Introduction to New Generation Solution Processable Solar Cells: Perspectives and Challenges

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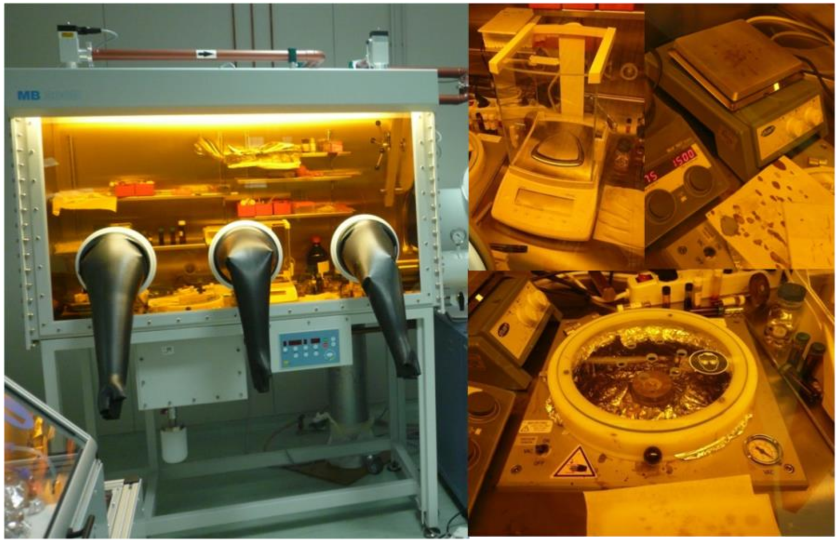
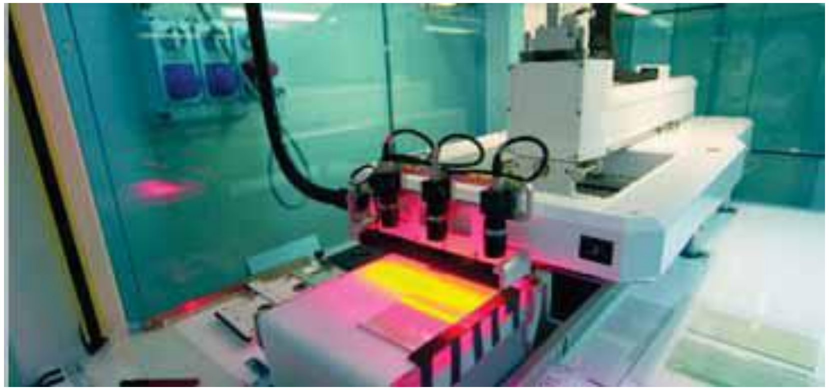
CHOSE is research center with a lab of about 1000 m^2 located in Rome devoted to the research on DSC and BHJ-SC





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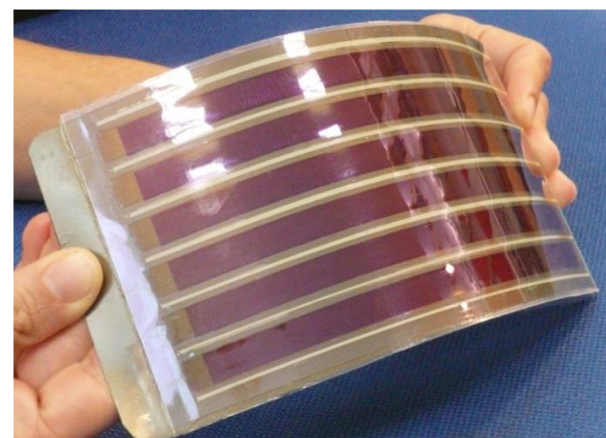
Glass based technology

Dye Sensitized Cells

Flexible solar cells

Dye Sensitized Cells →



← **Polymer solar cells**

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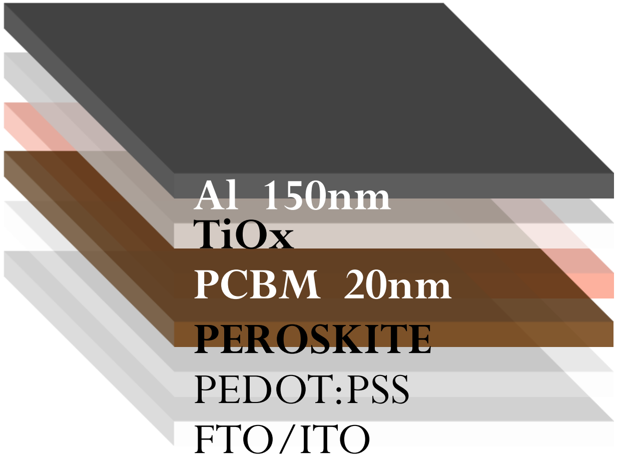
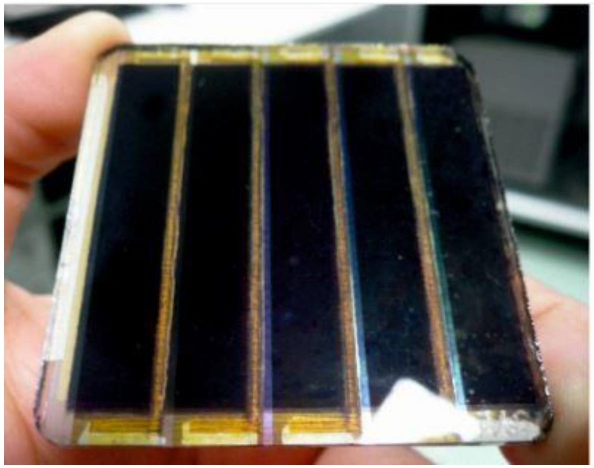
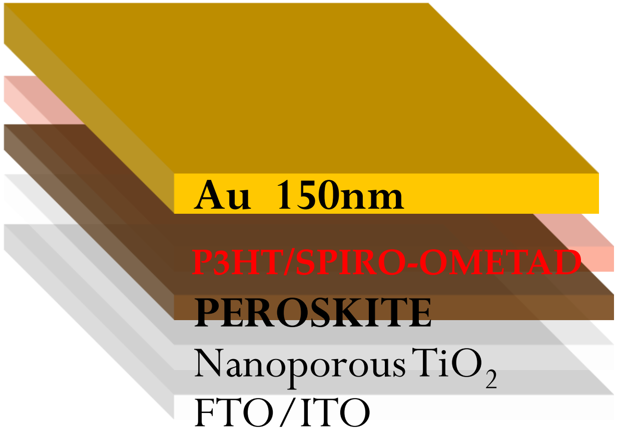
Perovskites based technology



9% eff.





13% eff.

Perovskite module formed by 5 series connected cells (monolithic architecture). Aperture area = 25 cm2, Active area = 16.8 cm2, Efficiency on active area = 5.1% (Matteocci et al. PCCP 2014)

SPIN-OFF & START-UP

- Technological transfer with Spin-off and Start-up

DYERS — **8 Engineers and PhD**

8 Engineer and PhD — tiberlab

intellienergia S.r.l.
renewablenergyengineering

10 **Engineer and PhD**

5 **Engineer and PhD** — INGEM S.R.L.

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DYEPOWER: Objectives

L'obiettivo del consorzio è lo sviluppo di un processo di produzione industriale per la fabbricazione di pannelli DSC per applicazioni in facciate di vetro. Ciò comporta l'individuazione dei materiali, processi e soluzioni tecnologiche che consentano a tali pannelli di raggiungere livelli adeguati di stabilità, di efficienza energetica e di costo.

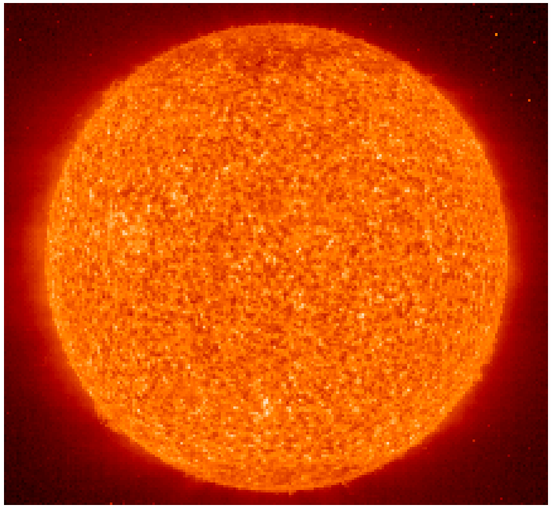
Main Milestones

- Prototype of Photovoltaic Glass Envelope based on DSC technology
- Pilot Plan for the production of such DSC Photovoltaic Glass Envelope

Building Integrated Photovoltaics

Background

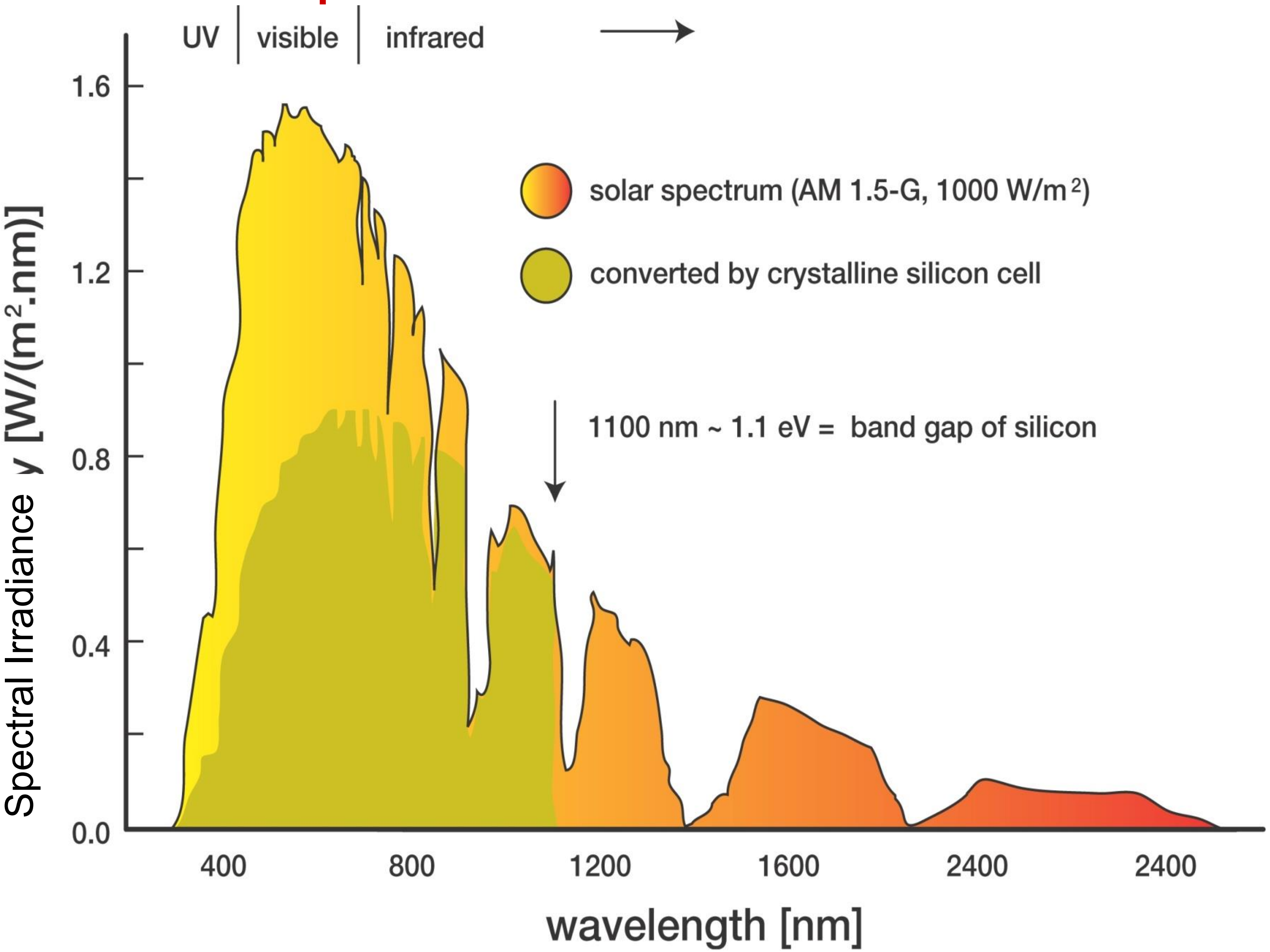
Energy from the sun



• Averaged over a year humanity consumes over 13 TW of power.
• The sun deposits 120000 TW of power on the earth surface.

• Typical sunlight conditions in central Italy give1400 kWh/m^2 per year.
• To satisfy a good fraction of the electricity needs of a typical family one needs at least a 2kWp PV system, i.e. ~20m^2 of photovoltaic surface (assuming system efficiencies of 10%).

Sun’s Spectral Irradiance on earth’s Surface



The origins

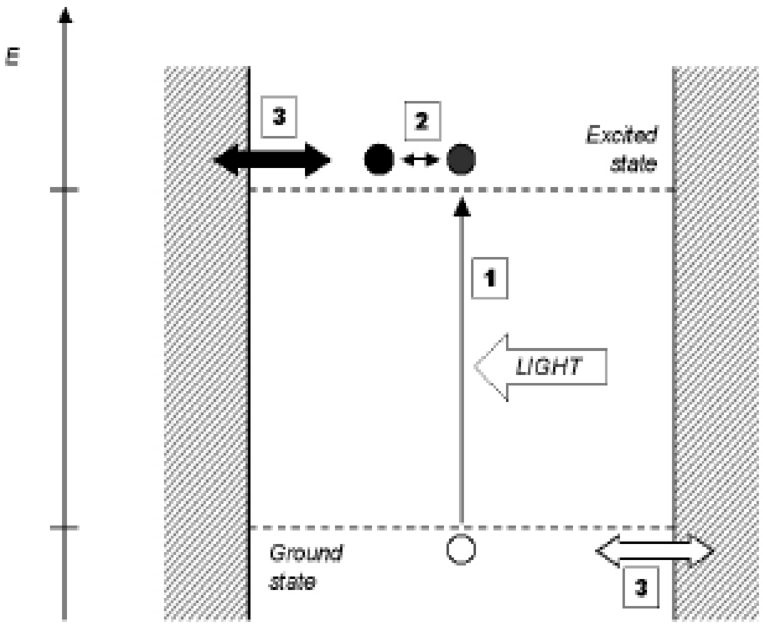
1941

The american Russell Ohl (Bell Labs) discovers accidentally the use of a pn junction as solar cell

1954

The Bell Labs researchers Pearson, Chapin, e Fuller realize a photovoltaic cell with 4.5% power conversion efficiency

Solar Cells (1/2)



1- Light harvesting
2- Charge separation
3- Charge transport

Light harvesting: photons are absorbed and their energy used to excite electrons.

Charge separation: the excited electrons are separated spatially from the ground state to avoid recombination.

Selective charge transport/extraction: electrons and holes are transported to the terminals of the device, where the high-energy electrons are selectively extracted at one terminal while the holes selectively are replenished from the other terminal.

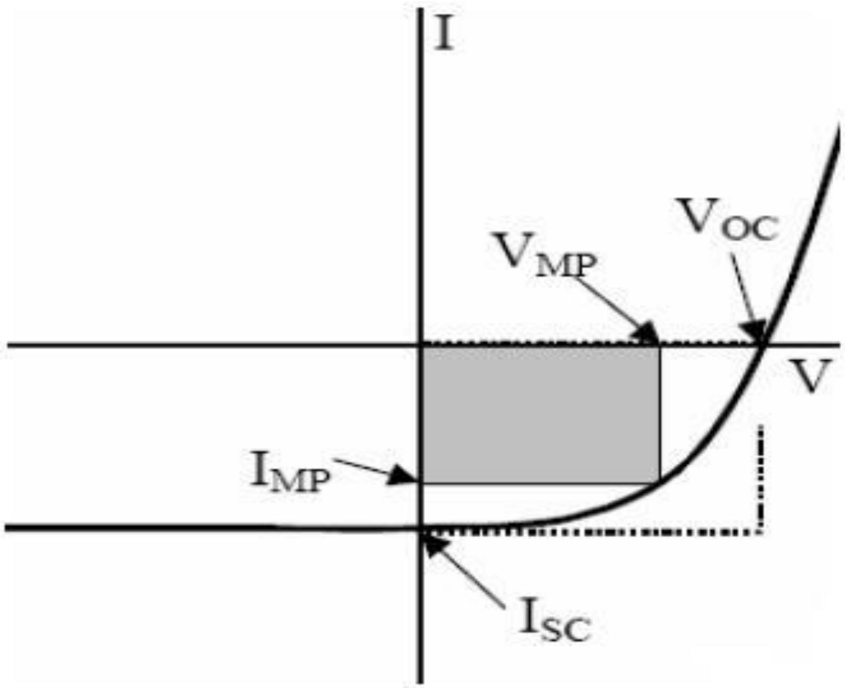
Ideally, there should be a one-to-one relationship between light and electric current: Each photon that strikes the device deliver its energy to an electron, which in turn transports the energy to an electrical load connected to the terminals of the device. Here the energy can be released in the form of work.

Source: K. West

Solar Cells (2/2)

- **The I-V characteristic allows to evaluate the behaviour of the solar cells**

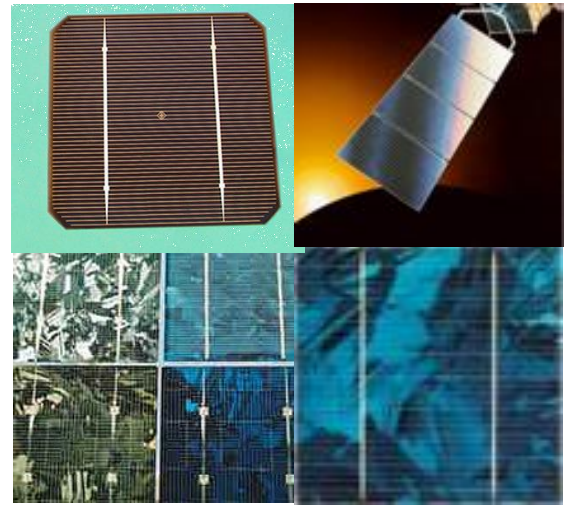
- **The most important parameters are : the Fill Factor (FF) and the power conversion efficiency (η):**



$$FF = \frac{P_{max}}{V_{oc} \cdot I_{sc}}$$

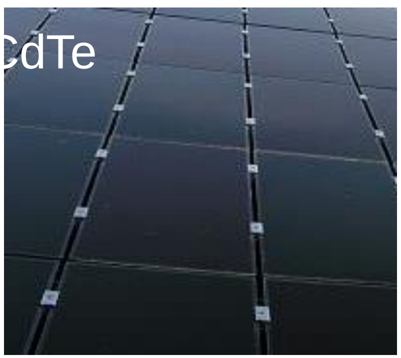
$$\eta = \frac{P_{max}}{P_s}$$

Which materials for the Solar Cells?



Thick crystalline semiconductors

– **Crystalline silicon**
  - •Single crystal
  - •Polycrystalline
- **–Gallium Arsenide(GaAs)**
- **–Other materials from the group III-V**

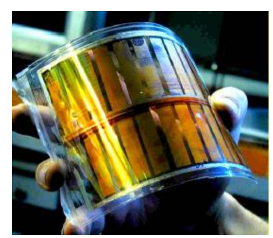


"Thin Films" Materials

- **Amorphous Silicon (a-Si)**
- **Cadmium Telluride (CdTe)**
- **Cupper and Indium diselenide (CuInSe2, o CIS)**
- **Cupper Indium gallium diselenide (CIGS)**

Organic Materials

- **Small molecules(antocianine etc.)**
- **Polymers**
- **DSC**
- **Perovskites**



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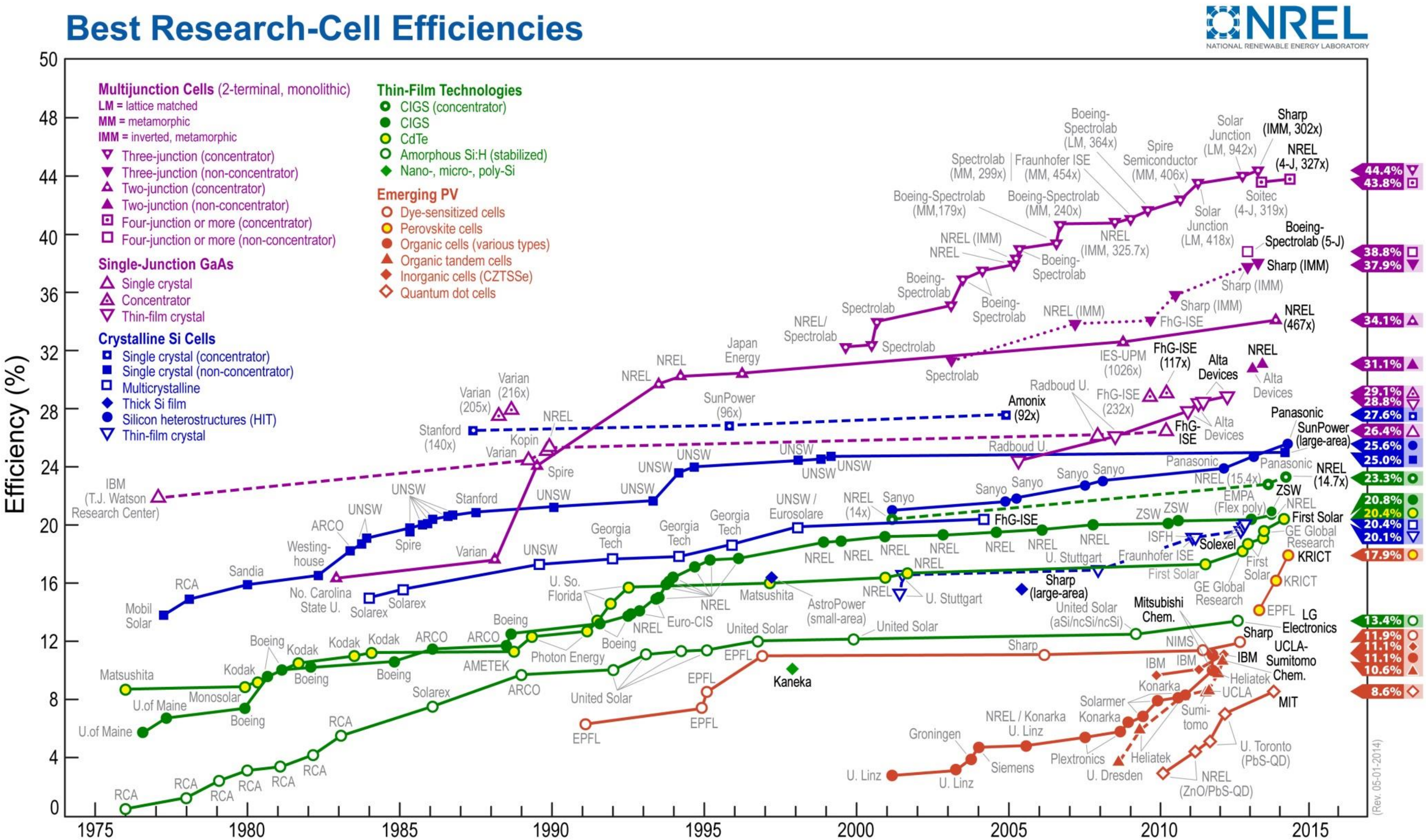
Efficiency table



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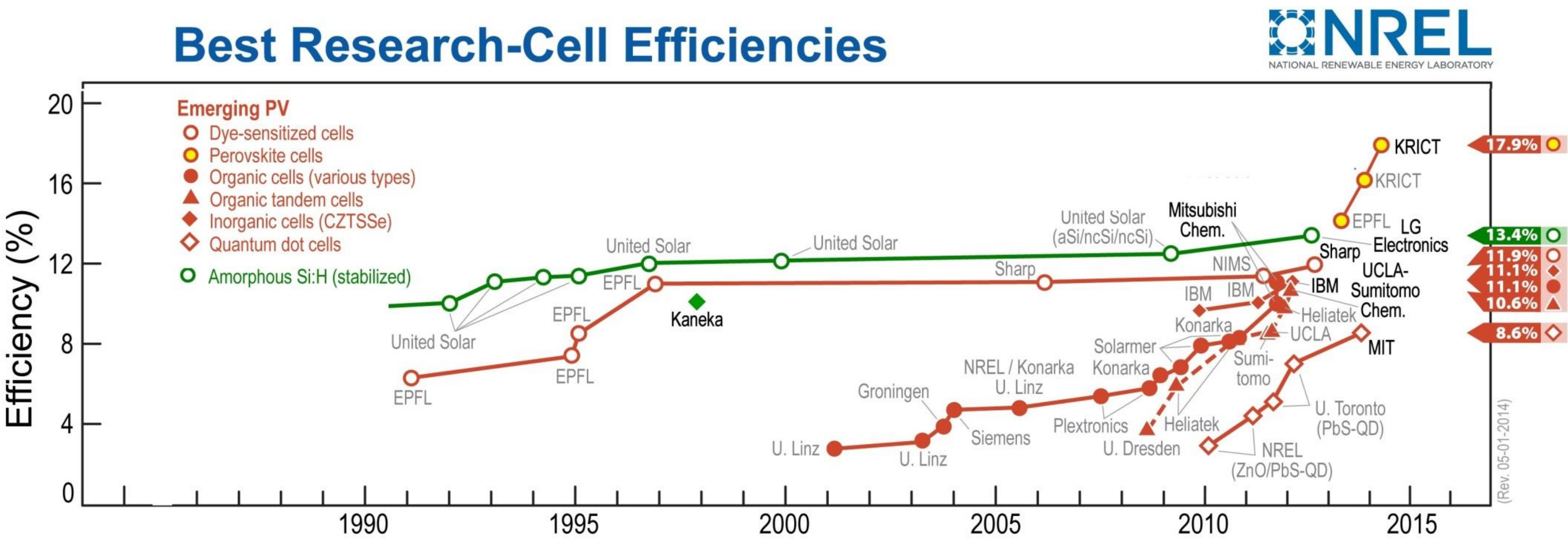
Efficiency table:detail on organics



Different approaches have been developed to achieve high efficiency devices:

- OPV standard architecture: 9.15%
- OPV tandem architecture: 10.6%
- Planar perovskites:12.1%
- Perovskites with scaffold: 17.9%

Outline

- Solution processable OPV devices
  - Working principle
  - Architectures
- Fabrication process
- New carbon based electrodes
- Conclusions

Solution processable OPV devices

Organic Photovoltaics-New Perspectives

The fabbrication processes of the "conventional" solar cells are expensive and complex.

