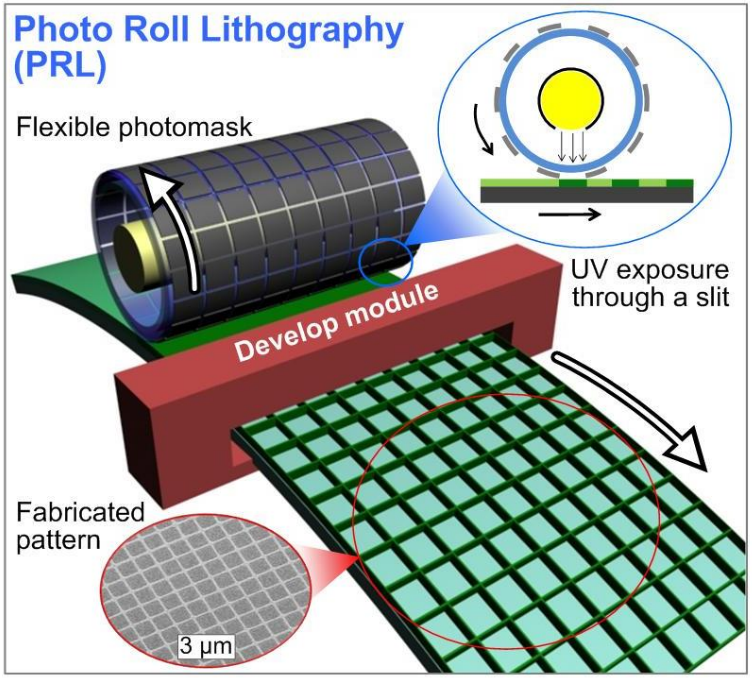
z-studio

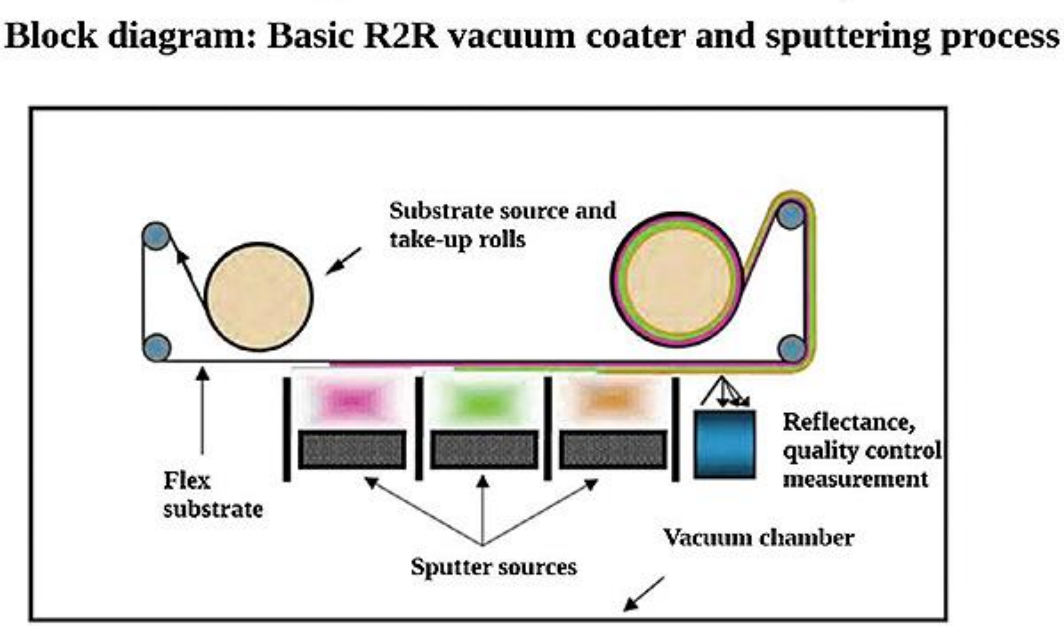


University of Minnesota

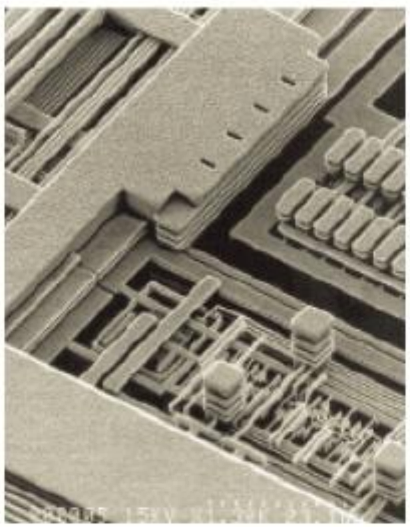
Important

- LAM is not limited to printing: many clean room / vacuum processes available

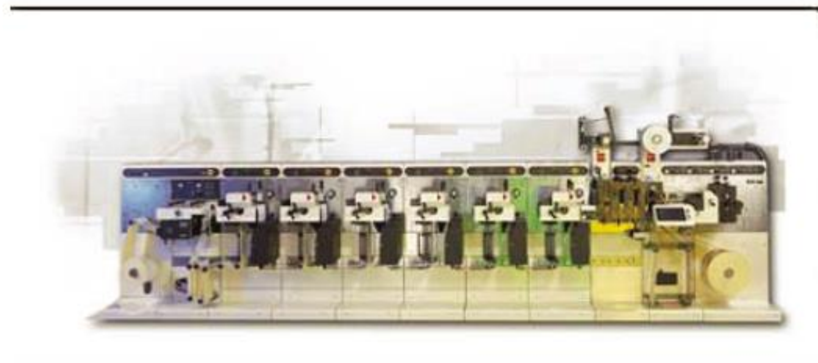




Printed vs. conventional electronics



Si chips: > 500 process steps (IEEE.org)



