Overview of intelligent solutions/functionalities and technologies behind them

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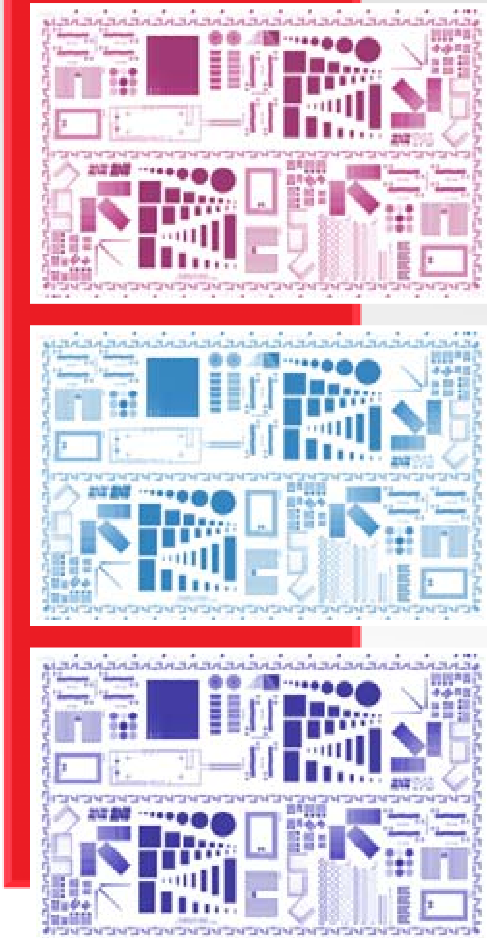
Program **Centra kompetence**

Program **Alfa**

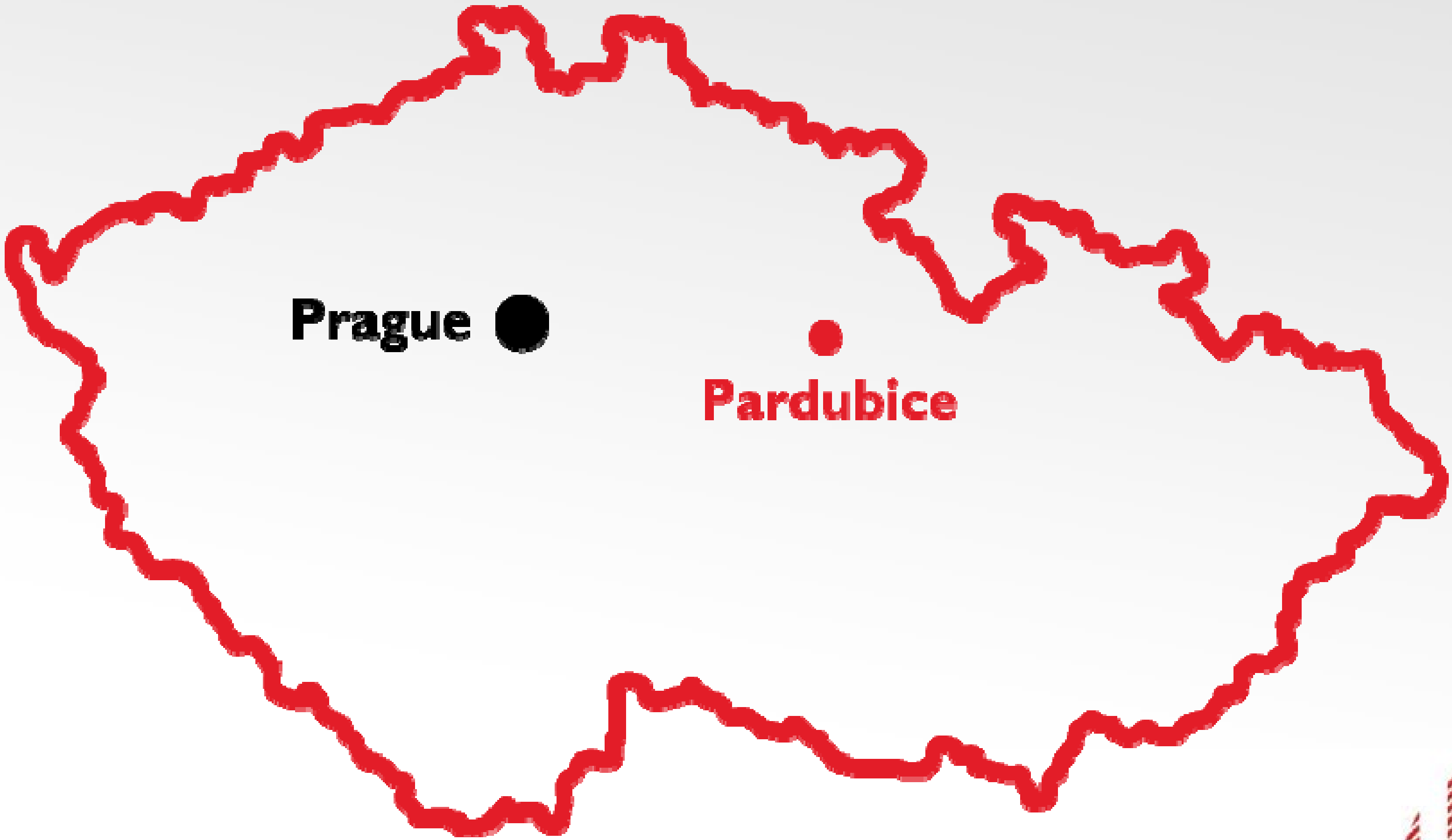
Agenda

- Interduction of R&D activities
- Challenges and aspects
  of printed/coated functionalities
- Materials
- Selected devices/functionalities
- Coating techniques
- Printing techniques
- Drying/Sintering techniques
- Conclusion



Syrovy

Pardubice



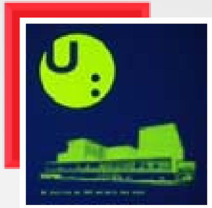
University of Pardubice

- 1950 – Institute of Chemistry
- 1994 – University of Pardubice
- 2014 – 7 Faculties
  - Jan Perner Transport Faculty
  - Faculty of Economics and Administration
  - Faculty of Electrical Engineering and Informatics
  - Faculty of Arts and Philosophy
  - Faculty of Chemical Technology
  - Faculty of Restoration
  - Faculty of Health Studies
- www.upce.cz

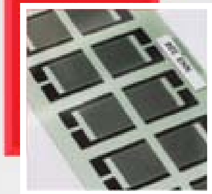
Department of graphic arts and photophysics

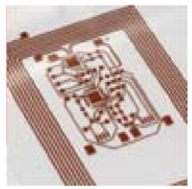
- 1984 – Founded
- 2013 – 170 students
- 10 academicals, 2 researchers, 6 lab. and admin. stuff
- The only department in the Czech Republic providing university studies, research, and testing in the whole field of printing
- Close cooperation with the industry
- Member of IARIGAI, IC (of Educational Institutes for Graphic Arts Technology and Management), OE-A

R&D activities

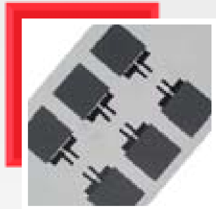


- Simple functional layers
  - Antistatic, Antimicrobial, Security Luminescent, Photochromic



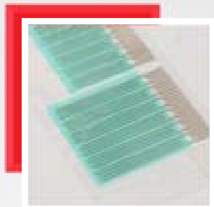


- Passive components
  - Resistors
  - Capacitors, Coils
  - Etc.



- OECT, OFET
- Printed batteries
  - Alkaline, Li-on

- Sensors
  - Temperature s.
  - Rel. humidity s.
  - Gas s.
  - Air/Gas flow s.
  - Acceleration s.
  - Tactile s.
  - Light s.



- Display elements
  - LEC, OLED
  - Electrochromic

- Smart Labels

With NFC communication over Android devices

- Experiences
  - R&D of Inks & printing/coating technology process
  - Upscaling, Lab2Fab experineces incl. Wide Web
- Core Projects - TE01020022 www.flexprint.cz

TA04010085 - Flexible autonomous energy harvesting systems for smart textiles

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R&D activities, printing/coating techniques competency

- R&D of technology of preparation of functional structures
- R&D of ink formulation and benchmarking of comercial ink formulation
- Personally 400-800 mixed/tested ink formulations per year for several type of printing/coating techniques and applications

- Screen printing (Sheet fed, R2R)
- Flexo
- Gravure
- Pad printing
- Offset
- IJ

- Spin coating
- Dip coating
- Spiral bar coating
- Spray coating
- Zone casting
- AJP

- Negative patterning – lasers – UV/VIS, NIR, IR

- Lab2Fab experiences
- Narrow web (410 mm), Wideweb production trials, pilot plant trials incl. high speed materiál printing (1.3 m, 320 m/min)

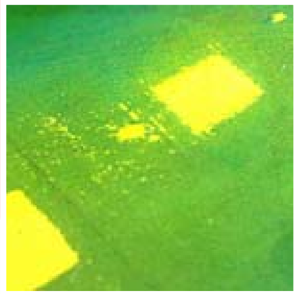
Why coating and printing technologies?

- The printing and coating techniques should provide cheap and fast production of low cost and low-end functionalities
- Printed/coated functionalities are sometimes tens years behind to products made by traditional technologies in terms of their characteristics

SOMA

Differences to conventional coating/printing process?

- Safety - printing materials, fabrication process
- Printing/coating materials, printing substrates
- Printing forms
- Interaction of materials
- Strict observance of technology
- Printing/coating process quality/stability
- Post treatment condition
- Storing of the products
- Long term stability
- Never-ending and limitless opportunities to use or characterize anything



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(NASA)

Printed/coated functionalities

Active components/structures

- Battery (primary, secondary)
- Battery Charger
- Photovoltaic – PV – (OPV, DSSC)
- Display, Light source – OLED, EL, electrochromic, thermochromic, electroforetic
- Sensor – chemical,
  bio, climatic, pressure, etc.
- Memory
- RFID
- diodes
- Transistors – OFET, OECT
- ISS – Smart Objects, Smart Sensor, Smart Textiles

Passive components

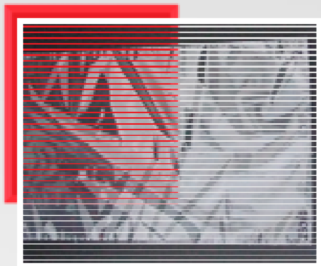
- Electronic circuits
- Antennas – RFID
- Capacitors, resistors, induction coil, transformers

Functional layers

- Healtcare aplication
- Drugs
- Termochromic, photochromic
- Catalytic layer
- Textile finishing layers
- Explosives

Simple functional layers

- Antistatic
- Antimicrobial
- Barrier
- UV protective
- Luminescent
- Thermochromic
- Photochromic
- Electromagnetic shielding



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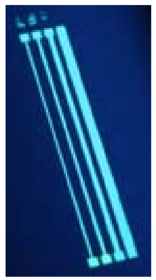
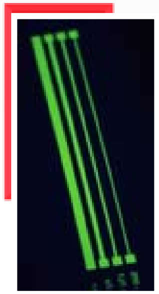
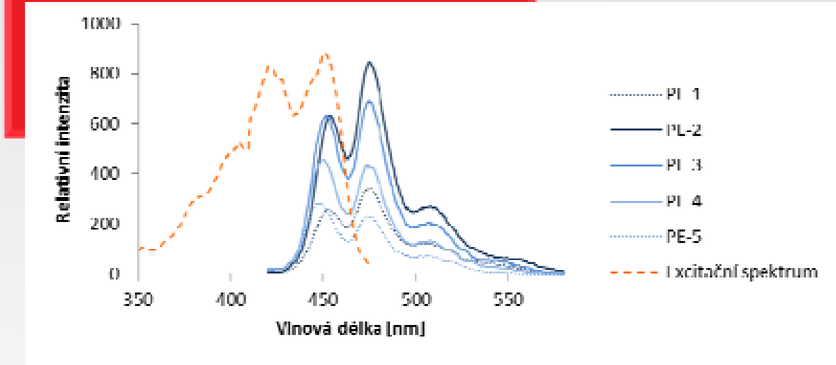
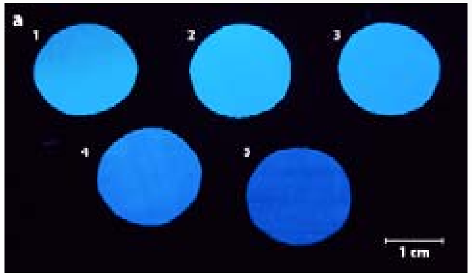


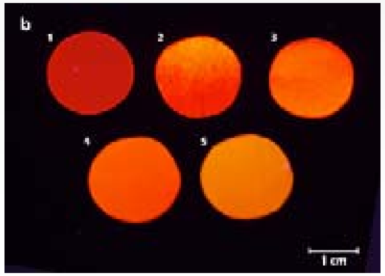


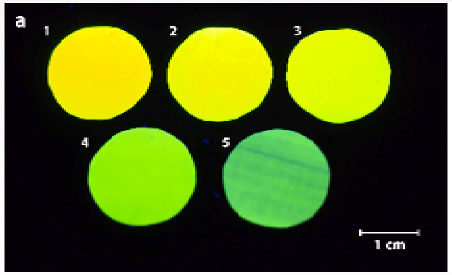
Luminiscent materials

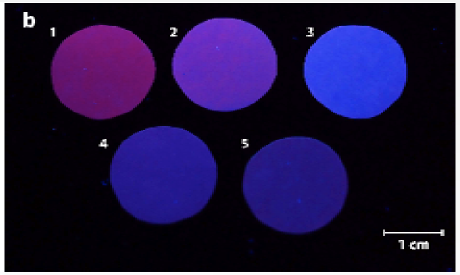
- R&D of specific effect layers
  - Fluorescencent

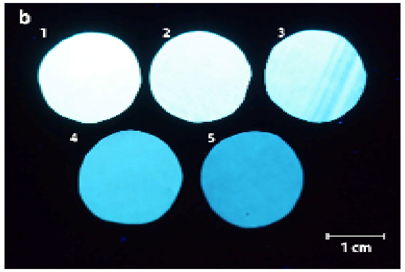




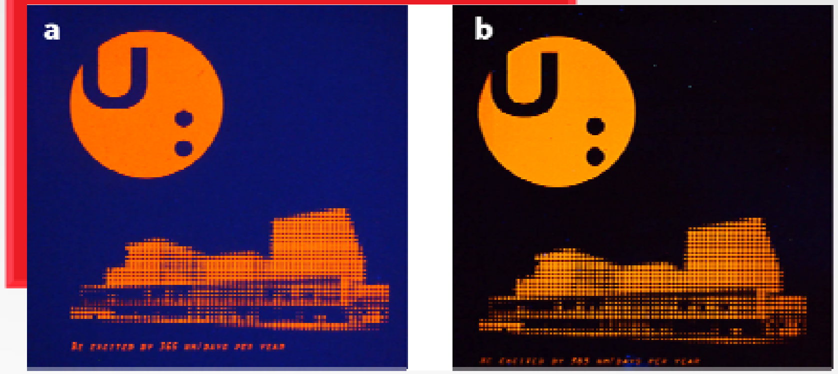


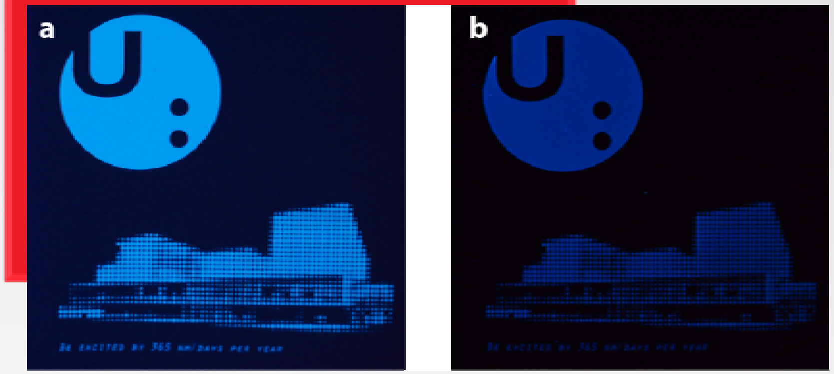


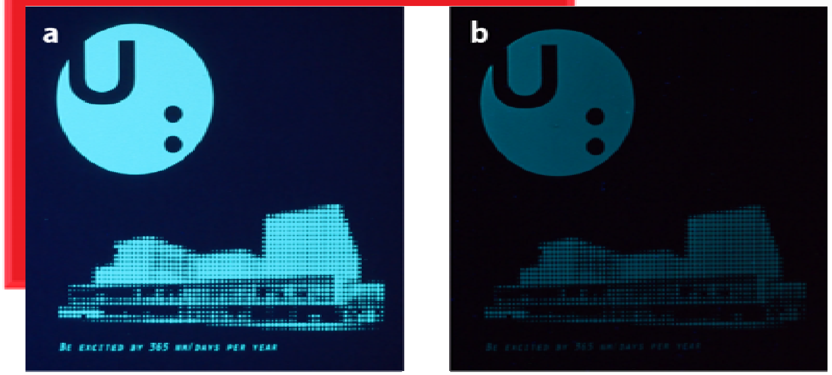


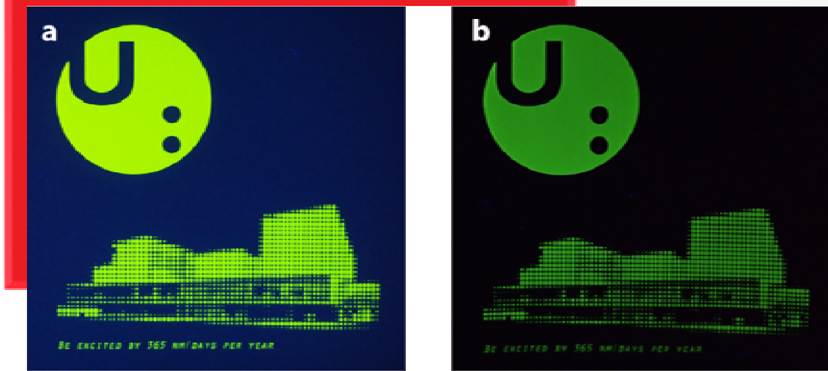


Luminiscent materials - Fluorescence



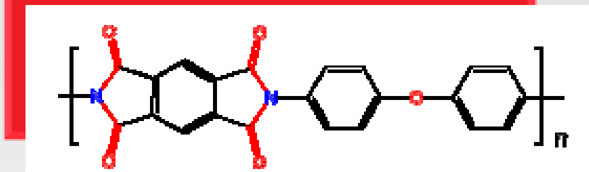




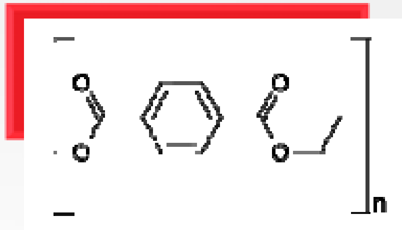


Substrates for printed functionalities/electronics

- **Flexible**
  - PET, PEN, PI (Kapton, Neopulim), PC, PVC
  - Polyolefins - PE, PP
  - Synthetic papers – Pretex (PES/PA), Synaps (PES), Tyvek (HDPE), Teslin (polyolefin)
  - Paper – un/coated paper, primer
  - Nanocellulose
  - Glass – 25 to 100 µm
  - Metals
- **Rigid**
  - Paper - heavy ream weight
  - Cardboard
  - Thick polymeric susbtrate (PET, PEN, PI, PC, PE, PP, etc.)
  - Glass – float, quartz, etc.
  - Ceramic – Al_2O_3 (Rubalit, Alunit), AlN, etc.
  - Metals