The cost for the setting of a production factory is very high

Is it possible to reduce both the material and the production costs for the realization of solar cells?

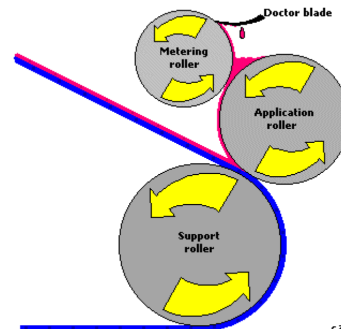
Yes! With the introduction of new materials and new fabrication techniques

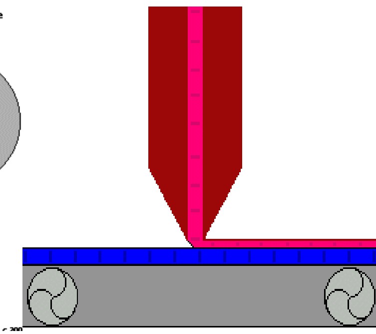
→ **Solution processable solar cells**

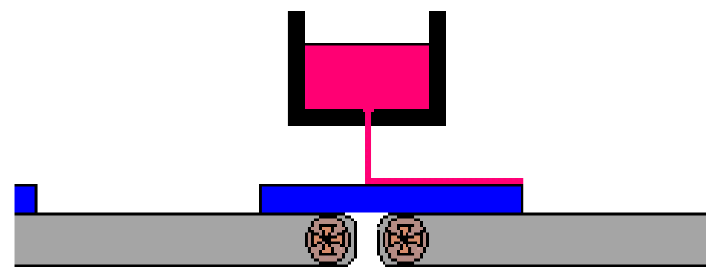
“New” manufacture processes

Conventional Electronics → **Organic Electronics**

Conventional semiconductor industry → **Printing methods**



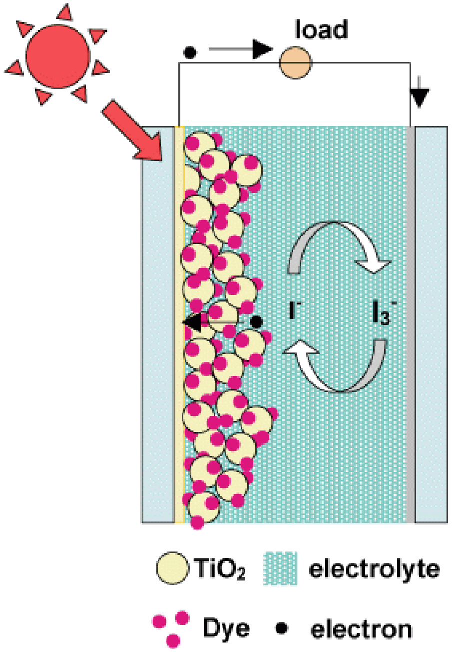


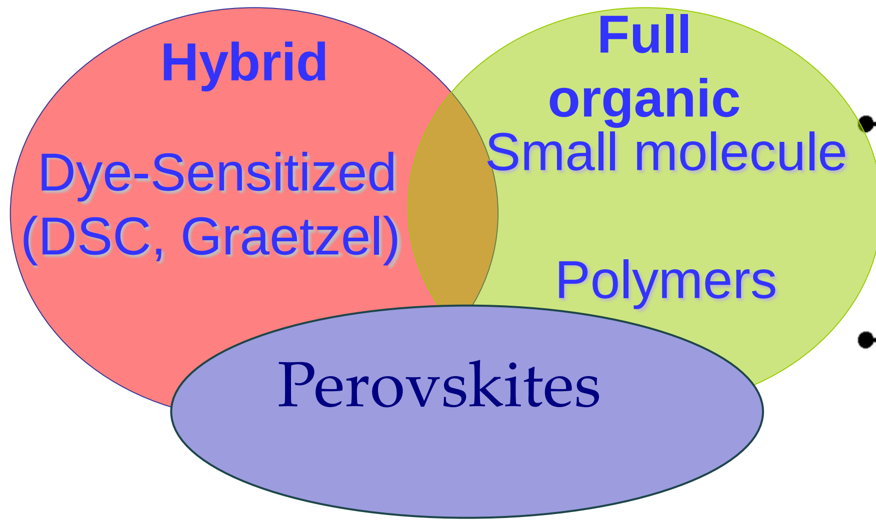


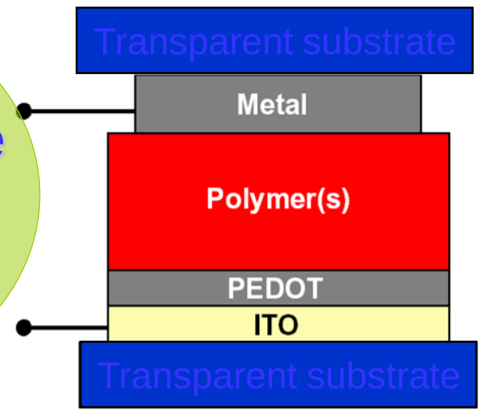
High temperature, doping, vacuum → **Liquid deposition**

Very Large enterprises → **Small Medium enterprises /local productions**

Organic photovoltaics







Type	Max lab efficiency	Stability	R&D
Hybrid Dye Sensitized (Graetzel)	~ 11-12%	IEC 61646	University and industry
Full organic solar cells	~ 10%	IEC 61646	University and industry
Perovskites	~ 18%	-	University

Organic Photovolatic

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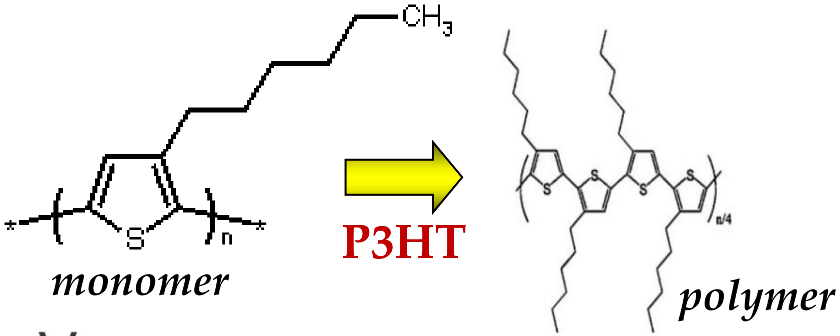
Working pronciple

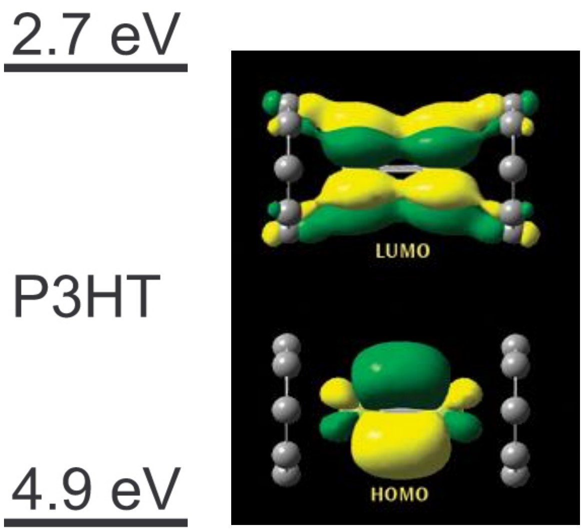
Polymers

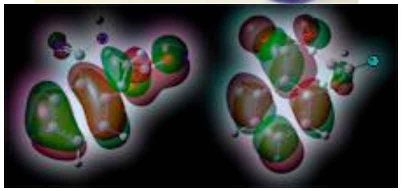
<u>Conjugated polymers</u>: macromolecules based on repetition of monomers (same or different species); principally made of carbon (**C**), they can have different and distinctive properties (both optical and electrical), and can be tailored ***"ad hoc"*** for several purposes.

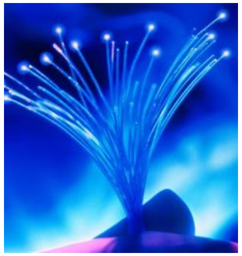


Pro

- ✓ low-cost fabrication (solution-processing)
- ✓ large-area and mass production
- ✓ flexible devices
- ✓ customizable







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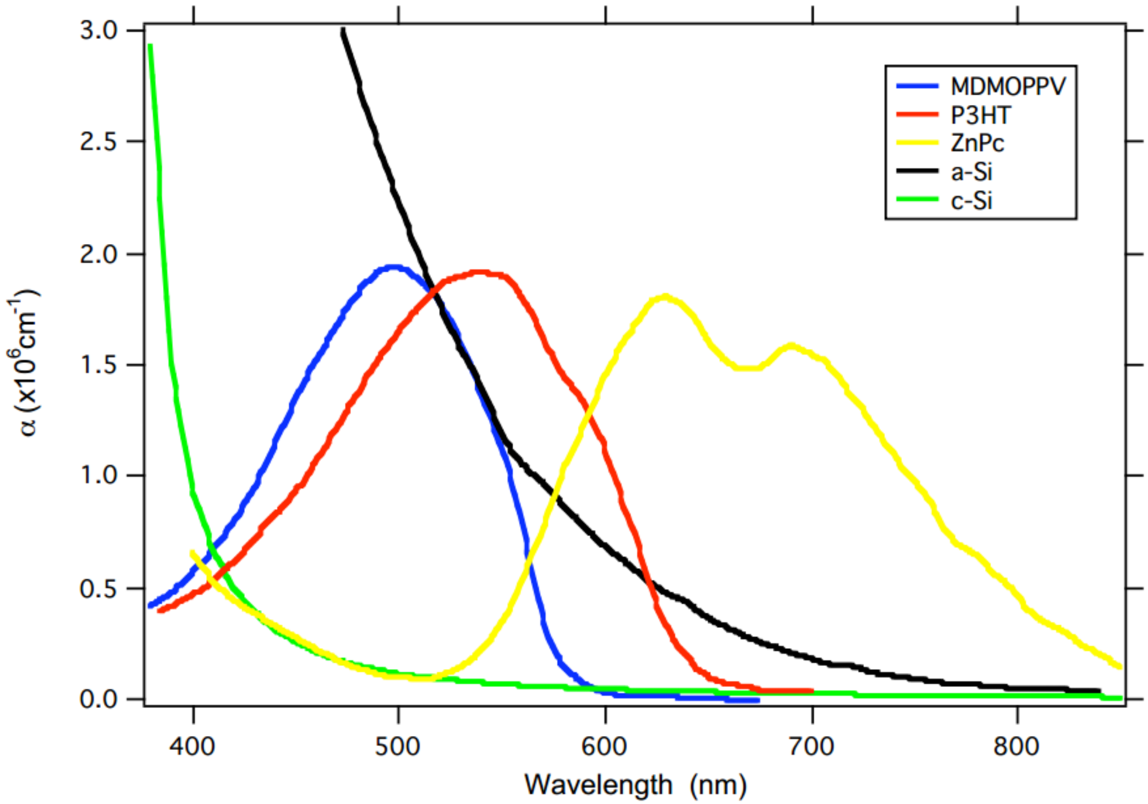
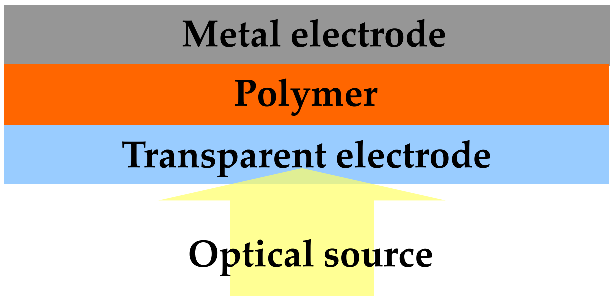
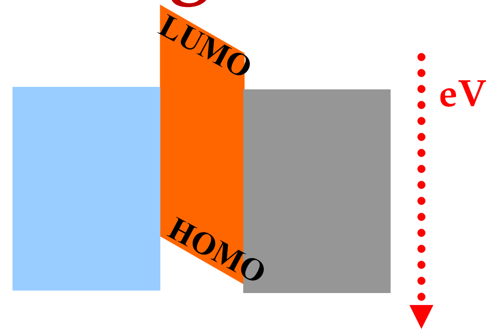
Absorption Coeff. of Organic Semiconductors



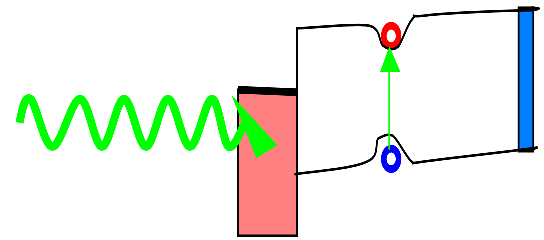
Generally the optical absorption coefficient (α) of organic materials is much higher than that of crystalline or multicrystalline silicon as shown in Figure. For the conjugated polymers MDMO-PPV and P3HT and for the molecular dye, zinc phthalocyanine (ZnPc) α exceeds $1\times10^5 cm^{-1}$ in the major part of the visible spectrum.Effective thicknesses of the order of ~ 100nm are required.

Single layer Organic Solar Cell

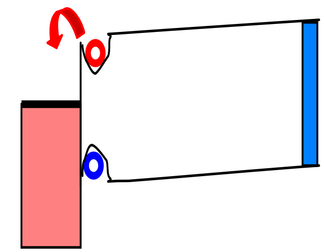




Short-circuit



- ❑ Excitons are mobile, electrically neutral, optically excited states, which exist because they do not have enough energy to separate into an electron and a hole.
- ❑The exciton separate at the iterfaces
- ❑Exciton diffusion length 1-10 nm, absorption depth >100 nm



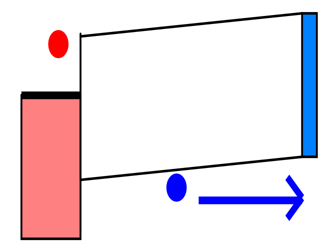
A Key Cell Parameter

the exciton diffusion length

$$L_n = \sqrt{D\tau}$$

→ **The exciton diffusion lenght is shorther than the light absorption lenght**

→ **Power efficiency η< 0.1%**



Source: J. Nelson, ICCMP 2004

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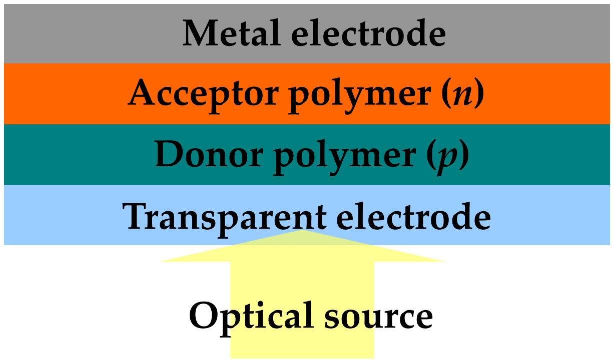
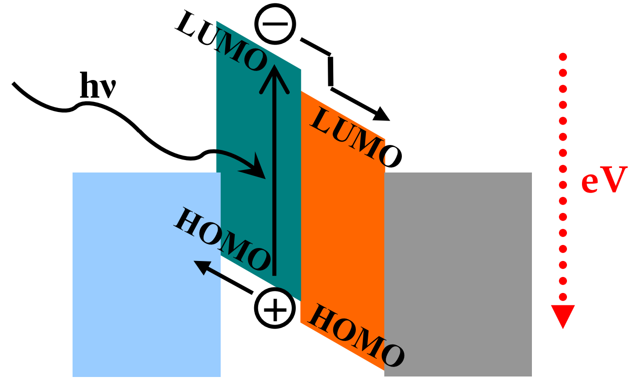
Double-layer

Bi-layer device (heterojunction)





Use of two polymers, donor and acceptor (***p*** and ***n*** type) → better conversion efficiency (~1%)

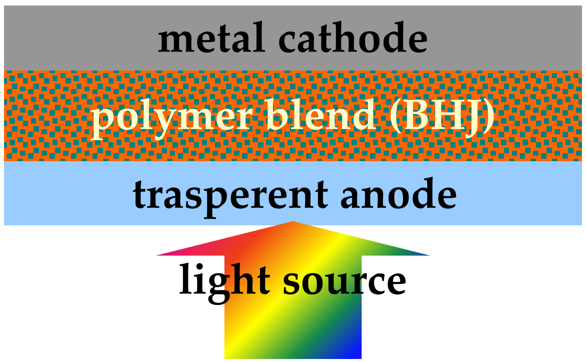
- photon absorption and exciton formation next to interface
- exciton dissociation favored by energetic levels

Remaining problems:

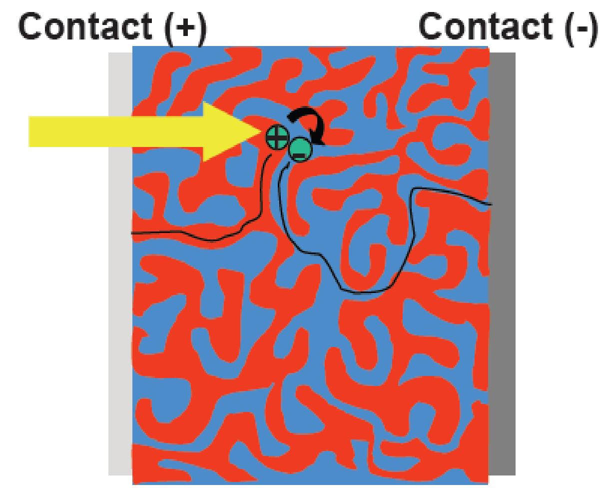
? higher series resistance

? solvent-crossing

Bulk-Heterojunction (BHJ-layer)



- Blend hole accepting with electron accepting material
- Length scale of blend ~ exciton diffusion length
- Charge separation at D-A interface
- Continuous paths for electron and hole percolation