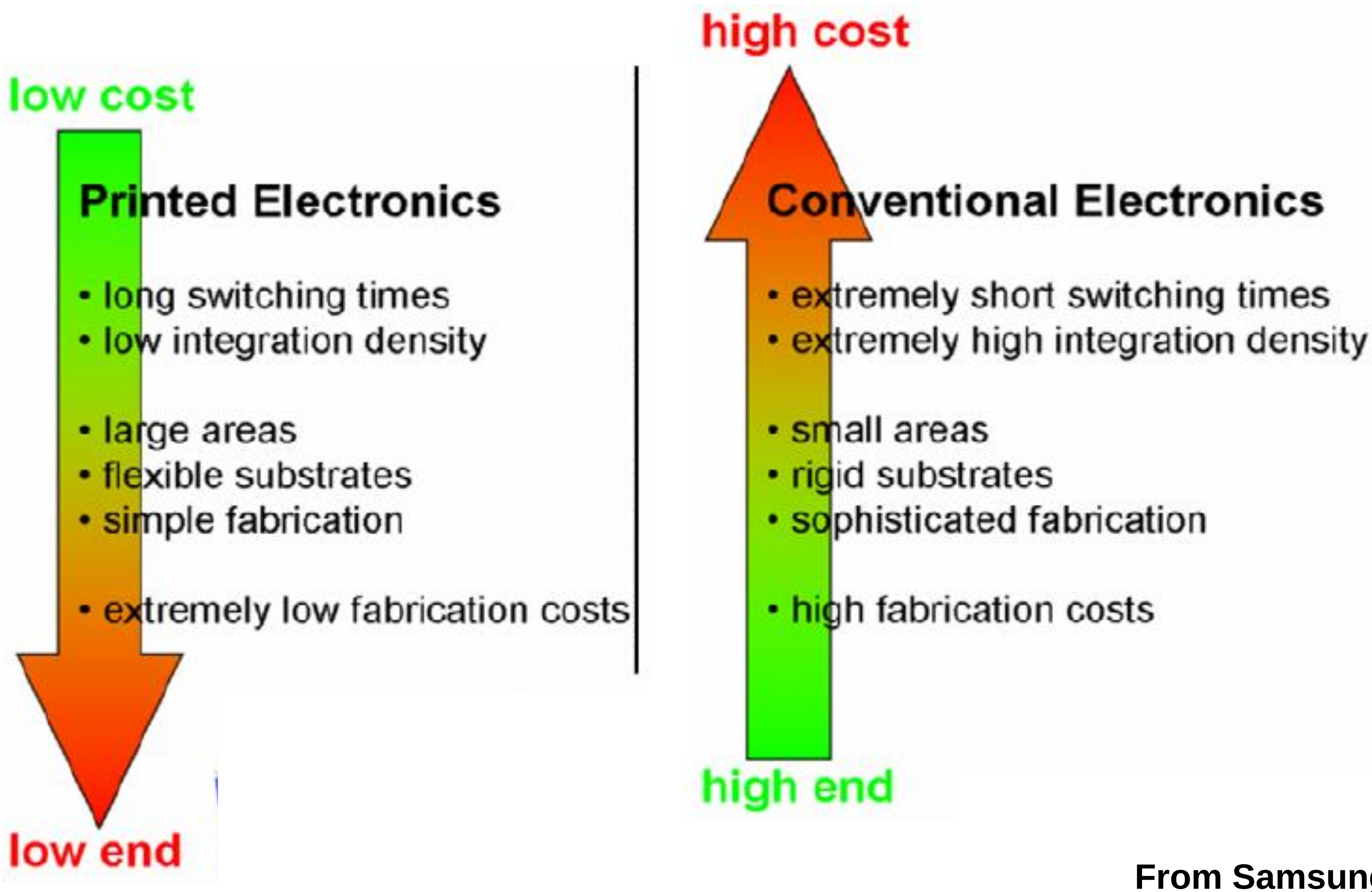
Nilpeter Label Printer

A R2R printing machine

1. Typically 5 to 15 patterning steps are lined up.
2. Time for post-processing before next process event < 1s.

Large area manufacturing: Printing

Printed vs. conventional electronics



From Samsung

Terminalogy

Printed Electronics:
focuses on the technique employed for the fabrication of devices

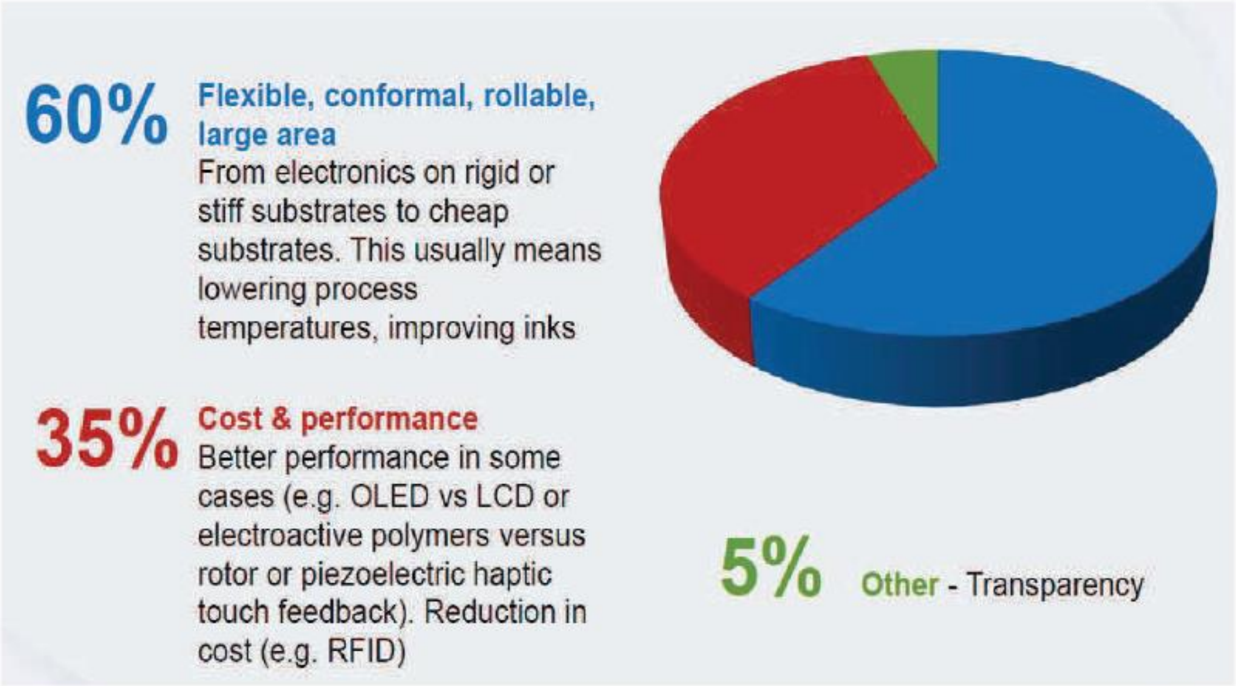
Plastic Electronics:
focuses on the molecular weight of the materials employed (high molecular weight) for the fabrication of devices

Flexible and Stretchable Electronics:
focuses on the mechanical properties of the substrates employed for the fabrication of devices

Organic Electronics:
focuses on the chemical nature of materials employed for the fabrication of devices (organic = carbon based)

OVERLAP, due to the fact that organic, plastic materials are usually solution-processable, which makes them suitable to be deposited on flexible substrates by means of printing techniques!