Polyimide

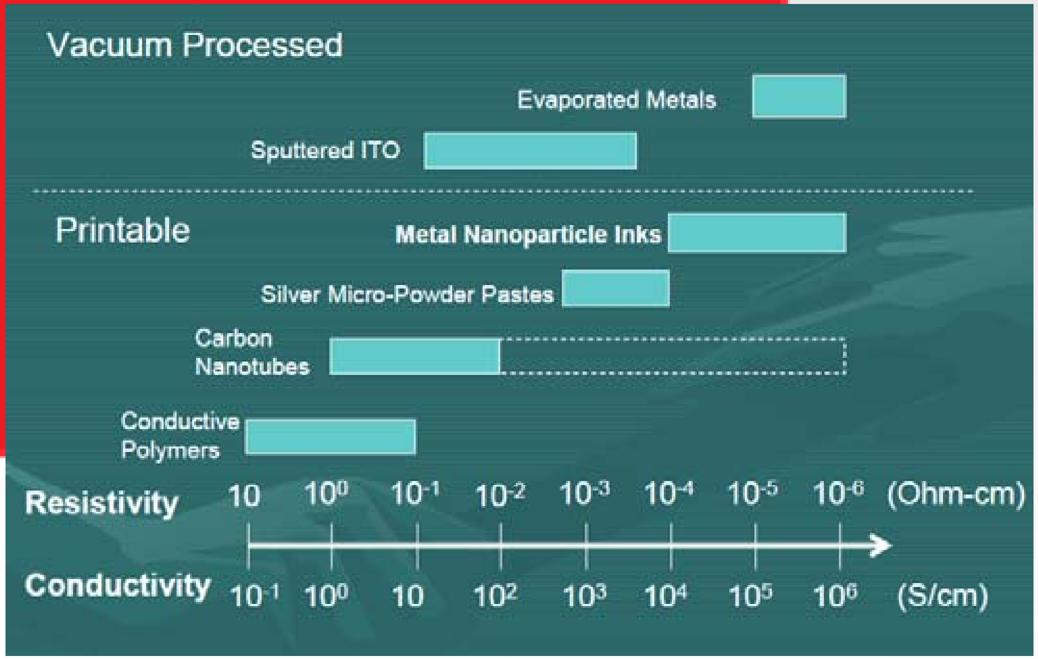


PET

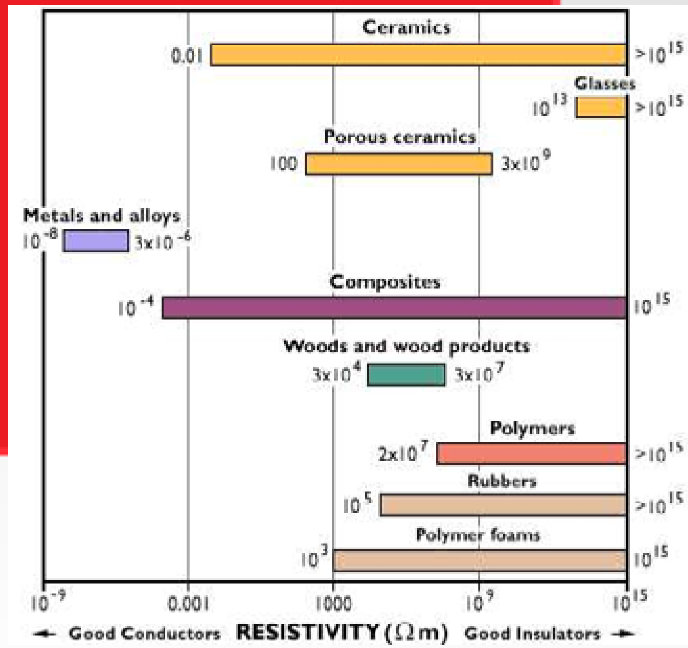
Ultra-Thin Glass - SCHOTT

CeramTec

Materials for printed/coated structures



Yang

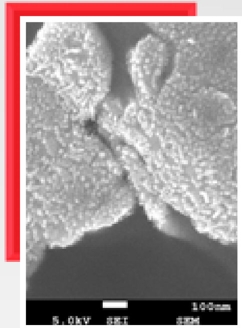
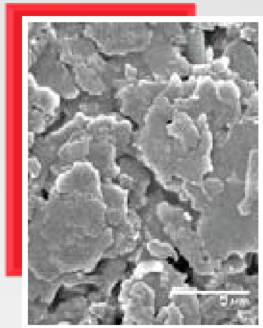
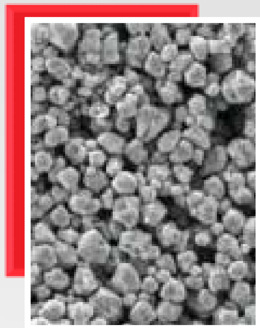


www.lehigh.edu

Materials for printed/coated structures

- Conductive
  - Metal composite – based on (Ag, Cu, Au, Ni, Pt, etc.)
    - Different shape and sizes of particles (globular, flakes, rods, wires)
    - Ag based most used
      - Up to 30 % of conductivity of bulk Ag
    - Cu – usually based on precursors CuO
      - Photonic sintering, reduction agents
    - Other metal for specific purposes
  - High temperature firing – Ag, Au, Pt, etc.
  - Precursors of metals

  - Carbon composite (graphite, carbon black, etc.)
  - Carbon based (graphene, GNP CNT (SWCNT, MWCNT))

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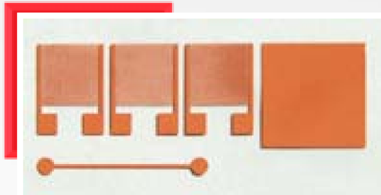
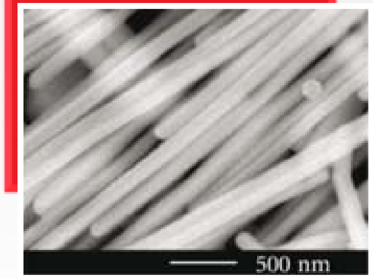
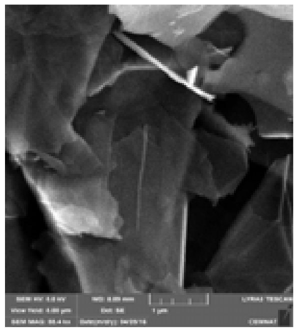




Zhu et All.



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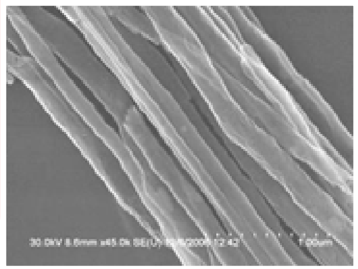
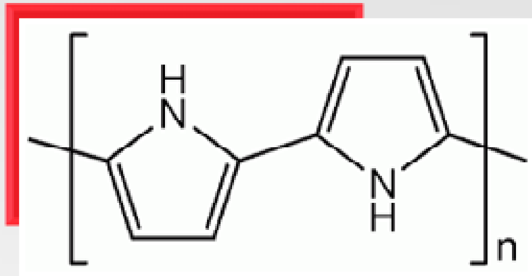


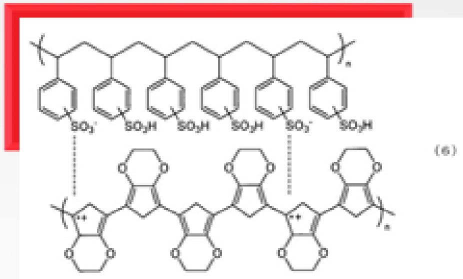
mntl.illinois.edu

Materials for printed/coated structures - (Semi)conductive

- Polymers
  - PEDOT:PSS – (in-situ 3000 S/cm, disp. 1000 S/cm)
  - Polyaniline
  - Polyacetylene
  - Polypyrrole
  - Polythiofene
  - MEH-PPV
  - PVK, etc.

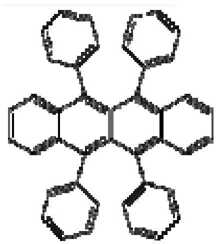


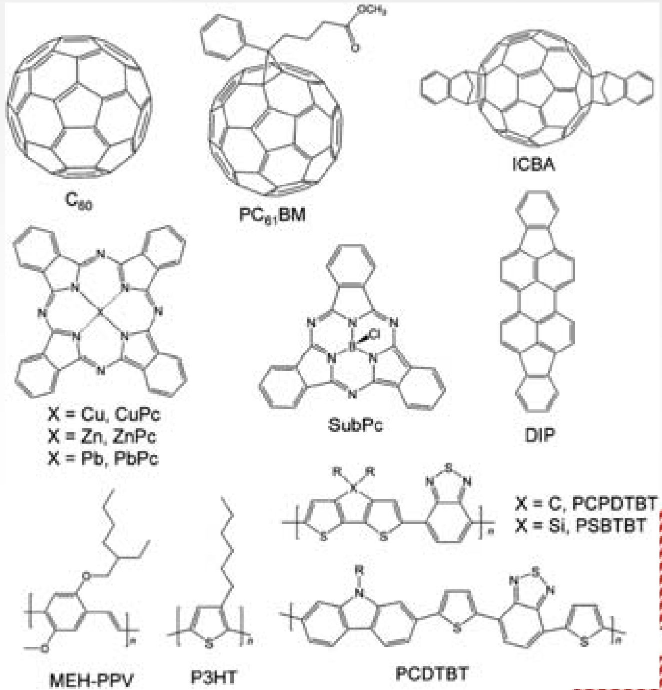
polypyrrole



PEDOT:PSS

- Small molecules
  - TIPS - Pentacene
  - Rubrene
  - Phtalocyanines
  - Diketopyrrolopyrrole
  - Perylenes
  - Alq3, NPD, TPD, Ru cpx
  - Some others
  - Fullerenes



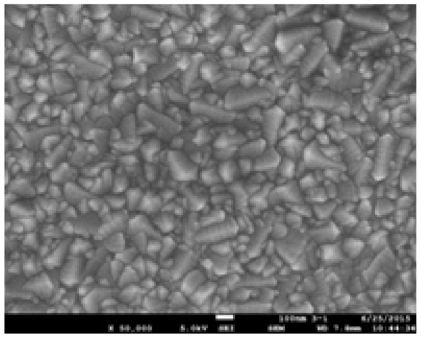


2014, Xue et Al.

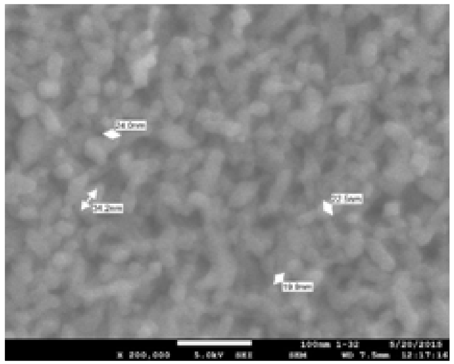
Materials for printed/coated structures - semiconductive

- Inorganic semiconductors
  - ZnO, ZnS, As_2S_3, TiO_2, WO_3, MoO_3, etc.
  - Si dispersions
  - **TCO**
    - Sn doped oxide s ITO, FTO, ATO
    - Zinc doped oxide AZO, GZO
    - Mainly as a transparent conductors
    - Prepared by sol-gel, nanoparticles ink, CVD

ITO/PET
www.opticalfiltersusa.com/



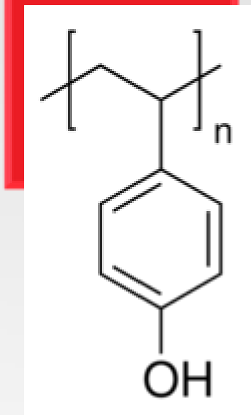
ITO



TiO_2

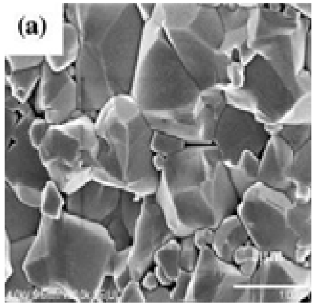
Materials for printed/coated structures - dielectrics

- Polymer based
  - From solution/dispersion of various polymers
    - PVC (ε' ~ 3)
    - PC (ε' ~ 2.8 – 3.4)
    - PVDF (ε' ~ 6)
    - PMMA (ε' ~ 3)
  - Radiation induced polymerization (UV, EB) (Acrylate based (ε' ~ 3))
  - Thermally induced polymerization (PVP, acrylates with proper iniciators)



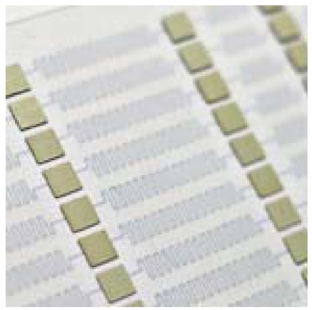
Poly(4-vinylphenol)

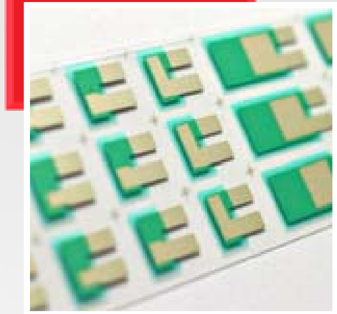
- Composites
  - Based on particles of inorganic materials with high dielectric constant
    - $BaTiO_3$ (ε' ~ 1000)
    - $SrTiO_3$ (ε' ~ 300)
    - TiO_2 (ε' ~ 100)
    - Al_2O_3, MgO (ε' ~ 9)
    - HfO_2 (ε' ~ 20)

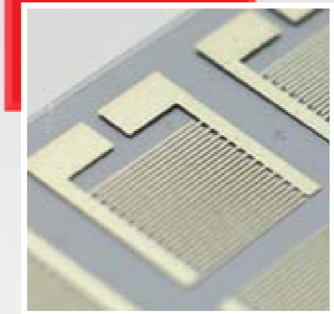


Kharisov et Al.

Passive electronic components







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Resistors

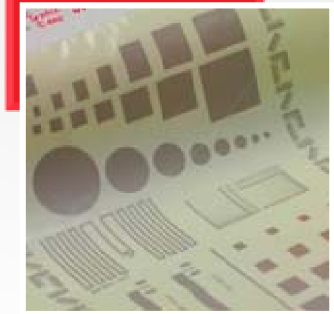
Capacitors

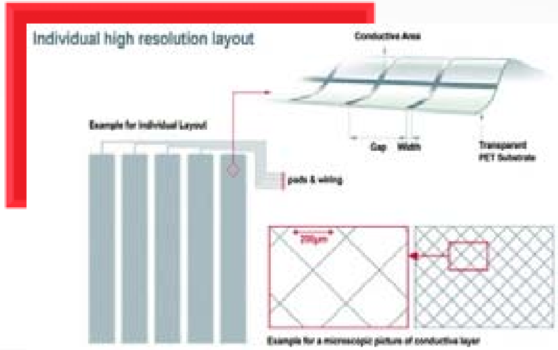
Circuits and conductive structures

Transparent conductive electrode

- (Semi)conductive polymers
- CNT, graphene based layers
- Metals nanowires layers
- high-resolution conductive metal (metal mesh)

Syrovy

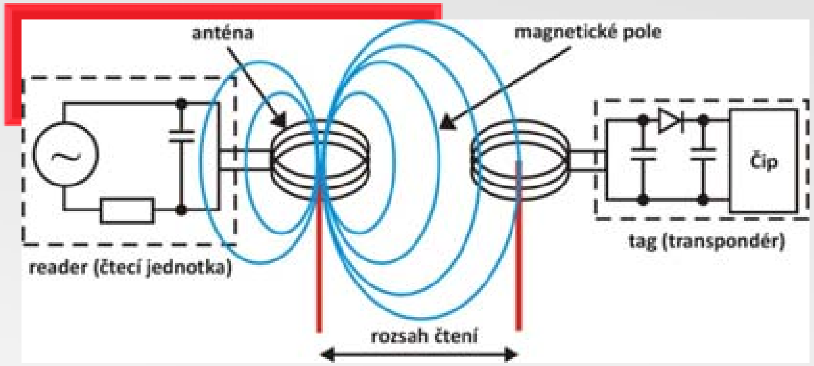




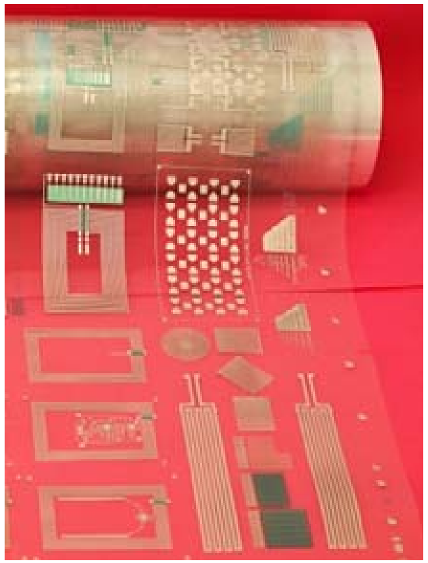
PolyIC

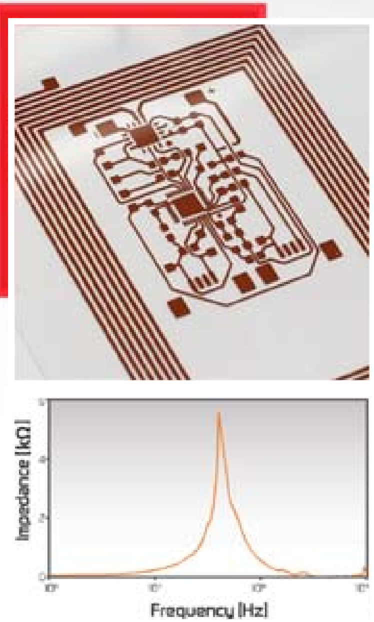
RFID

- RFID (Radio Frequency Identification) – system which through the radio-frequency electromagnetic fields transfer data, usually for the automatic identification and tracking tags attached to objects.
- The datas are stored inside tag. These datas is possible to read or rewrite in dependance to type od tag.
- Every TAG has an unique EPC.
- Implementation of RFID requires except tag, readers and „middleware" (Central systém for data exchange, storing, it is gate to MIS)



(Hrachovcová)





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RFID – type of TAGs

Active TAG

- Battery is a main source of the energy, which limit lifecycle.
- This type of TAG is usually equiped by MCU, sensors, I/O ports.
- It is used for more advance type of aplication – ISS. Usually has a higher price due to more complicated production than for passive tags.
- Tag start the communication as a first, followed by response of reader, peridodically transmits its ID signal.
- The active tags are used for identification, localization of fast moving object too.
- The read distance is in range of hundreds meters.

