

Solution-processed semitransparent organic solar cells: Efficiency limits, materials and large-area processing

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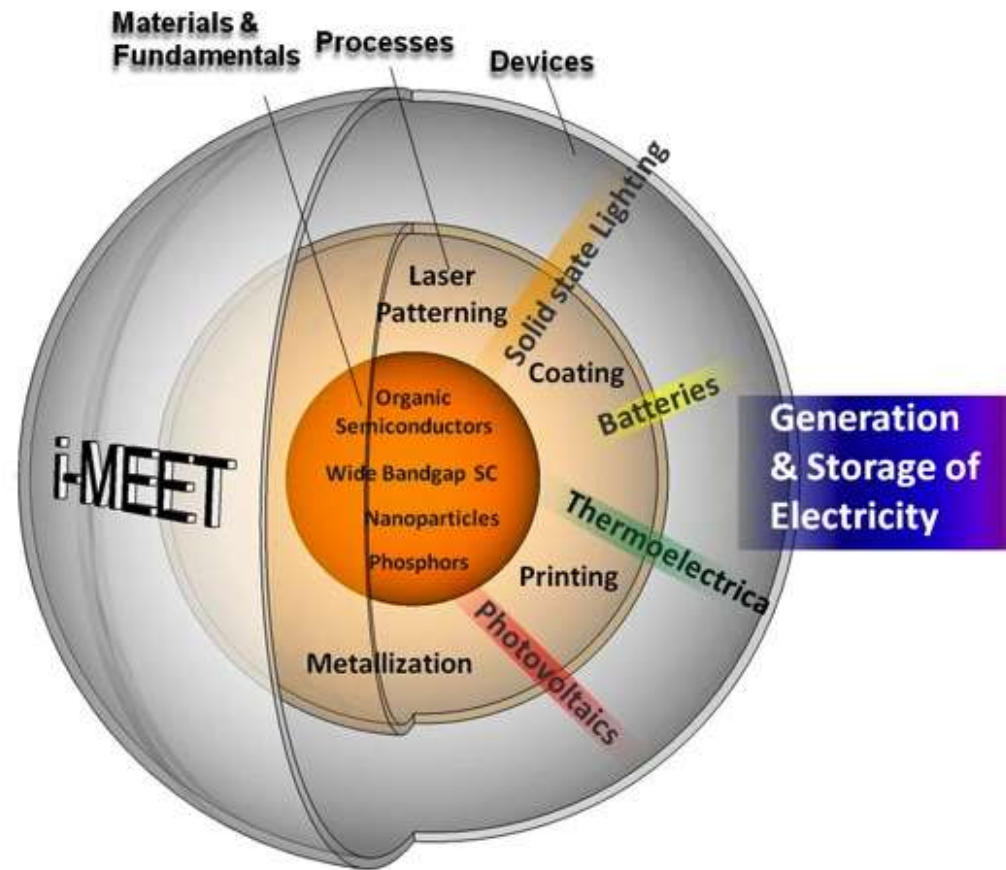
Outline

- Printed Photovoltaics in Erlangen and Nürnberg
- A brief introduction to Organic Solar Cells
- Efficiency limits of semitransparent organic solar cells
- „Large“ area fabrication of semitransparent cells and modules
- Outlook: Semitransparent cells with printed dielectric mirrors

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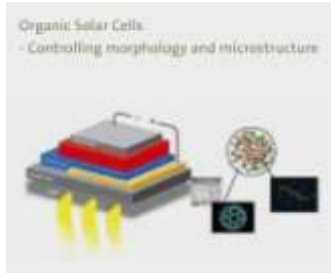
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i-MEET: Institute Materials for Electronics and Energy Technology



Printed Photovoltaics in Erlangen and Nürnberg

THERMODYNAMIK >



Understanding the physics behind & design of materials

MATERIAL >



Printed active layer material

PROCESS >



Roll-to-roll coater with robust high-quality process

SYSTEM >



Device design: monolithic series connection of cells

APPLICATION



Semi-transparent OPV module as BIPV

FAU / i-MEET / ZAE Erlangen

Industrial partners

Solar Factory @ EnCN

Characteristics:

- High throughput
- Semiconductor coatings @ $> 1 \text{ m / s}$
- Laser structuring @ $> 1 \text{ m / s}$

Innovative technology steps:

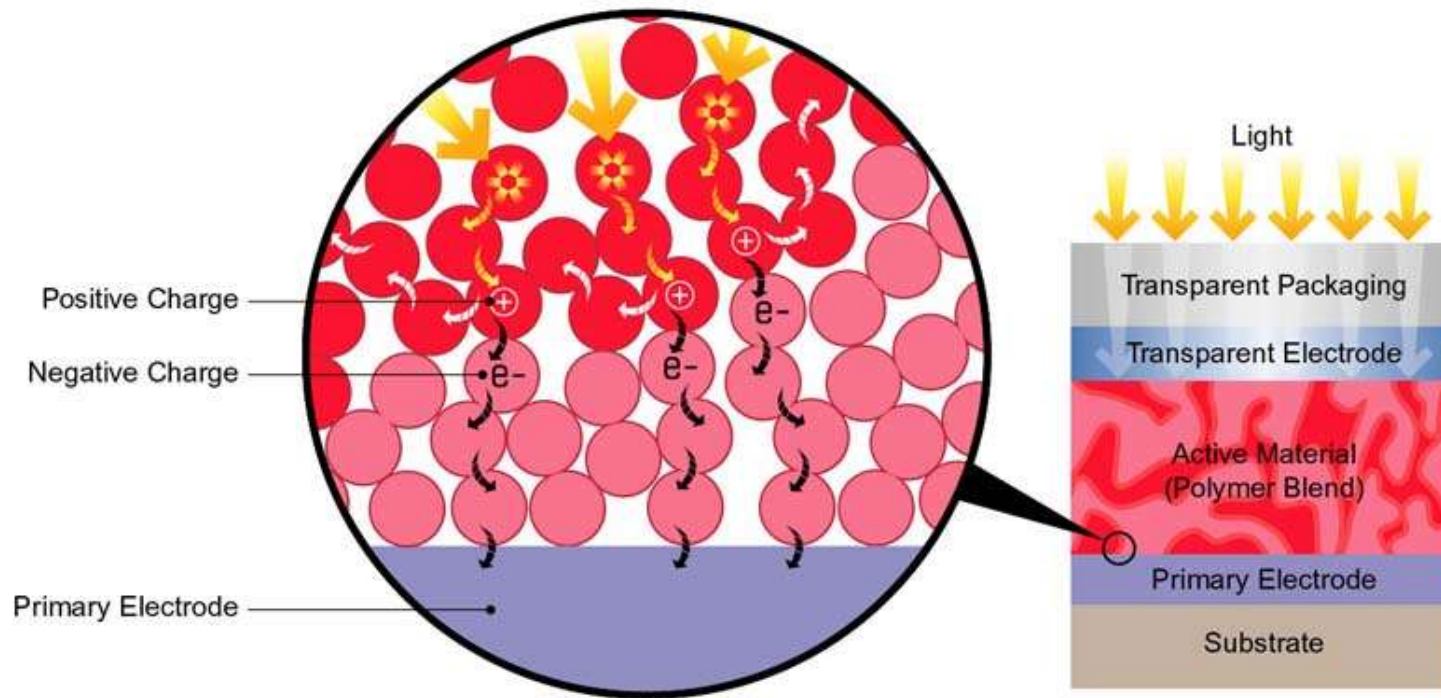
- Printed, transparent electrodes
- Printed organic / inorganic semiconductors
- Smart, self-assembled films
- ...