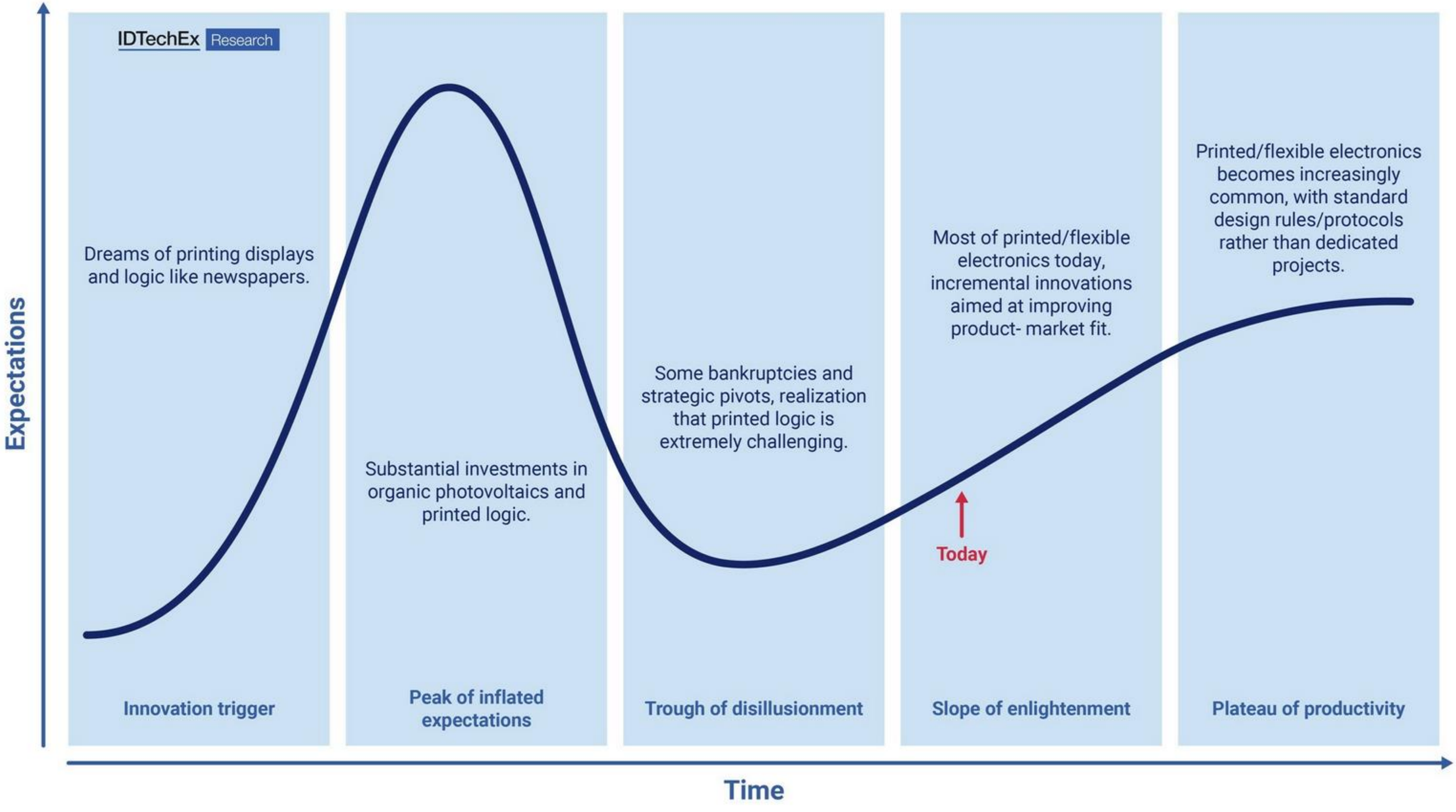
Market drivers for printed electronics



IDTechEx 2012

- 97% of the companies globally related to printed electronics have been profiled as materials, equipment or component providers.
- Only 3% of the companies make products or do integration.

Status and trends



Status and trends

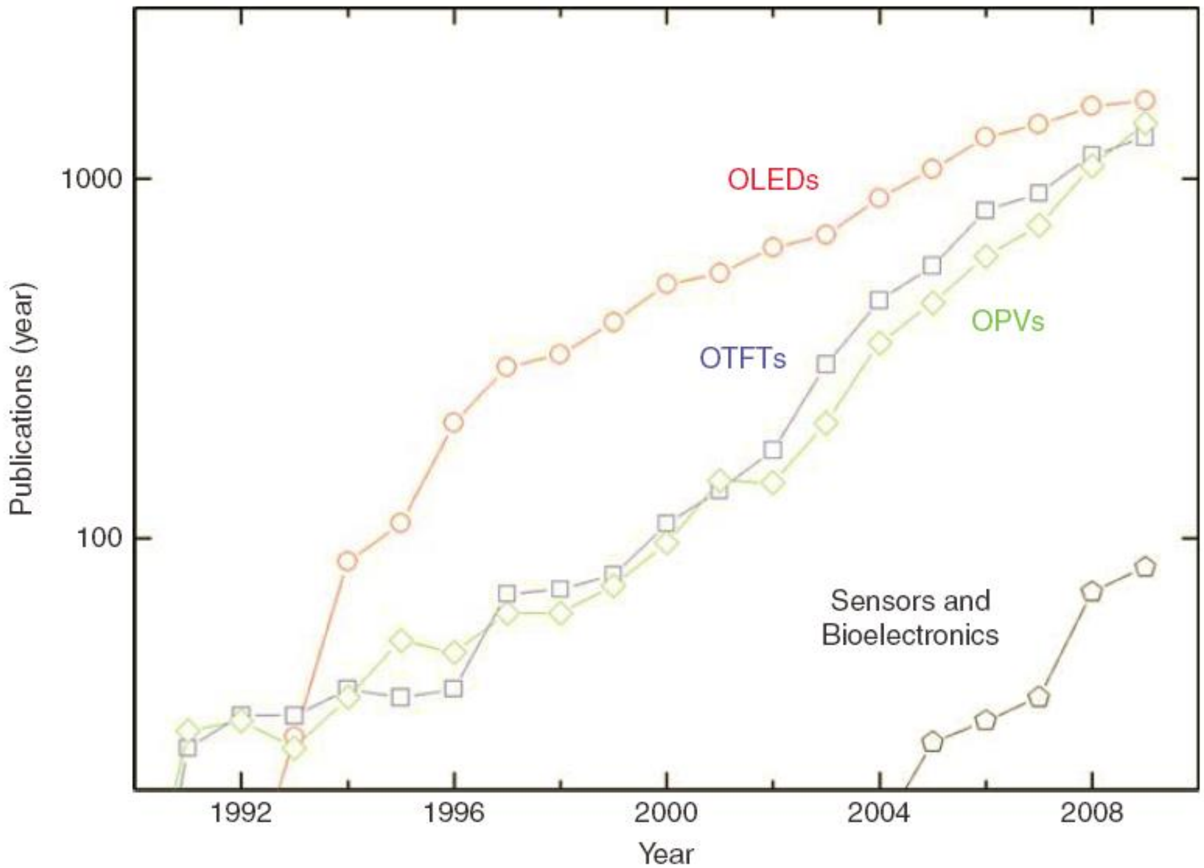


Figure 1. Publication trends in organic electronics compiled using data from ISI Web of Science. The number of publications on organic light-emitting diodes (OLEDs), organic thin-film transistors (OTFTs), and organic photovoltaics (OPVs) show a dramatic increase in the past decade. A clearly visible recent trend involves the use of these devices in sensors and bioelectronics.

MRS BULLETIN • VOLUME 35 • JUNE 2010

Energy storage:
Batteries and
supercapacitors

The field of organic and printed electronics:

- is well established in terms of academic, scientific, and technological research;
- but is still an emerging one in terms of mass industrial applications.

Market for flexible, printed and organic electronics of **US$ 51 billion in 2022**

Predicted market of **US$ 68 billion dominated by OLED in 2027**, relatively small part of the overall electronics market of € 4,517 billion in 2020.

Key industrial sectors for OPE: consumer electronics, automotive, medical/pharmaceutical, and building/architecture.

The trend **from "technology push" to "market pull"** defined by the needs of the end users has continued and become even stronger.

EXECUTIVE SUMMARY - OE-A ROADMAP WHITE PAPER, 9th EDITION

Status and trends

- **OLED displays** continue to be a major success story for OPE, with a trend from flat and rigid to curved, bendable and foldable
- OPE has started to reach mass market penetration in the **automotive** industry, with touch panels widespread and displays and OLED interior lighting appearing
- **Organic photovoltaics** have also started to find larger suitable markets, with large building-integrated PV installations and use of OPV flexible modules for indoor IoT
- The **healthcare and wellness** industry has also seen strong growth in the introduction of OPE-based products

EXECUTIVE SUMMARY - OE-A ROADMAP WHITE PAPER, 9th EDITION

Status and trends

- Organic and printed electronics is becoming more **flexible, stretchable and foldable**, and more complex products are appearing
- **Hybrid system integration** continues to be a key technology for products
- **Sustainability** and compatibility with a **circular economy** are receiving increased attention
- **Production:** low-cost, scalability, inspection/yield, reliability, standardization…

EXECUTIVE SUMMARY - OE-A ROADMAP WHITE PAPER, 9th EDITION

Opportunities

- New opportunities to deploy **electronics on surfaces to date unreachable**
- **Organic semiconductor molecules** can be designed and engineered to create new semiconductor types, for example, with specific color emission or absorption properties
- **Liquid processing**
  - Mixed solutions to form compounds
  - Tuning of materials properties
  - Can be printed
  - Compliant to match mechanical stiffness/softness where needed
- Development of low-cost and high speed **coating, printing, structuration and characterization processes** for large area manufacturing (e.g. roll to roll)
- **Green** electronics/microsystems and manufacturing
  - Enviromental friendly materials and processes
  - Additive manufacturing (deposition of material only where needed)
  - Manufacturing at lower energy with reduced infrastructure
  - End of life: disposable being recyclable or biodegradable