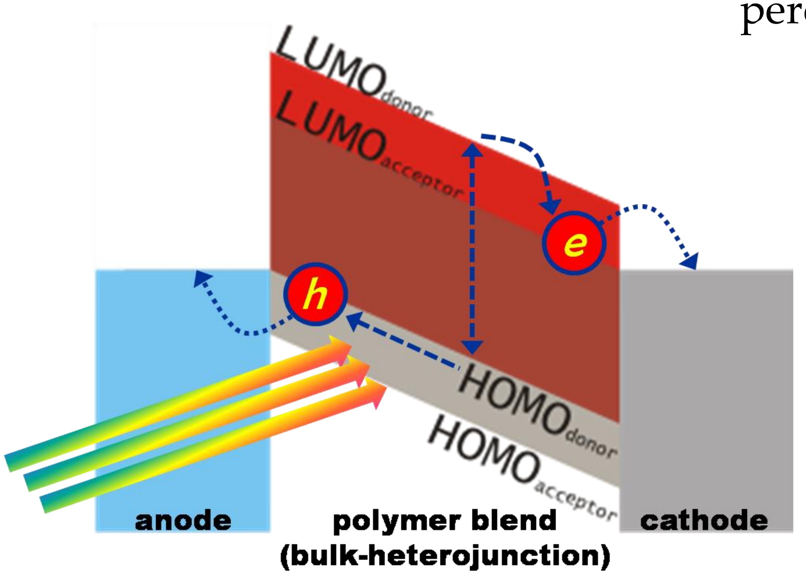
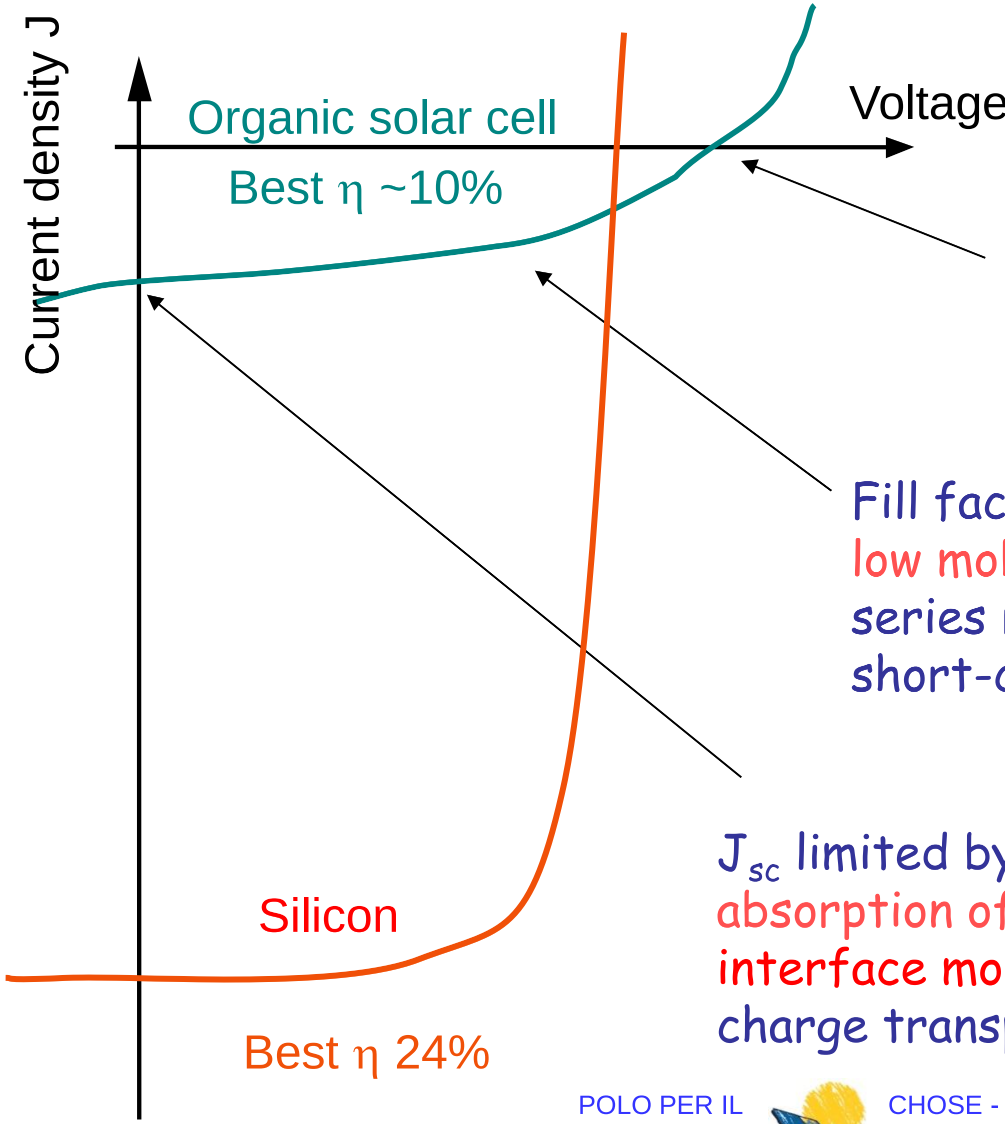


Photo-Voltaic effect in organic bulk-heterojunction:

1) Photon absorption
2) Exciton formation
3) Exciton diffusion to heterojunction ***a-d*** (acceptor-donor)
4) Exciton dissociation (electrons ***"hop"*** from LUMO_{donor} to $\text{LUMO}_{acceptor}$)
5) Carriers transport towards electrodes
6) Harvesting of carriers at electrodes

Improving organic solar cell efficiency



V_{oc} limited by:
interfacial recombination
interfacial energy levels
shunt losses

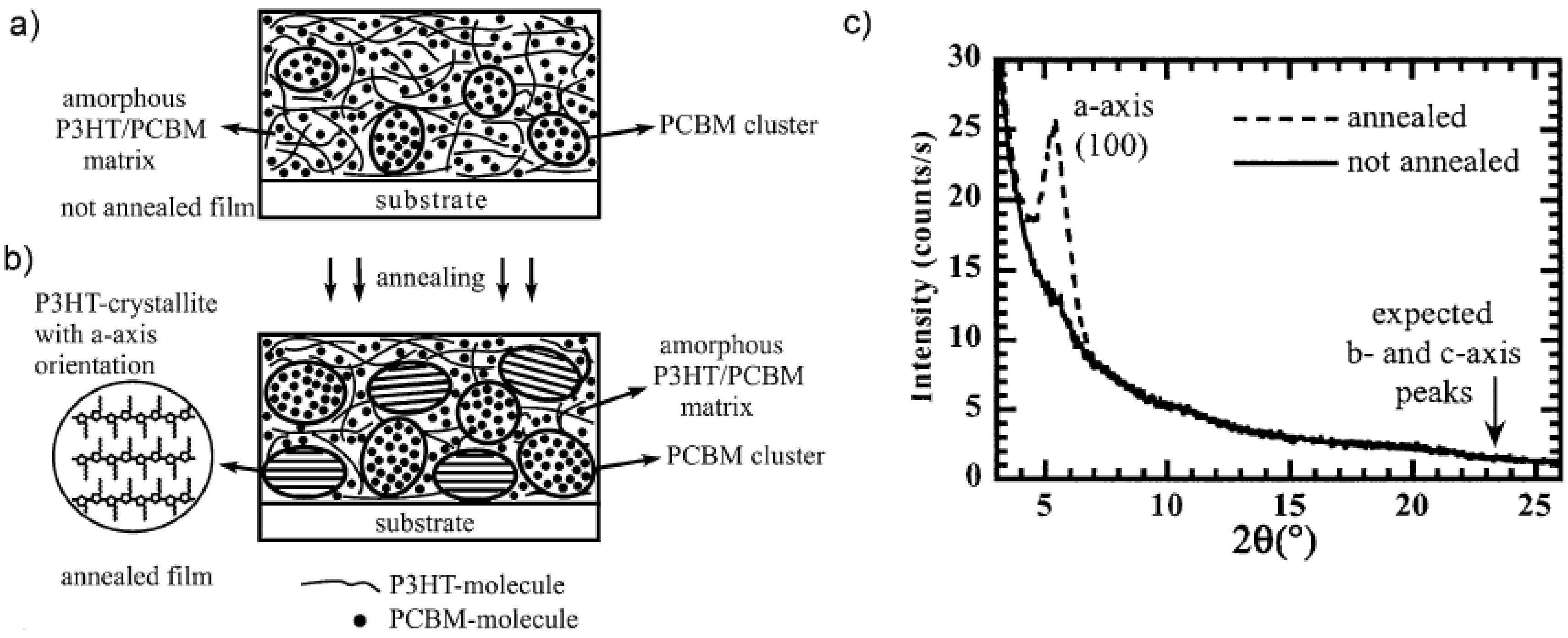
Fill factor limited by:
low mobility
series resistance
short-circuits

J_{sc} limited by:
absorption of red light,
interface morphology
charge transport

Source: J. Nelson, ICCMP 2004

Morphology

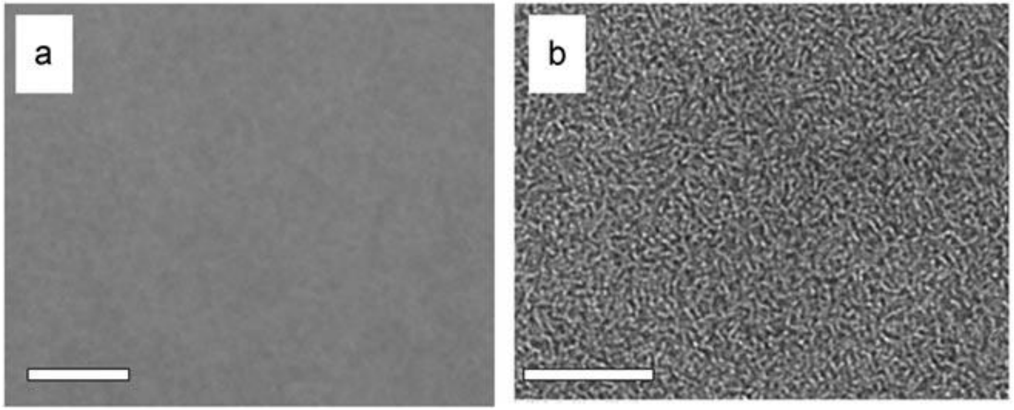
Morphology



a,b) Schematic pictures showing the microscopic process during annealing. c) Grazing incidence X-ray spectrum on a blend before and after annealing, showing the evolution of the a-axis oriented P3HT crystals.

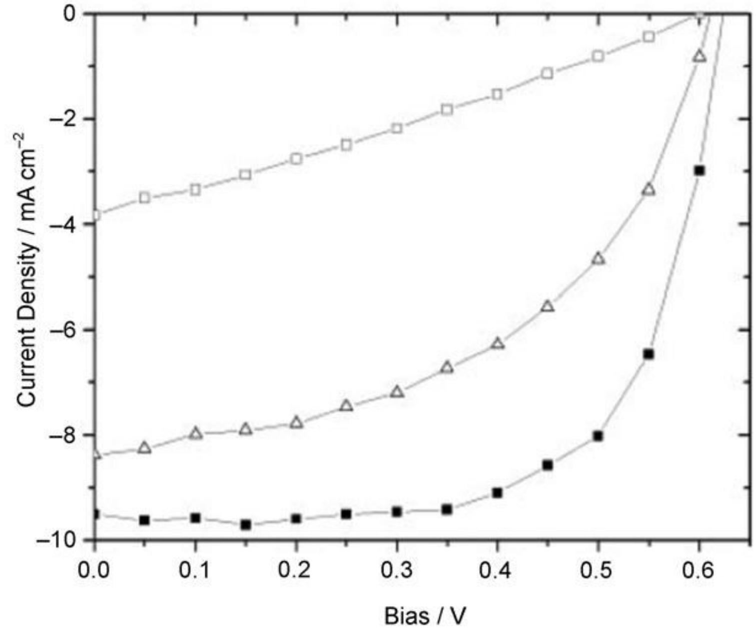
Dennler et al., *Adv. Mater.*, 2009, 21, 1–16

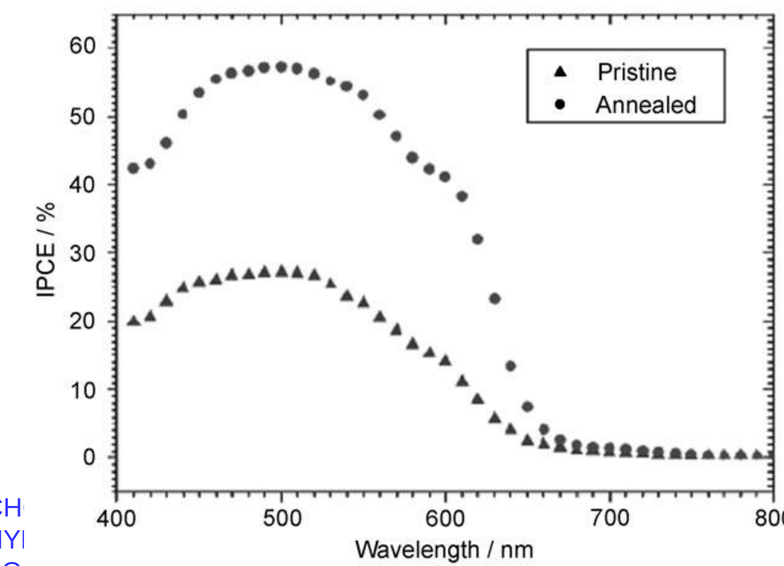
Effect of thermal annealing



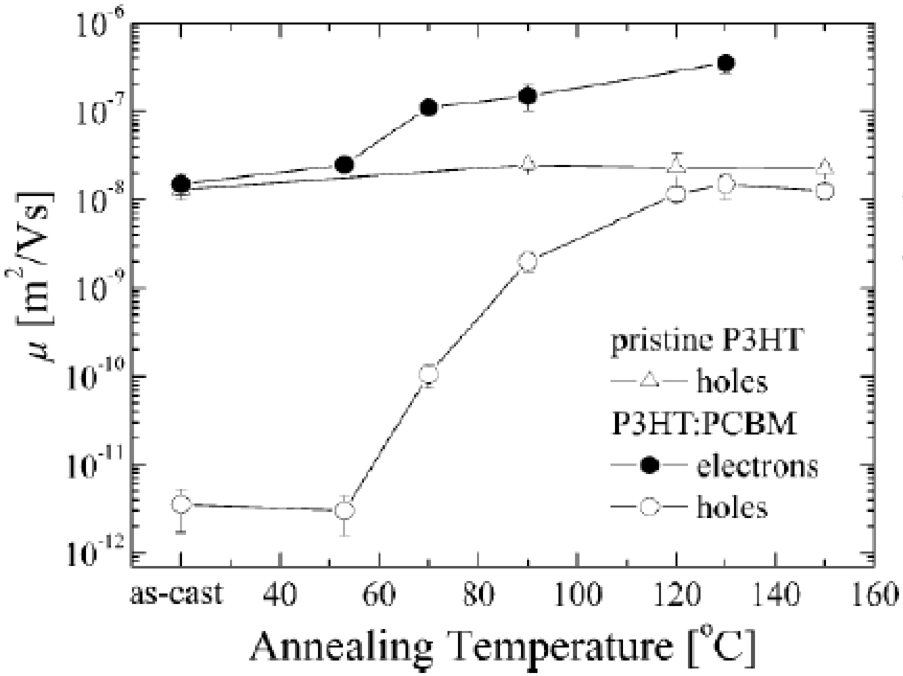
TEM images of 1:1 blend of P3HT and PCBM prior (a) and after (b) thermal annealing at 150°C for 30 minutes (scale bar 0.5 mm).

Thomson et al., *Angew. Chem. Int. Ed.*, 2008, 47, 58–77

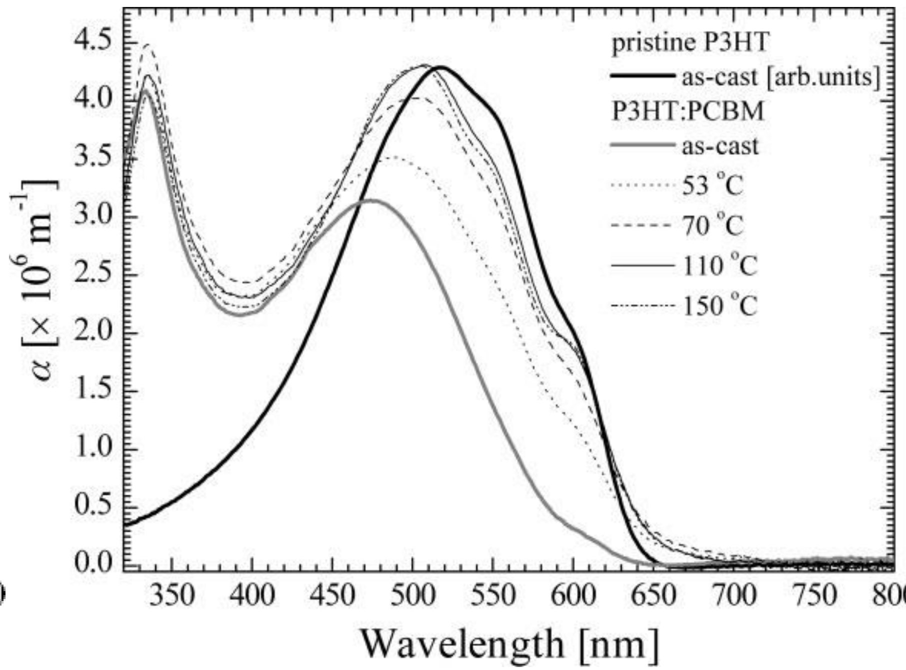




Effects of morphology



Room-temperature electron (●) and hole (o) zero-field mobilities in (1:1) blends of P3HT:PCBM as a function of postproduction annealing temperature of the completed devices. For comparison, the hole mobility measured in pristine P3HT devices (Δ) is also shown.

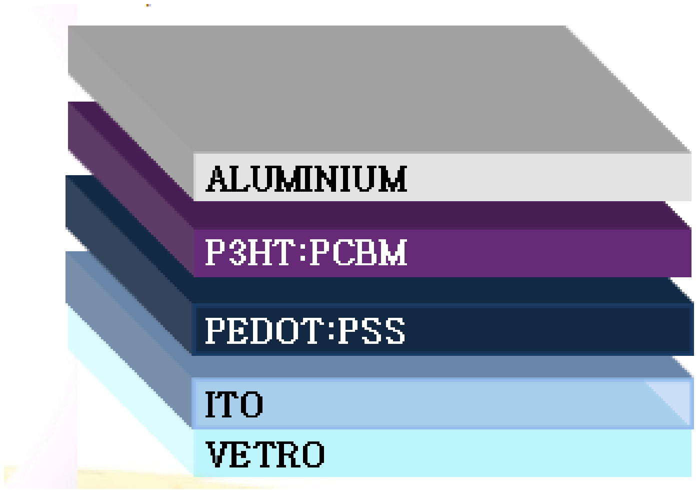


Absorption spectra of P3HT:PCBM blend films for different annealing temperatures.

Mihailetchi et al., *Adv. Funct. Mater.*, 2006, 16, 699

Architectures

Standard architecture

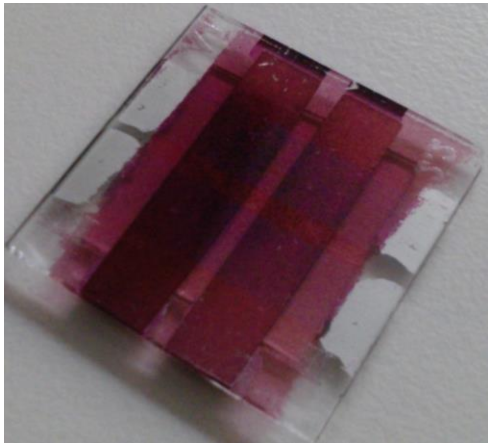


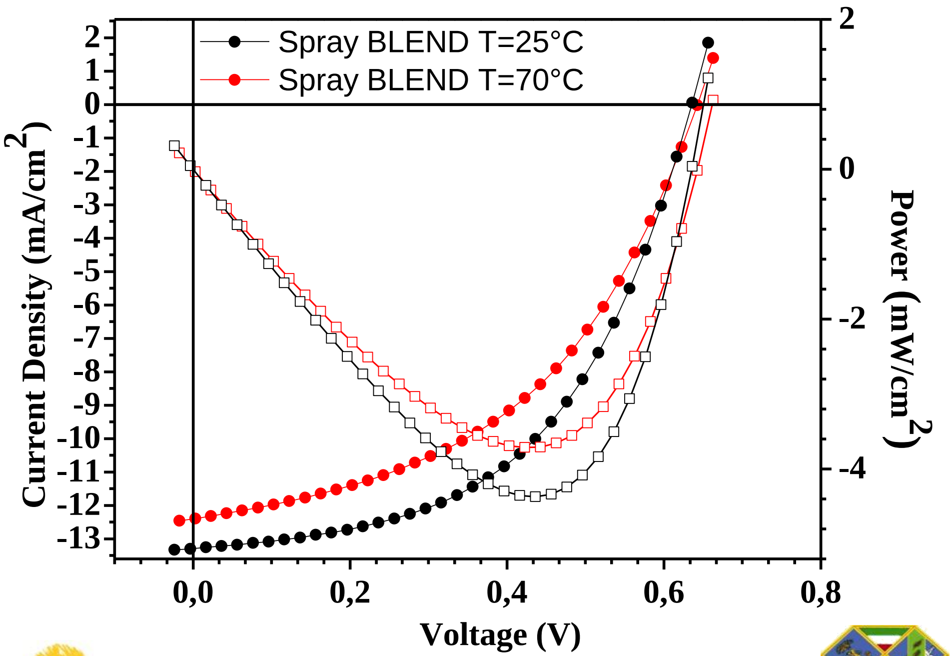
Cathode: Al, Ca/Al

Active layer

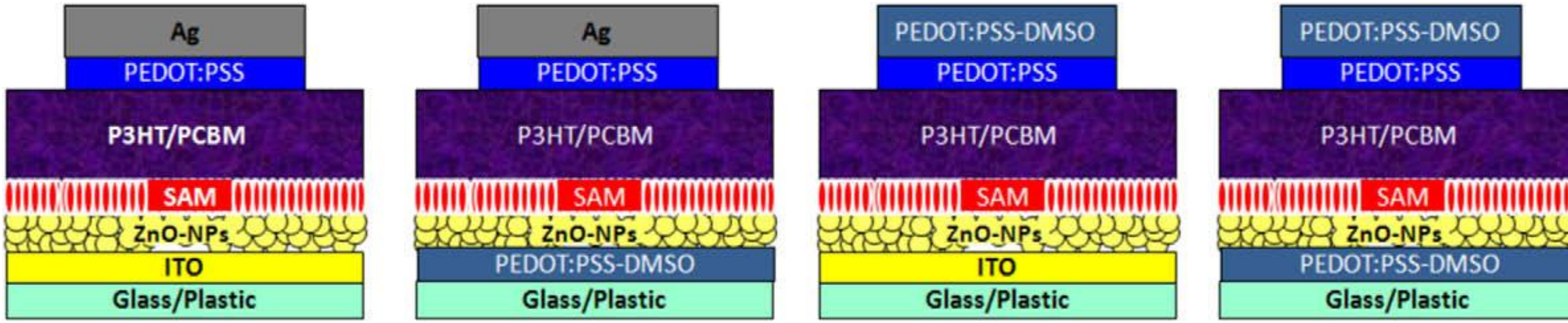
HTL: PEDOT:PSS, MoO_3, Cs_2Co_3, V_2O_5, TiO_2, ZnO, NiO