Semi-active TAG

- For transfer of datas use energy emmited by readers. Communication is activated by reades, the battery source is used for data transfer to higher distances.
- The read distance is in range of tens of meters (UHF, MW).
- Identification, localization of fast moving object.
- Longer lifecycle than for active tag.

RFID – type of TAGs

Passive TAG

- The communication starts reader.
- Energy for communication is obtained from electromagnetic filed generated by reader.
- Low cost, more simple structure, durability and resistance to extreme condition (temperature to 200 °C, acids, bases)
- The passive tag consist from antenna and chip. At higher frequencies there are difficulties with interferences and identification close to metals and liquids.
- The passive tags are cheaper and smaller in comparison to active tags.
- Usability –logistics (material flow), personal ID cards, passports, credit cards, identification of vehicles, animals, books in libbraries

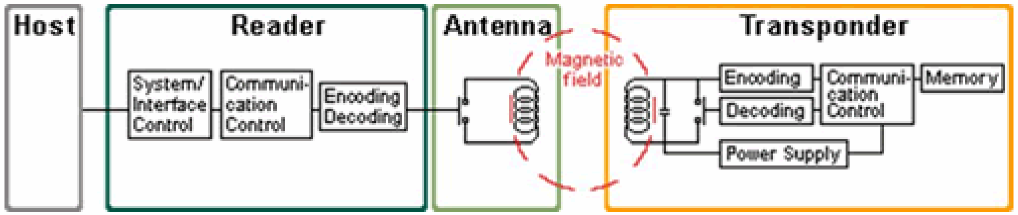


Figure 1. RFID System--Reader/Writer, Antenna, Tag

2012, Schmoldt

RFID – Frequencies

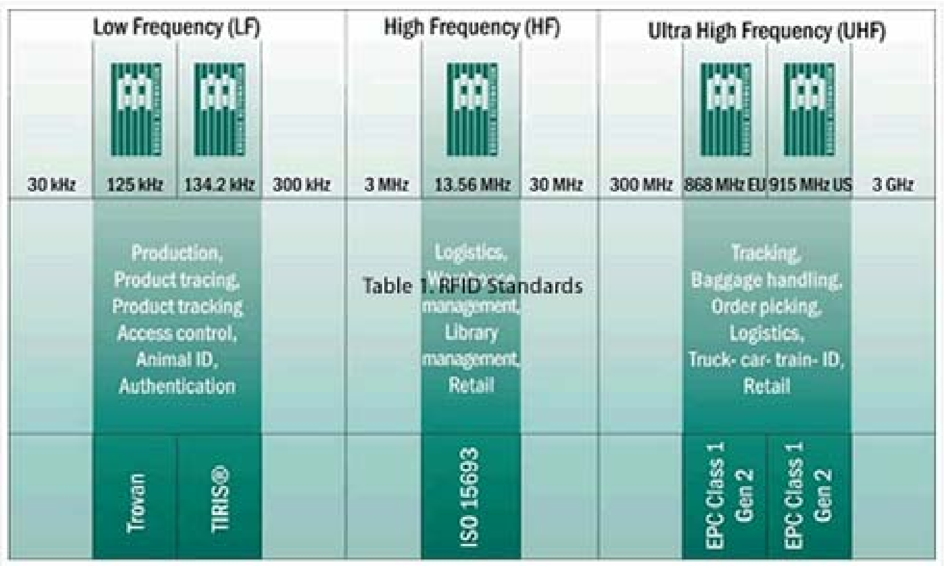


Table 1. RFID Standards

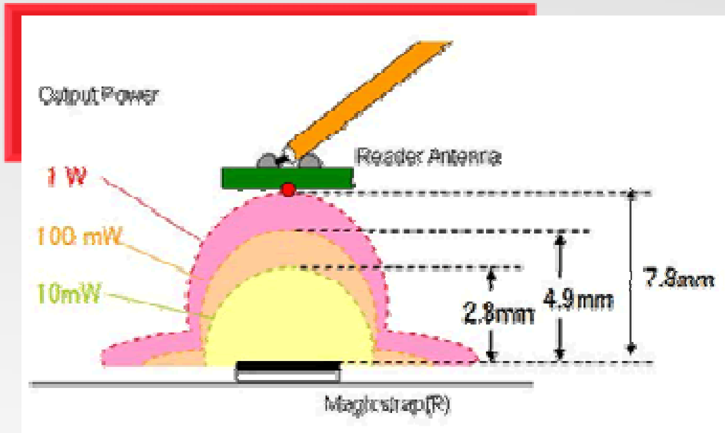


Figure 4. Output Power versus Read Range

2012, Schmoldt

- Read distance – Induction (Near Field Comunication), reflection (Far Field)
- Memory - Tag RO (Read-Only), Tag WORM (Write Once Read Many), Tag RW (Read-Write)
- Class – according abilities, Class 0 - 5

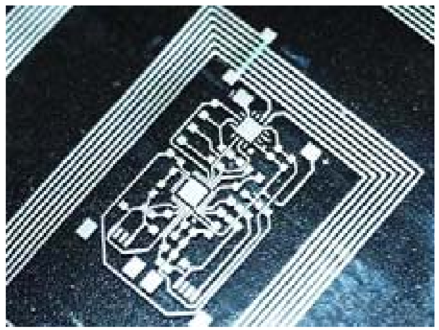
RFID - Frequencies

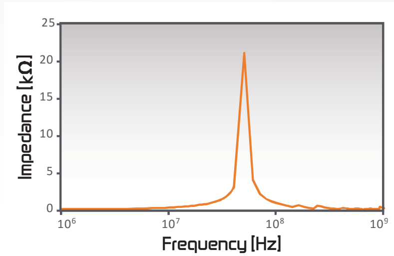
Low Frequency 125 a 135 KHz LF Tag	- Read distance up to 0,5 m, low communication speed
	- High cost of production
	- no difficult to read when placed within a few millimetres of a metal or liquid surface
	- ID card, animals identification
High Frequency 13,56 MHz HF Tag	- Read distance up to 1 m, moderate communication speed
	- High cost of production
	- Difficulties with reading through the liquid
	- logistics, identification of goods
Ultra High Frequency 868 MHz UHF Tag	- Read distance up to 3 m, high communication speed
	- Low cost production
	- Difficulties with reading through the liquid and metals
Microwave 2,45 a 5,8 GHz MW Tag	- Read distance up to 10 m
	- identification of fast moving objects
	- High cost of tag

RFID – Production

- Etching Cu, Al (18 – 35 µm)
- Galvanic metallization of vacum evaporated/sputtered structures
- Laser ablation – negative patterning
- Printing technique
  - Silver, copper (precursor) based inks
  - Screen printing – the most used
  - Gravure
  - Flexography

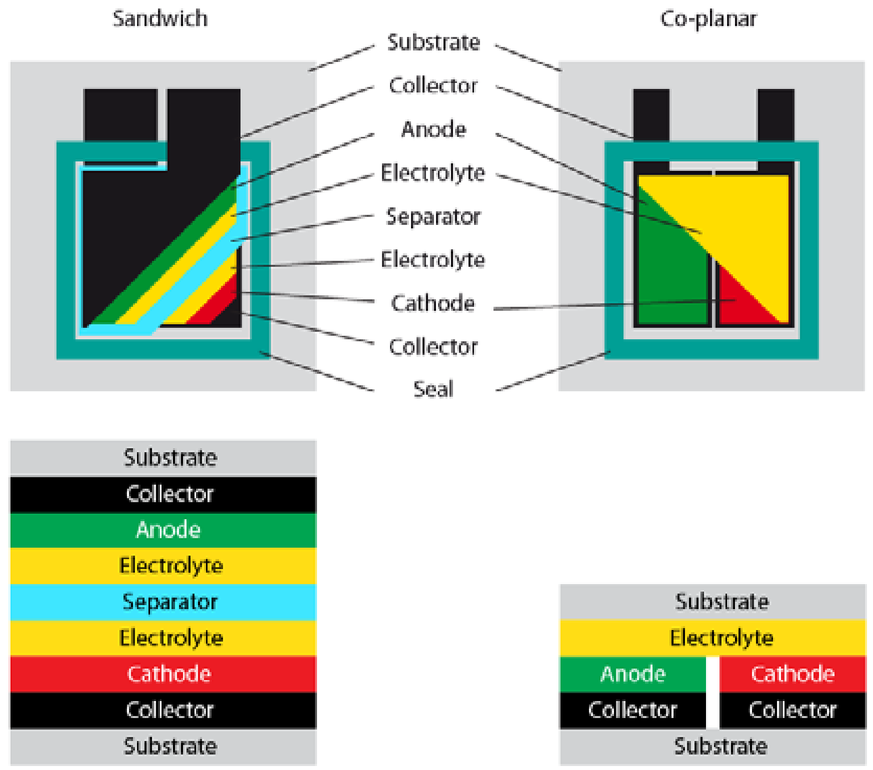
OTK Group





Printed batteries

- Based on typical materials and chemistry as for conventional batteries
- Flexible, Thin - usually below 1 mm
- R2R compatible production process
- Capacity in range of tens of mAh
- Voltage in dependence to electrode materials and electrolytes
- Basic patrameters – Nominal Voltage, Capacity, short-circuit current, UI characteristics
- For device with low consumption of electrical energy < 1 mW
- Usage – ISS, RFID, sensors, chip cards, etc.



Syrovy

Printed baterries, accumulators - materials

Primary

- Zn/MnO_2 Zn + 2MnO + H_2O ZnO+ 2MnO(OH)
- Electrolyte $ZnCl_2$, NH_4Cl, KOH, NaOH, thickener (PEO, CMC, HEC)
- 3V battery

Enfucell	10 mAh@4 mAh/cm^2
Fraunhofer ENAS	8 mAh@1 mAh/cm^2
Blue Spark	5 mAh @ -- mAh/cm^2
Flexprint	11 mAh@1.7 mAh/cm^2

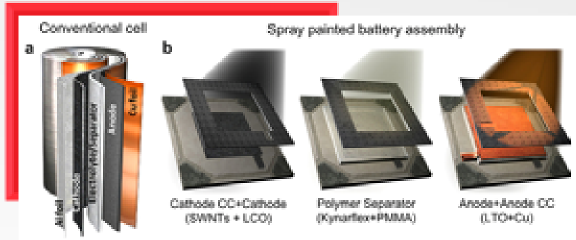
- Zn/Ag_2O Zn + Ag_2O → 2 Ag + ZnO

Rechargeable

- Lipol battery
  Anode $LiCoO_2$, $LiMn_2O_4$, cathode Li,
  electrolyte Li salt + polyethylene oxide
  $Li_{1-x}CoO_2 + x\,Li^+ + x\,e^- \rightarrow LiCoO_2$
- All-solid polymer lithium (ITSUBO/Hatanaka),
  45 mAh, operation voltage 1.8 V
- Nickel metal hydride
  Alloy(H)+ 2 NiOOH → Alloy + 2 $Ni(OH)_2$
- Varta 32 mAh

Blue Spark

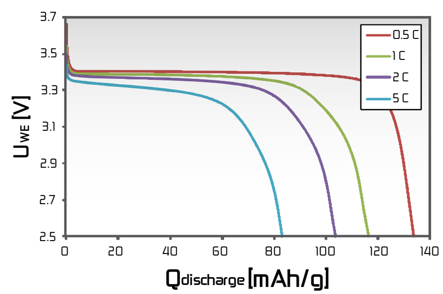
Syrovy. Fraunhofer ENAS



(Singh at Al.)

ITSUBO

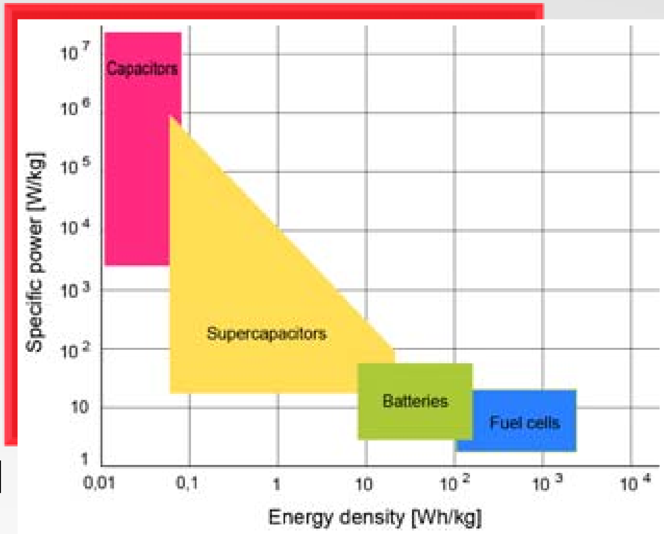
Varta



Syrovy

Supercapacitors, Hybrid capacitors

- Charge/discharge current is in range 1-100 A.
- Very low value of internal resistance
- 10 times higher energy density in comparison to clasic capacitors.
- Charging time is in orders shorter to batteries.
- Capacity is directly proportional to the area and inversely proportional to the distance between the electrodes
- Capacity is given by electrodes materials too.
- Usability – ISS, RFID, sensors, chipcards, etc.
- Basic patrameters – Nominal Voltage, Capacity, short-circuit current, UI characteristics

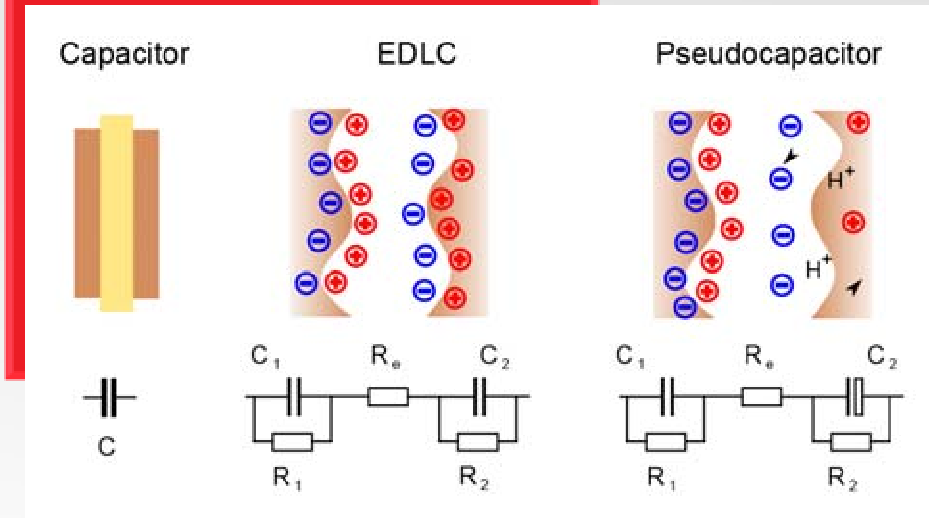


Dvorak

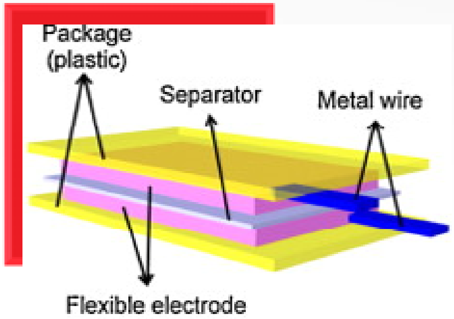
Parameter	Batteries	Capacitors	Supercapacitors
Energy density [Wh/kg]	100	0,2	10
Specific power [kW/kg]	1-3	500	10
Charging time	5 h	0,001 s	10 s
Life cycle	100	1 000 000	1 000 000

Storage principles

- Pseudocapacitance storage of the electrical energy based on reversible redox reactions with charge-transfer.
- EDLC (Electric Double Layer Capacitor) Based on separation of charge in a Helmholtz double layer.



Dvořák



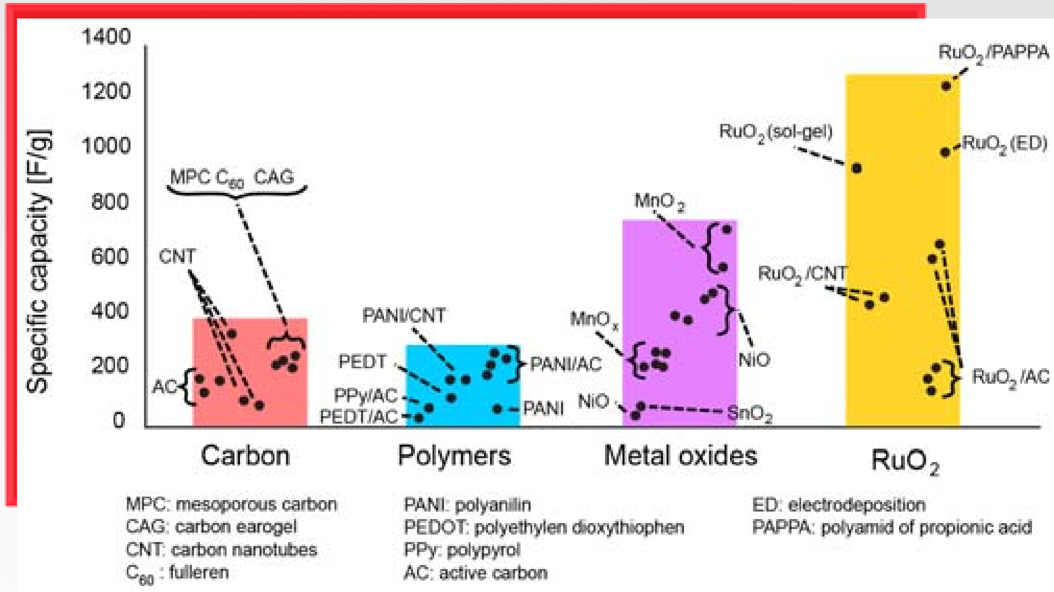
ScienceDirect

Syrovy

Electrode materials, electrolytes

Electrode materials

- Carbon based materials with large specific surface (> 1000 m^2/g)
- (Semi)conductive polymers
- Metal oxides



Dvořák

Electrolytes

- Water based solution of acids (H_2SO_4. H_3PO_4), bases (KOH) and salts ($NaClO_4$, $LiClO_4$, $LiAsF_6$)
- High specific conductivity (100-1000 mS/cm), Low operation window ~ 1 V per electrode, low operation temperature.
- Organic solvents – the most often solvents are propylene carbonate, ethylene carbonate, tetrahydrofuran, diethyl carbonate, γ-butyrolactone. Salts - $LiClO_4$, Et_4NPF_6, Bu_4NPF_6.
- An advantage of organic solvents is higher operation voltage (up to 4 V). The electrical conductivity of electrolytes based on organic solvents is lower (10 to 60 mS/cm). Energy density increases with the square of the voltage.