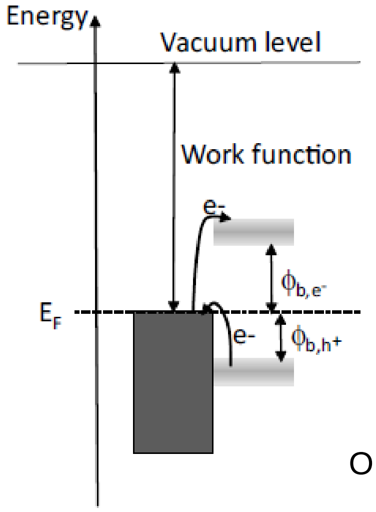
Challenges: Materials

- Inherent mismatch between high performance device materials and soft carrier materials
- Formulation of stable and suitable printing inks
- Electronic properties of organic materials ⇒ Hybrid approach can be needed (e.g. Si)
  - Electron transfer process (band structure) different than for inorganic materials
  - Mobility, opto-electronic properties not reaching those of best inorganic materials

TFT properties	Oxides	a-Si:H	poly-Si (LTPS)	Organics
μ (cm² V⁻¹ s⁻¹)	1 to 100	1 max	50 to 100	0.1–1
S (V dec⁻¹)+	0.1 to 0.6	0.4 to 0.5	0.2 to 0.3	0.1 to 1.0
Leakage current (A)+	10^{-13}	$\sim 10^{-12}$	$\sim 10^{-12}$	$\sim 10^{-12}$
Reproducibility	High	High	Low	Low
TFT for AMOLEDs	4 to 5 masks	4 to 5 masks	5 to 9 masks	Poor applicability*
Manufacturing cost	Low	Low	High	Low
Long term TFT reliability	High (forecast)	Low	High	Low in air
Yield	High	High	Low	High
Process temperature (°C)	RT to 350	~250	<550	RT
CMOS fabrication	Yes and large areas	Very low performance	Yes, not for large areas	Low performance

+Highly dependent on the dielectric layer.
*Most organic semiconductor layers are patterned using shadow masks.

From «Transparent oxide electronics», Wiley, 2012



OPE book

Sketch of injection barriers (ϕ_b) involved when injecting an electron into an organic semiconductor, forming a negative polaron, or injecting a hole (extracting an electron), forming a positive polaron. The positive and negative polaron densities of the organic semiconductor film at the interface of the metal electrode are drawn assuming vacuum level alignment.

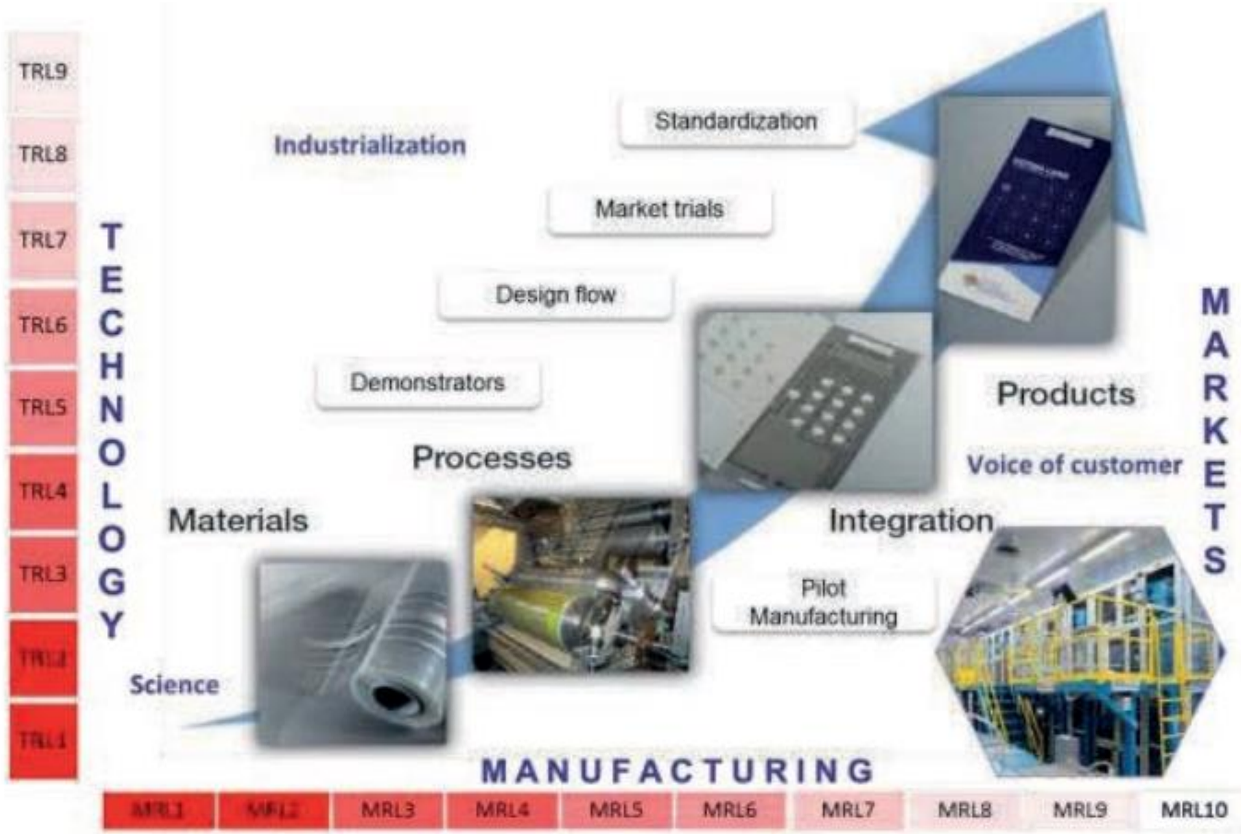
Challenges: Manufacturing

- Solution process: wetting $\Rightarrow$ ink-substrate interaction
- Printing and curing, all processes, at high speed
- Printing on multiple layers: topography, solvent/curing compatibility, alignment, mechanical stability of the substrate in the machine and after curing
- Limited thermal resistance of organic and polymer materials and associated process compatibility issues
- Large area: uniformity, reproducibility at high speed, yield
- Characterization on large area and at high speed
- Integration of different components / functionalities (e.g. printed with non printed)
- Transfer to industry

Challenges: Reliability

- Material stability / Aging: $\Rightarrow$ robust materials & hermetic / flexible / transparent encapsulation for organic electronic materials
- Compliant electrical conductive electrodes, metallisation
- Interfaces / mechanical adhesion
- Huge property contrast between device materials (stiffness, thermal expansion …) and associated distortion and damage problems
- Mechanical reliability under deformation

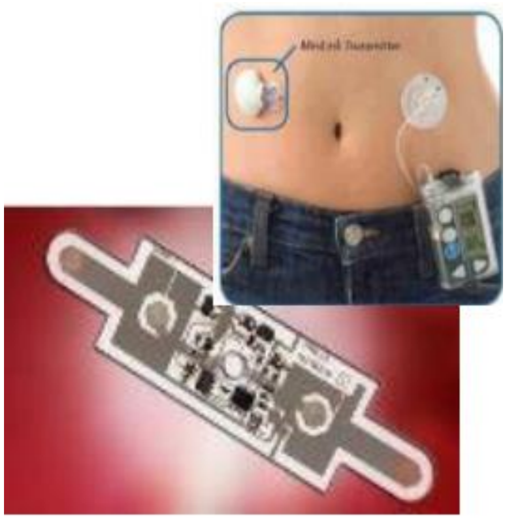
Development of Printed Electronics products