➔ Disruptive technology with high cost-reduction potential

Outline

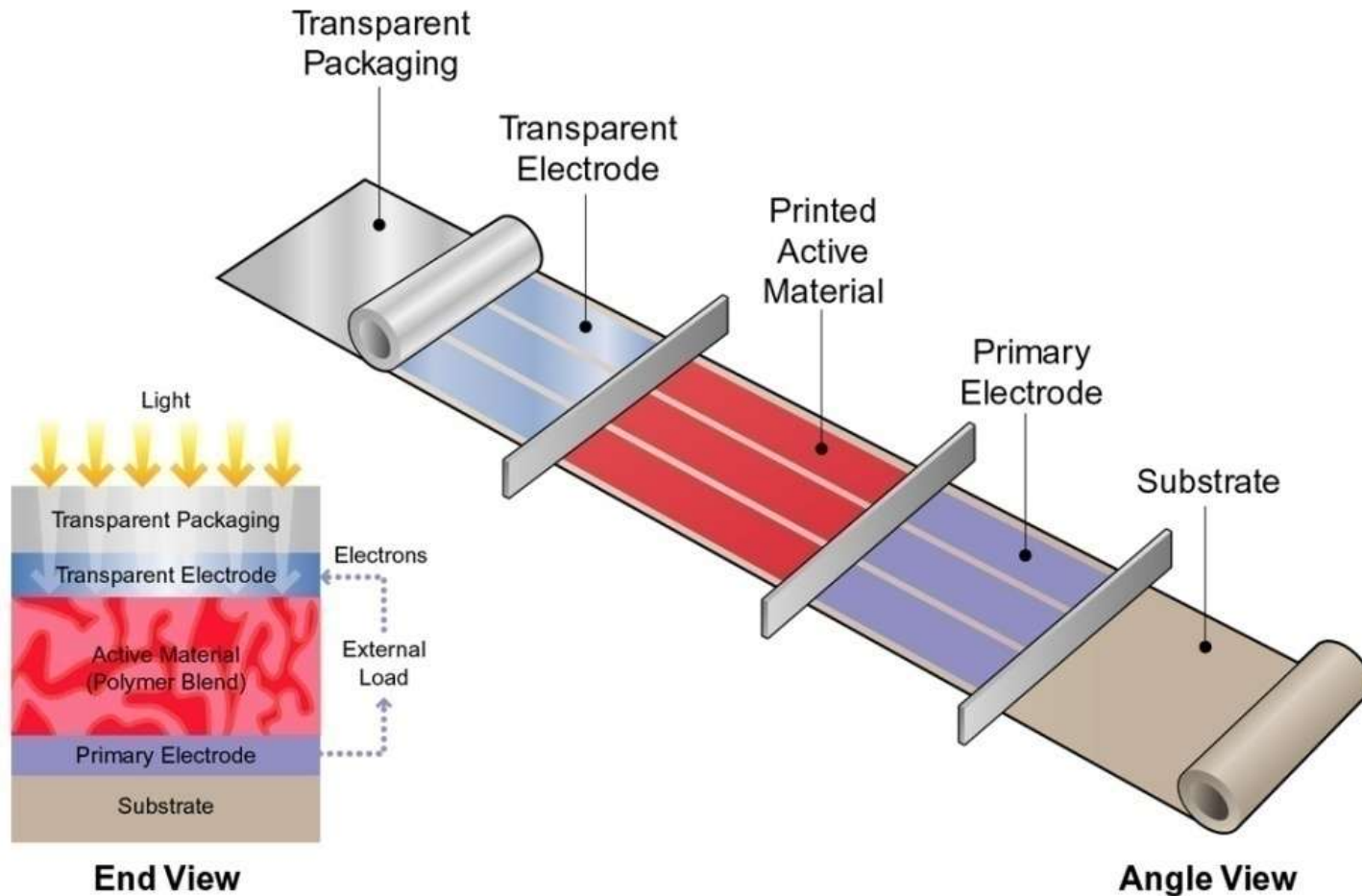
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“Bulk-heterojunction” principle



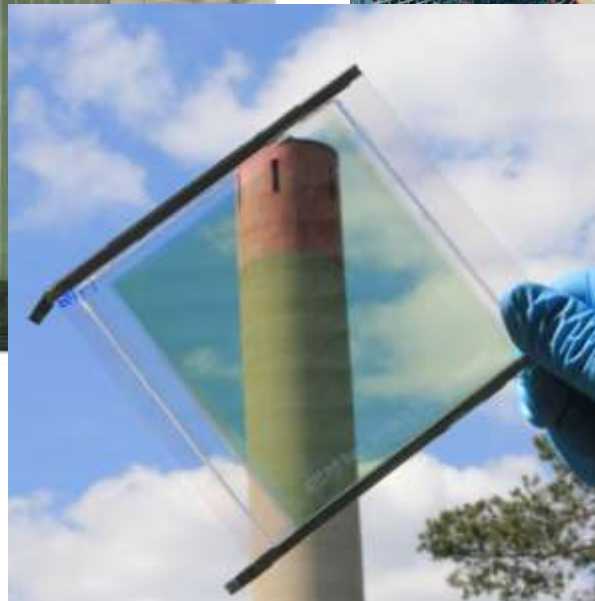
A Brief Introduction to Organic Photovoltaics

The advantage of solution processing:



A Brief Introduction to Organic Photovoltaics

Semitransparent modules:

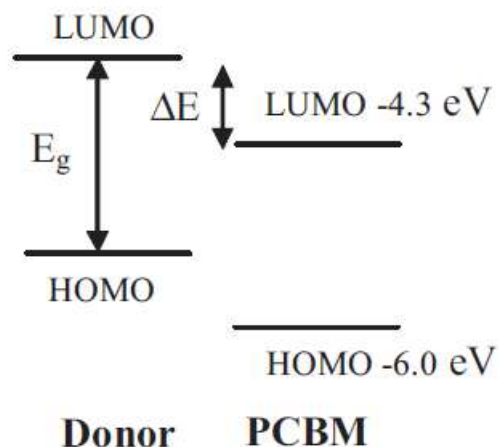


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Efficiency limits of semitransparent organic solar cells