Anode: ITO/FTO

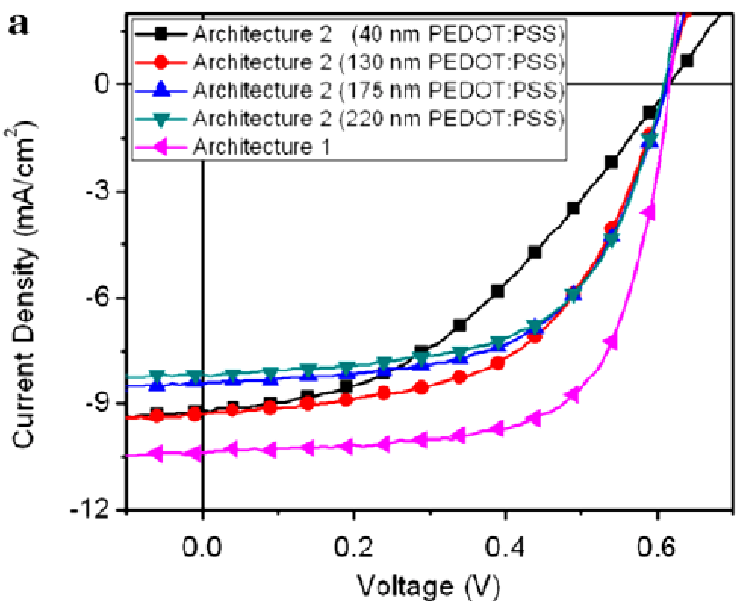


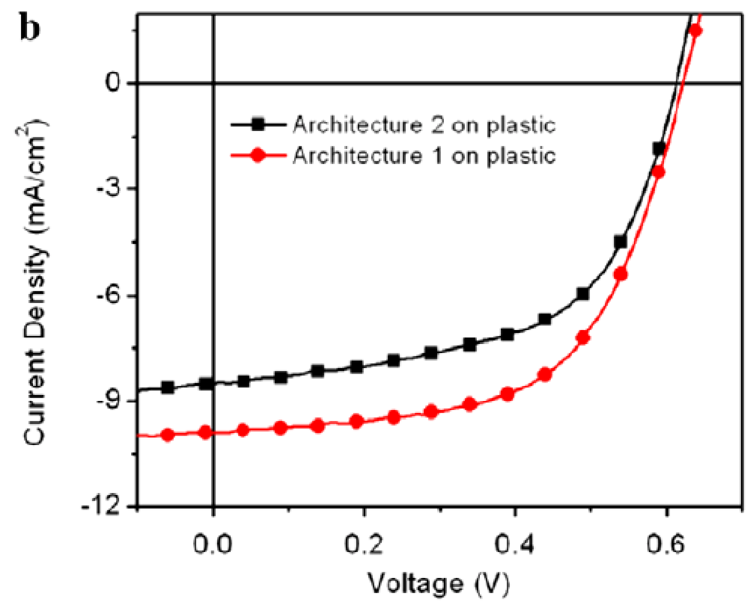


Inverted Solar Cells



Architecture 1 **Architecture 2** **Architecture 3** **Architecture 4**





Hau et al., *Org. Electr.*, 2009, 10, 1401–1407

Università di Roma Tor Vergata

POLO PER IL FOTOVOLTAICO A CELLE ORGANICHE DEL LAZIO

CHOSE - CENTER FOR HYBRID AND ORGANIC SOLAR ENERGY

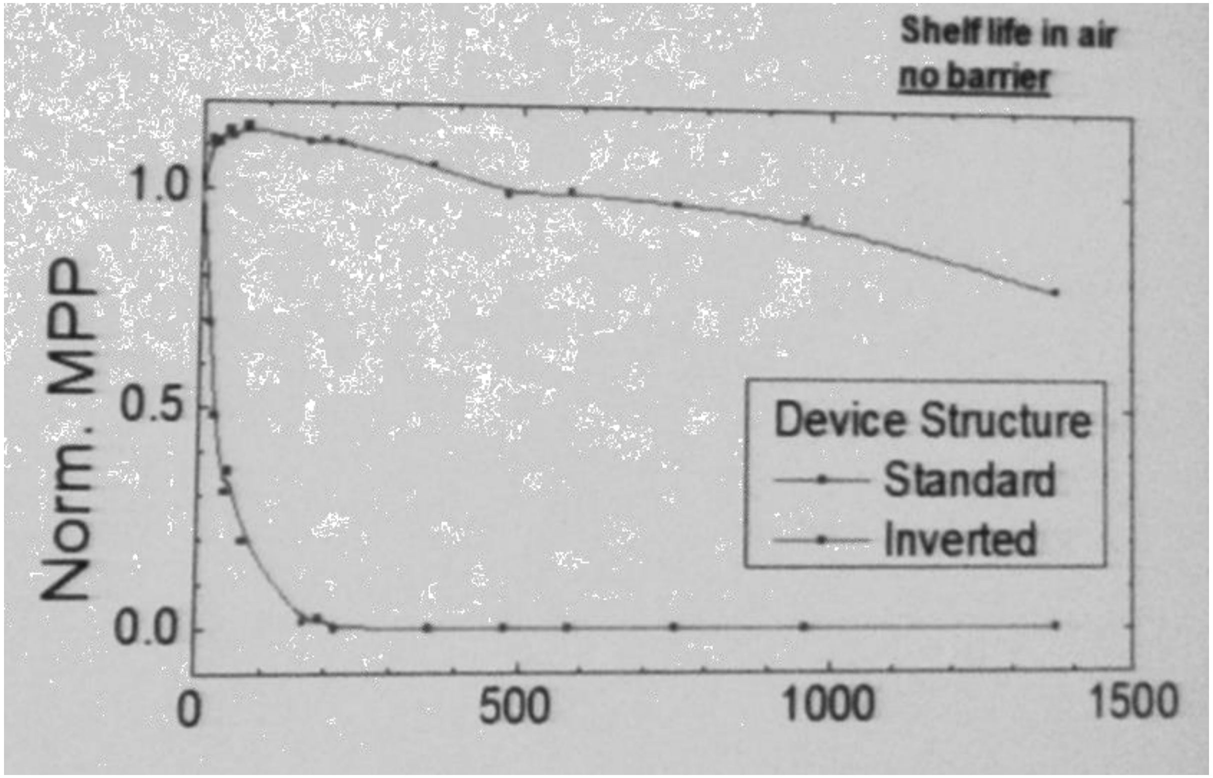
Inverted solar cells: higer stability

LiF/Al
Blend
PEDOT
ITO
Glass

Standard

Ag
PEDOT
Blend
ZnO
ITO
Glass

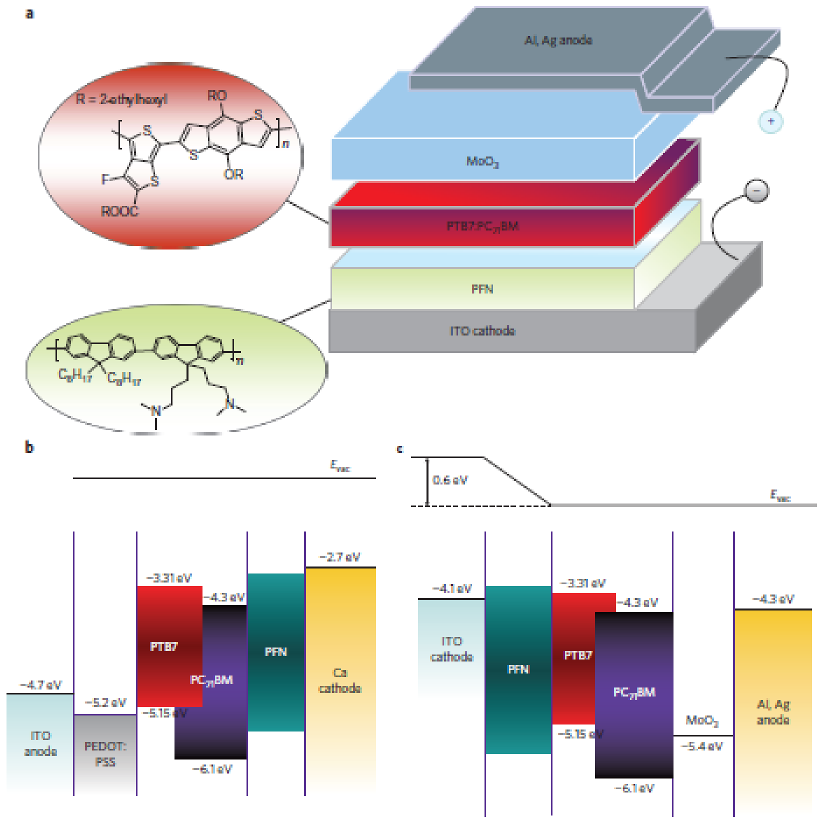
Inverted

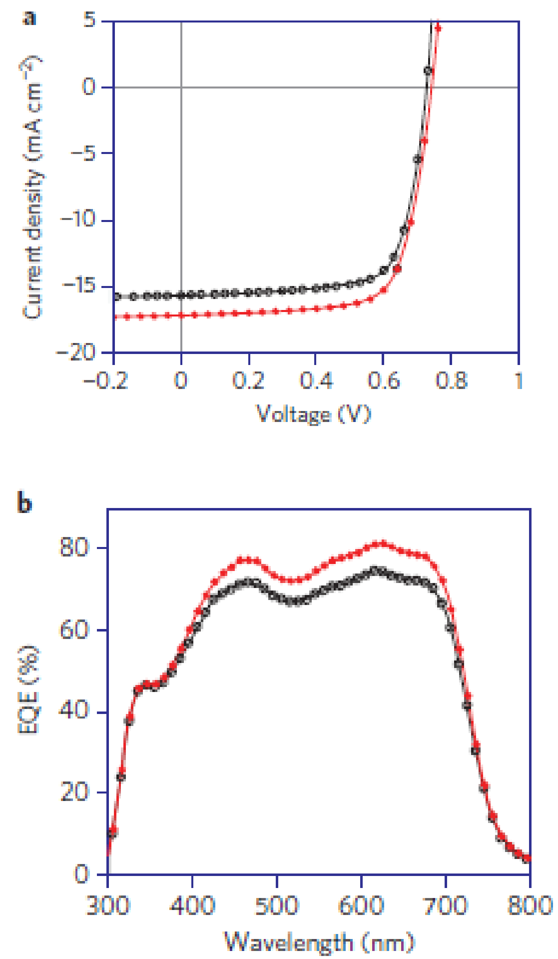


The use of an inverted architecture leads to a substantial increase of the device lifetime

Holdst center PVSEC 2011

Inverted architecture: the record for a single junction BHJ

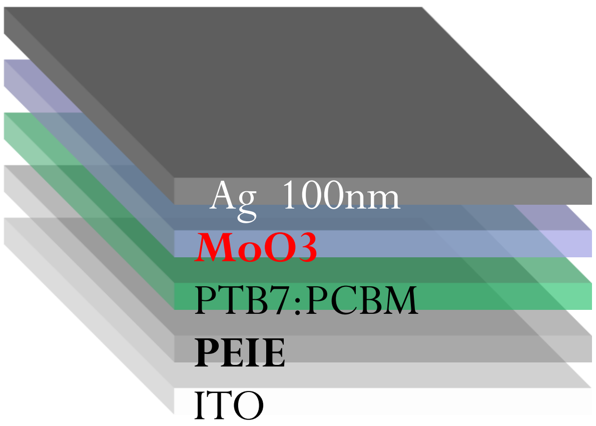


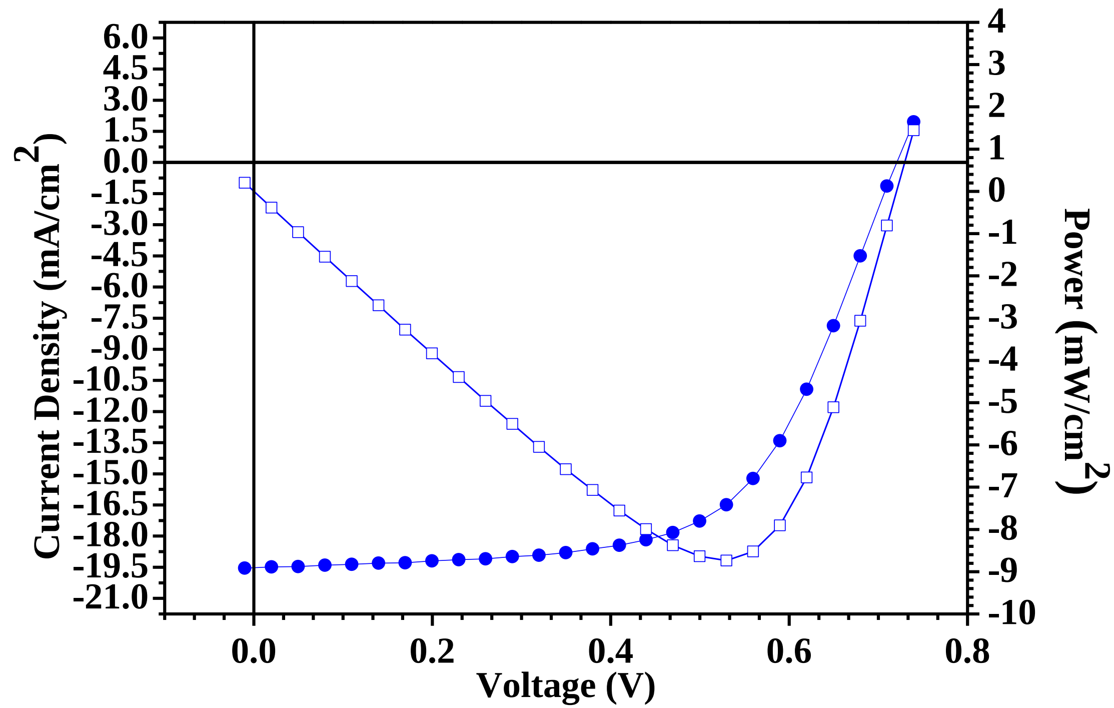


Device type	PCE (%)	J_{SC} (mA cm^{-2})	FF (%)	V_{OC} (V)
Conventional	8.24	15.4	70.6	0.759
Inverted	9.15	17.2	72.0	0.740
Inverted, tested by CPVT	9.214	17.46	69.99	0.754

Z. He et al. NATURE PHOTONICS , VOL 6, pp591-595 SEPTEMBER 2012

PTB7:PCBM active layer/inverted architecture





		Voc(V)	Jsc(mA/cm2)	FF(%)	PCE(%)
PEIE	**CHOSE**	**0.72**	**19.52**	**63.55**	**8.73**
	Reference	**0.74**	**17.2**	**72**	**9.15**
	Z.He et al., Enhanced power-conversion efficiency in polymer solar cells using an inverted device structure, NATURE PHOTONICS DOI:10.1038/nphoton.2012.190				

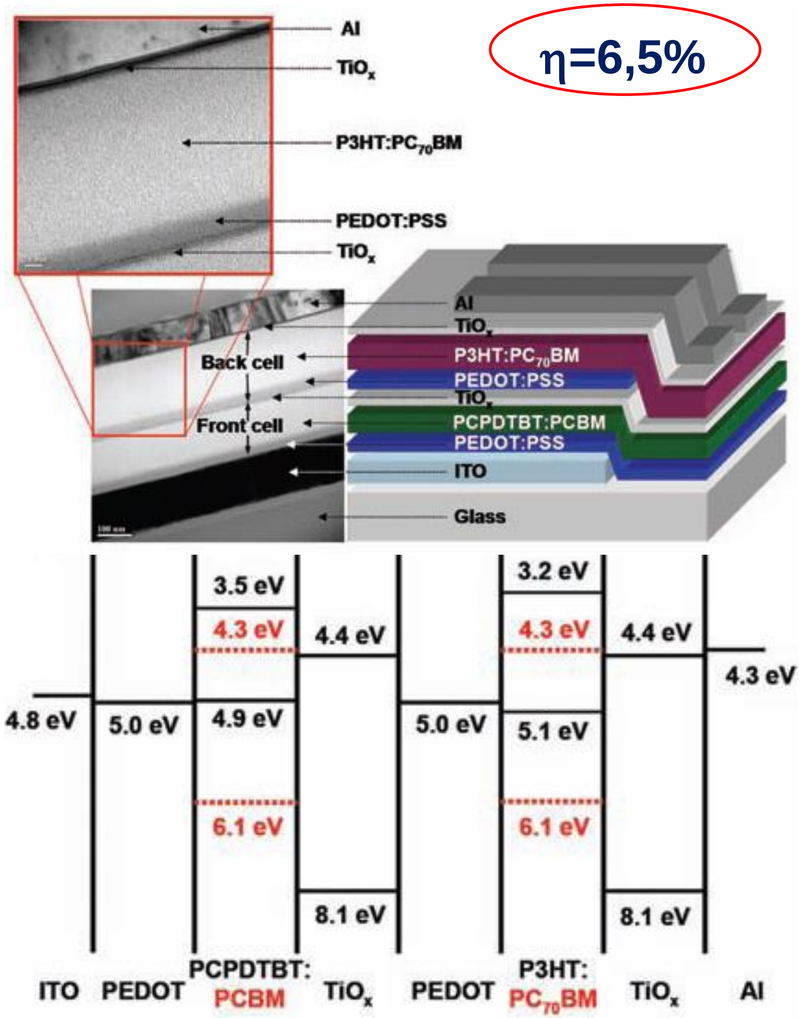
Susanna et al. Submitted

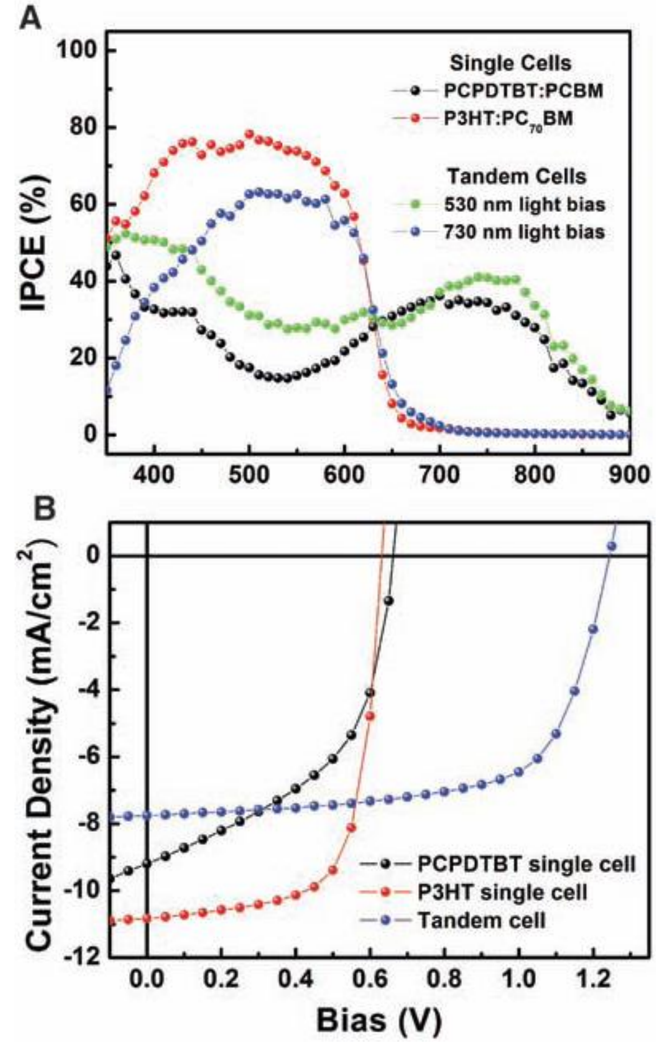
POLO PER IL FOTOVOLTAICO A CELLE ORGANICHE DEL LAZIO

CHOSE - CENTER FOR HYBRID AND ORGANIC SOLAR ENERGY

Tandem Solar Cells

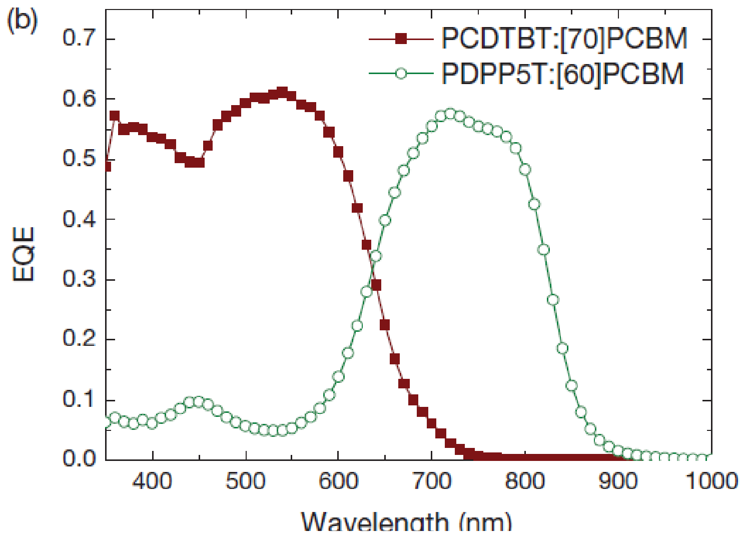
η=6,5%

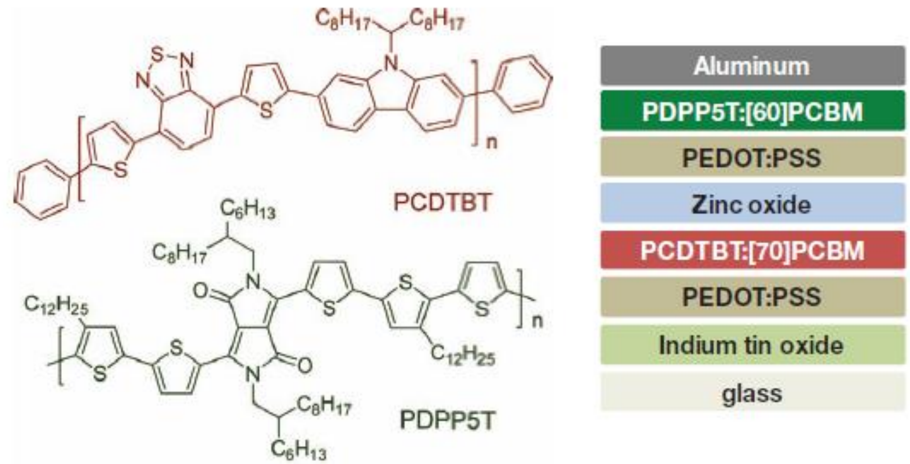


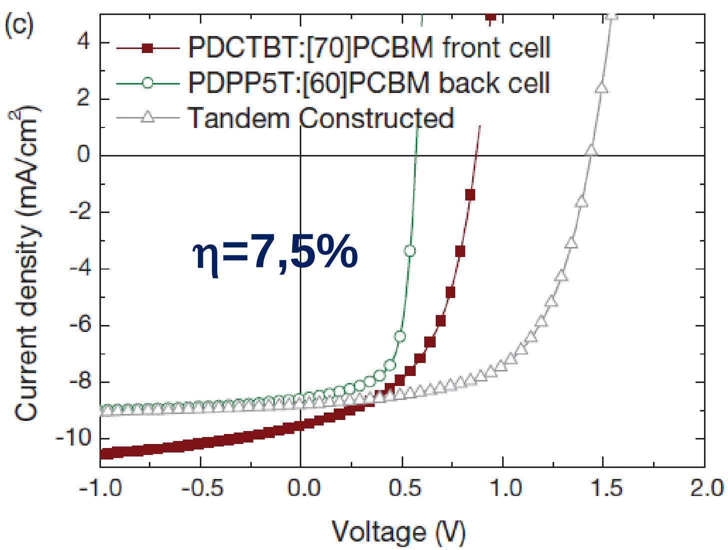


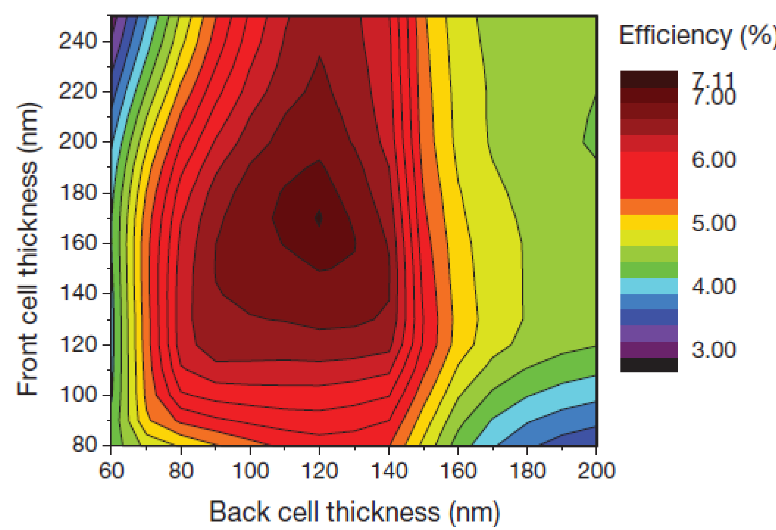
Kim et al., ***Science***, **2007, 317, 222**

Optimization of tandem solar cells









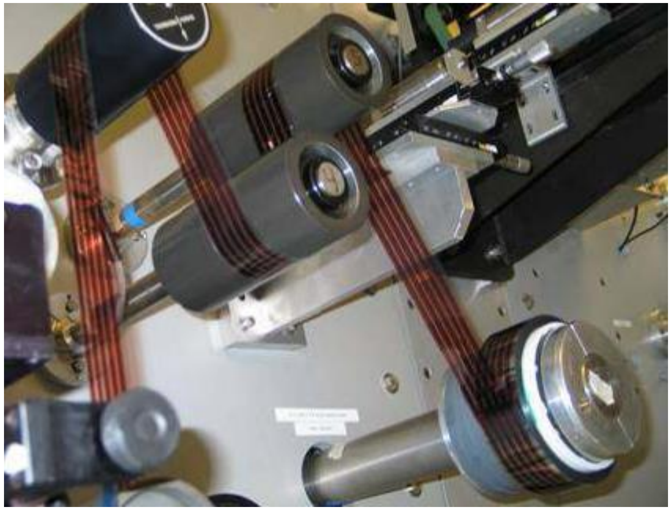
Veronique S. Gevaerts et al Adv. Mater. ***2012, 24, 2130–2134***

Large area realization techniques

Large area BHJ processing

The requirements for an ideal process on large area are:

- Solution processing of all layers on flexible substrates controlling the film thickness, uniformity and shape
- Few coating and printing steps
- Free from costly indium, toxic solvents and chemicals
- Low environmental impact and a high degree of recyclability.
- Low costs
- High speed
- High throughput

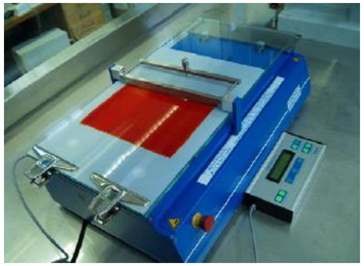


Konarka Technologies, Inc.