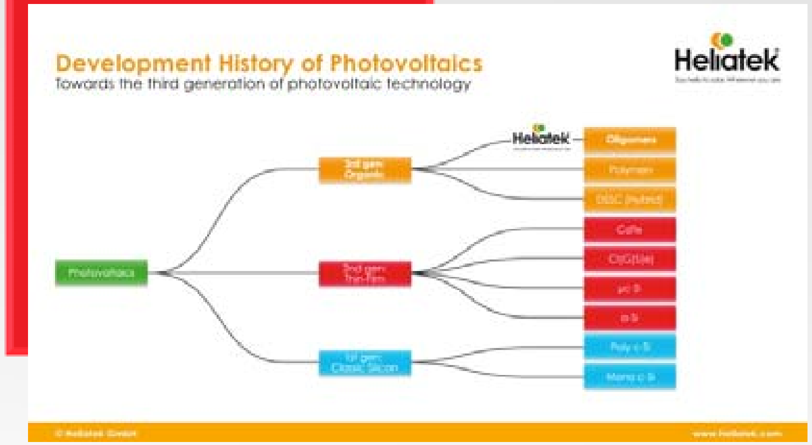
Photovoltaic cells

DSSC

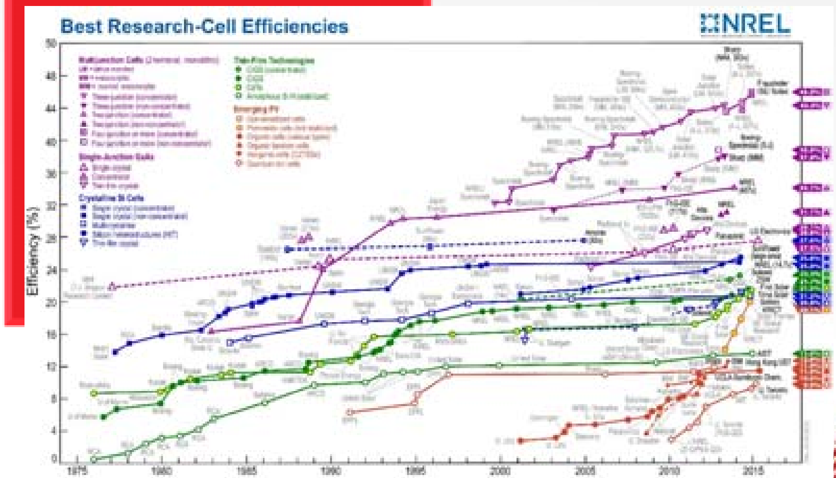
- „Grätzel cell" – 1991
- High efficiency up to 12 %
- 2014 DSSC with perovskite up to 20.5 %

OPV

- Commercial avaiable from 2009 with Wp 1 – 28 W
- Efficiency at 12 % is comparable with 15 % for conventional Si panels
- Integration of OPV from 2010



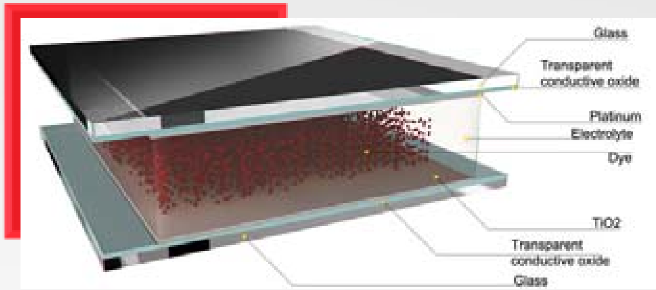
Heliatek

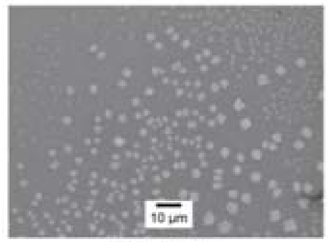


NREL

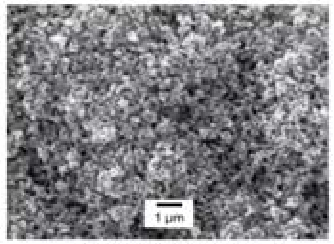
DSSC - materials

- Photoelectrode TiO_2, ZnO, Fe_2O_3, ZrO_2, Nb_2O_5, Al_2O_3, CeO_2, $SrTiO_3$, Zn_2SnO_4
  - Shapes of particles - globular, microsheets, nanorods, nanotubes, nanorods
- Sensibilizing dyes
  - Bipyridyl ruthenium complex
- Counter electrode
  - Platinum (H_2PtCl_6)
  - Carbon based (graphite, CNT)
  - (Semi)conductive polymers
- Electrolytes
  - Liquid, gel, solid state
  - redox systems I^-/I_3^-, Br^-/Br_3^-, SCN^-/SCN_2^-, $SeCN^-/SeCN_2^-$, 1-hexyl-3-methylimidazolium iodide
  - Acetonitrile, propionitrile, methoxyacetonitrile, NMP, EG, etc.
  - polyethylene glycol (PEG), 1,3:2,4-di-O-dimethylbenzylidene-D-sorbitol (DBS), poly(acrylic acid)-poly(ethylene glycol) (PEG-PAA), polyvinylpyridine (PVP), polyacrylonitrile (PAN)

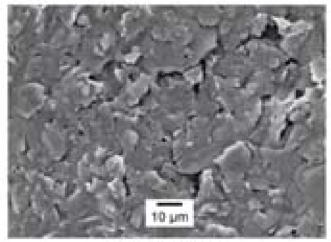




e) Pt layer 1000 ×



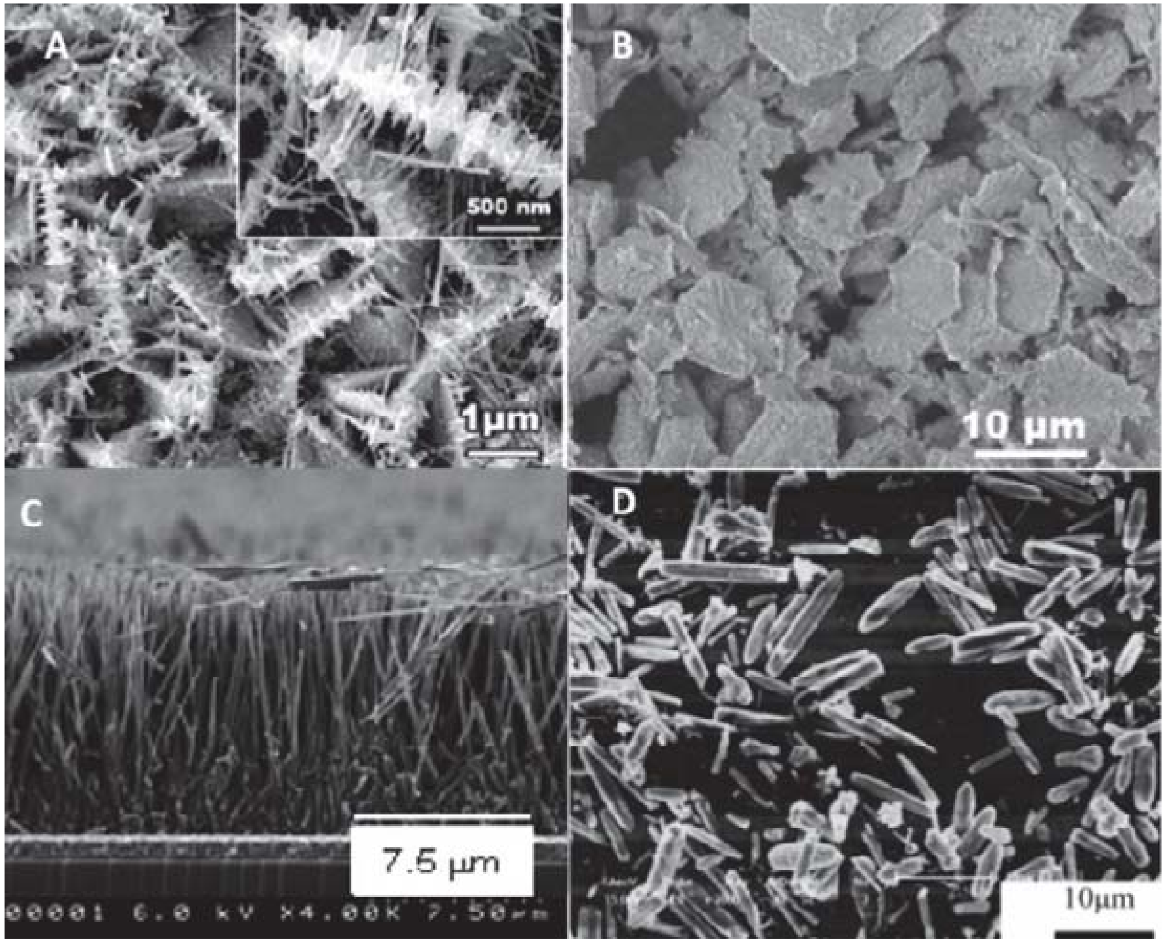
b) TiO_2 4 layers (21 nm) 10000 ×



c) C layer 1000 ×

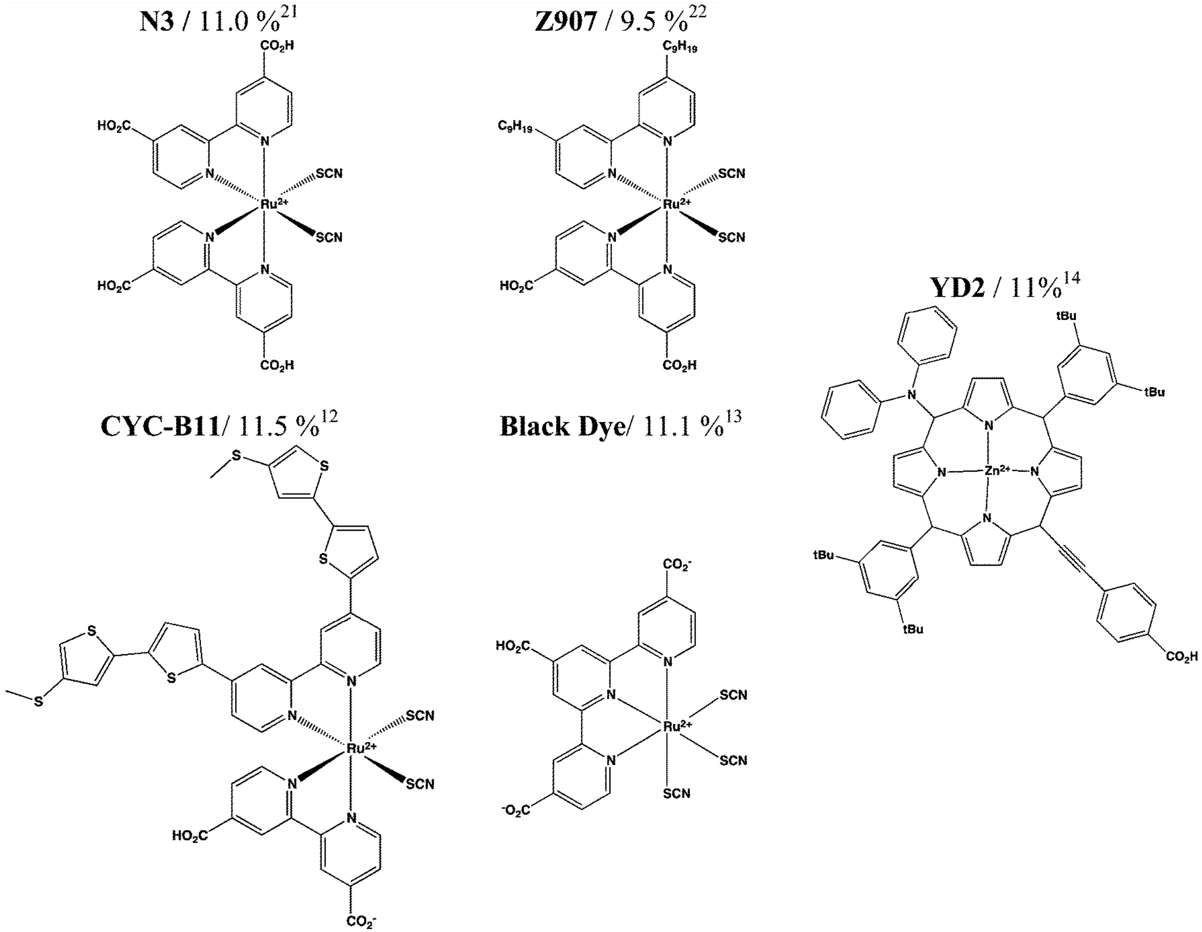
Syrový et Al.

Photoelectrode

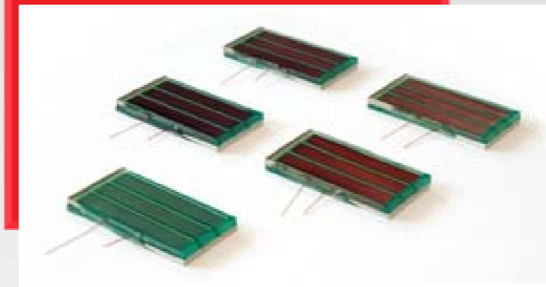


Xu et al., 2010;
Wang et al., 2010;
Gao et al., 2007;
Pang et al., 2007

Sensibilizing dyes



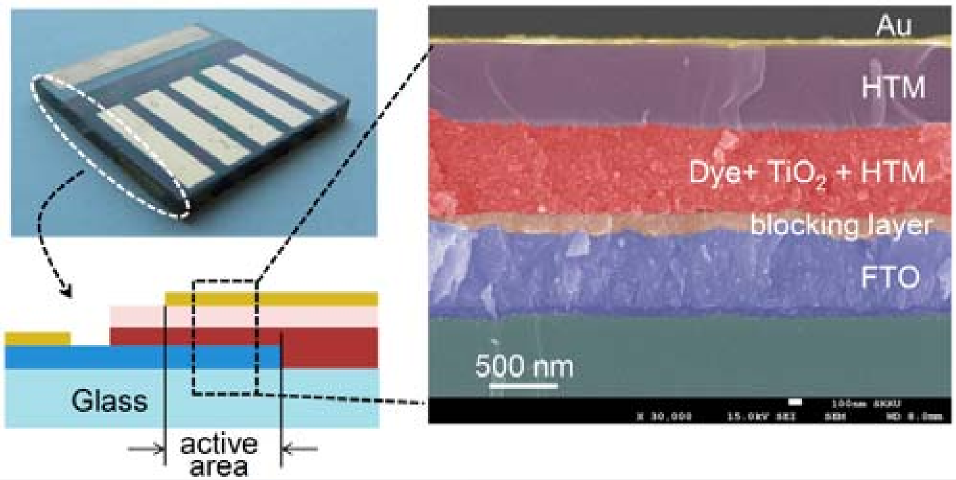
Le Bahers et Al.