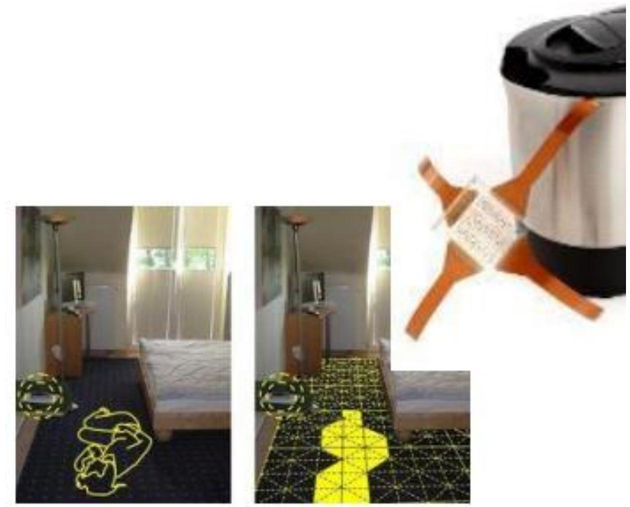
Printocent book

Printed electronics in everyday life

Applications



Personalized Health



Ambient Intelligence

- Smart lightning
- Disposable diagnostics
- Interactive packaging
- Large area sensors
- …