Roll to roll approach represent the preferred solution

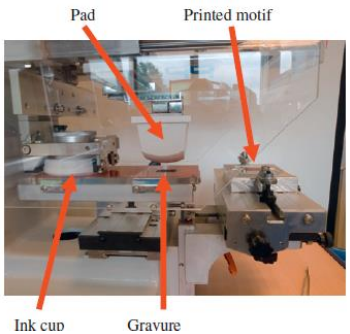
Large area coating tecniques

There is a huge amount of film-forming techniques, but still no established approach for the realization of polymer solar cells.



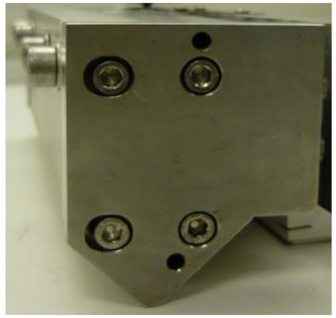
SCREEN-PRINTING

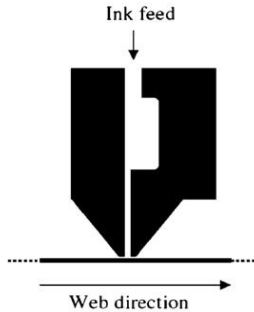
DOCTOR BLADING



PAD-PRINTING

SLOT-DIE





SPRAY-COATING

INK-JET PRINTING

Università di Roma Tor Vergata

POLO PER IL FOTOVOLTAICO A CELLE ORGANICHE DEL LAZIO

CHOSE - CENTER FOR HYBRID AND ORGANIC SOLAR ENERGY

Comparison of the deposition techniques

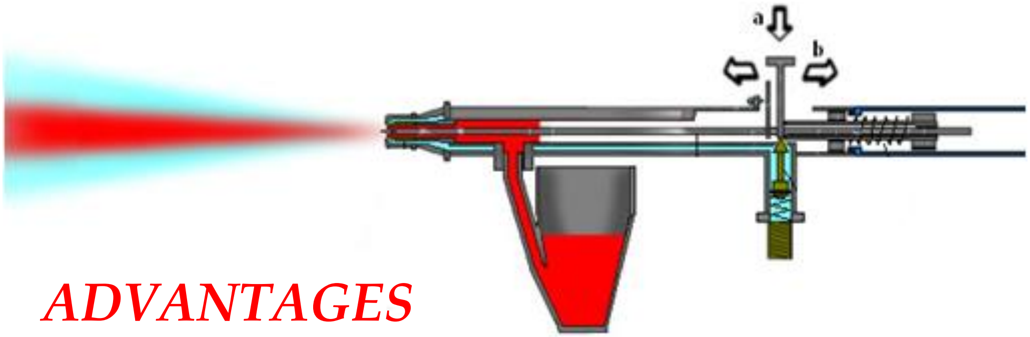
Technique	Ink waste	Pattern	Speed	Ink preparation	Ink viscosity (cP)	Wet thickness (μm)	R2R compatible
Spincoating	5	0	–	1	1	0–100	No
Doctor blade	2	0	–	1	1	0–100	Yes
Casting	1	0	–	2	1	5–500	No
Spraying	3	0	1–4	2	2–3	1–500	Yes
Knife-over-edge	1	0	2–4	2	3–5	20–700	Yes
Meniscus	1	0	3–4	1	1–3	5–500	Yes
Curtain	1	3	4–5	5	1–4	5–500	Yes
Slide	1	3	3–5	5	1–3	25–250	Yes
Slot-die	1	1	3–5	2	2–5	10–250	Yes
Screen	1	2	1–4	3	3–5	10–500	Yes
Ink jet	1	4	1–3	2	1	1–500	Yes
Gravure	1	2	3–5	4	1–3	5–80	Yes
Flexo	1	2	3–5	3	1–3	5–200	Yes
Pad	1	2	1–2	5	1	5–250	Yes

Ink waste: 1 (none), 2 (little), 3 (some), 4 (considerable), 5 (significant). Pattern: 0 (0-dimensional), 1 (1-dimensional), 2 (2-dimensional), 3 (pseudo/quasi 2/3-dimensional), 4 (digital master). Speed: 1 (very slow), 2 (slow $<1\,\mathrm{m\,min^{-1}}$), 3 (medium $1–10\,\mathrm{m\,min^{-1}}$), 4 (fast $10–100\,\mathrm{m\,min^{-1}}$), 5 (very fast $100–1000\,\mathrm{m\,min^{-1}}$). Ink preparation: 1 (simple), 2 (moderate), 3 (demanding), 4 (difficult), 5 (critical). Ink viscosity: 1 (very low <10 cP) 2 (low 10–100 cP), 3 (medium 100–1000 cP), 4 (high 1000–10,000 cP), 5 (very high 10,000–100,000 cP).

F.C. Krebs / Solar Energy Materials & Solar Cells 93 (2009) 394–412

Spray-coating technique

Commercial Airbrush



ADVANTAGES

- **Solution processing → Low-cost deposition**
- **Large Area deposition** suitable also for **flexible** substrates with **different morphologies**
- **Fluid waste reduced** respect to spin-coating
- **Easy to use**

ISSUES

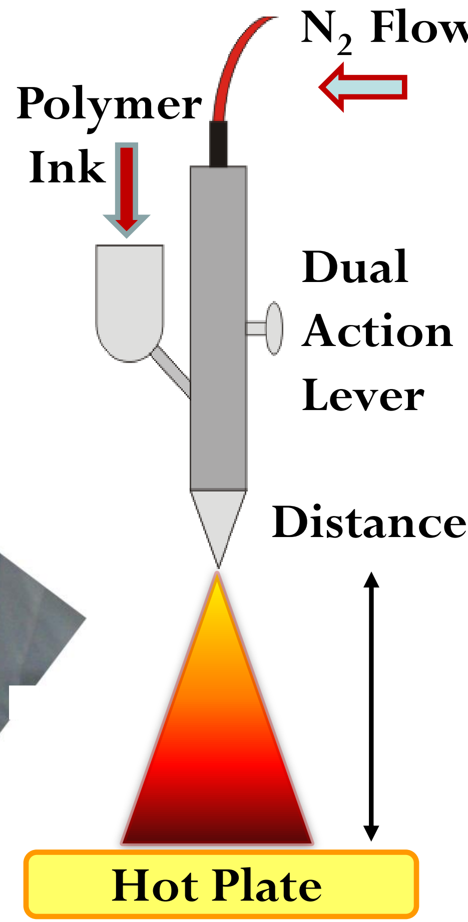
- **Film control →** thickness, uniformity and roughness
- **Many process-variables to be controlled**

Spray-Coating set-up

Instrument variables

1. **Distance** sample / airbrush: 10-18cm
2. **Flow Rate**: ~17-25µl/s (~1-1,5ml/min)
3. **Pressure** N_2 flow : 10-15 Psi
4. **Substrate Temperature** : 25°-70°C

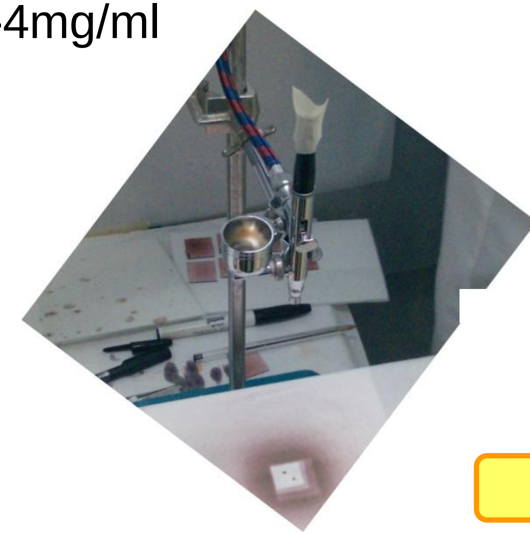
Conventional environment
(under chemical hood)

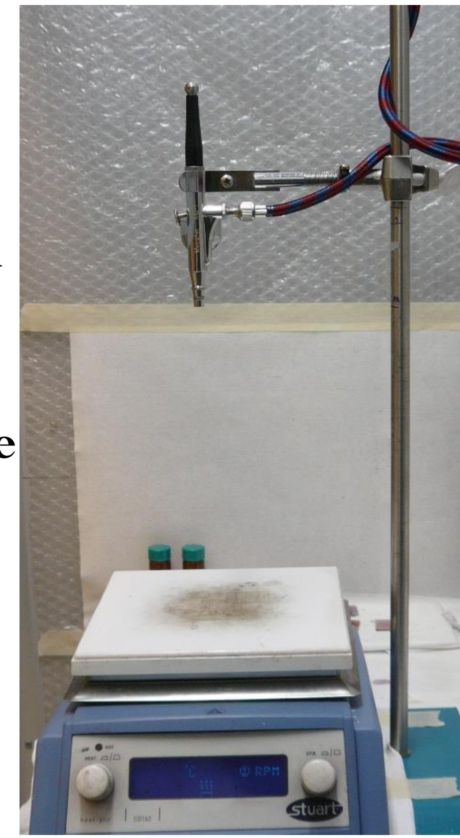


Film Parameters

5. **Time** of spray: 10-60s
6. **Number** of passes: 1-
7. **Concentration**: 1-4mg/ml
8. **Solvents**

} Thickness

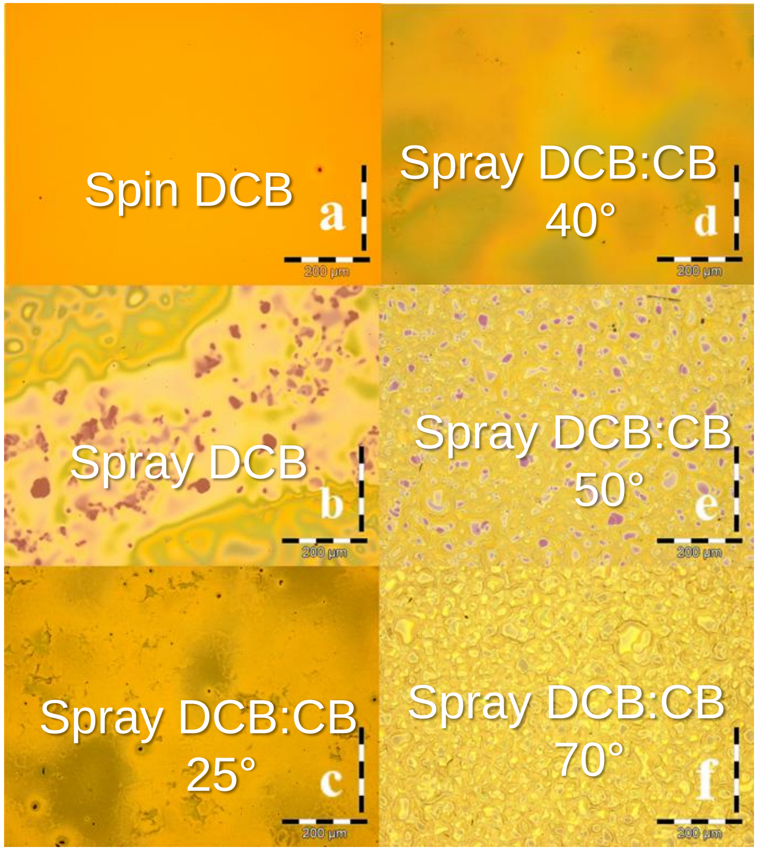


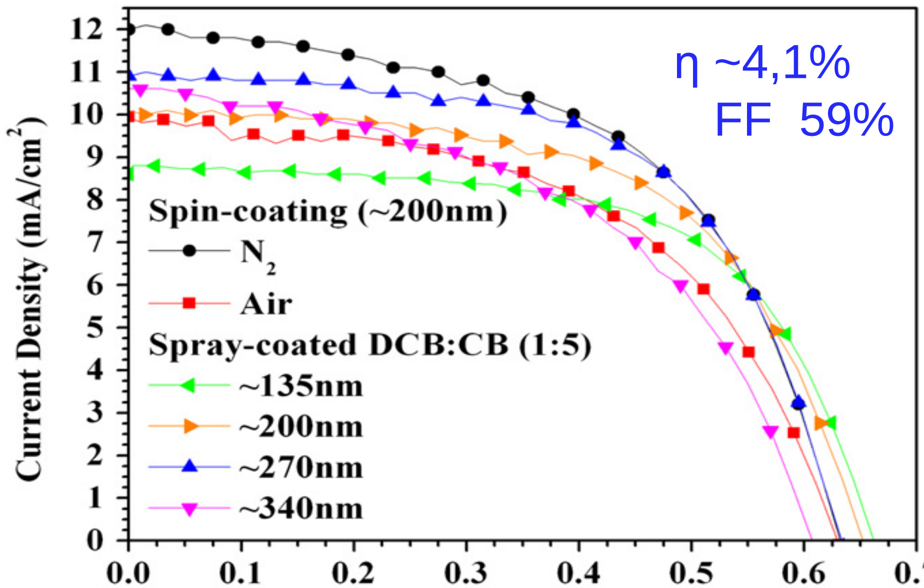


Co-Solvent optimization: temperature effect

Co-solvent mixture: <u>*DCB:CB (1:5)*</u>

<u>DCB</u>: improves the phase separation
<u>CB</u>: allows better spray deposition

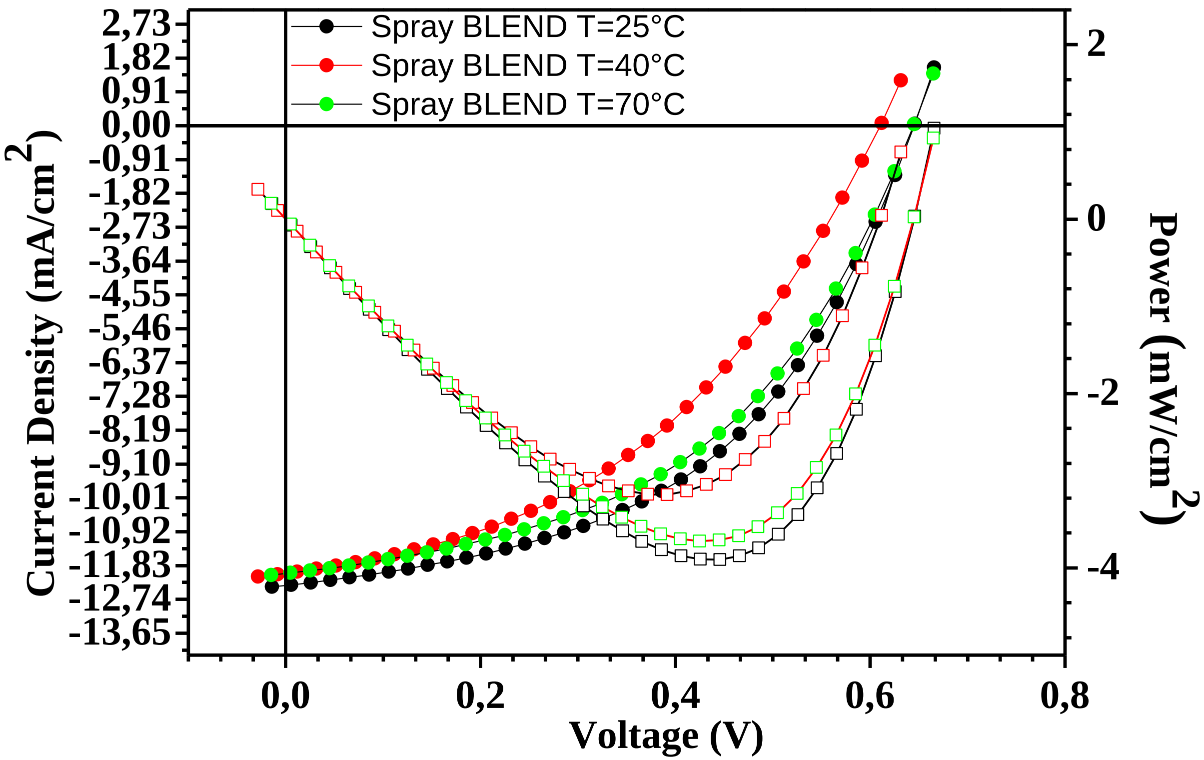


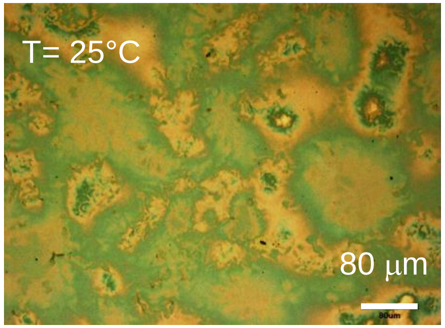


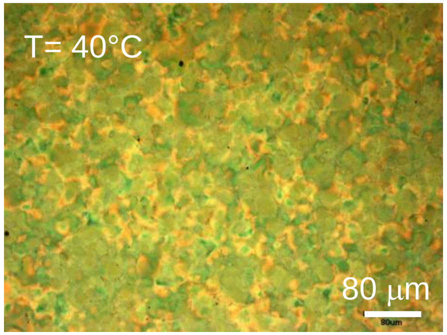
Dep	Amb	Tk (nm)	V_{oc} [V]	J_{sc} [mA/cm²]	FF [%]	η [%]
Spin	N_2	200	0.63	11.96	55	**5.1**
	Air			9.97	53	3.3
Spray		135	0.66	8.89	60	3.6
		200	0.64	10.34	57	3.8
		270		10.98	59	**4.1**
		340	0.61	10.62	50	3.2

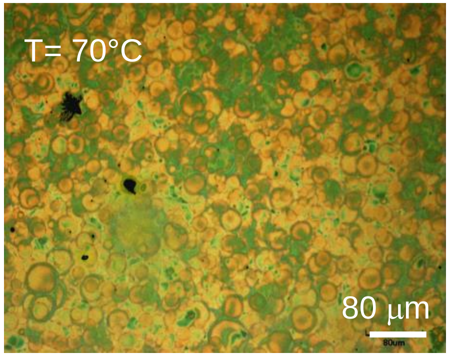
G. Susanna et al., Solar Energy Materials & Solar Cells 95 (2011) 1775–1778

Spray coating HTL + Active layer



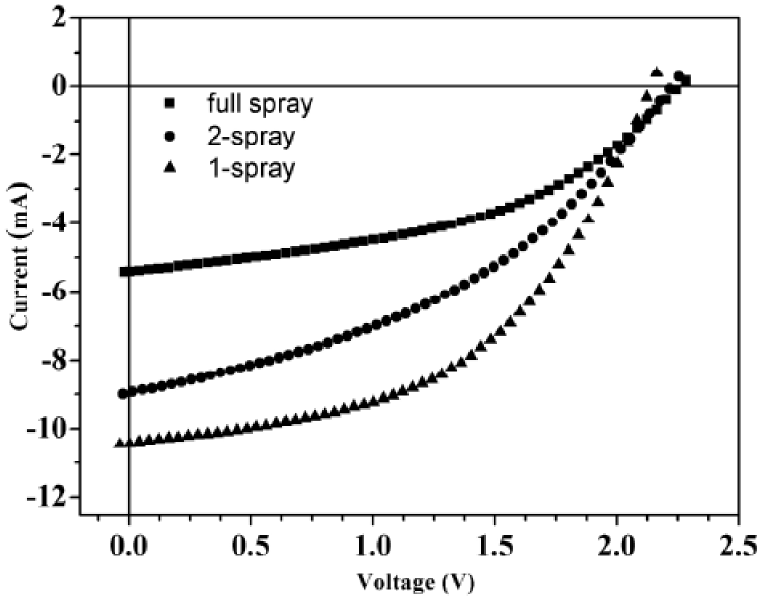


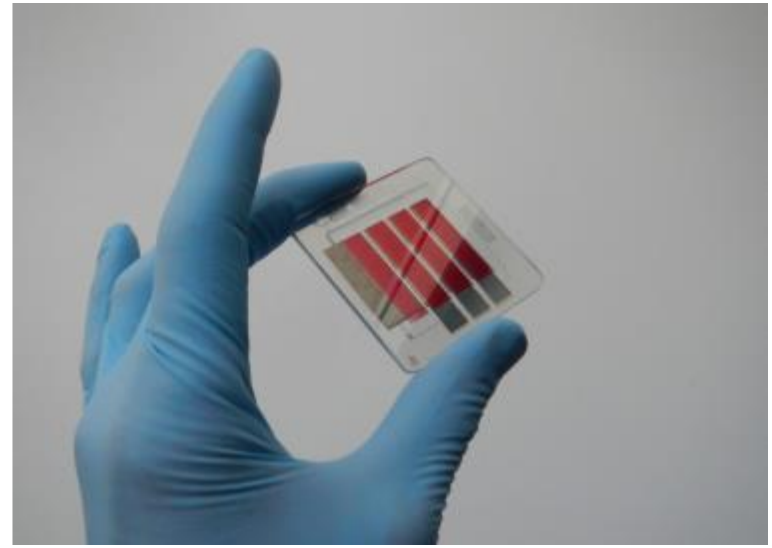




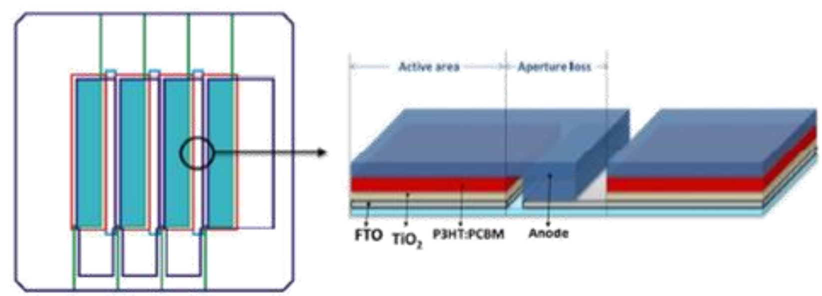
$T_{substrate}$	PCE %	FF %	Voc (V)	Jsc (mA/cm²)
25 °C	3.9	49	0.64	12.4
40 °C	3.5	48	0.62	11.62
70 °C	3.7	46	0.64	12.04