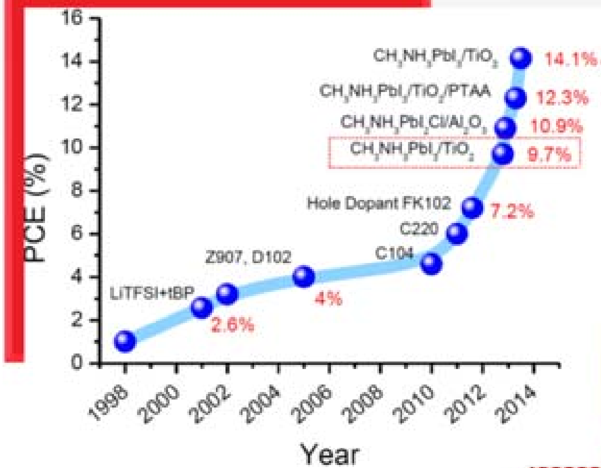
Hatala, Syrovy

DSSC with perovskite

- In 2009 3.8% efficiency
- Based on TiO_2, Al_2O_3 photoelectrode
- Perovskite acting not only as a light absorber, but as a charge-carrying semiconductor
- Organometal halides $CH_3NH_3PbI_3$ with perovskite structure
- efficiency approaching 20% is realistically possible from a solid-state mesoscopic solar cell based on CH3NH3PbX3
- In tandem cells with silicon based panel efficiencies should be expected 30% or more
- Extremely sensitive to oxygen, water vapor dissolves the salt like perovskites

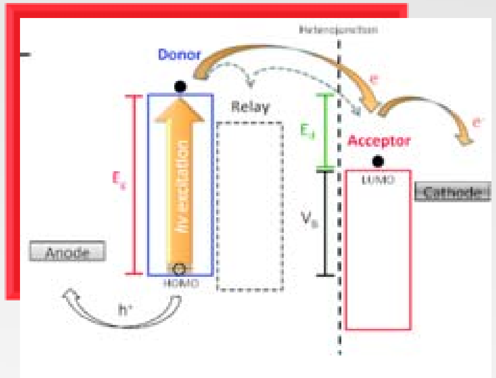


Park

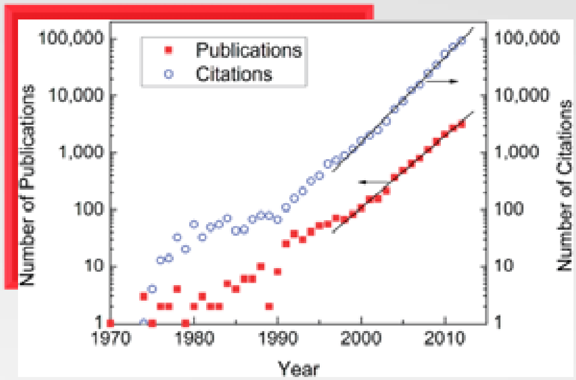


OPV

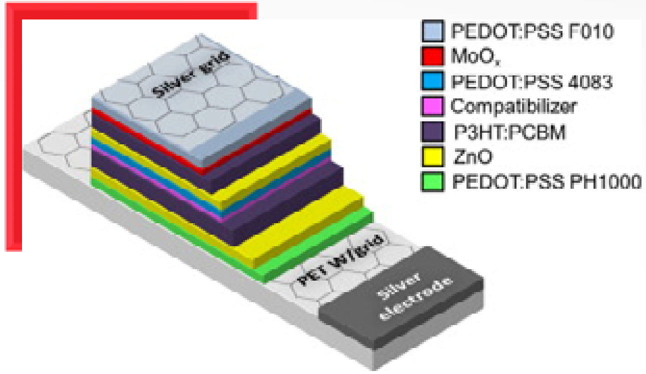
- Based on p-conjugated small molecules or polymers
- Typical energy gaps of 1 to 3 eV between LUMO and HOMO
- Power conversion efficiency (PCE, ηP) has steadily increased over the years from about 6% to 14%



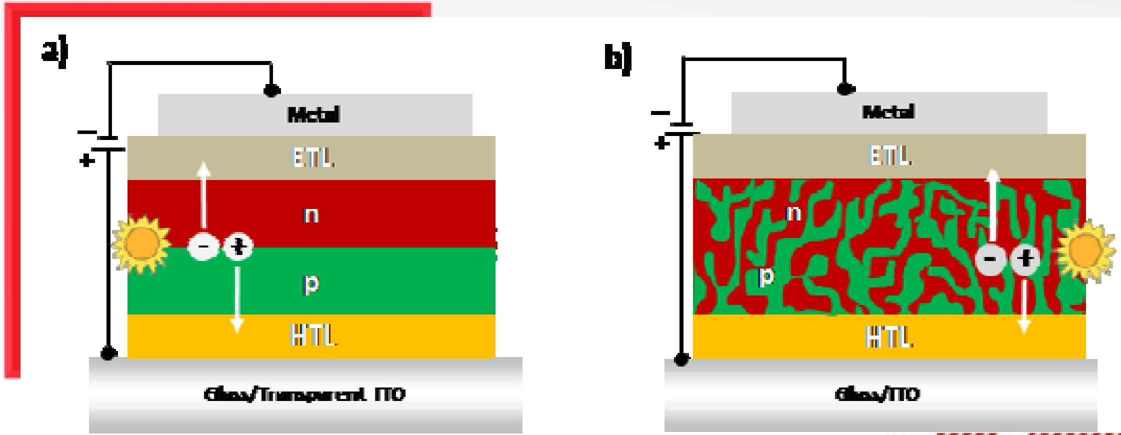
2014, Bessette



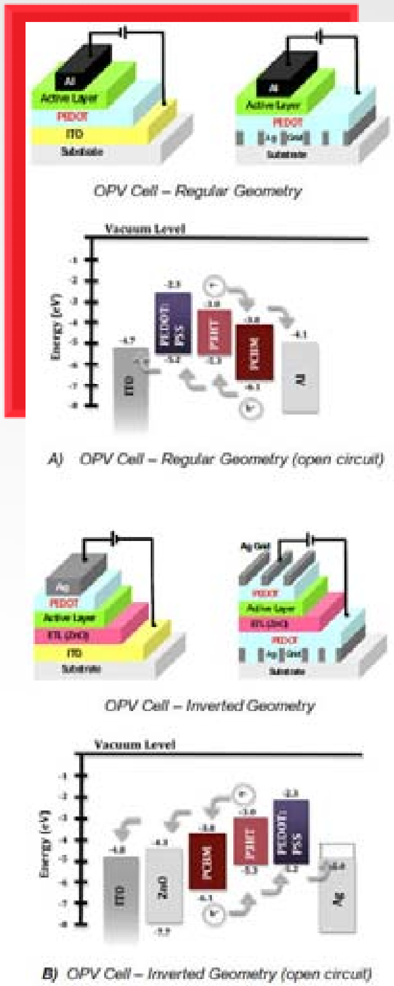
2014, Xue et Al



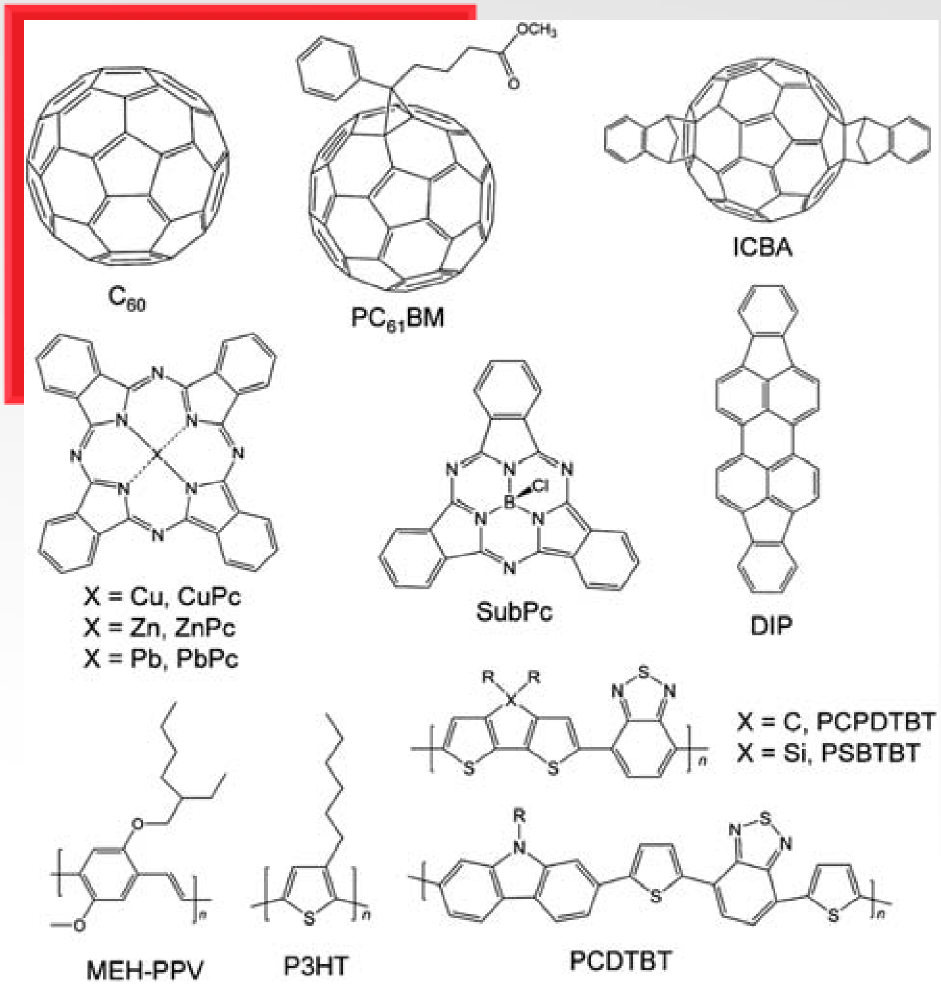
2014, Andersen



OPV - materials



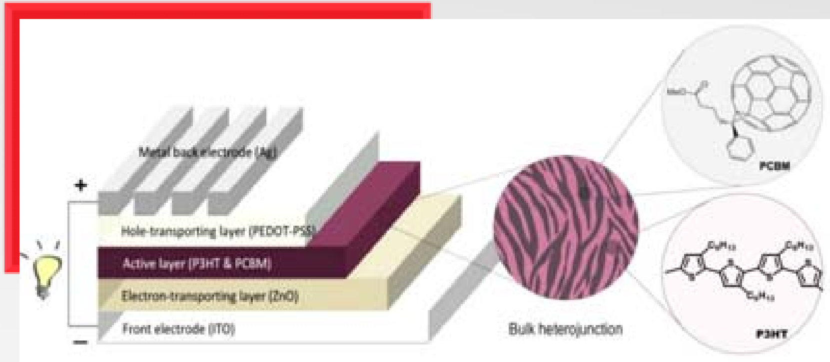
Vanmaele



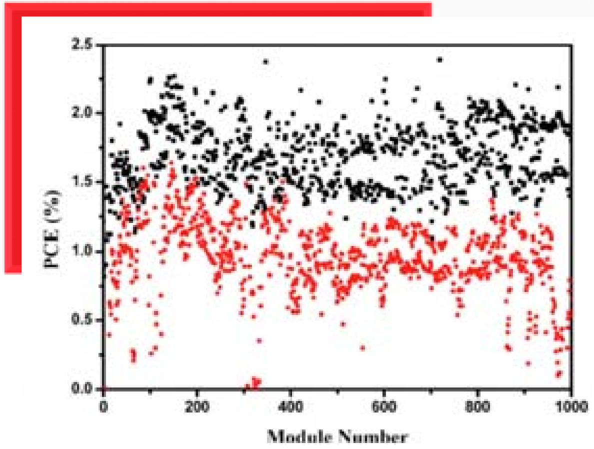
2014, Xue et Al.

OPV R2R fabrication

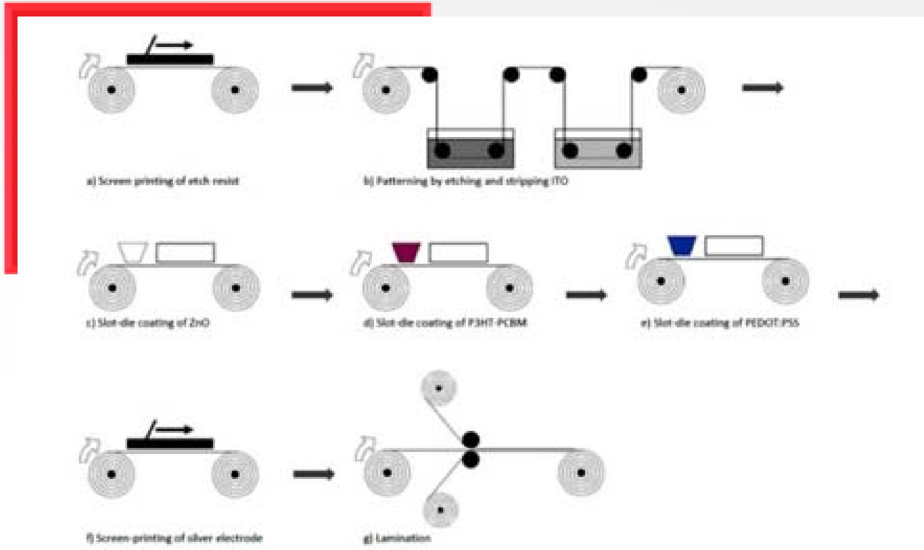
- Typical eficiency ~ 2 %
- Project in progress to achieve 4-5 % efficiency in R2R process.
- Lifecycle 1-2 years



2014, Xue et Al.



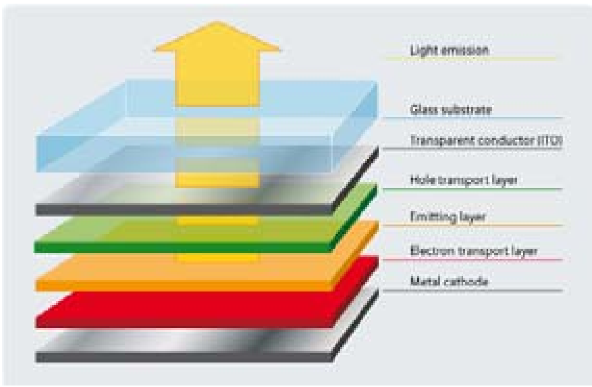
2011, Krebs

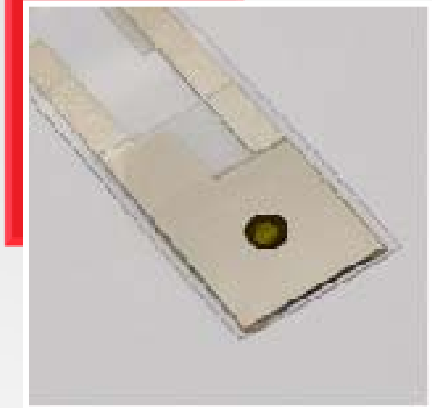


2012, Lauritzen

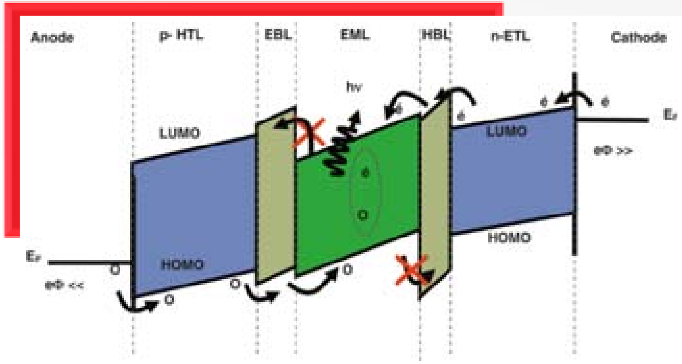
OLED

- Several types called PMOLED, AMOLED, PHOLED, WOLED, FOLED, TOLED, SOLED
- High efficiency 50.7 lm/W at 1000 cd/m^2, 140 lm/W for SOLED
- Up to 200 000 cd/m^2

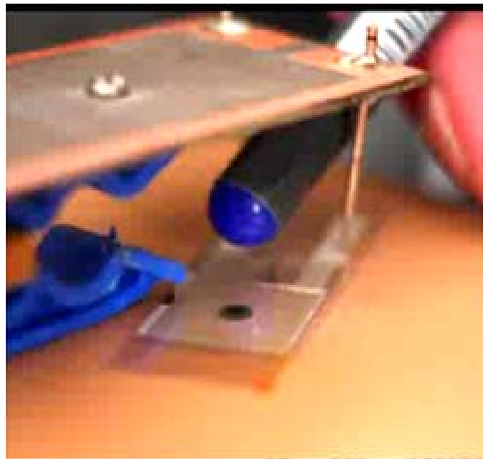




Novaled



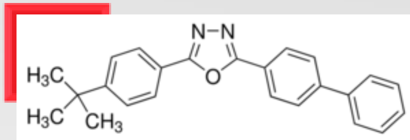
Guaino



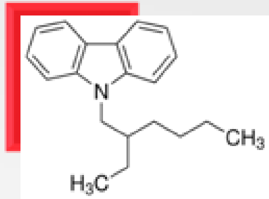
Syrovy

OLED – materials

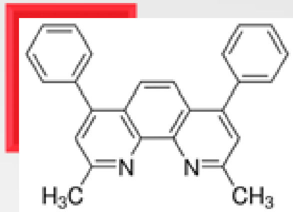
- Cathode – Al/Li, Ag/Mg, LiF/Al/Ag, LiF/Al, Ca/Al
- ETL – Bphen, Alq3, BCP, PBD, PVK, EHCz, TAZ
- EML – Alq_3, Alq3/TPP, Rubrene, PtOEP, MEH-PPV, F_2Irpic, QD
- HTL – HMTPD, TPD, NPD, PVK, CBP, TAPC