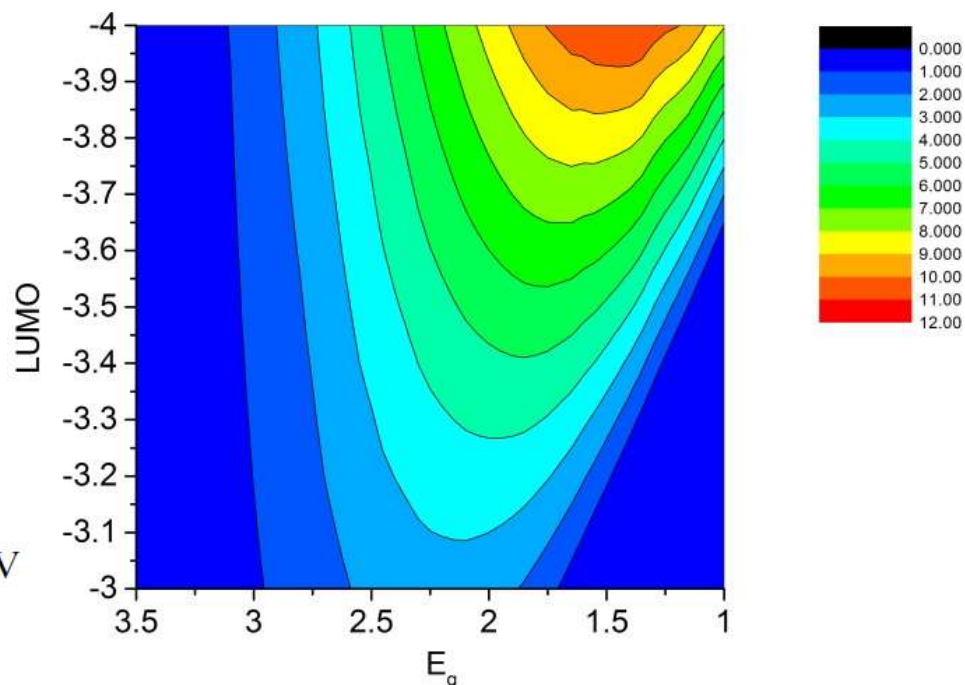
Efficiency limit of bulk-heterojunction organic solar cells:
The “traditional model” for a single junction



$$V_{oc} = (1/e)(|E^{\text{Donor}} \text{HOMO}| - |E^{\text{PCBM}} \text{LUMO}|) - 0.3 \text{ V}$$

$$EQE = 0.65 = \text{const.}$$

$$FF = 0.65 = \text{const.}$$

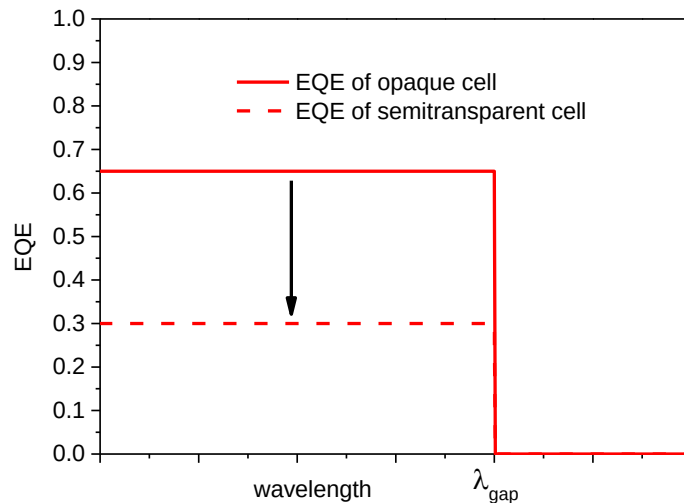


Efficiency of single junction cell

Efficiency limits of semitransparent organic solar cells

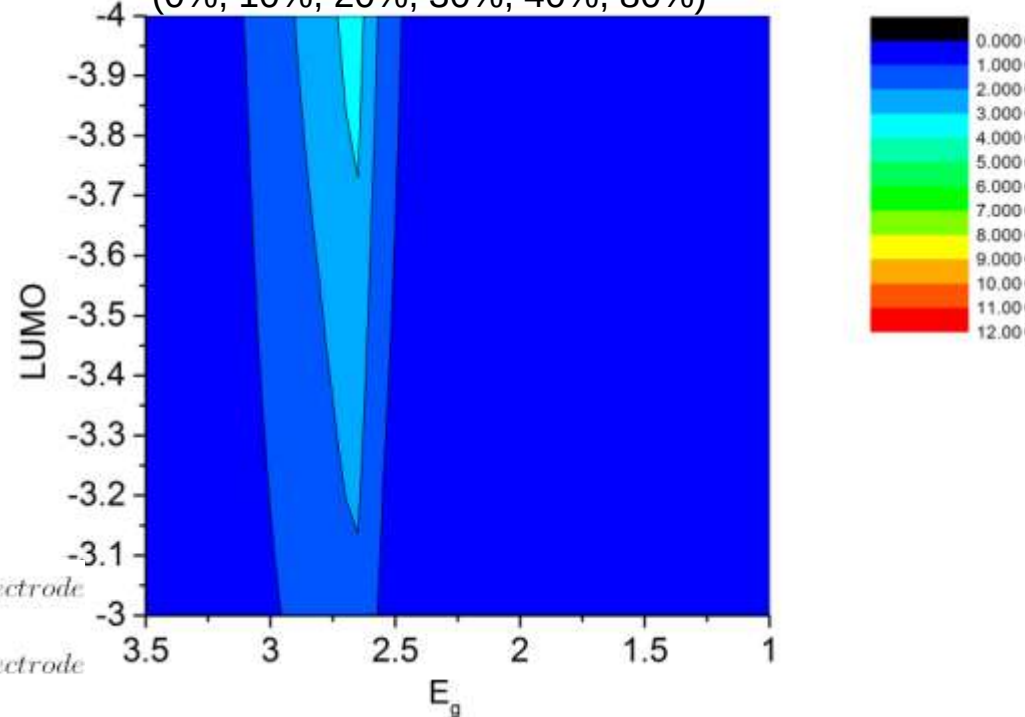
Semitransparent cells:

Transmittance is increased at the cost of a reduced EQE



$$T = T_{\text{bottom electrode}} * (1 - A_{\text{active layer}}) * T_{\text{top electrode}}$$
$$= T_{\text{bottom electrode}} * \left(1 - \frac{EQE(\lambda)}{IQE(\lambda)}\right) * T_{\text{top electrode}}$$

Efficiency of semitransparent cell
(0%, 10%, 20%, 30%, 40%, 80%)