Fully spray coated solar cell





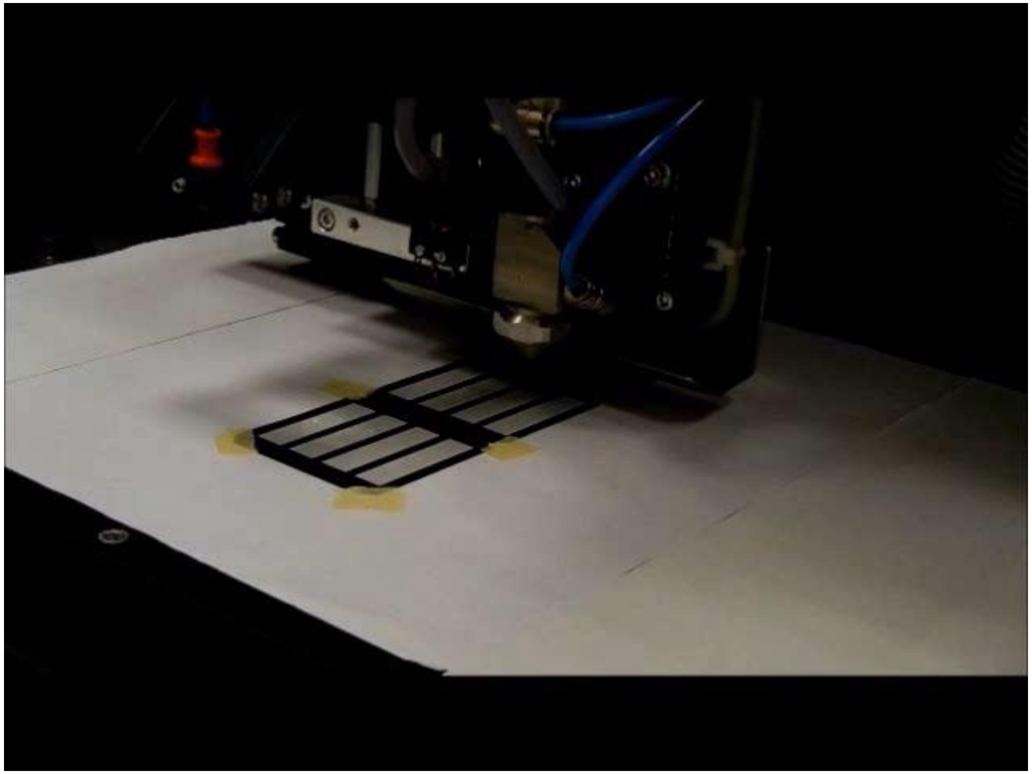
Active Area: 6 cm^2
Efficiency: 1,8%



246x92mm (96 x 96 DPI)

L. La Notte, et al., Energy Technology, 1, 12 (2013) 709.

Perspectives: large area OPV using spray coating techniques



Devices on flexible substrates

Semi-trasparent

Flexible

Università di Roma Tor Vergata

POLO PER IL FOTOVOLTAICO A CELLE ORGANICHE DEL LAZIO

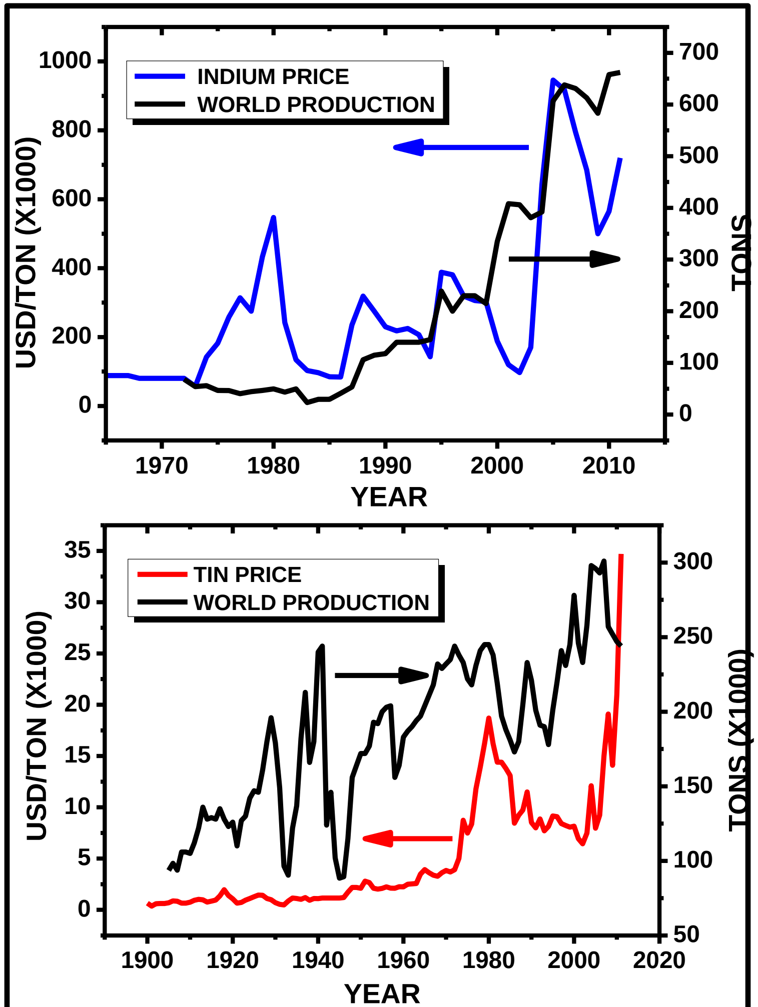
POLOSOLAREORGANICO RegioneLazio

CHOSE - CENTER FOR HYBRID AND ORGANIC SOLAR ENERGY

Carbon based semitransparent elecrodes in new generation solar cells

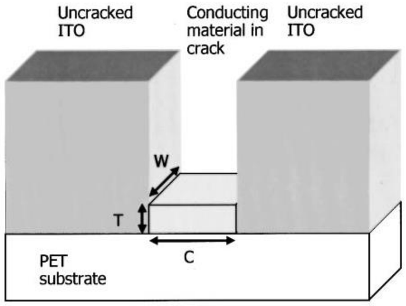
The Indium Tin Oxide issue

INDIUM AND TIN PRICE

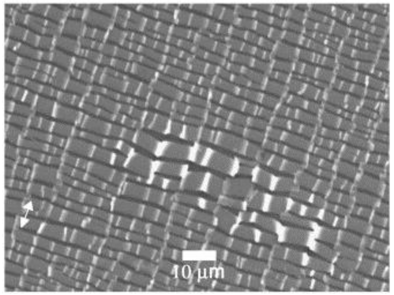


U.S. Geological Survey 2012

CRACK AND FRACTURE AT STRAIN OF 2÷6%

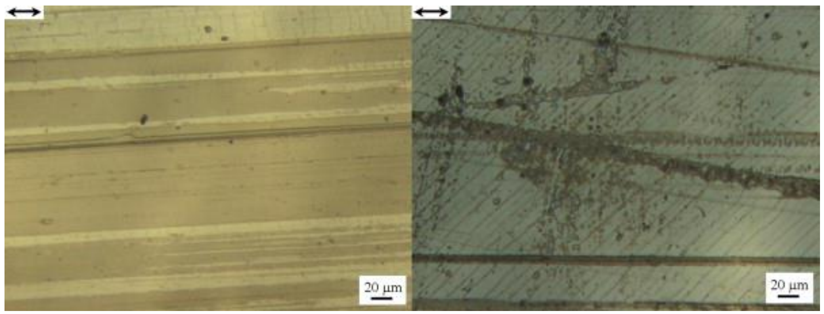


Cairns *et al.* 2000



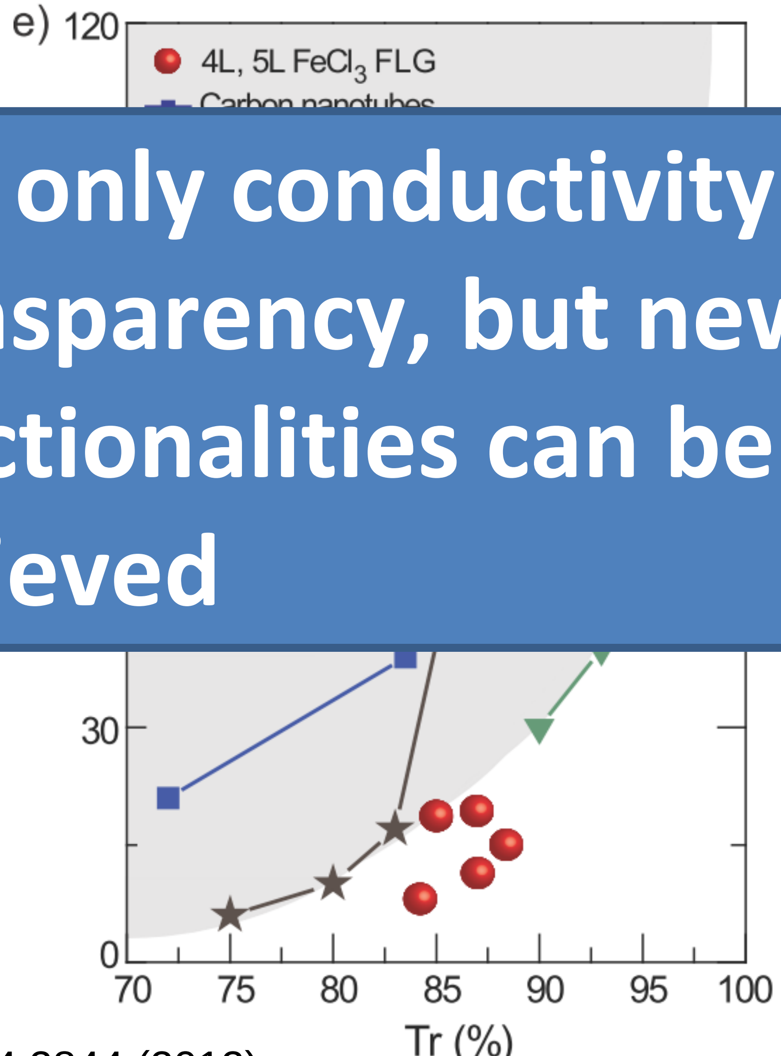
Sierros *et al.* 2009

SALTS AND ACIDS CAN REDUCE LIFETIME



Sierros *et al.* 2009

Carbon based alternatives to TCO



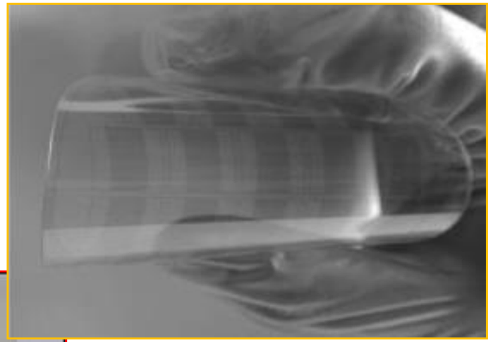
Not only conductivity and transparency, but new functionalities can be achieved

I. Khrapach et al., Adv. Mat. 24,2844 (2012).

CNTs as TCO in new generation solar cells

CNTs Transparent Electrodes

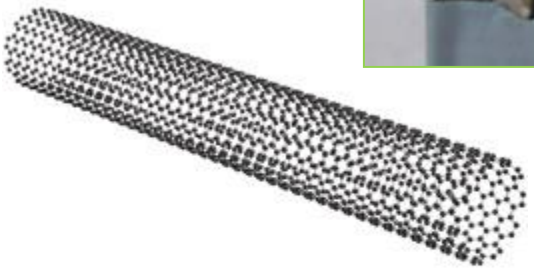
CNTs TRANSPARENT CONDUCTIVE LAYERS
- HIGH TRANSPARENCY
- FLEXIBLE
- EXELLENT ELECTRICAL CONDUCTIVITY
- COMPATIBLE WITH INDUSTRIAL PROCESS



Kim *et al.* 2010

Tenent *et al.* 2009

Hu *et al.* 2007

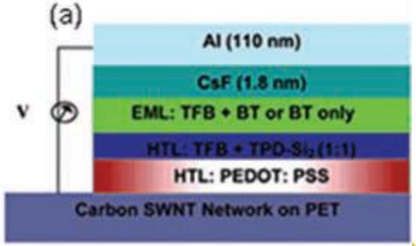


APPLICATIONS

DISPLAY

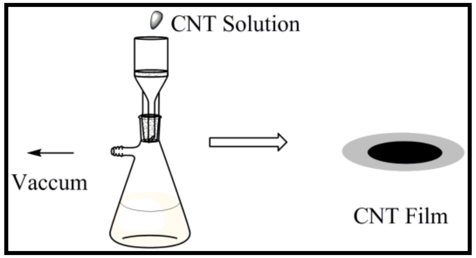
Unidym/Samsung

SOLAR CELLS



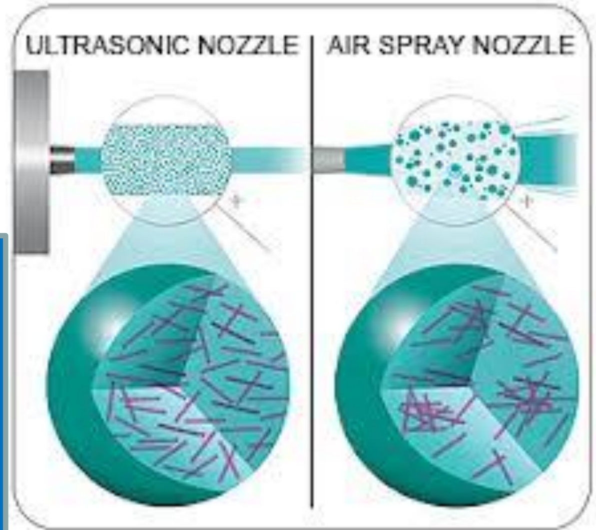
Yu *et al.* 2009

CNTs Deposition Techniques



VACUUM ASSISTED FILTRATION
PRO:
- INEXPENSIVE
- CONTROL OVER FILM THICKNESS
- NO SURFACTANTS

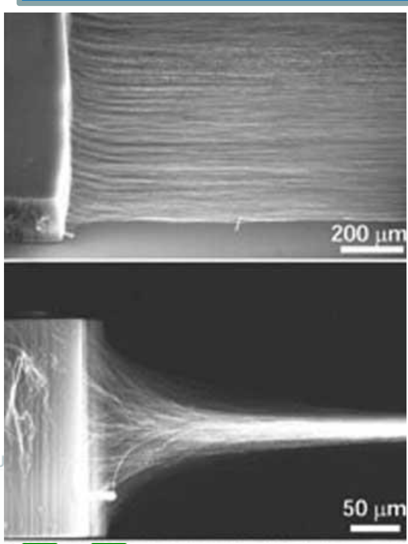
CONS:
- VERY LIMITED FILM SIZE
- SLOW PROCESS



Sono-Tek Corp.

SPRAY COATING
PRO:
- SCALABLE
- EFFECTIVE FOR CONTOURED SURFACES

CONS:
- INHOMOGENEUS IF NOT AUTOMATIC
- AVERAGE ADHESION



Zhang *et al.* 2005

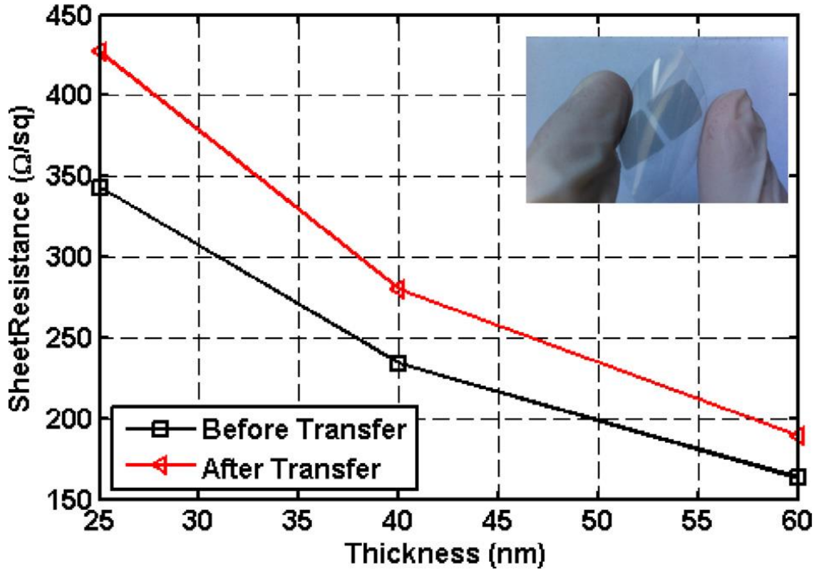
EXTRUSION OF THREADS FROM CNTs FORESTS
PRO:
- SCALABLE
- VERY STRONG THREAD

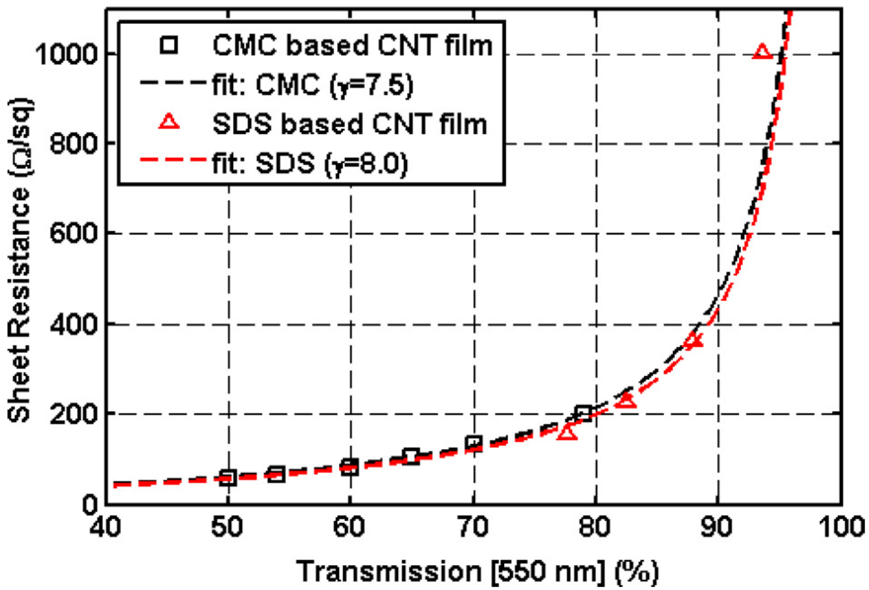
CONS:
- RELATIVELY COMPLEX PROCESS

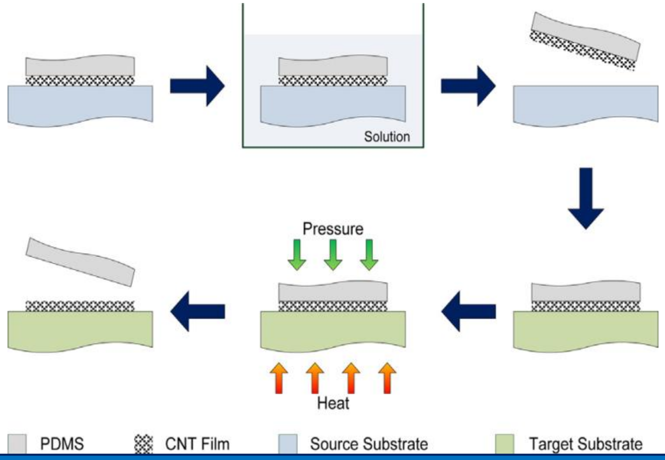
ROLL-TO-ROLL
PRO:
- SCALABLE
- VERY FAST PROCESS

CONS:
- STILL NOT OPTIMIZED

Spray coating CNTs on flexible substrates





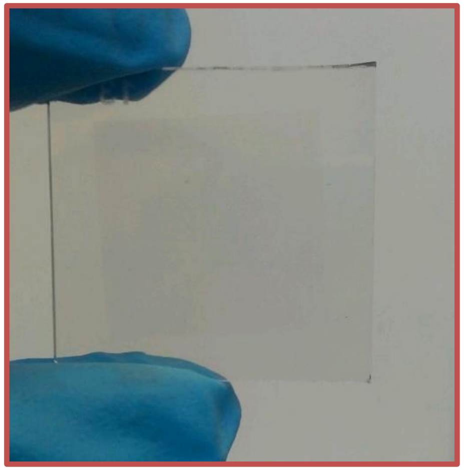


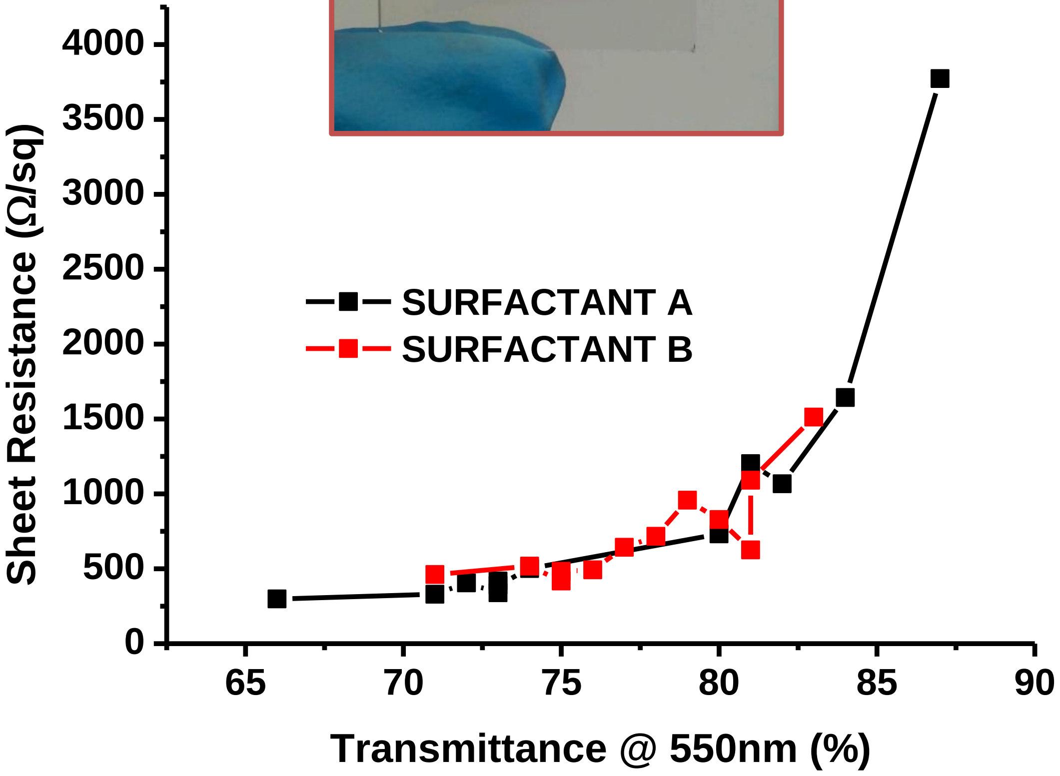
Transmittance 86% at a sheet resistance of 250 O/sq have been fabricated on flexible substrates