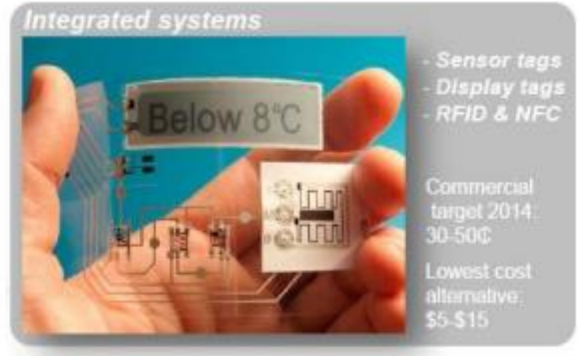
Machine-Human Interface

Smart Labels / Objects

Applications: 1st Demonstrators

Smart Blister Stora Enzo

Ecran OLED Samsung



Mémoires imprimées ThinFilm

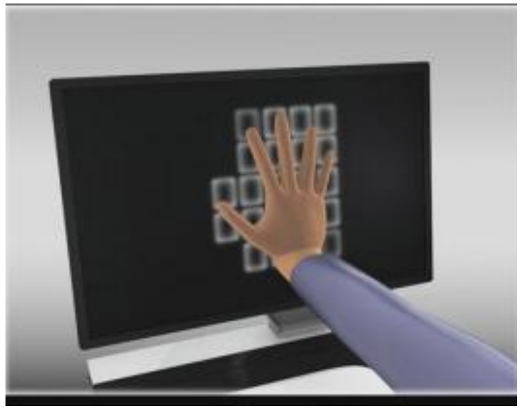
Luminaires OLED AstroFiamm Blackbody

Sac solaire KONARKA

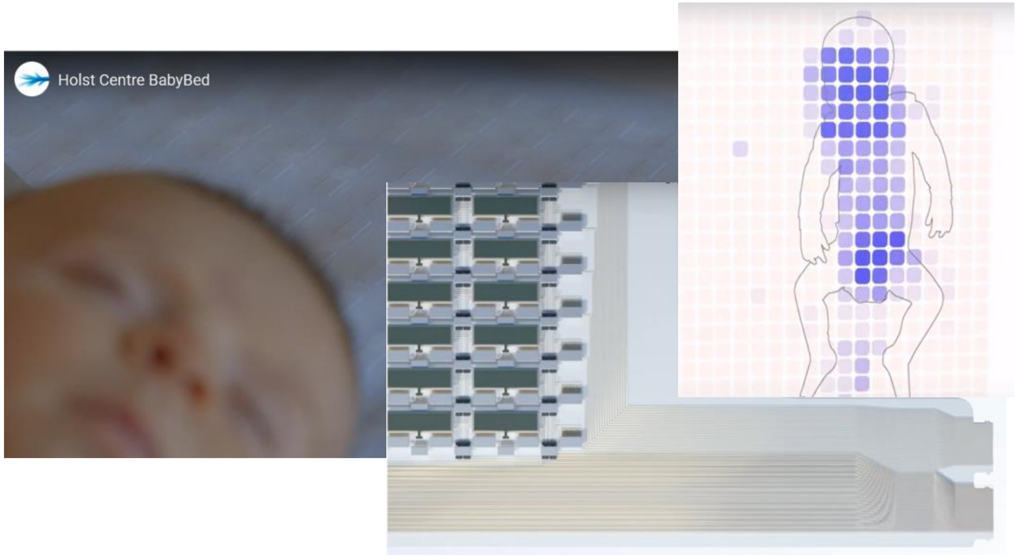
E-Paper Plastic Logic

Affiche intercative ISORG

Applications: Large Area



Sensors matrix



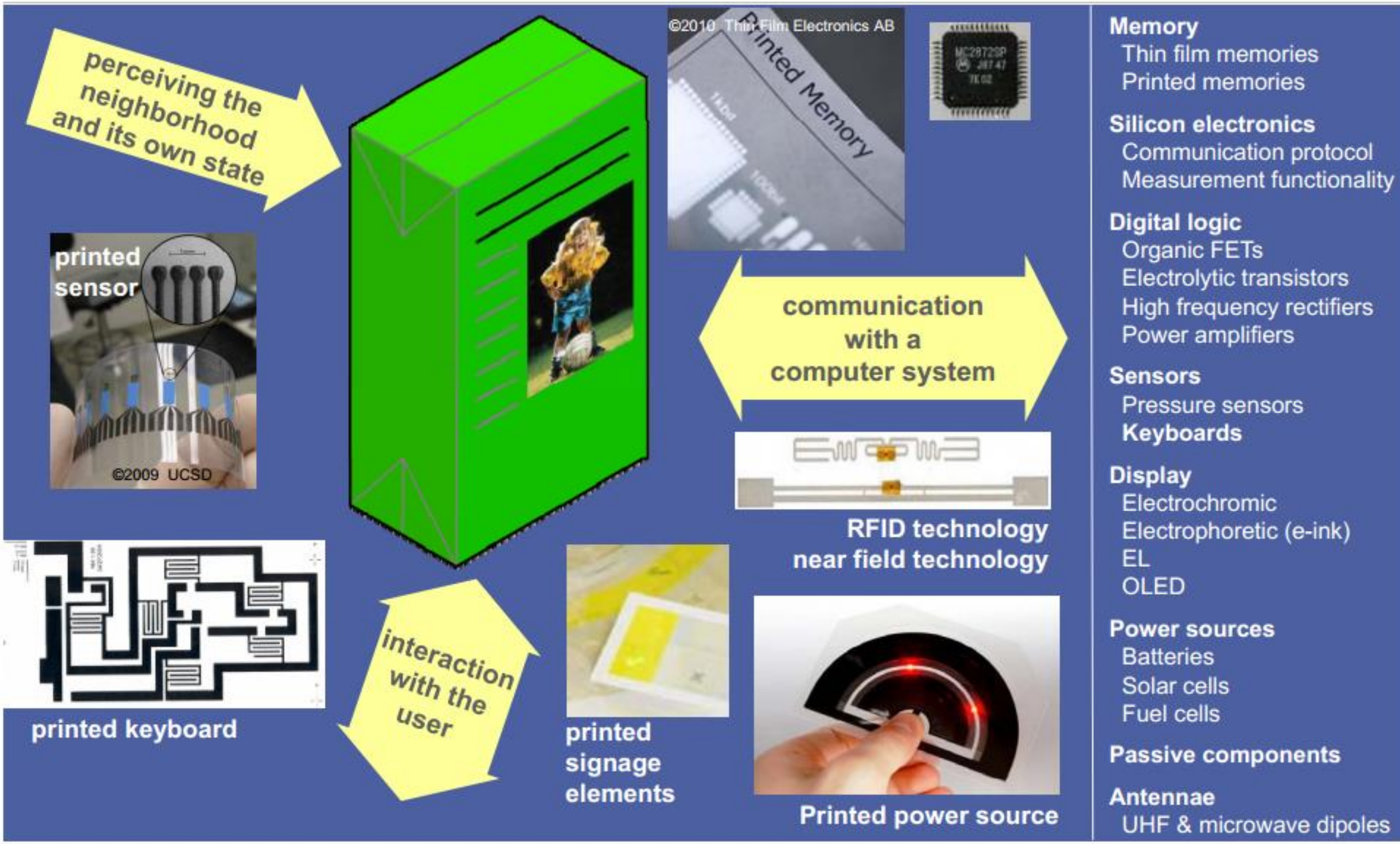
Solar cells

OLED TV

Applications: Large Area for Automotive

Lightning and display made from OLEDs

Applications: Smart Objects



From R. Baumann, TU-Chemnitz

All printed smart sensing NFC label

SOLVAY

InkTec

parc
A Xerox Company

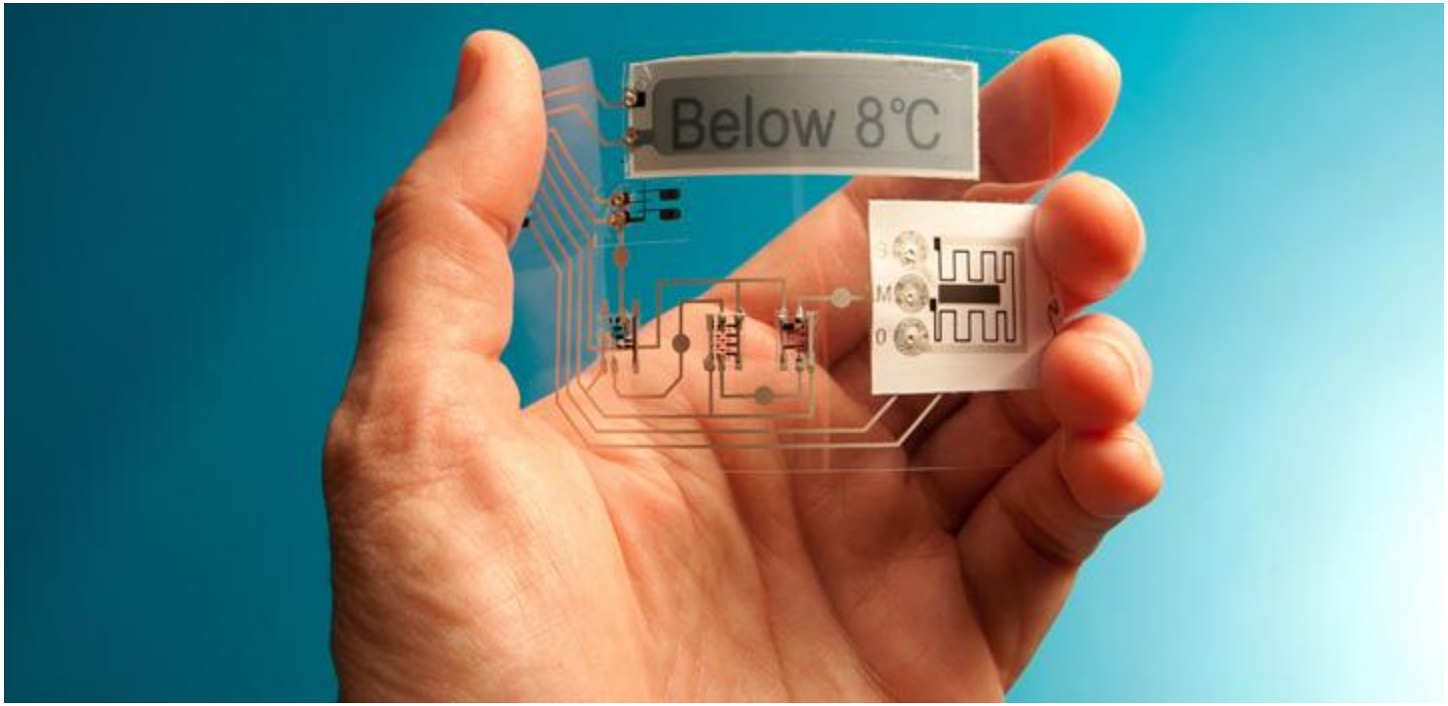
Polyera

SWEDISH ICT ACREO

PST SENSORS

IMPRINT energy

THINFILM Memory Everywhere™



- Printed silicon thermistor
- Printed organic read-out electronics
- Printed memory and display

All printed smart sensing NFC label

PragmatIC flexible IC labels

Pragmatic has raised $400m to date and has grown to over 275 employees

Pragmatic Park, a 58,000m^2 production site which can accommodate 8 x 300mm FlexLogIC lines

High volume
Billions of chips per line per year

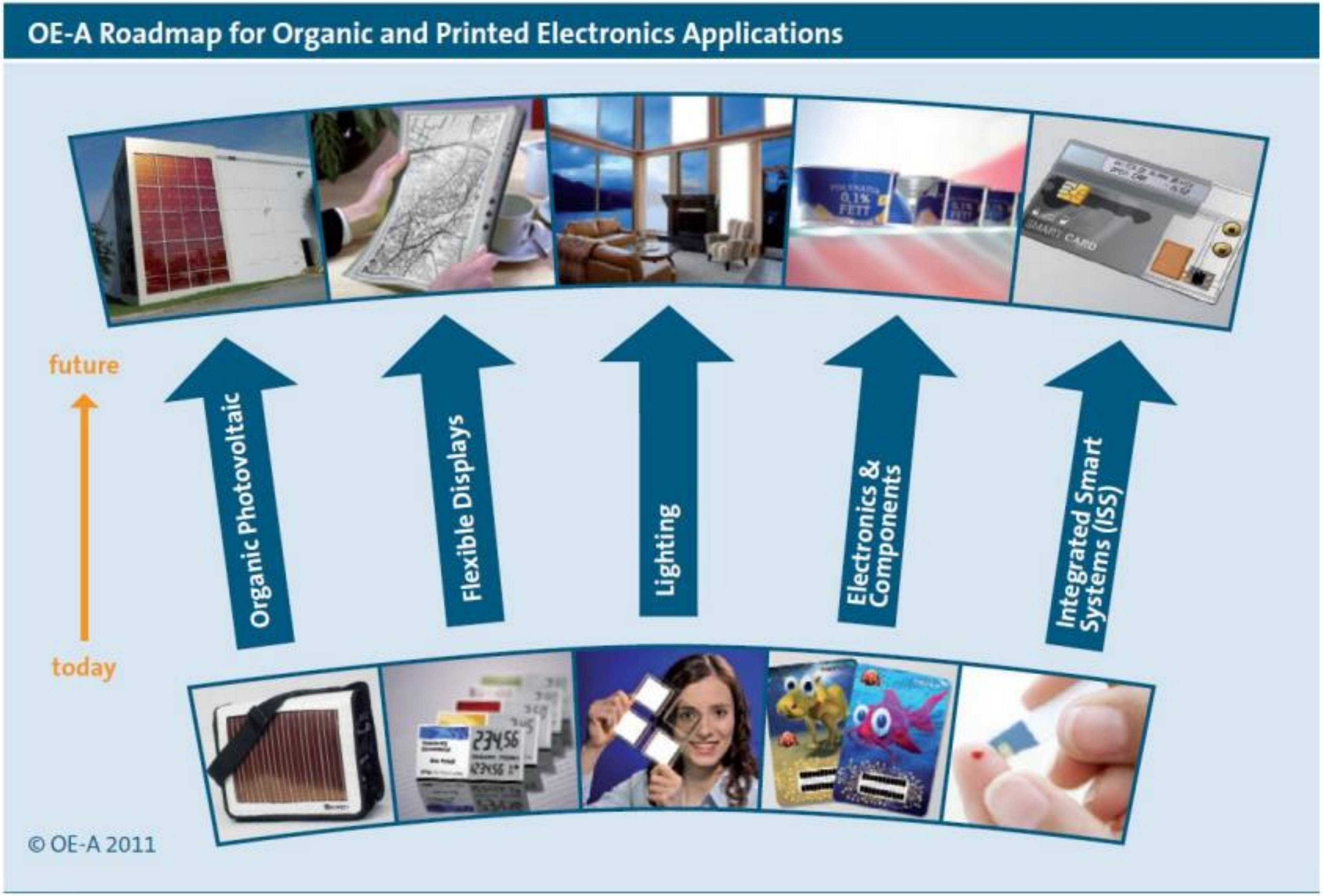
Fast production
<48hr 'just-in-time' production cycle

Compact footprint
<1000 sqm (each 300mm line)

Environmental impact
significantly lower environmental impact

Their novel fabrication process offers high throughput FlexIC production with a capital expense 100x lower than traditional semiconductor manufacturing and is also significantly more sustainable with 100x less energy and water, and 1000x lower CO_2 emission.