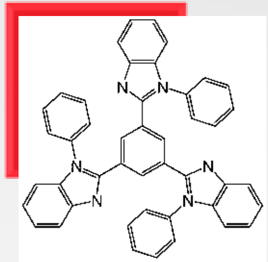
Butyl-PBD



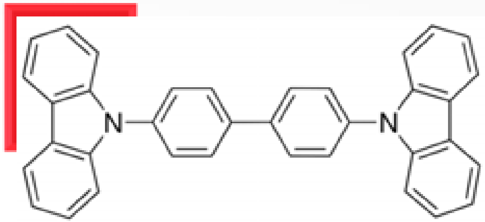
EHCz



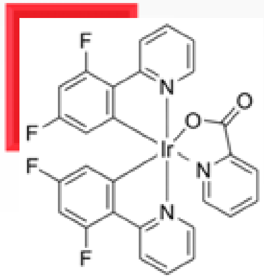
BCP – Bathocuproine



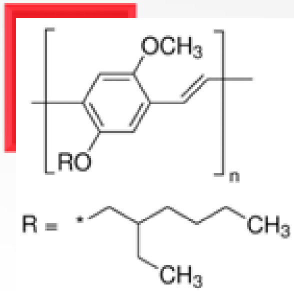
TPBI



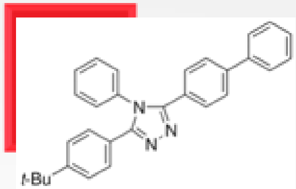
CBP



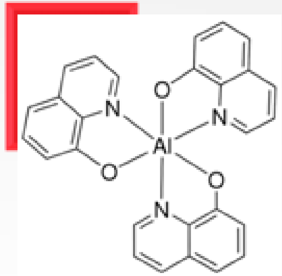
F_2Irpic



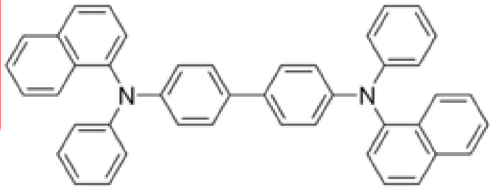
MEH-PPV



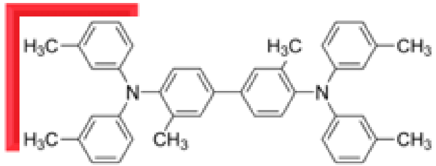
TAZ



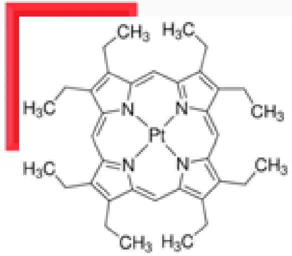
Alq3



NPD

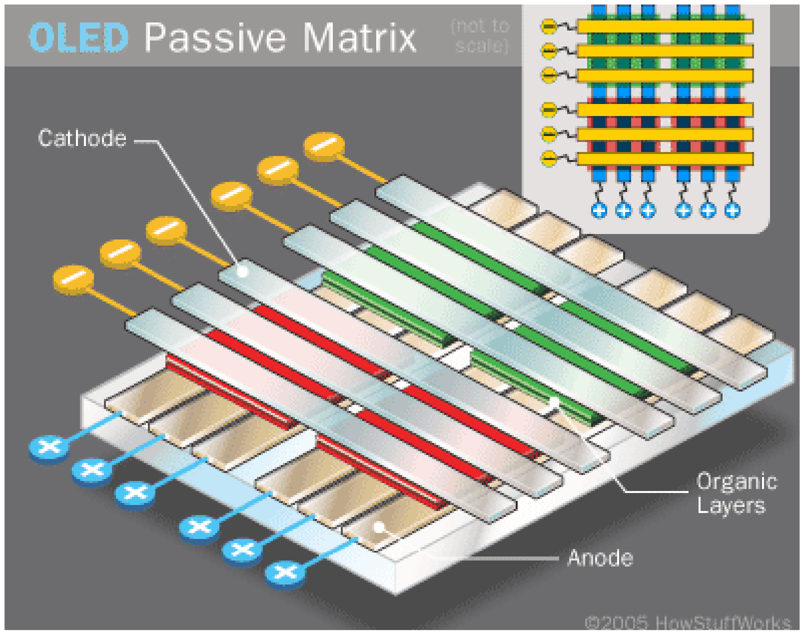


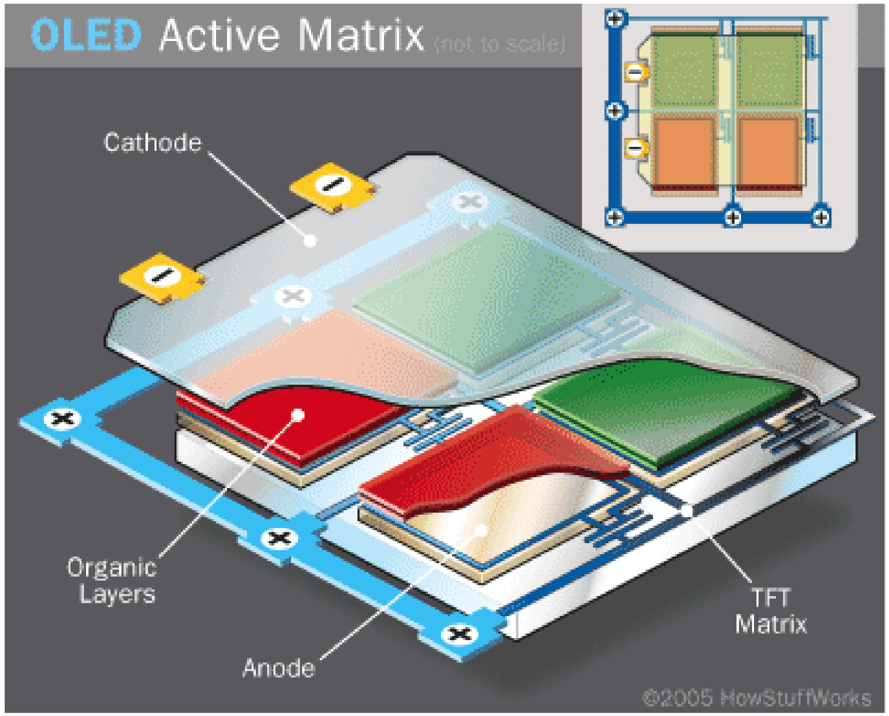
HMTPD



PtOEP

OLED

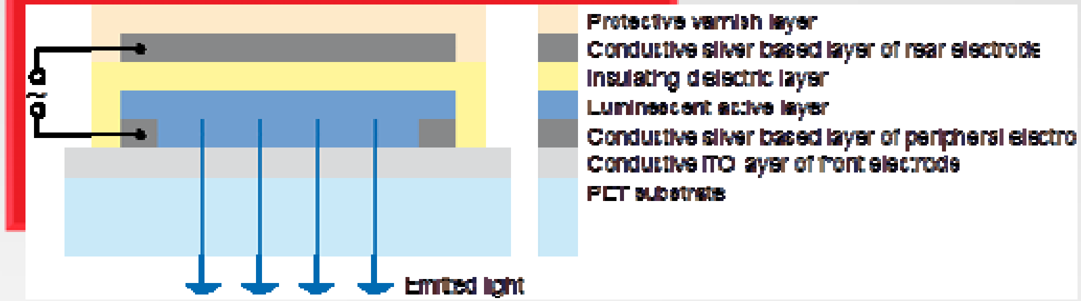




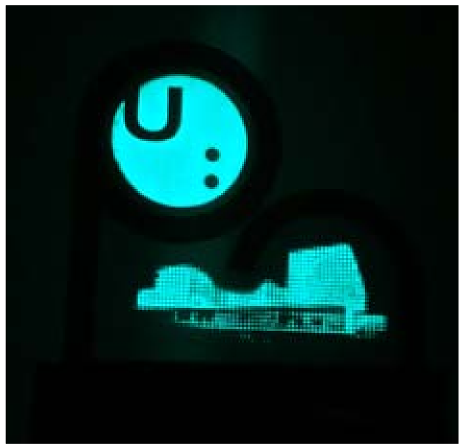
HowStufWorks

Light emmiting capacitors - LEC

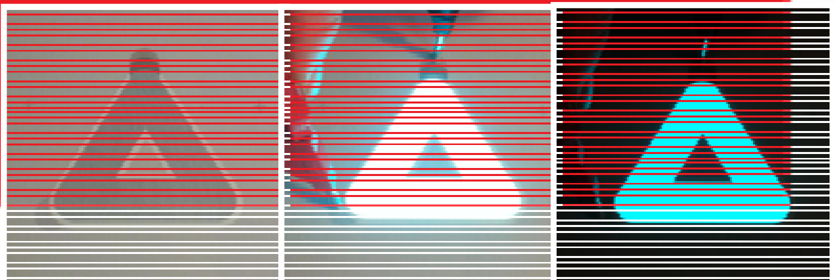
- Based on doped luminofors of ZnS, SrS, etc.
- High efficiency up to 37 %, rsp. 160 lm/W, low consumption 34 W/m^2
- Life cycle > 12 500 hour
- Backlight for advertising displays, decorative lighting, security lighting, backlighting dashboards.



Syrovy



Syrovy



Syrovy

Electrochromic, electroforetic displays

Electrochromic displays

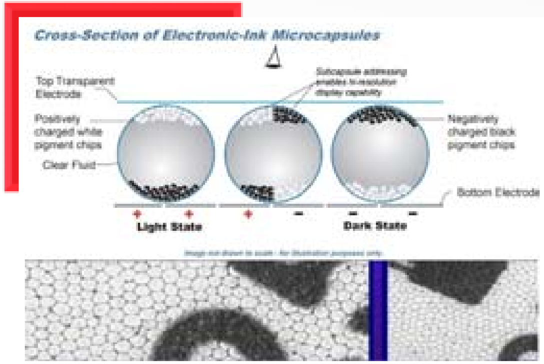
- Switching of redox states generates new or different visible region bands.
- Metal oxide films – WO_3, MoO_3, V_2O_5 Nb_2O_5, $Ir(OH)_3$
- Conducting polymers (PEDOT:PSS, PANI, PPY, Polythiophenes)
- Dyes (Ethyl Viologen, heptyl viologen, Prussian blue, Phthalocyanines)

Guaino

Syrovy, ENAS

Electroforetic displays

- Reflective displays
- Based on bistable states
- Low consumption
- Encapsulated pigments

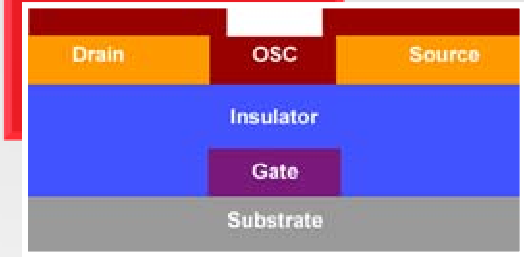


AMEPID

Eink

OFET

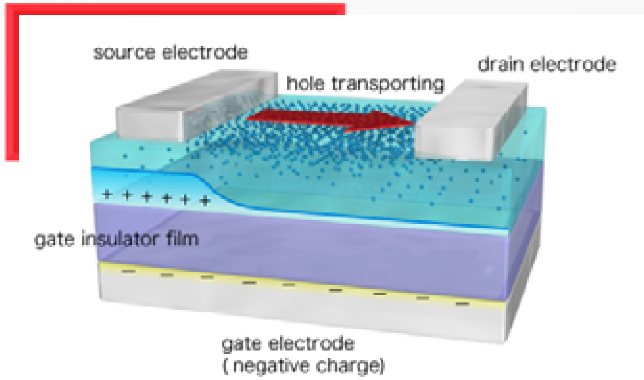
- Based on formation of a conduction channel between source and drain at the insulator-semiconductor interface
- Solution processed, low temperature manufacturing
- Two main architecture – Top-Gate and Bottom gate
- The main parameter is mobility (graphene 3900 cm^2/Vs, Si 1450 cm^2/Vs, organics 1-40 cm^2/Vs)



Silvaco

Challenging factors

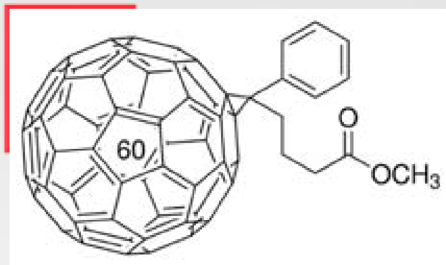
- Mobility Performance
- Switching characteristics
- Process-ability
- Solubility
- Long-Term Stability
- Facilitate Hopping Process
- Impurity charge traps



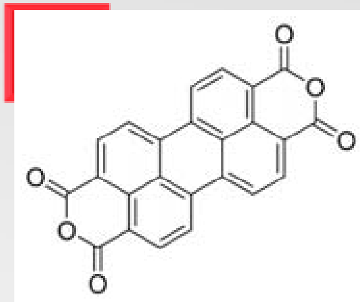
Kyushu University

OFET – materials

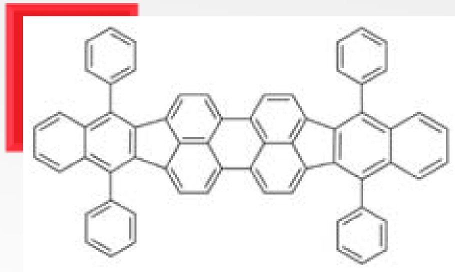
- n type – PTCDA, PCBM, DBP, BBL
- p type – P3HT, PQT, PTAA, TIPS pentacene, CuPc, Caronene, Rubrene
- Dielectric – PMMA, PS, etc.



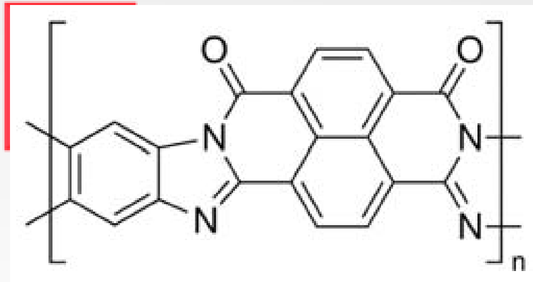
PCBM



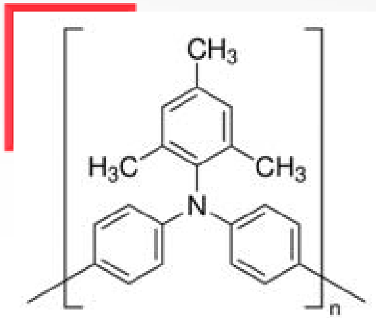
PTCDA



DBP

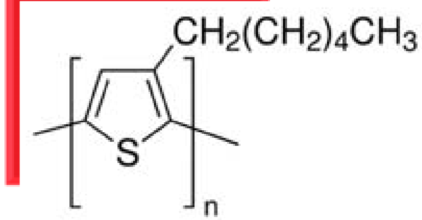


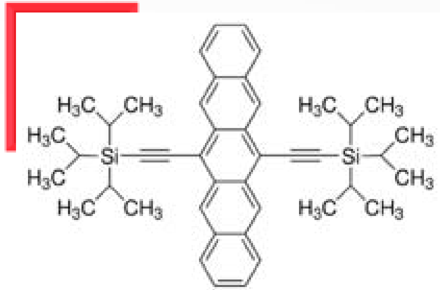
BBL



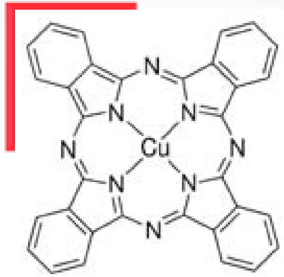
PTAA

P3HT





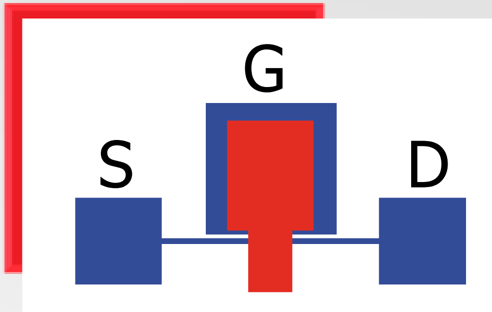
TIPS P.

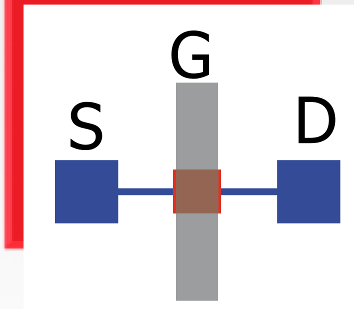


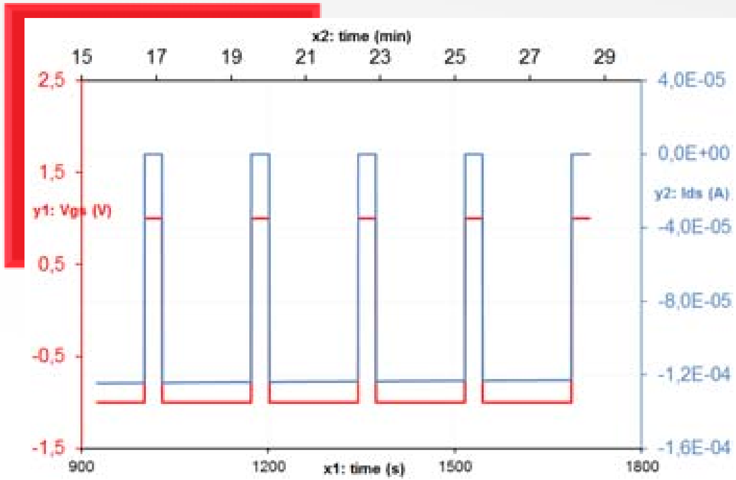
CuPc

OECT

- Switching of redox states of channel affects Ids, resistivity of channel respectively.
- Two main architecture – Latteral, sandwich
- Low voltage operation, On/OFF up to 10^5
- Response time in ms



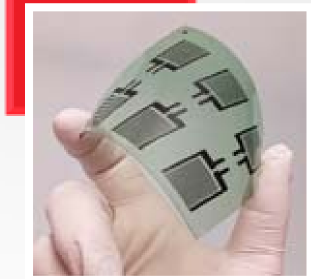




Syrovy

Sensors

- Temperature
- Relative humidity
- Gas detection – NO_2, SO_2, H_2, NH_3, H_2S, Ethylene, hydrocarbons
- Movement sensors, acceleration sensors
- Tactile sensors, pressure sensors
- Light sensors
- Biosensors
- Electrochemic
- Microfluidic



Syrovy

Others printed functionalities

Printed memory

2013, Jung

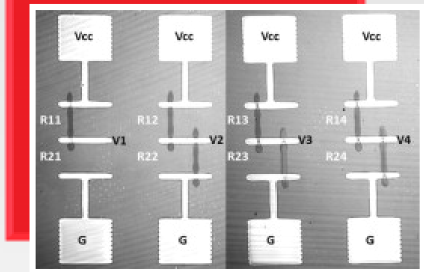
- ROM, WORM, NVRAM

Printed speakers

- Electromagnetic induction
- Piezoelectric

Electro active polymers

- Artificial muscles
- Tactile sensors
- Haptic feedback
- Tactile displays „artificial skin“
- Energy generator

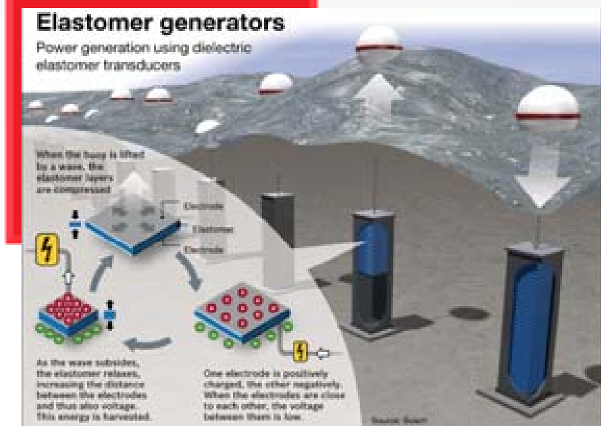


Hübler

Rowland

OE-A

Heydt



Bosh

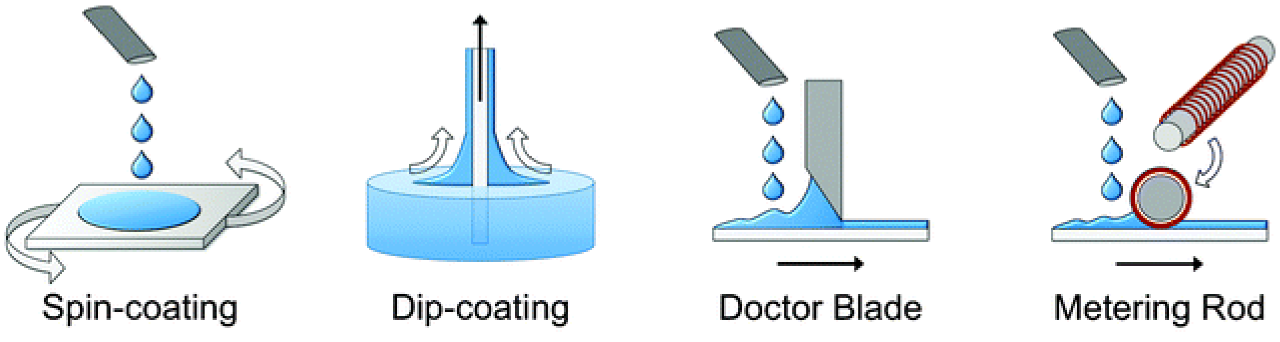
Coating and printing techniques – laboratory

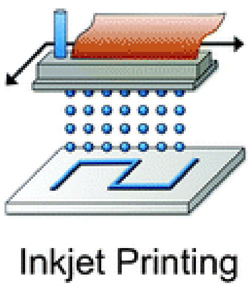
- Spin coating
- DIP coating
- Doctor blade,

  Bar Coating
- Spray coating
- Ink-Jet
- Aerosol printing
- Electro-Hydrodynamic and

  Reciprocating System

Pasquarelli et Al.