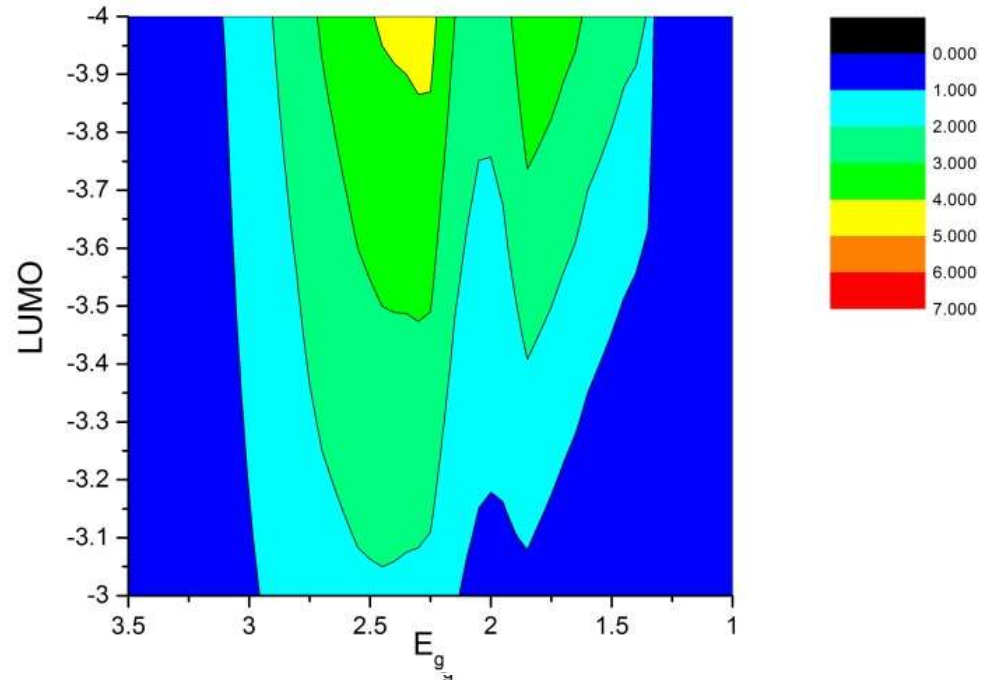
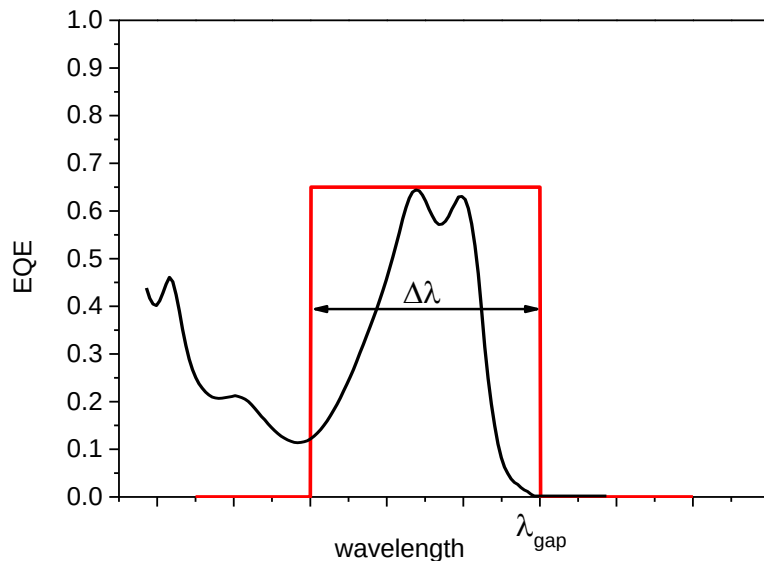


For high transparencies, the optimum band gap is shifted to higher values

Efficiency limits of semitransparent organic solar cells

Semitransparent cells:

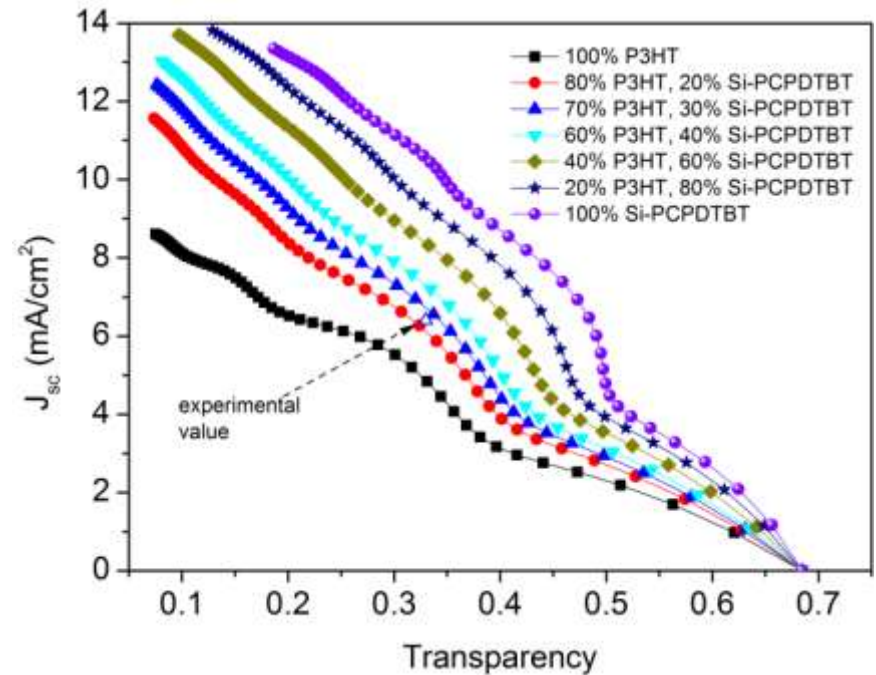
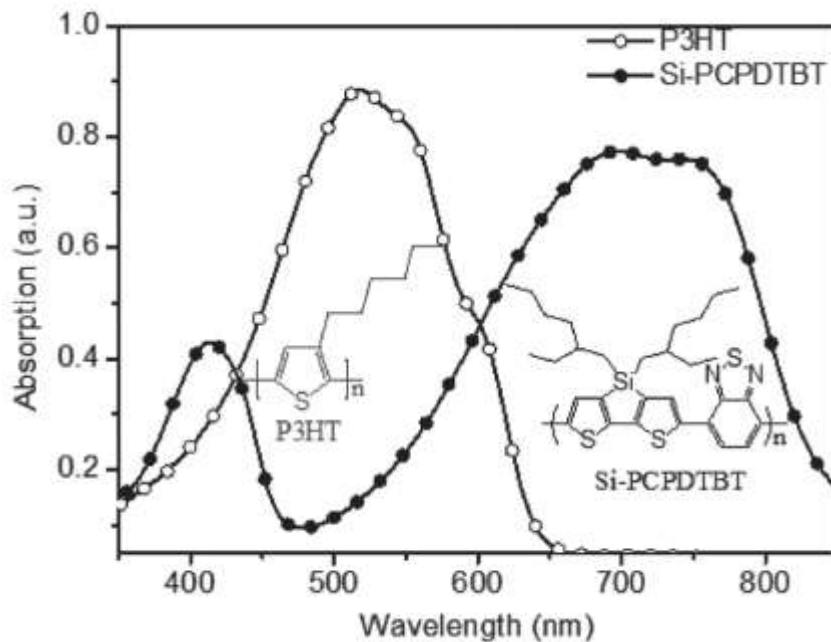
More “realistic” EQE that extends only over a limited wavelength range



Efficiency of semitransparent cell
(50% transparency, $\Delta\lambda=700\text{nm}$, 500nm,
400nm, 300nm, 200nm, 100nm)