Applications: Roadmap



OE-A Roadmap for Flexible, Organic and Printed Electronics Applications 2023
Market entry in large volume

	Existing 2023	Short Term 2024-2026	Medium Term 2027-2029	Long Term 2030+	
Flexible & OLED Displays	Foldable OLED Rollable TV QD-OLED displays Low PPI MicroLED TV Printed OLED Displays LTPO backplanes	Organic LCD (OLCD) MicroLED displays AR/VR displays Improved reflective color Transparent OLEDs Perovskite QDs	In-mold displays 3D curved displays Flexible QD-OLED	Flexible MicroLED Stretchable displays EL-QD displays Light field displays	
OPV	OPV foil OPV for BIPV	OPV for IoT (sensors, etc.) OPV smart objects, lamps, portable chargers OPV for energy harvesting combined with energy storage OPV power supply for consumer goods Color & shape on demand	Transparent OPV (T<50 %)	OPV on „all“ available surfaces, mobile devices, combined with thin film battery Highly transparent OPV (T>50%)	

OE-A Roa

	Existing 2023	Short Term 2024-2026	Medium Term 2027-2029	Long Term 2030+	
Electronics & Components	Printed devices: RFID antenna, primary battery, Early-gen printed secondary batteries; piezoelectric elements; Sensors: glucose, pressure, temperature, humidity; printed phone case integrated antenna; thin flexible Si-chips, Input Devices and machine interfaces, stretchable conductors / resistors, 3D touch sensors;	High-performance printed supercapacitors Flexible printed secondary batteries Integrated; supercapacitors/batteries light sensor; stretchable conductors/ resistors; (OTFT backplanes for low energy displays and OPD); 3D & large area flexible electronics; active touch sensorsactive backplane,	Printed secondary ion battery; printed super caps; gesture sensors, integrated antenna patches, phase array antenna patches.	Complex stretchable electronics; Printed complex logic; Washable batteries, bio-compostable batteries Printed energy harvesting capacitors active switchable phase array antenna patches	
Integrated Smart Systems	Touch, force and pressure sensors; Printed biopotential electrodes; Sensors embedded in cars and other products; Blood glucose sensor patches; ECG patches; Sweat sensors for hydration; Smart labels with printed logic; Smart diapers; Building leak detectors; Smart matt for baby care	Sports tracking with smart watches, textiles with printed tracks and sensor electrodes linked to phone; Digital medication adherence monitoring; Wearable textiles and patches with several measurement channels; Sweat-based sensors beyond electrolytes	Sensor patches with improved functionalities and wear comfort; Environmental sensors; Sensors for assisted living; Biosensors embedded in food packages; Breath analyzer for medical prevention	Connected ambient intelligence; smart floors and other building / interior surfaces; Printed wireless sensor labels; Patches with skin-like stretchability	