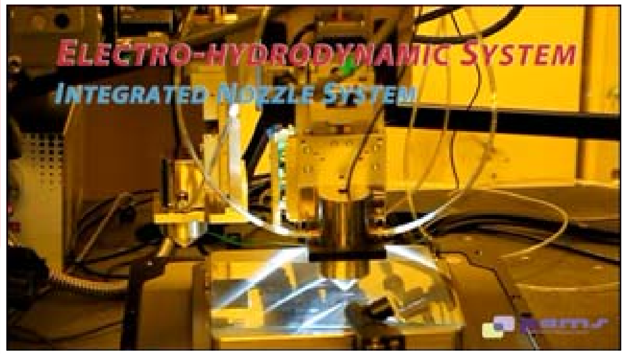




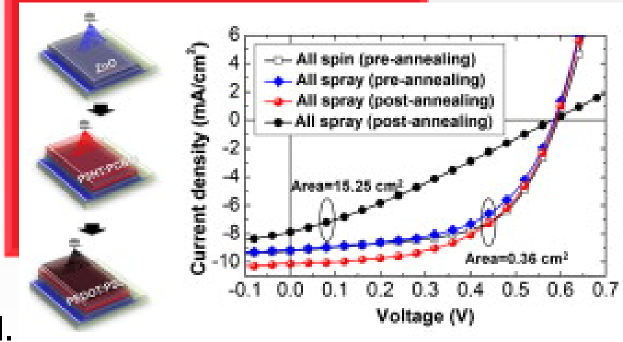
Optomec

Laboratory scale Printing/Coating techniques in photovoltaics

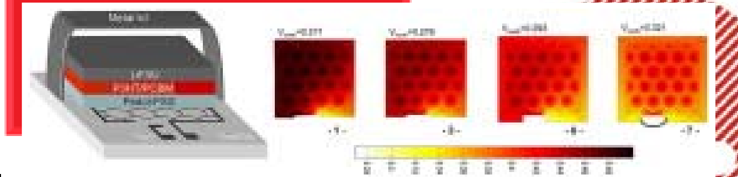
- Spin Coating. Spray Coating, Blade Coating, Spiral Bar Coating
  - DSSC – TiO_2 photoelectrode, counter electrode
  - OPV – HIL layer, ETL, BHJ layer
  - Transparent conductive layers
  - Metal bus bars, wiring



PEMS



Kang et al.



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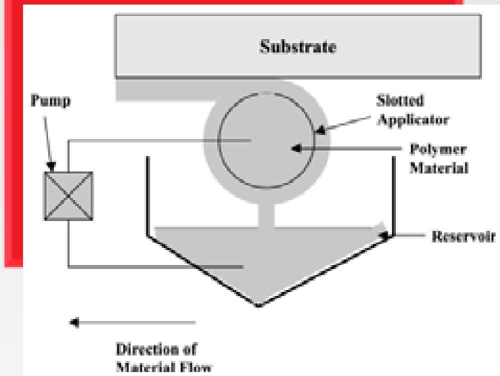
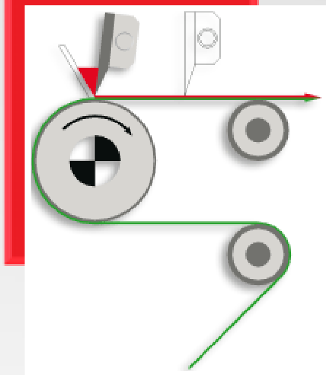
Coating techniques

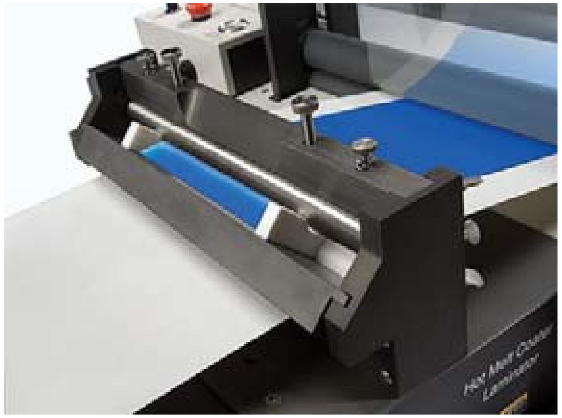
- Knife-over-edge/Blade coating
- Mayer Bar, Spiral Bar Coating, Stripe coating
- Meniscus coating



www.3dit.de



Coatema



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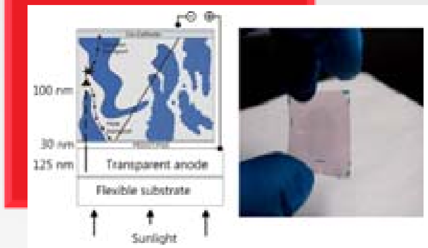
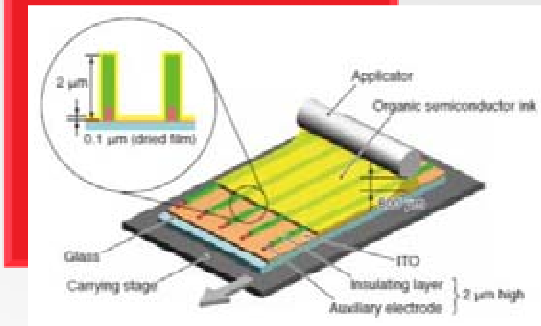
PEMS Co.,Ltd

Coating techniques

- Knife-over-edge/Blade coating, Mayer Bar, spiral bar coating
  - DSSC – TiO_2 photoelectrode, counter electrode, gel electrolyte
  - OPV – HIL layer, BHJ layer
  - OLED – emissive layer, transparent and rear electrode
  - Sensors – gas, bio
  - Batteries – electrode material, electrolyte
- Meniscus coating
  - Photoelectrode - TiO_2
  - Transparent conductive layers
  - Sensors



Wengeler et Al.



Toshiba

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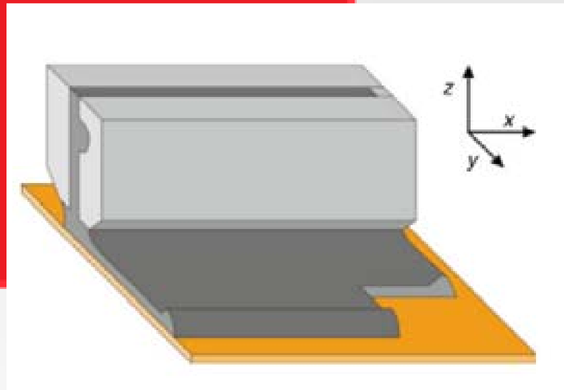
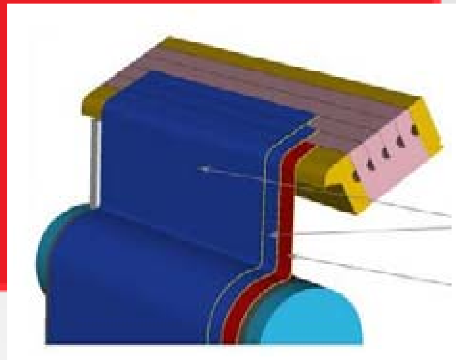
Coating techniques

- Slot Die
- Curtain coating
- Multiple slot
- Slide coating



Schmitt et Al.



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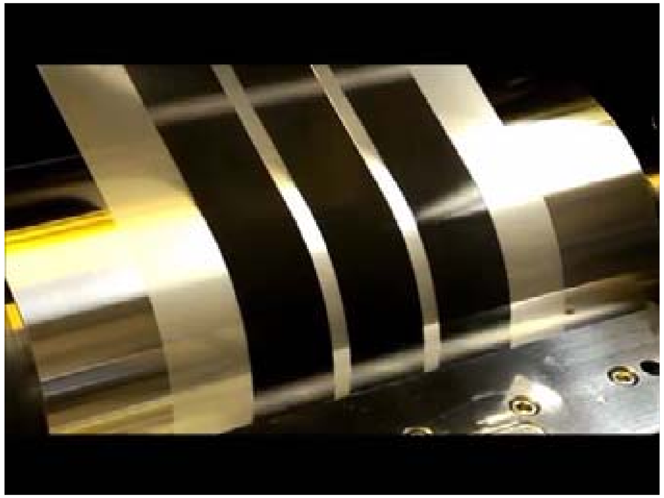
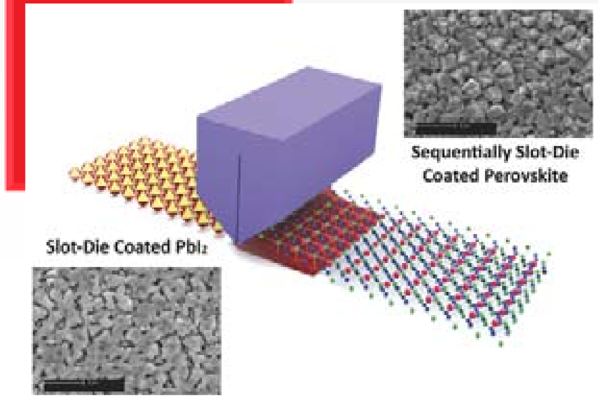
Media Format	R2R, Sheets
Ink Waste	Low
Coating Speed	100- 500 $m.min^{-1}$
Ink Viscosity	10-25 000 mPa.s
Wet Thickness	5-500 µm
Dry Thickness	0.01-100 µm
Resolution	Given by shim

Coating techniques applications

- OPV – transparent electrode, BHJ layers (P3HT:PCBM), ETL
- Lamination adhesives – pressure sensitive
- HTL (PEDOT:PSS), ETL layers (TiO_2, ZnO)
- Electrochromic display
- OLED – PLED – emissive layers, HIL layers, ETL
- Battery – electrode layers, collectors



Frontier



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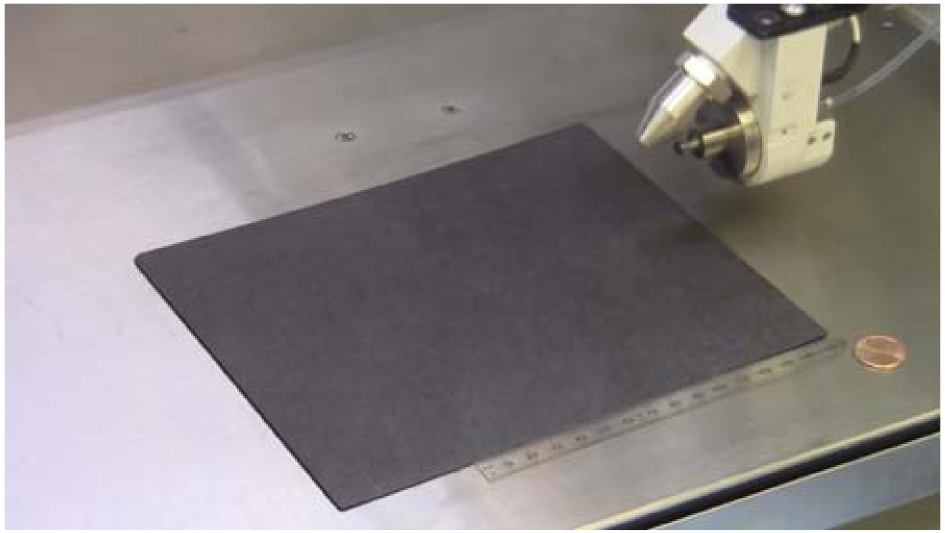
Coating techniques – Spray Coating

+ High uniformity of layers
+ Deposition to 3D object
+ Relatively high range of thickness of layers



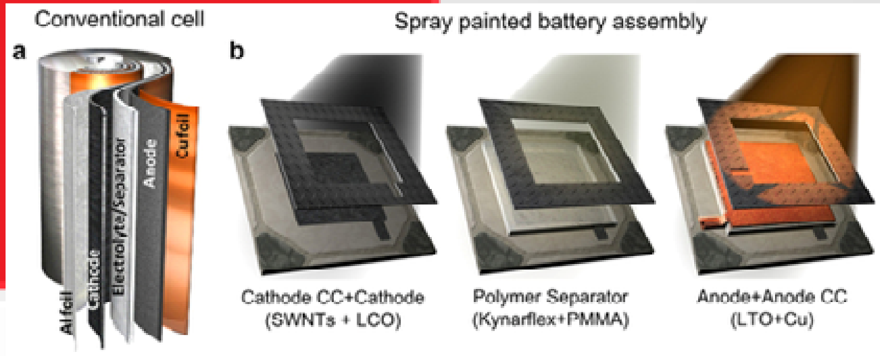
Sono-tek

- Ink Waste
- Complicated patterning
- Low resolution of patterning

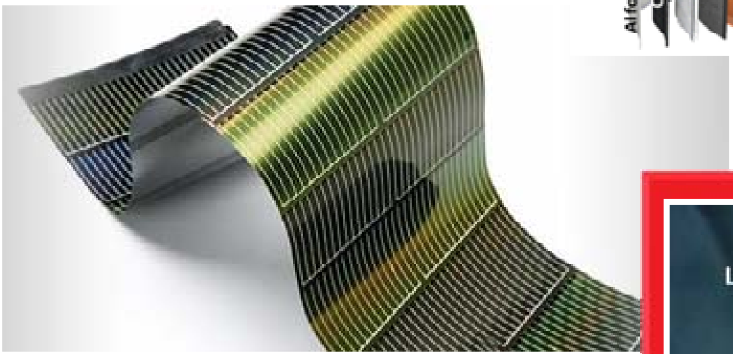
Media Format	Sheets, R2R
Ink Waste	moderate
Coating Speed	Up to 100 $m.min^{-1}$
Ink Viscosity	10-1000 mPa.s
Wet Thickness	1-500 µm
Dry Thickness	0.01-100 µm
Resolution	Tech. Sol. dependent

Coating techniques – Spray Coating

- OPV - HIL, BHJ, ETL
- Transparent conductive layers (CNT, PEDOT:PSS, PANI:HCl)
- Memory
- OFET
- Battery
- OLED



Singh at Al.



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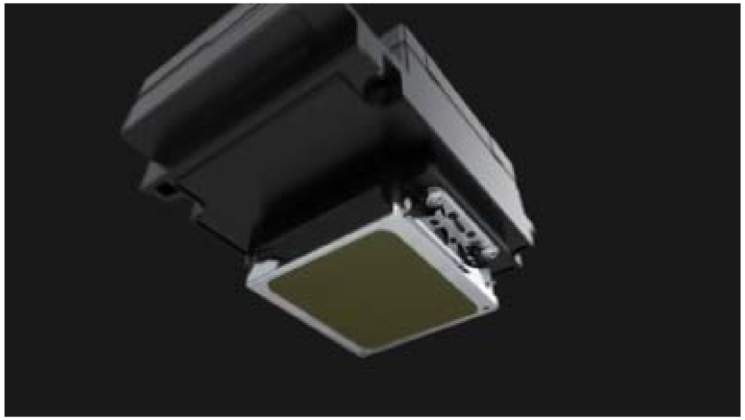
Printing techniques - InkJet

+ Absence physical printing form
+ Relatively high resolution and high precise registration
+ Relatively high range of thickness of printed layers



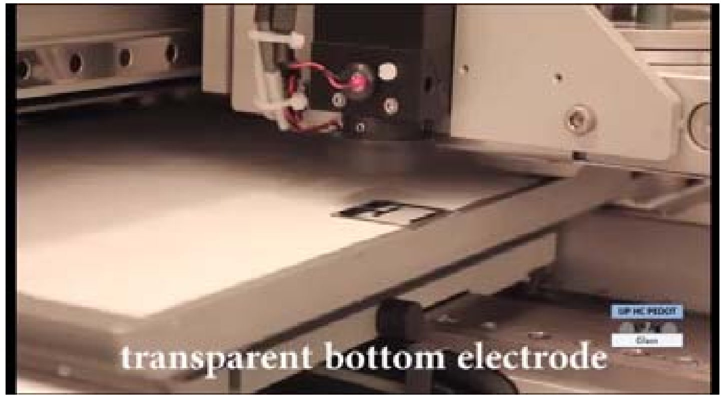
Epson

Media Format	Sheets, R2R
Ink Waste	Low
Printing Speed	Up to 280 $m.min^{-1}$
Ink Viscosity	1-50 mPa.s
Wet Thickness	1-500 µm
Dry Thickness	0.01-100 µm
Resolution	10 µm

- Problems with clothing of nozzles
- Quality strongly influenced by printing speed
- long time run stability
- Large amount of interfaces

Printing techniques - InkJet

- BHJ, ETL (PFN, ZnO, TiO_2), HTL (PEDOT:PSS, MoO_3)
- Transparent conductor (Ag nanowire, CNT, SWCNT, Graphene, ITO, AZO, ATO)
- Sensors
- Catalytic layers
- Conductive (Ag, Cu), semiconductive, dielectric layers for several type of devices
- Transistors – OFET, OECT
- OPV, DSSC
- OLED – POLED, SMOLED
- Piezoelectric elements – micropumps, tactile
- Baterries, supercapacitors
- Memory
- Reactive colors



Holst Centre

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[15] Yu et. al., Nanoscale 2012 10.1039/c2nr31508d

Printing techniques – Screen printing

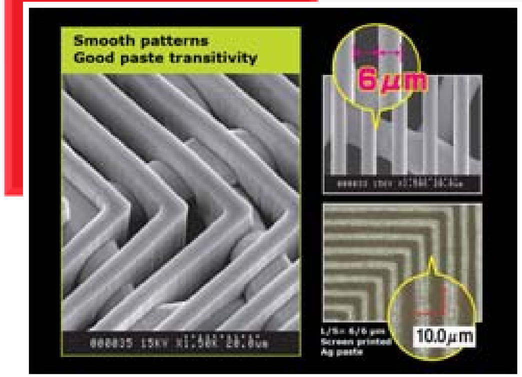
- + Most used production technique
- + Variety of thickness of layers
- + Relatively easy preparation of stencil