Optical simulations of real systems

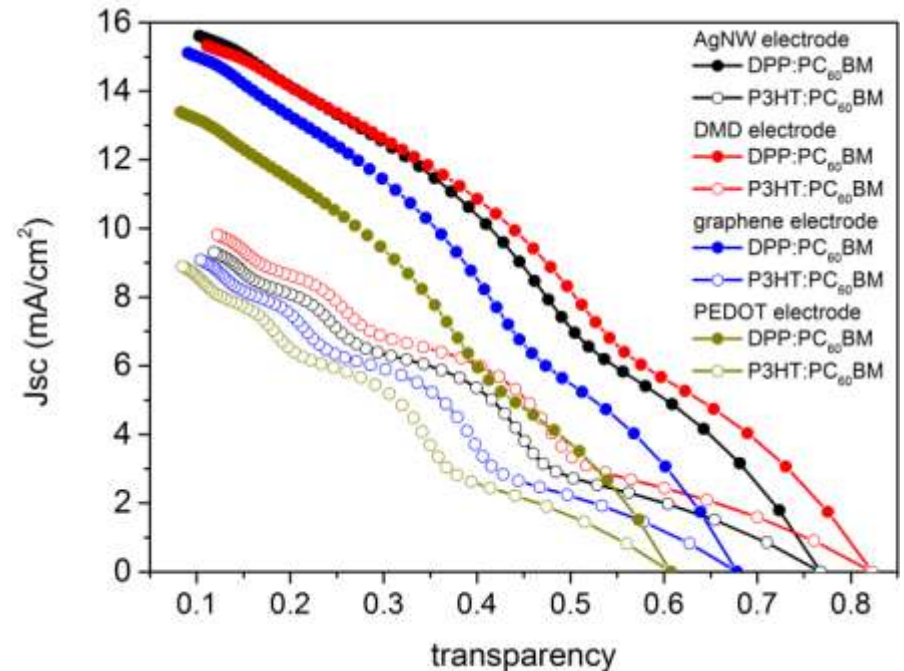
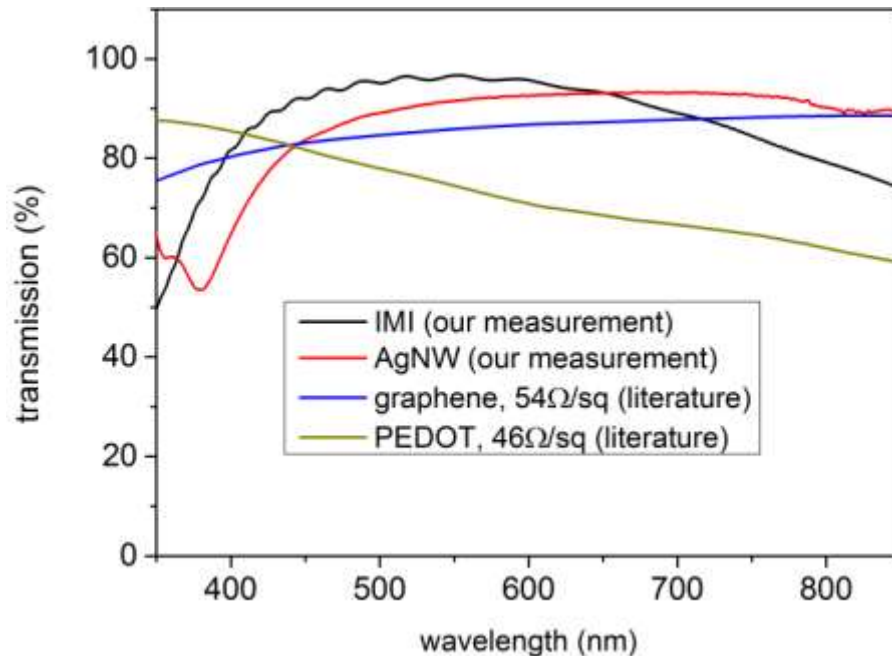
Optical simulations of actual solar cell stack: dependency on absorber material



The efficiency vs transparency increases with increased percentage of low band gap polymer

Optical simulations of real systems

Optical simulations of real system: dependency on electrode materials



Highly transparent electrodes like DMD and Ag nanowires lead to the highest efficiency vs transparency value

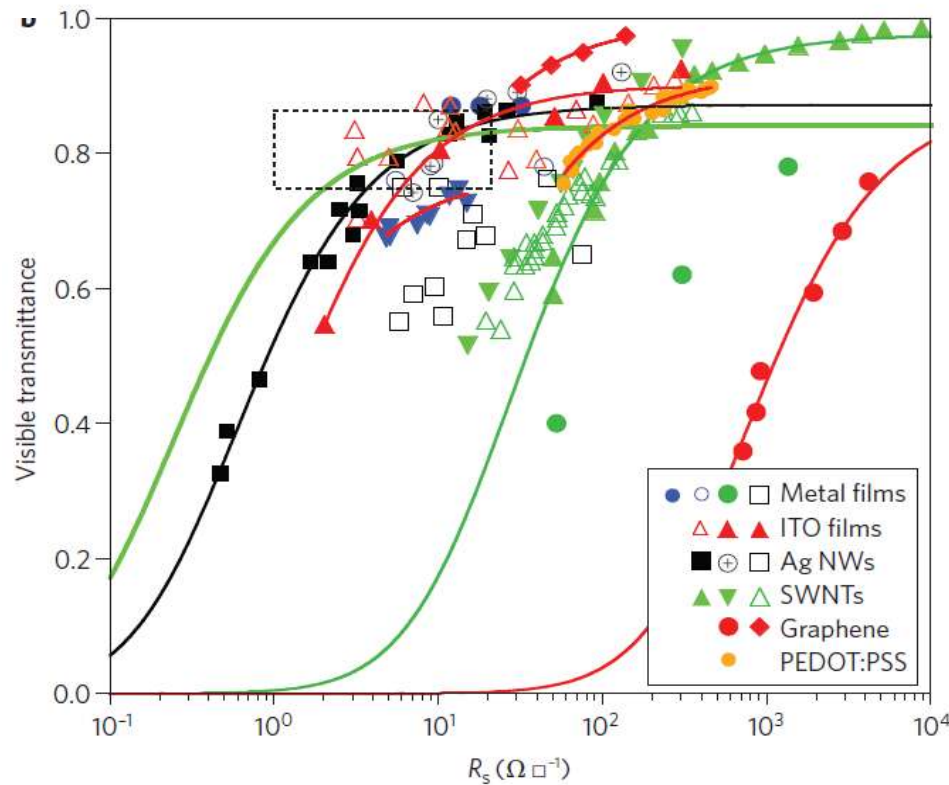
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Optoelectronic properties of silver nanowires