Emerging: In-mold electronics

Printed electronics foil molded into plastic parts

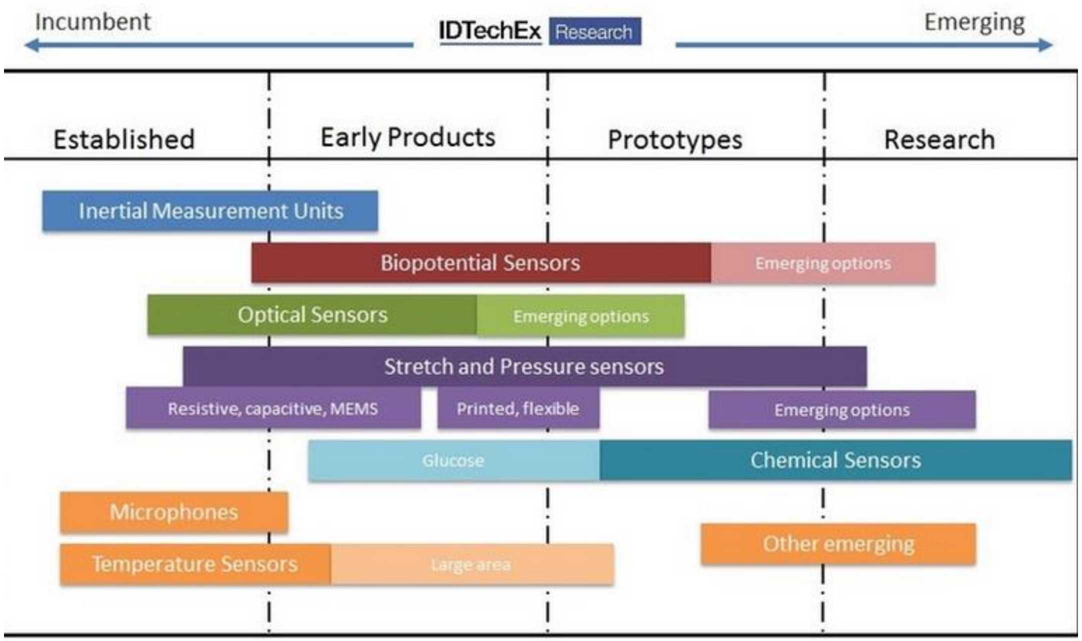
E2IP

Duratech

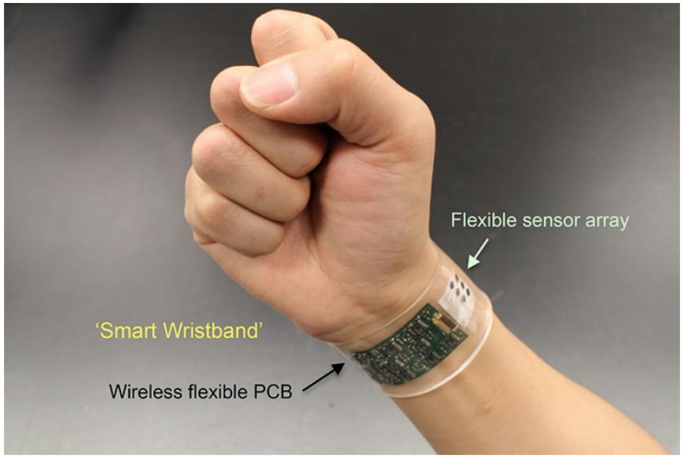
Canatu and Faurecia

Origo

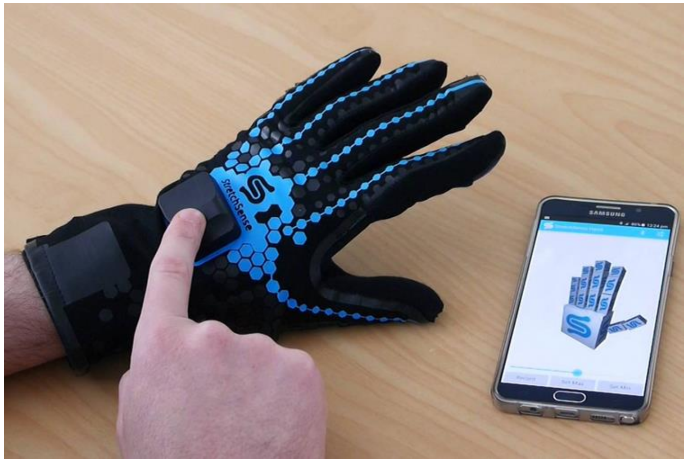
Emerging: Wearables



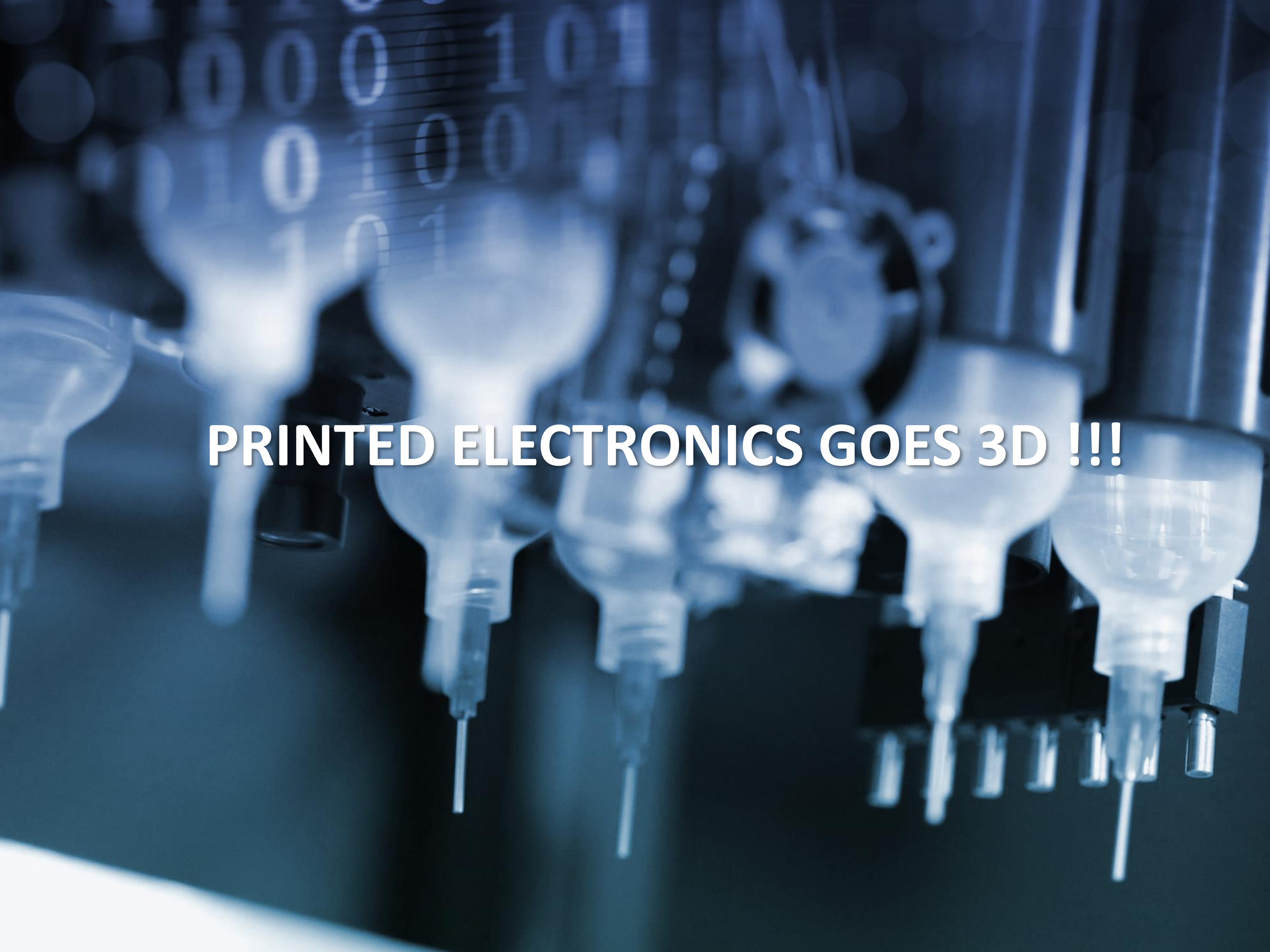
For more information, see the IDTechEx Research report:
Wearable Sensors 2015-2025: Market Forecasts, Technologies, Players
(www.IDTechEx.com/WTSensors)



UC Berkeley



Stretchsense


PRINTED ELECTRONICS GOES 3D !!!

Emerging: Hybrid 3D printing

```
G1 F9000
G92 E0 ;once more
G1 F1500 E-6.5 ;retract?
M400
M107
G0 F3600 X135.187 Y76.906 Z0.2
;START
M87 B9 D0 ; lower extruder head
;TYPE:SKIRT
G1 F1500 E0
G1 F900 X135.451 Y76.506 E0.01395
G1 X135.778 Y76.156 E0.02789
G1 X136.158 Y75.865 E0.04182
G1 X136.582 Y75.641 E0.05577
G1 X137.037 Y75.491 E0.06972
G1 X137.709 Y75.411 E0.08941
G1 X161.691 Y75.412 E0.78735
G1 X162.169 Y75.452 E0.80131
G1 X162.633 Y75.571 E0.81525
G1 X163.071 Y75.765 E0.82919
G1 X163.471 Y76.029 E0.84314
G1 X163.821 Y76.356 E0.85708
G1 X164.112 Y76.737 E0.87103
G1 X164.336 Y77.16 E0.88496
G1 X164.486 Y77.615 E0.8989
```

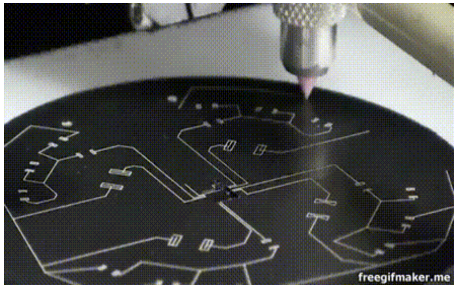
Digital Production File

Design of system with all parameters included

Additive manufacturing infrastructure

A set of computer driven tools

nScript



Printed electronic system

A system produced through additive manufacturing

Digital Manufacturing

CAD to part, Geometrical complexity, Fully automated, Multiple materials, Mask less, Minimal waste

- **Printing intelligence on and within objects and products**
- **In line with Industry 4.0 : digitalization and automation of manufacturing**
- **Personnalization and customization**
- **Strong interest for soft robots, wearables, implants, smart products…**

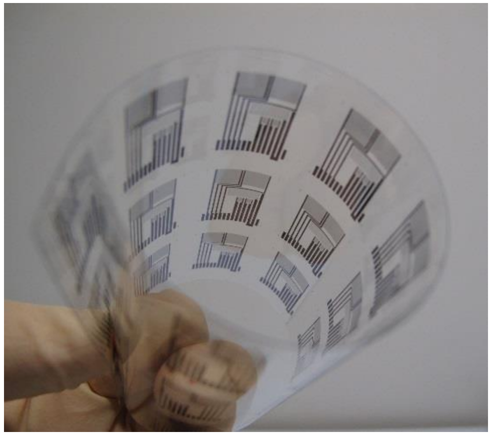
Digital 3D manufacturing platform

In this course on OPE we are focusing on:

- (Opto)-Electronics and Microsystems made on polymeric and cellulosic that can be potentially produced on large area and mechanically deformed.

Flexible / large area

- Electronics,
- Sensors,
- Actuators,
- Microsystems,
- Photonics.



Content

- Fundamentals,
- Organic electronic,
- Devices,
- Systems integration,
- Manufacturing,
- Applications.

Conclusions

- **Still intensive R&D efforts with in parallel industrialization taking place**

- **Large area and additive manufacturing can be applied also to other types of substrates and components**

- **Engineers needed for the industrial deployment of OPE**