Abdelhalim *et al.* C A R B ON 6 1 (2 0 1 3) 7 2 –7 9

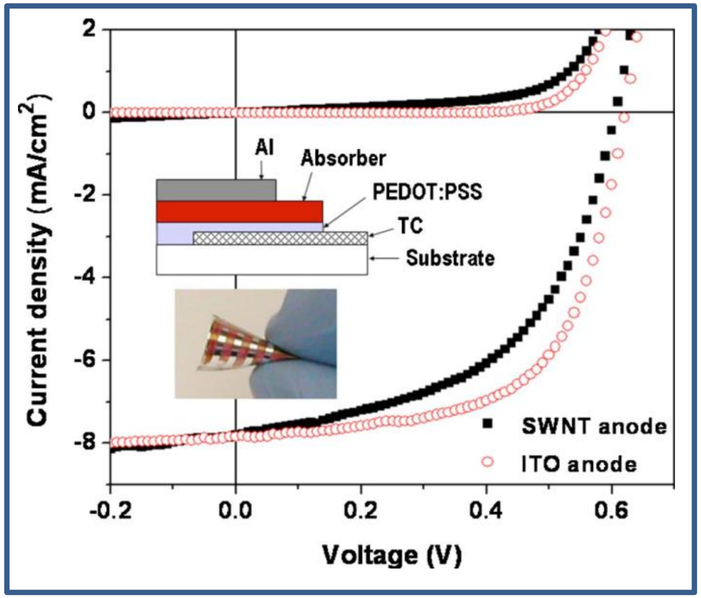
Spray Deposited CNTs @CHOSE

Sample	Transmit-tance (%)	Sheet-Resist. (Ω/□)	Transmit-tance (%)	Sheet-Resist. (Ω/□)
	SURFACTANT A		SURFACTANT B	
1	66	298	71	461
2	71	329	74	518
3	72	406	75	417
4	73	339	75	482
5	73	391	76	492
6	73	418	77	643
7	74	501	78	716
8	80	733	79	958
10	81	1202	80	828
11	82	1067	81	626
12	84	1643	81	1091
13	87	3773	83	1512





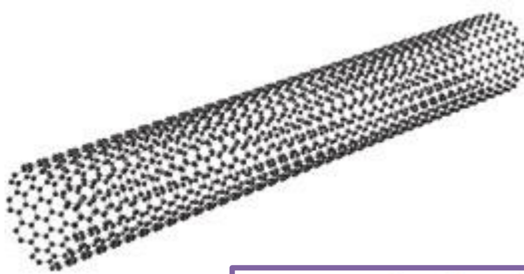
CNTs Electrodes in OPV

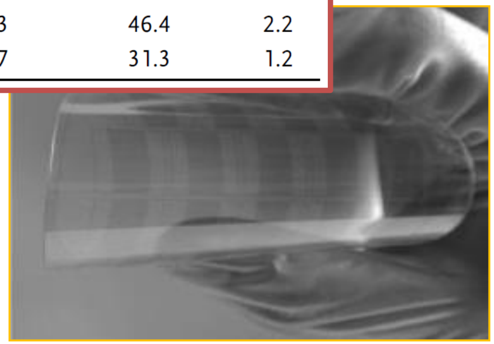


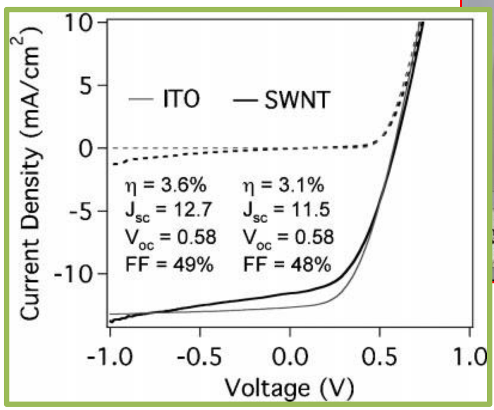
Rowell *et al.* 2006

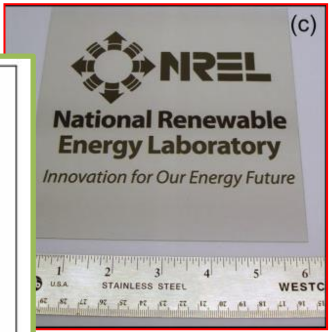
Anode	V_{oc} [V]	J_{sc} [mA cm^{-2}]	FF [%]	PCE [%]
ITO/glass	0.55	8.4	50.0	2.3
SWCNT/glass (DCE)	0.55	9.9	43.1	2.3
SWCNT/glass (H_2O:SDS)	0.59	7.3	46.4	2.2
SWCNT/glass (H_2O:SDBS)	0.55	6.7	31.3	1.2

Kim *et al.* 2010





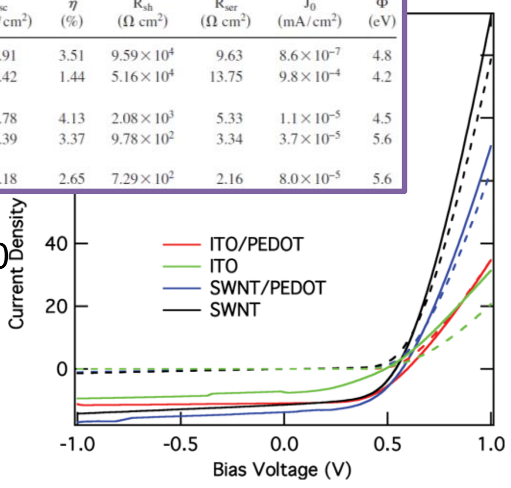




Tenent *et al.* 2009

Electrode	V_{oc} (V)	FF (%)	J_{sc} (mA/cm^2)	η (%)	R_{sh} (Ω cm^2)	R_{ser} (Ω cm^2)	J_0 (mA/cm^2)	Φ (eV)
ITO/PEDOT	594.9	55.3	10.91	3.51	9.59×10^4	9.63	8.6×10^{-7}	4.8
ITO 56 Ω/sq	487.3	40.6	7.42	1.44	5.16×10^4	13.75	9.8×10^{-4}	4.2
SWNT/PEDOT	570.2	52.9	13.78	4.13	2.08×10^3	5.33	1.1×10^{-5}	4.5
24 Ω/sq SWNT	539.8	55.4	11.39	3.37	9.78×10^2	3.34	3.7×10^{-5}	5.6
Certified Device– 60 Ω/sq SWNT	517	45.9	11.18	2.65	7.29×10^2	2.16	8.0×10^{-5}	5.6

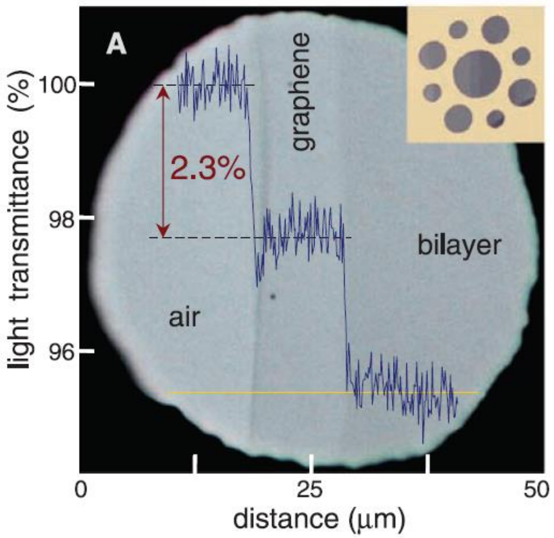
Barnes *et al.* 2010

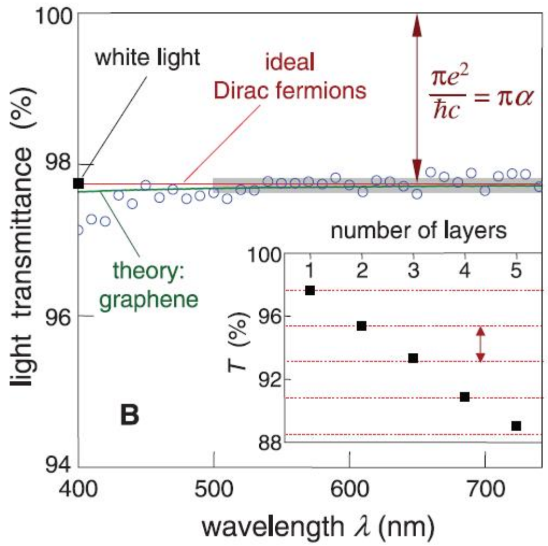


Graphene based BHJ solar cells

Graphene for Transparent Electrodes

Transparency of graphene monolayer: ~97.7 %

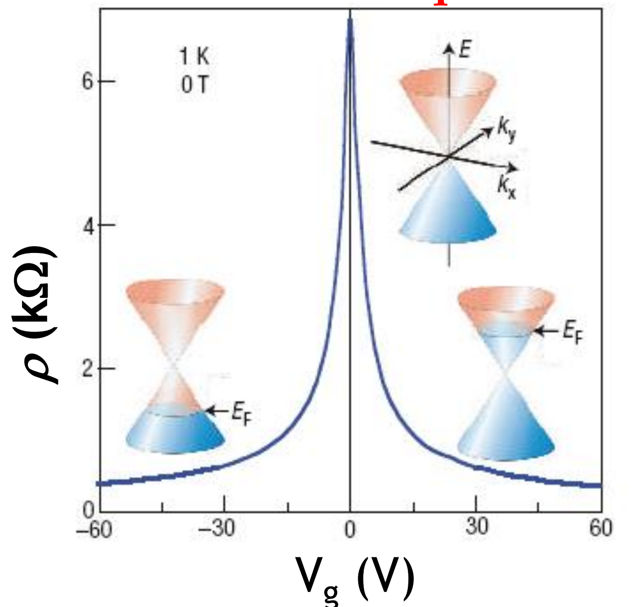




Mechanically exfoliated graphene

Nair et al. *Science* **320,** 1308, (2008)

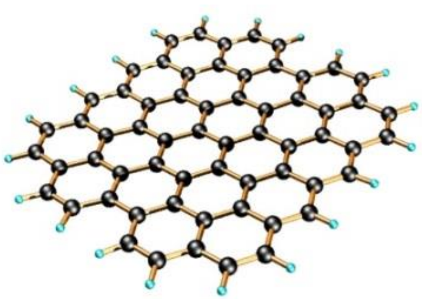
Intrinsic sheet resistance ($h/4e^2$): ~ 6 kΩ/square

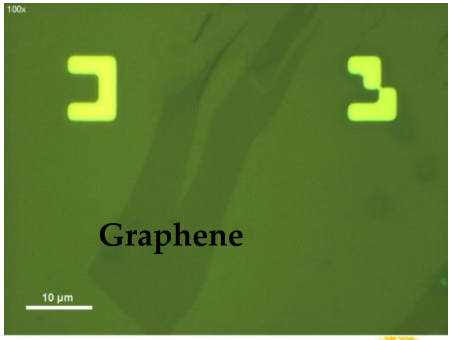


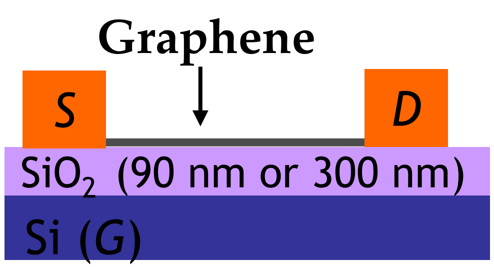
Geim & Novoselov

Nature Materials 6, 184, (2007)

Graphene is very susceptible to ambient adsorbates.







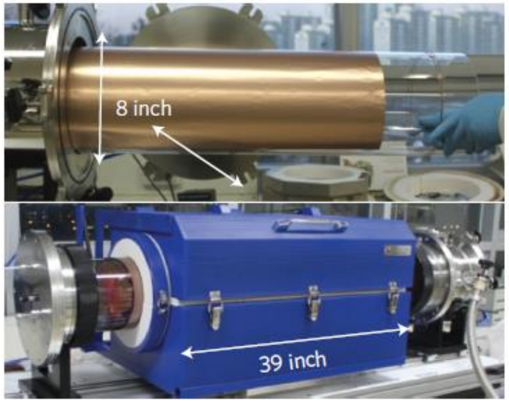
CVD of graphene

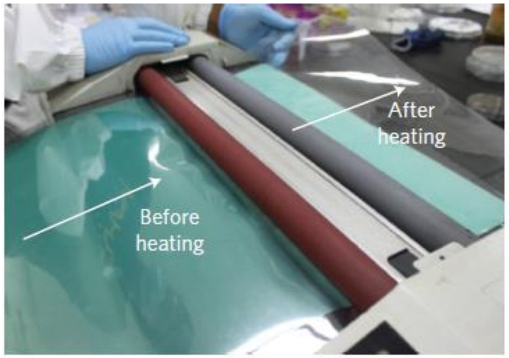
CVD Method (on Cu, Ni or Pt catalyst layer), e.g.,

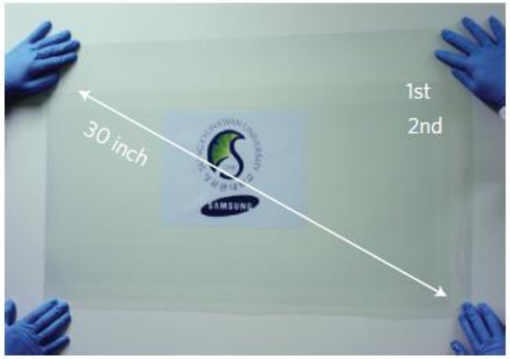
- Cu foil (catalyst, 25 μm thick), heated in H_2 at 1000ºC to increase grain size
- CVD of CH_4 & H_2 at 1000ºC
- Cool down, spin-on protective polymer layer (100 nm), etch away Cu foil (…..residue)
- Transfer graphene to substrate, dissolve polymer (….residue)

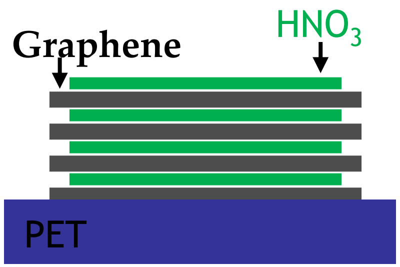
Properties

- Monolayer graphene transmission: ~97.7%
  Intrinsic graphene: R ~ 6 kΩ/ sq. (1 - 5 kΩ/ sq. for best CVD)
- Adsorbate-doped graphene:
  R ~ 100 Ω/ sq. using HNO_3 (record! …. Stability concerns)
- Stack of 4 monolayers (resistors in parallel):
  - R ~ 25 Ω/ sq.
    (400 – 800 Ω/ sq. at AMO: cm-scale)
  - ~90% transmission



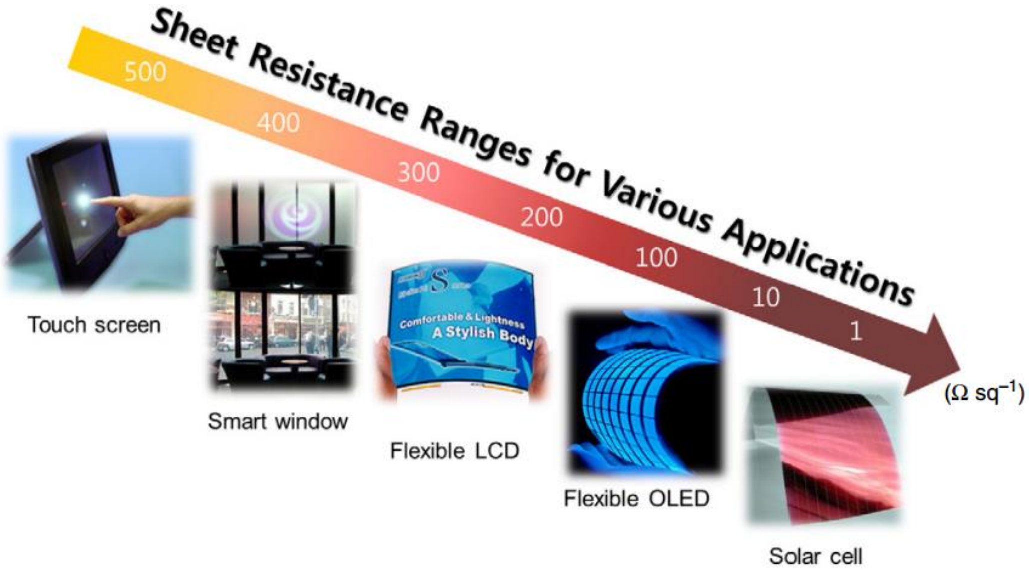




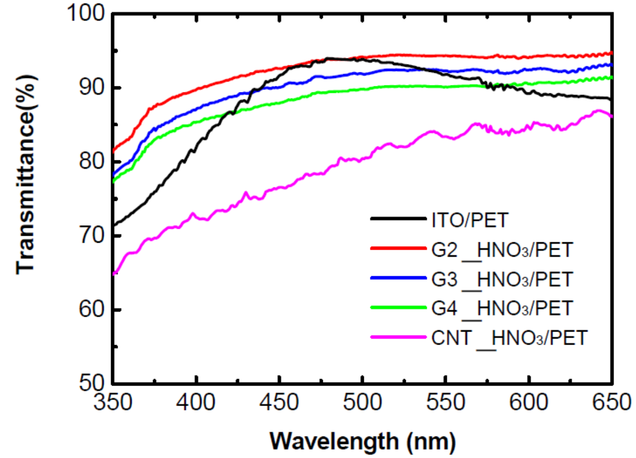


Ruoff Group, X. S. Li *et al.*, *Science* **324**, 1312 (2009)
Bae *et al.*, SKKU, Samsung *Nat. Nano* **5** 574 (2010)

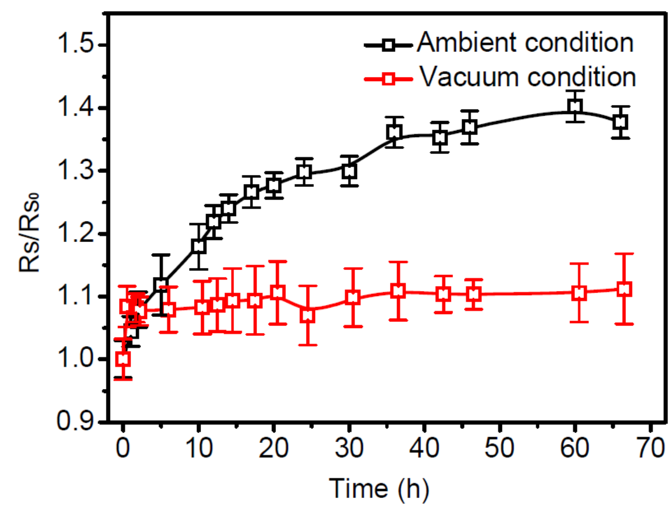
State of the art



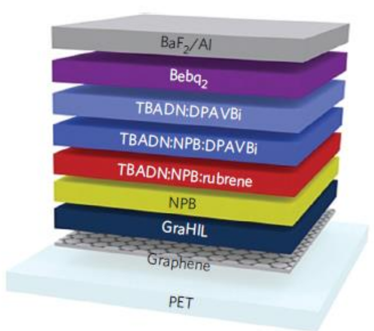
Transmission for 2, 3 & 4 layer graphene sheets doped with HNO_3