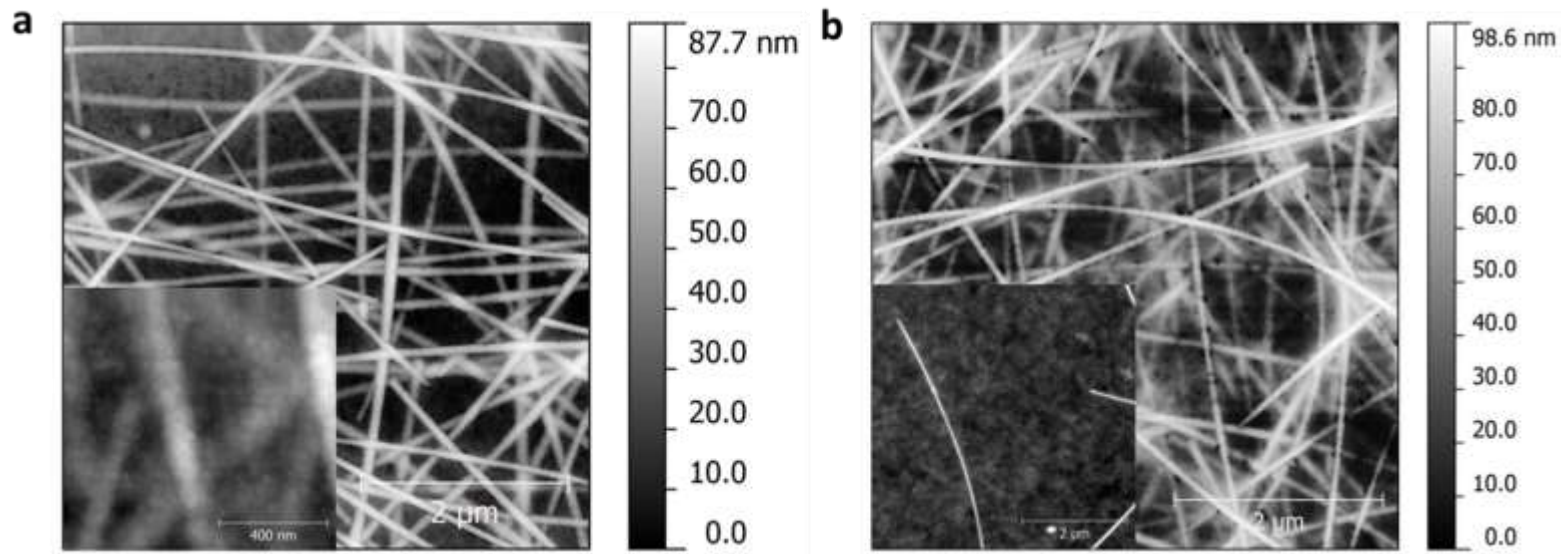
Comparison of different transparent electrodes:

Silver nanowires show the best transmittance vs sheet resistance



Optoelectronic properties of silver nanowires

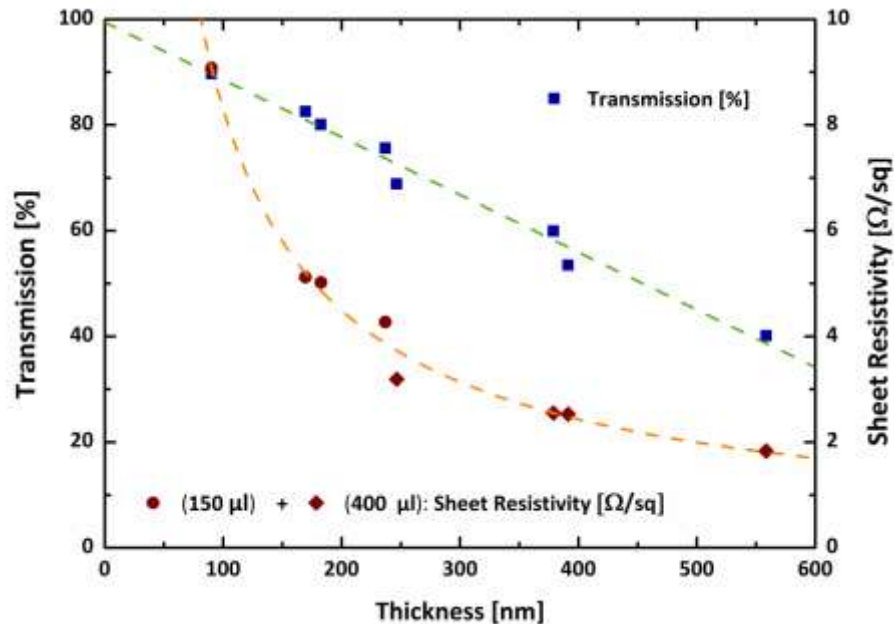
AFM images of printed (a) and spray-coated (b) silver nanowires



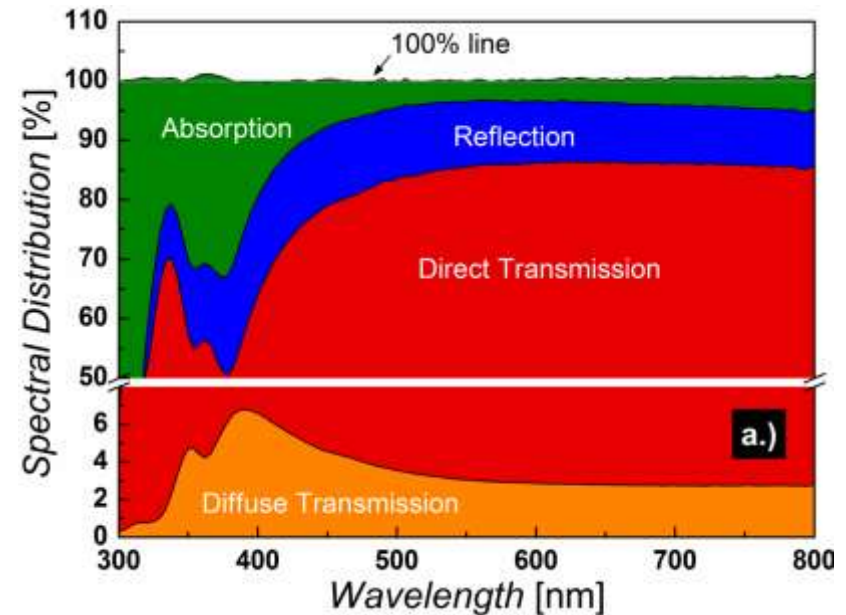
Transmittance is provided by the free space between the single wires, resistivity is determined by the contact points between the single wires