3D-Micromac AG

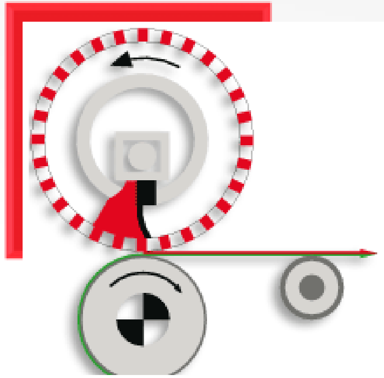
Media Format	Sheets, R2R
Ink Waste	Low
Printing Speed	Up to 50 $m.min^{-1}$
Ink Viscosity	100-20 000 mPa.s
Wet Thickness	3-1000 µm
Dry Thickness	0.02-1000 µm
Resolution	6 µm

– Printing speed, high viscosity

Kuroda



Coatema



Printing techniques – Screen Printing

- Photocathode (TiO_2, ZnO, etc.)
- Counter electrode (PEDOT:PSS, PANI, PPY, CNT, Graphene, Ag)
- Conductive patterns (Ag, Cu)
- Electrolytes
- BHJ layers, ETL, HTL
- Sealing layers, Barrier layers
- Sensors
- Catalytic layers
- Conductivee, (Semi)conductive, dielectric layers for several type of devices
- Transistors – OFET, OECT
- OPV, DSSC
- OLED – POLED, SMOLED
- Batteries, supercapacitors
- Memory
- Reactive colors
- Piezoelectric elements – micropumps, tactile

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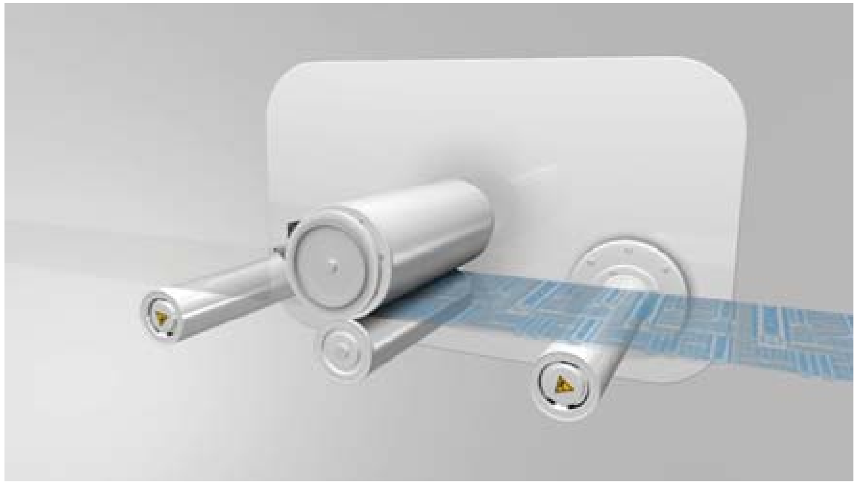
Printing techniques – Gravure

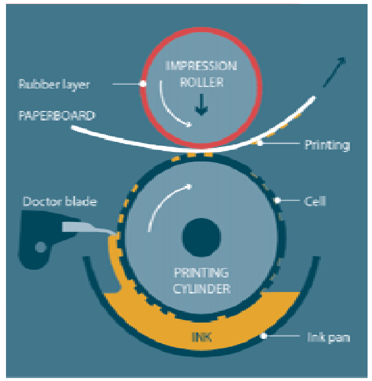
+ Very stable printing process
+ Highest printing quality
+ High printing speed
+ Printing form resistant to solvents
+ Reverse gravure for precise coating

Media Format	Sheets, R2R
Ink Waste	Low
Printing Speed	Up to 500 $m.min^{-1}$
Ink Viscosity	10-20 000 mPa.s
Wet Thickness	5-80 µm
Dry Thickness	0.02-80 µm
Resolution	3 µm



3D-Micromac AG

– Expensive printing form/ cyllinder
– Mainly gravure is suited to flexible substrates

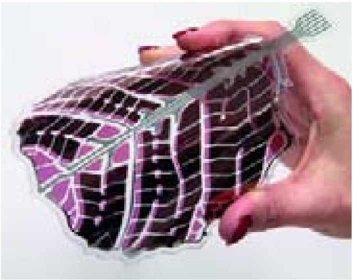


www.iggesund.com

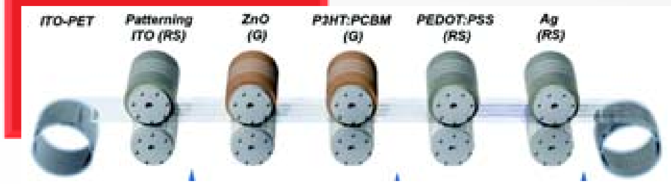
Printing techniques – Gravure

- HIL (MoO_3, PEDOT:PSS), BHJ
- ETL (ZnO_2, TiO_2)
- Conductive tracks (Ag, Cu)
- Dielectrics
- OLED – SMOLED, PLED – emissive layer
- OFET – ID structures, Dielectric layer, Semiconductor layer,
- RFID antenas
- Sensors – RH, Biosensing layer
- Voltage multiplier circuits
- Memory
- Antistatic layers
- Microfluidic chanells

CSEM



VTT



Välimäki et Al.

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[6] Kopola et. al., Solar Energy Materials and Solar Cells 2010 10.1016/j.solmat.2010.05.027
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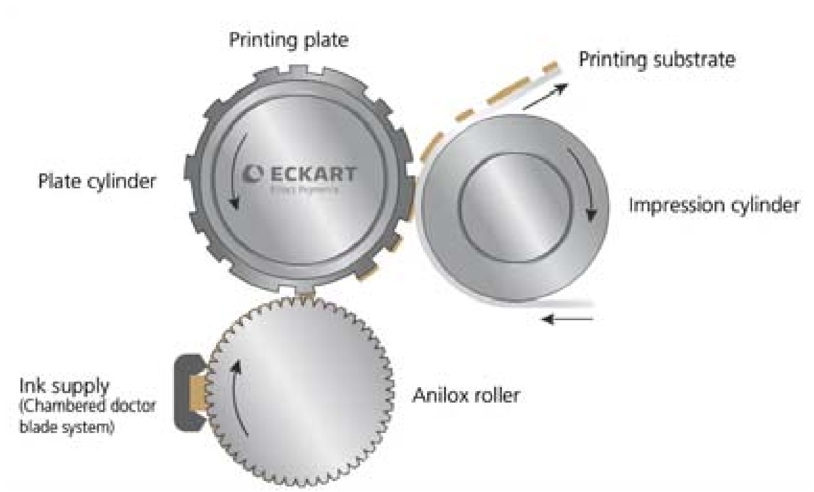
Printing techniques – Flexography

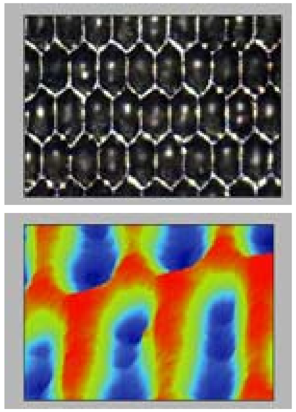
+ Stable printing process
+ High printing speed
+ Rigid and flexible substrates
+ Relatively inexpensive printing form

Altana



Media Format	Sheets, R2R
Ink Waste	Low
Printing Speed	Up to 1000 m.min^{-1}
Ink Viscosity	10 -1 000 mPa.s
Wet Thickness	5 - 30 µm
Dry Thickness	0.03 - 10 µm
Resolution	30 µm

Simec Group



- Limited thickness of layers
- Uniformity of topology of fine lines
- NIP pressure is crucial

Printing techniques – Flexography

- Conductive interconnection,
- Transparent conducive layers (CNT, PEDOT:PSS), conductive grids
- HTL (PEDOT:PSS, V_2O_5)
- RFID antennas
- Biostatic layers
- Dielectric layers (OFET, RFID)
- Laudspeakers
- Fuid-guiding channels
- Drug delivery systems

Syrovy

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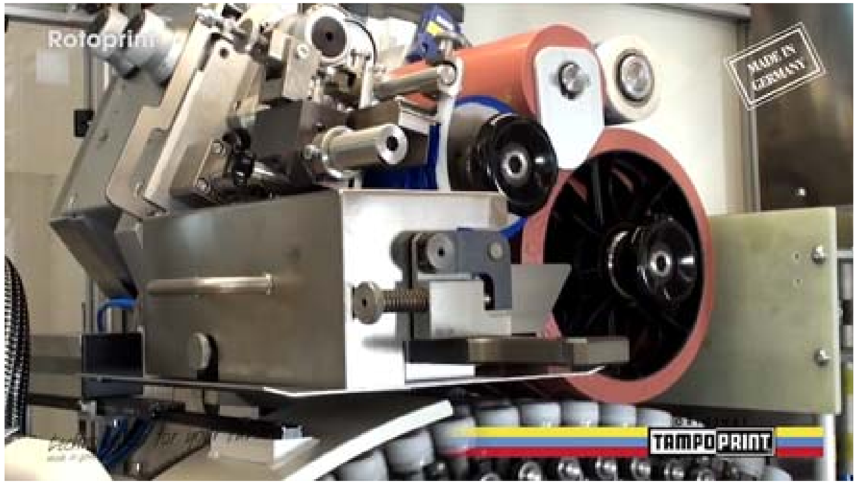
Plasticphotovoltaics.org

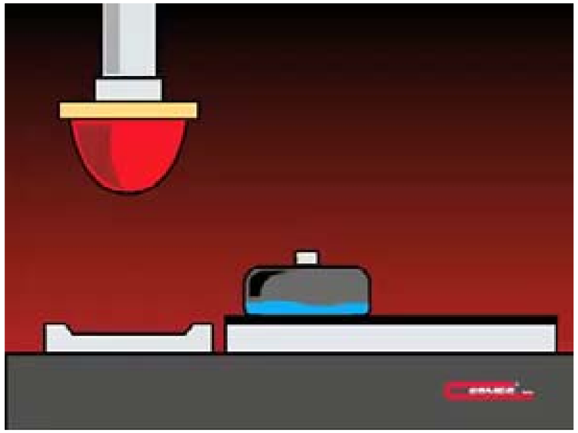
Printing techniques – Pad printing, offset gravure

- + Rigid and flexible substrates
- + Printability of 3D surface
- + Printing quality
- + Printing speed

Media Format	Sheets, R2R
Ink Waste	Low
Printing Speed	Up to 120000 parts/hr
Ink Viscosity	10 -1000 mPa.s
Wet Thickness	5- 80 µm
Dry Thickness	0.05 - 20 µm
Resolution	25 µm



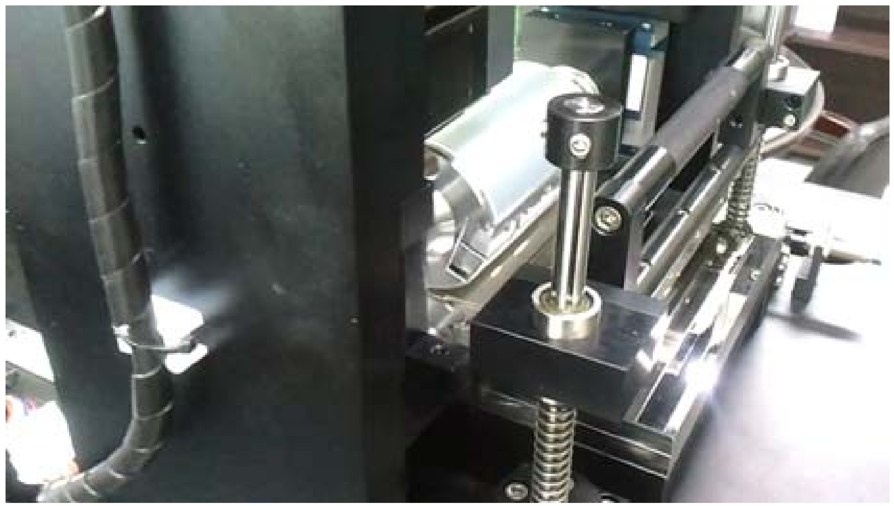
Tampoprint



TRI Elektronik

Printing techniques – Pad printing, offset gravure

- Conductive interconnection (Ag)
- BHJ layer (P3MHOCT/ZnO)
- transparent conducive layers (CNT, PEDOT:PSS), conductive grids



PEMS

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[3] Hahne et. Al., Solar Energy Materials and Solar Cells 2001 10.1016/S0927-0248(00)00119-7
[4] Krebs et. Al., Solar Energy Materials and Solar Cells 2009 10.1016/j.solmat.2008.09.003
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Printing techniques – Offset printing

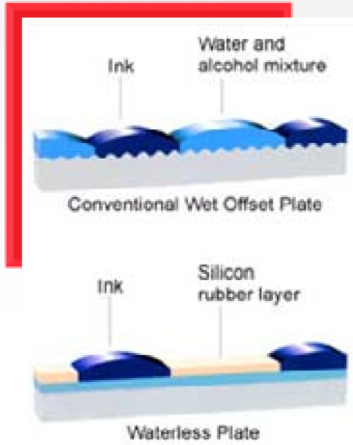
+ Printing speed
+ High resolution
+ inexpensive printing plates fabrication
+ Frequently used printing technique

Kim

www.brancher.com

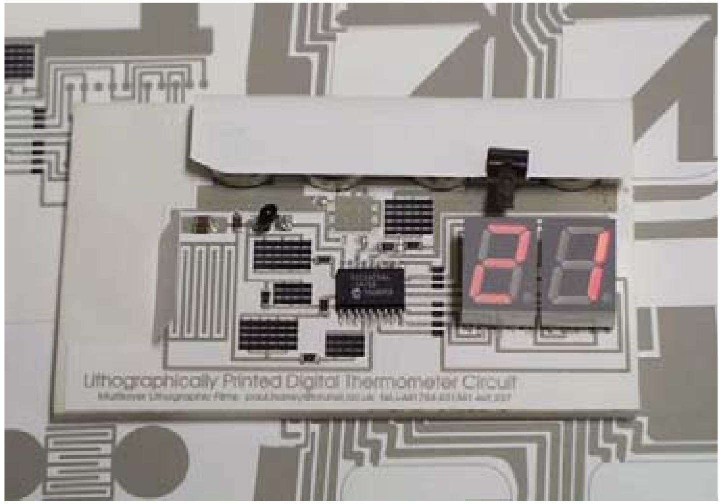
Media Format	Sheets, R2R
Ink Waste	Low
Printing Speed	Up to 1000 m.min^{-1}
Ink Viscosity	10 -100 Pa.s
Wet Thickness	10 µm
Dry Thickness	3 µm
Resolution	25 µm

– Limited thickness of layers
– High resistivity of conductive layers
– Lack of commercial functional ink

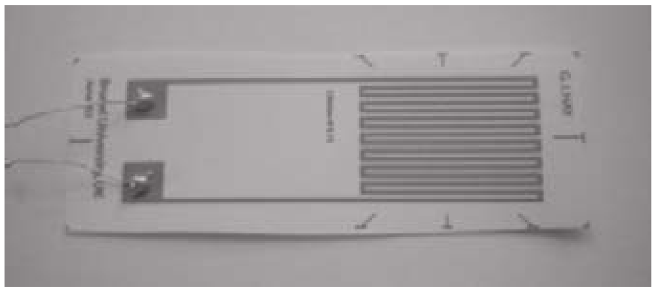


Printing techniques – Offset printing

- OFET ID structures
- Conductive circuits
- Passive components
- Sensors
- Thermochromic display
- Battery
- OPV



Brunel University



Brunel University

Others „printing“ techniques for µ-Patterning

- Nanoimprinting lithography NIL
- Soft Lithography
  - Microcontact Printig µCP
  - Micromolding in Capillaries MIMIC
  - Nanotransfer printing nTP
  - Replica molding REM
  - Microtransfer molding µTM
  - Solvent-assisted micromolding SAMIM

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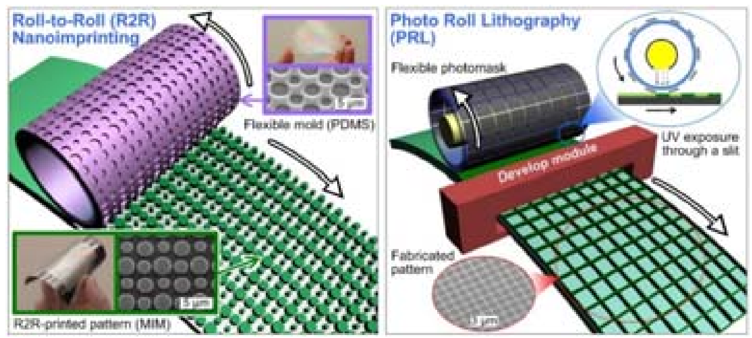
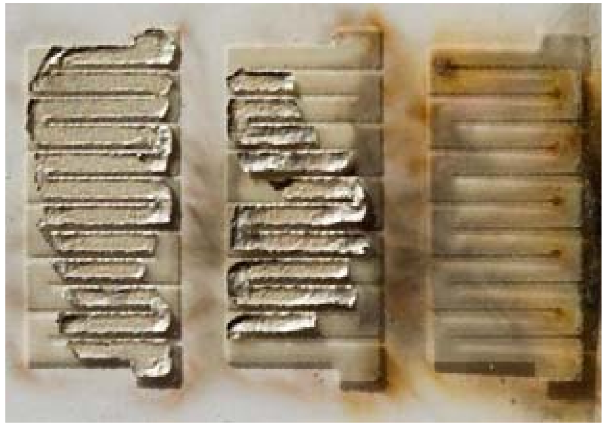
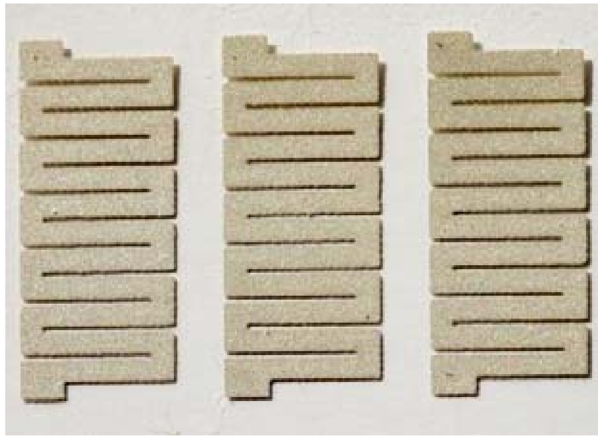


OKNANOLAB

Possibilities for rapid drying or sintering process

- Hot-air drying/sintering
- IR drying/sintering
- Curing by UV radiation or EB
- Photonic sintering
- Microwave drying/sintering
- Electrical sintering (DC or contactless AC)





Syrovy

Program Centra kompetence

Thank you for your attention