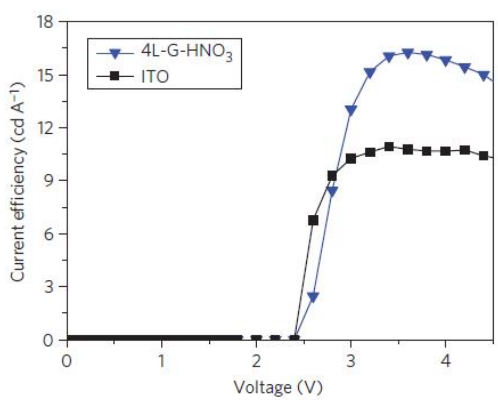


Stability of sheet resistance after doping with HNO_3



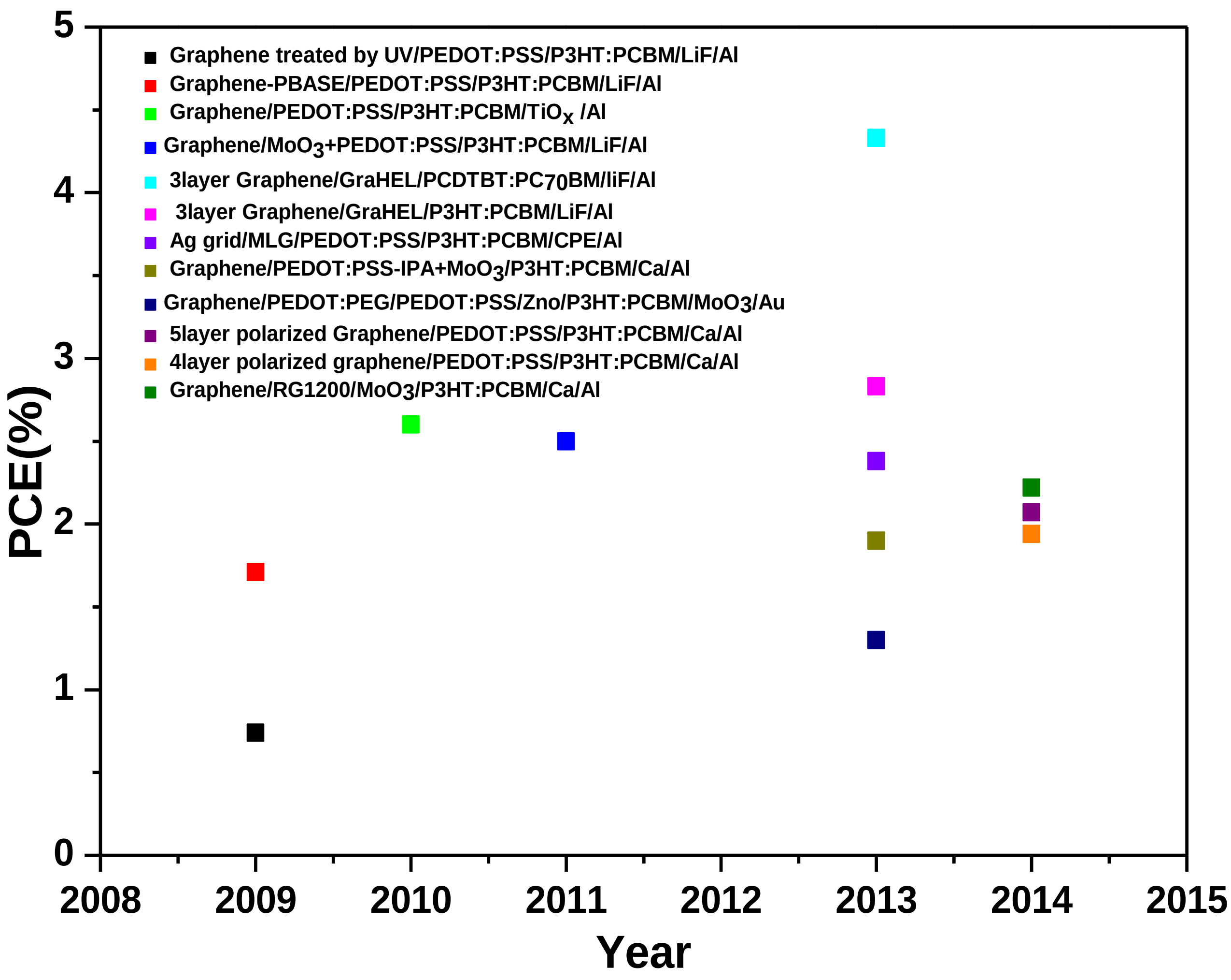
Graphene OLED



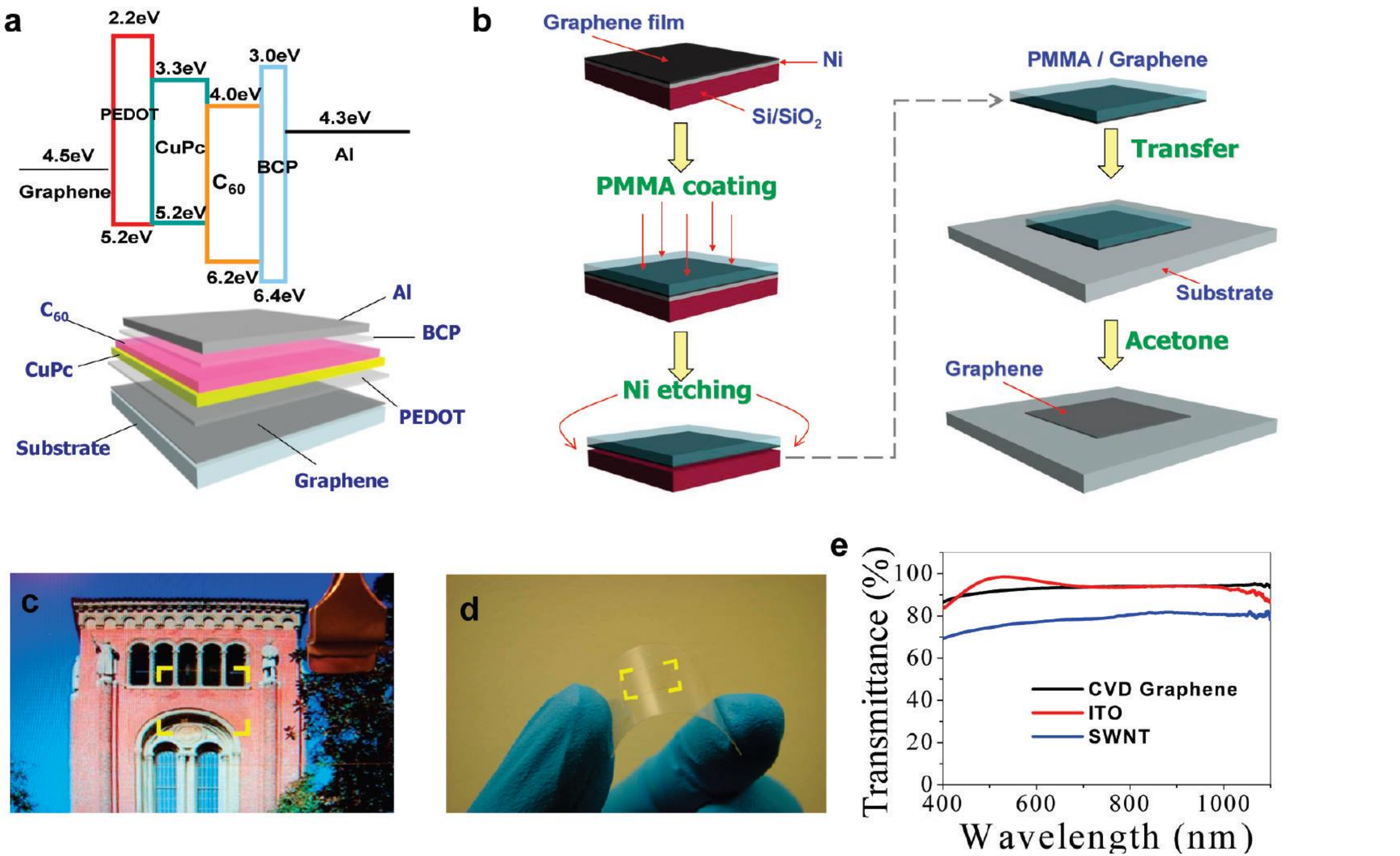


Han *et al.*, *Nat. Photonics* **6**, 105 (2012)

Graphene based OPV

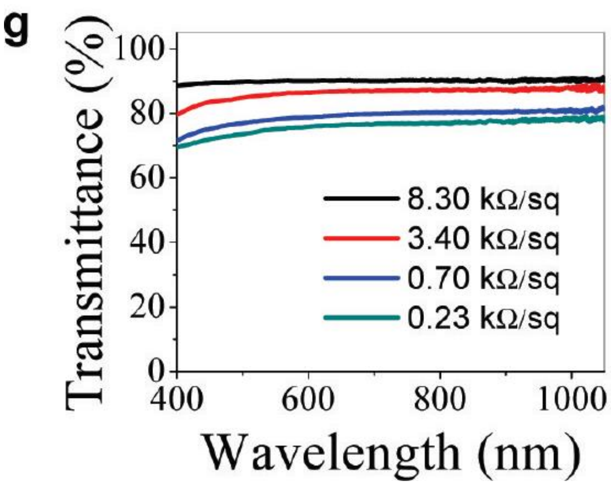


Graphene electrodes on glass



GOMEZ DE ARCO ET AL. ACS nano VOL. 4, NO. 5, 2865–2873, 2010

Graphene electrodes on glass



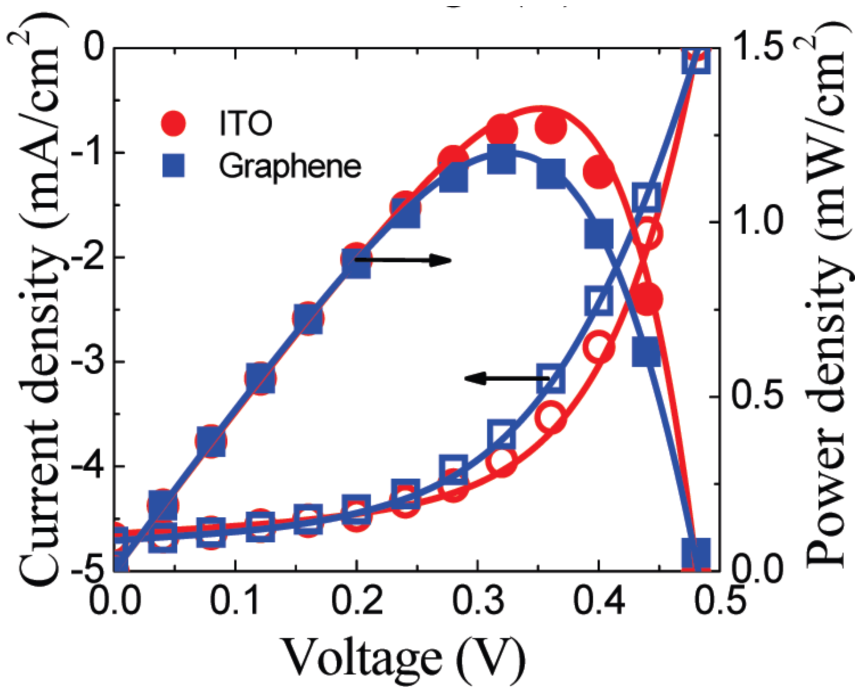


TABLE 1. Performance Details of OPV Cells Built on PET[a]

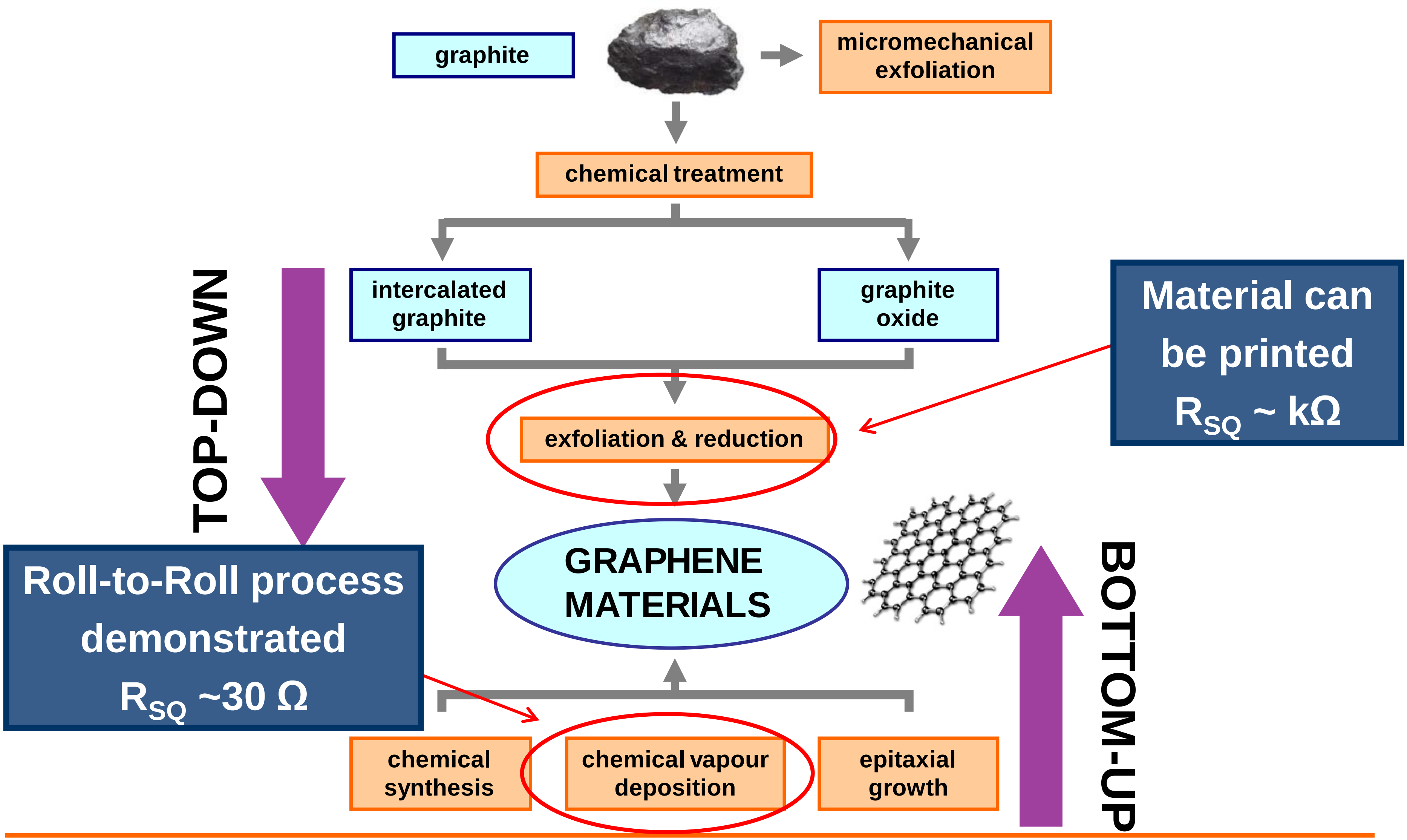
anode	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η (%)
CVD graphene	4.73	0.48	0.52	1.18
ITO	4.69	0.48	0.57	1.27

[a] The structure of the devices is given by [CVD graphene/PEDOT/CuPc/C_{60}/BCP/Al] and ITO/PEDOT/CuPc/C_{60}/BCP/Al] for CVD graphene and ITO OPVs, respectively.

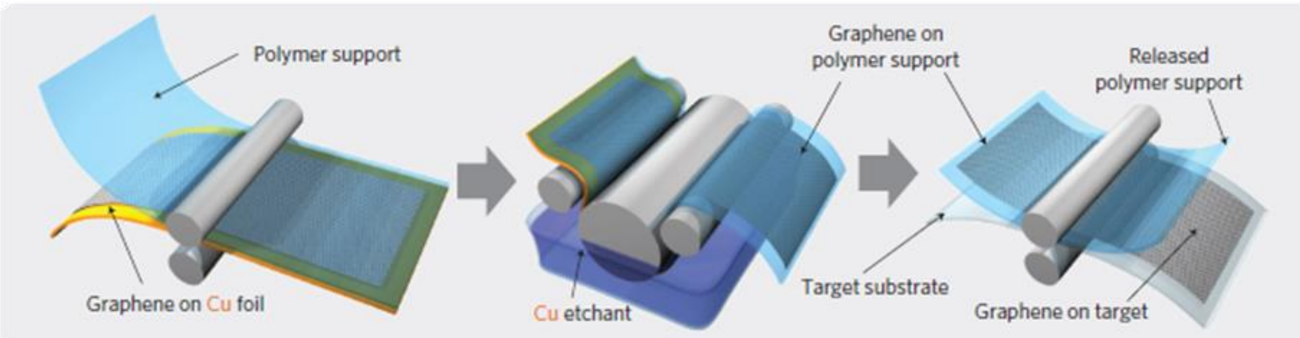
GOMEZ DE ARCO ET AL. ACS nano VOL. 4, NO. 5, 2865–2873, 2010

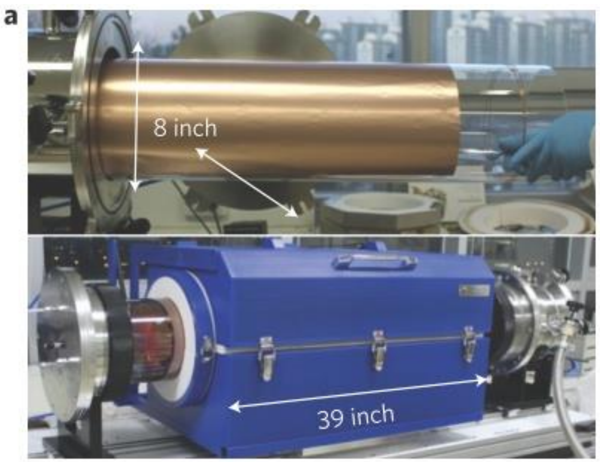
Is it possible to scale up?

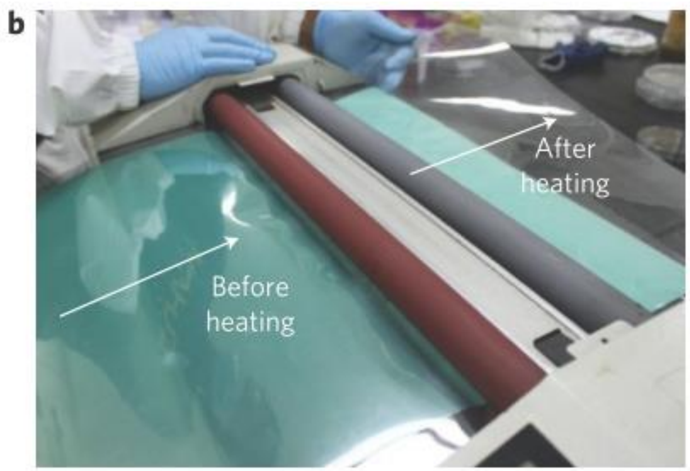
Graphene production



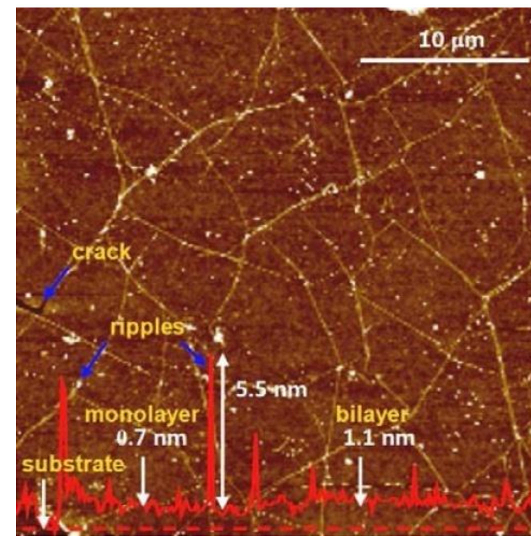
Graphene Roll-to-roll production on copper foil







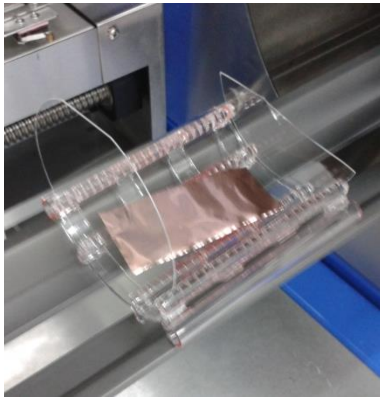
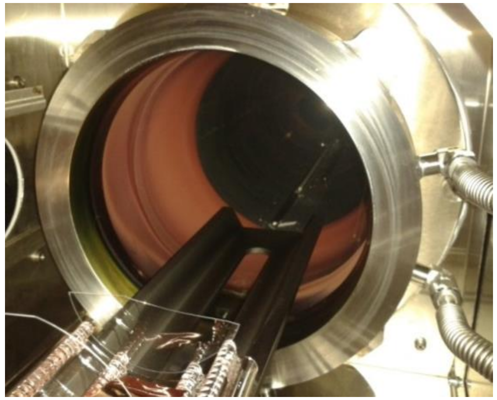
AFM of graphene on Cu



μ = 5000 cm^2/Vs at RT

S. Bae et al. Nature Nano. 5, 571 (2010)

Perspectives: scaling up the graphene growth


Tyndall CVD:

6” tube

Gas precursor: CH_4

Liquid: toluene (low temperature CVD)

CVD Method

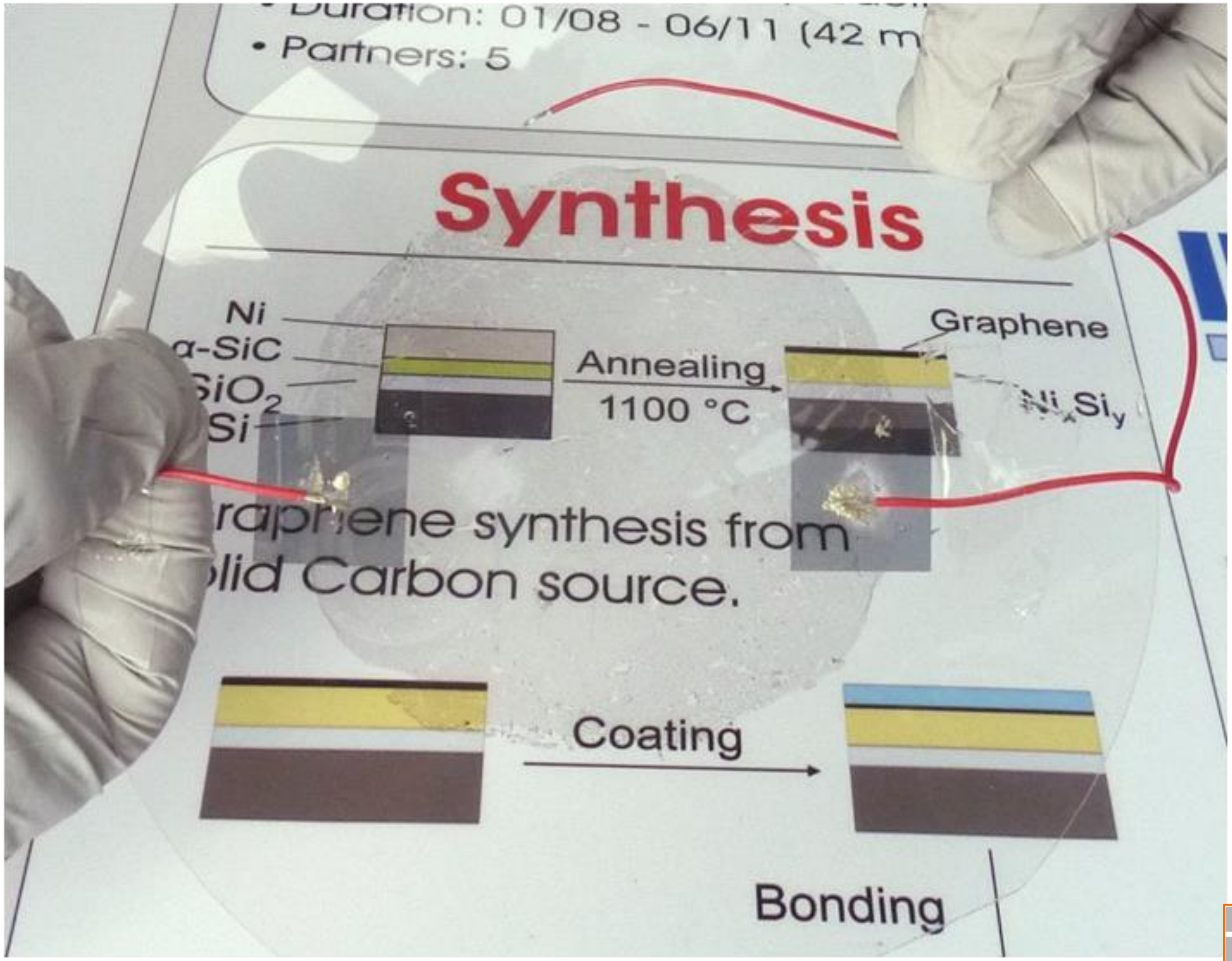
- Cu foil catalyst(25 μm thick) heated in H_2 at 1000 °C to remove contaminants/oxide and increase grain size
- CVD of CH_4 at 1000 °C, cool down to room temperature
- Spin-on protective polymer layer, wet-etch away Cu foil
- Transfer graphene to transparent substrate and dissolve polymer

Graphene for Transparent Electrodes

- Monolayer graphene transmission: ~97.3% (absorption = π/ehc)
- Intrinsic graphene: $R \sim 6000\ \Omega/$ *sq. (h/4e2)*
- Heavily-doped graphene:

  $R \sim 100\ \Omega/$ *sq.* (Bae *et al., Nat. Nano* 2010)
- Stack of 4 monolayers:
- $R \sim 25\ \Omega/$ *sq.*
- 90% transmission

6 inch wafer scale graphene contact on PET



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Thanks for the attention

Questions?