Optoelectronic properties of silver nanowires

Transmittance and sheet resistance vs layer thickness



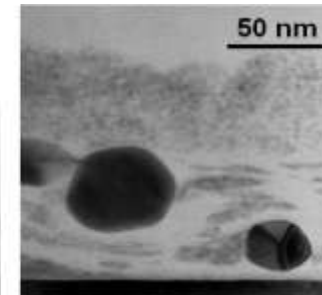
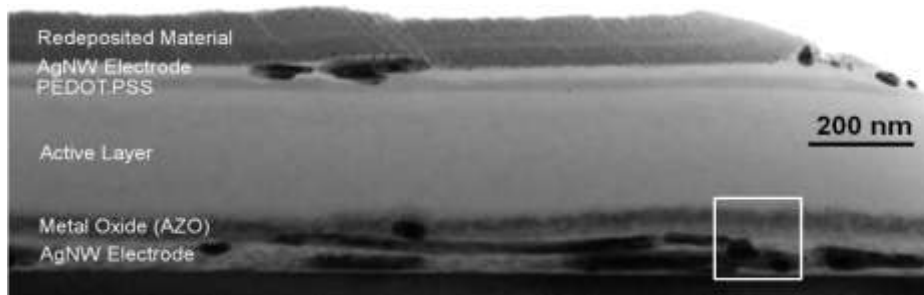
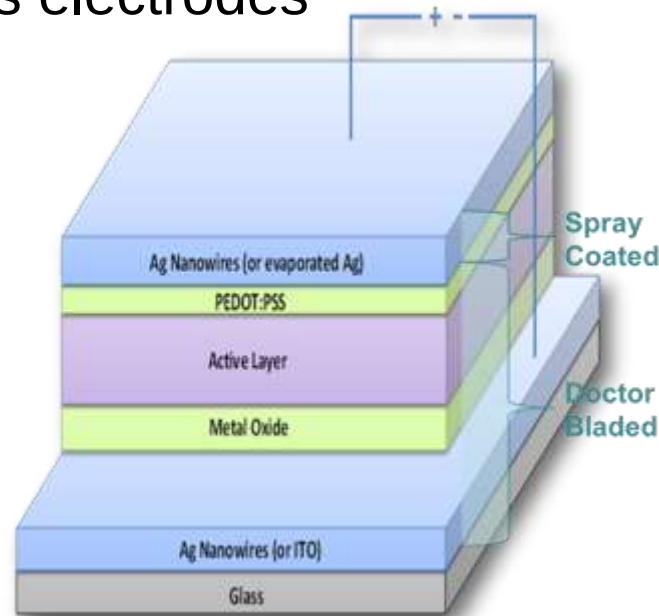
Optical properties:
Transmittance and reflectance



Average transmittance ~90%, sheet resistance below 10Ω/sq, haze <5%

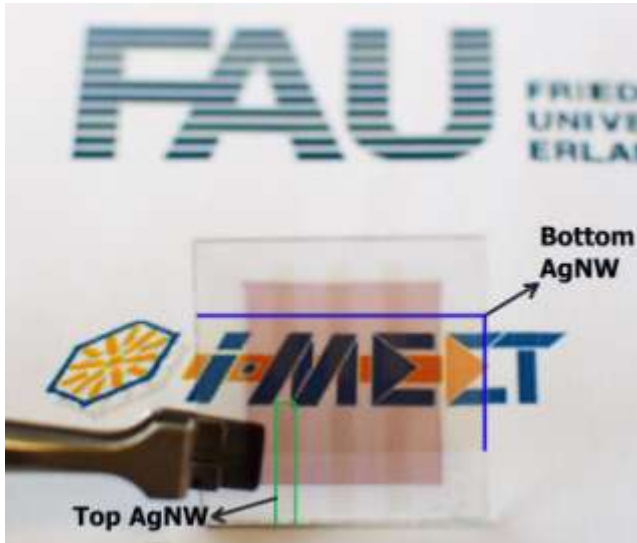
Fully solution-processed semitransparent organic solar cells

Architecture of a fully solution-processed cell with bottom and top nanowires electrodes

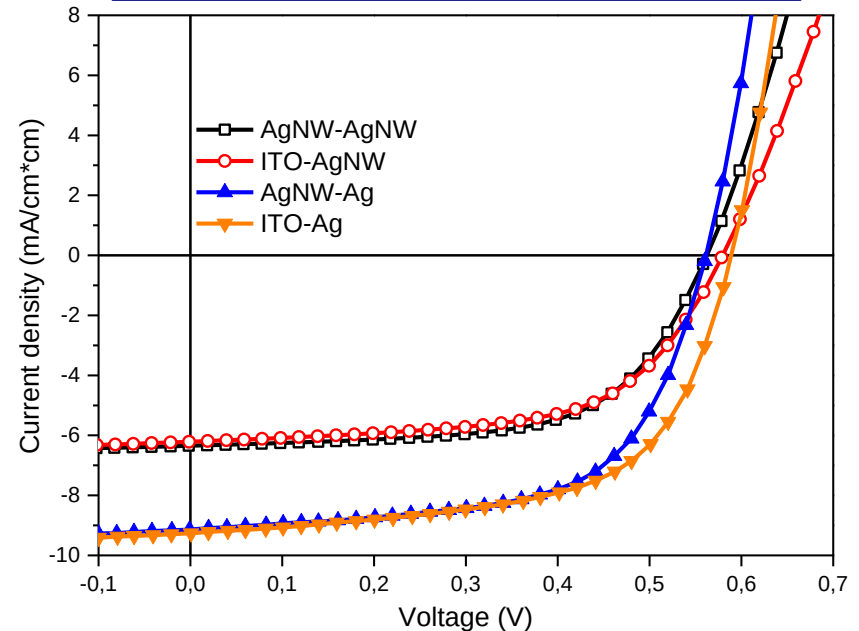


Fully solution-processed semitransparent organic solar cells

Visible transparency of 33%



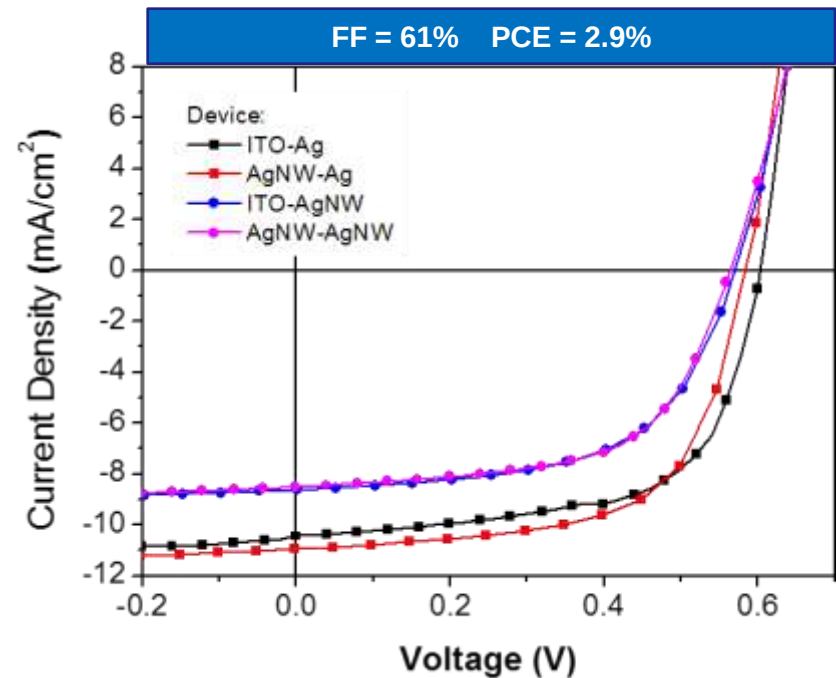
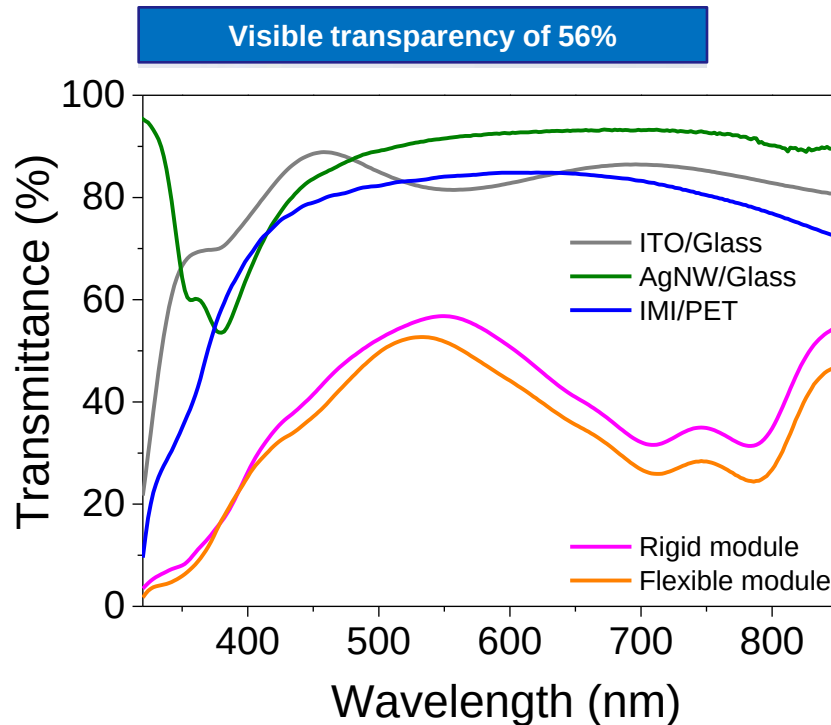
FF = 60% PCE = 2.2%



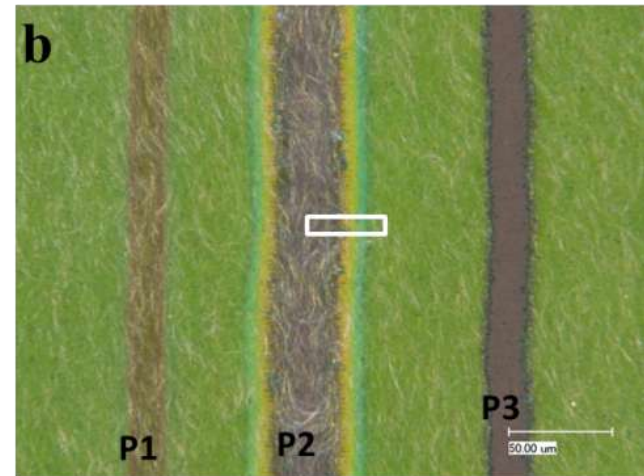
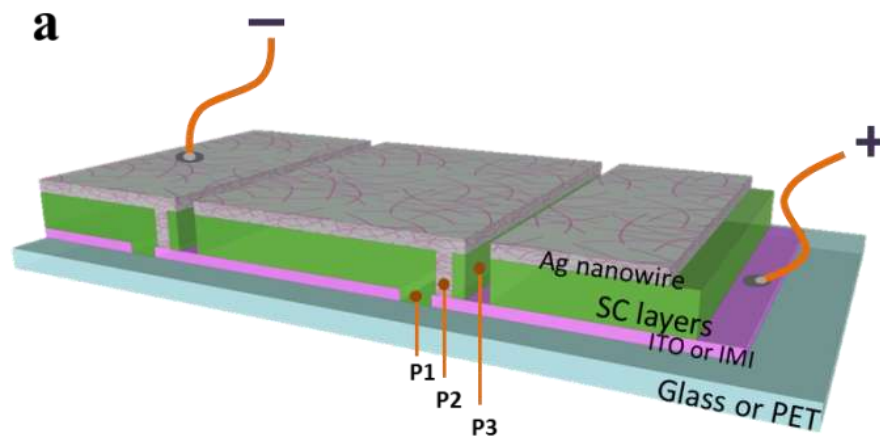
Devices with nanowires electrodes show comparable performance to the reference devices.

Fully solution-processed semitransparent organic solar cells

Fully printed cell with bottom and top nanowire electrode and low band gap absorber

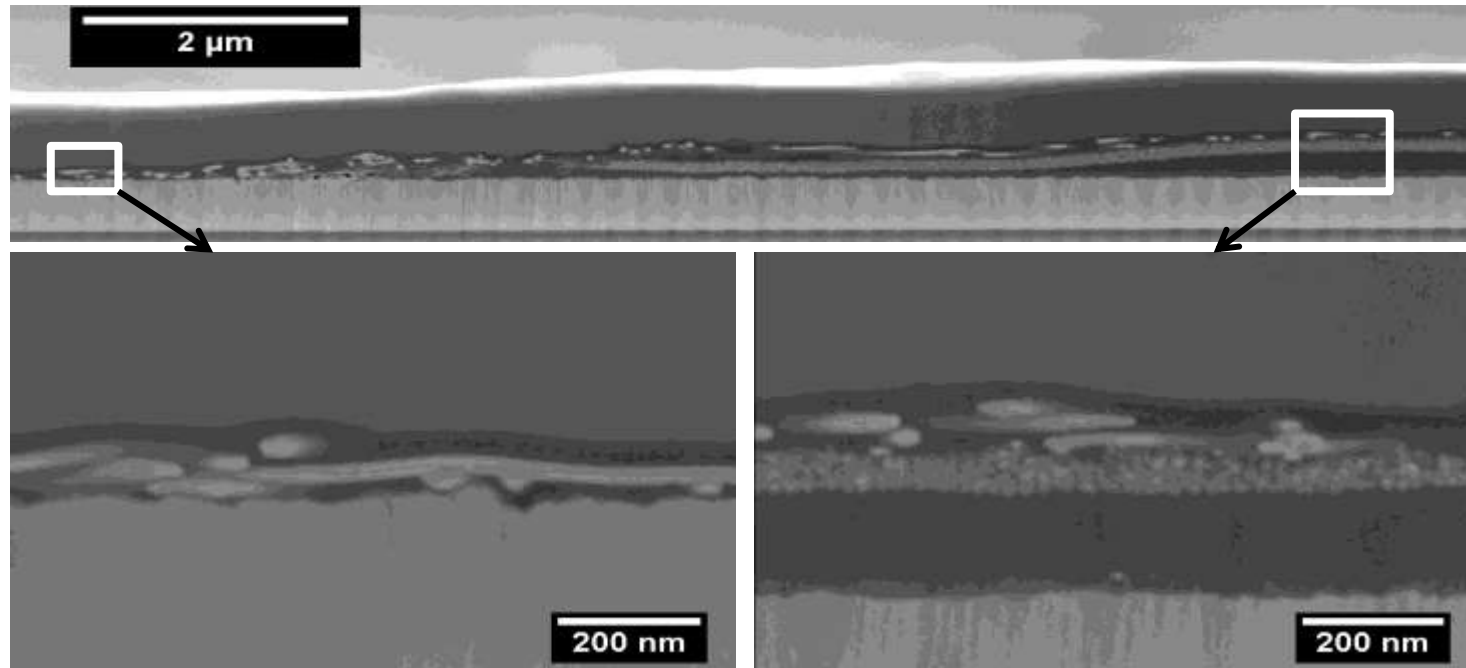


Semitransparent modules: laser structuring



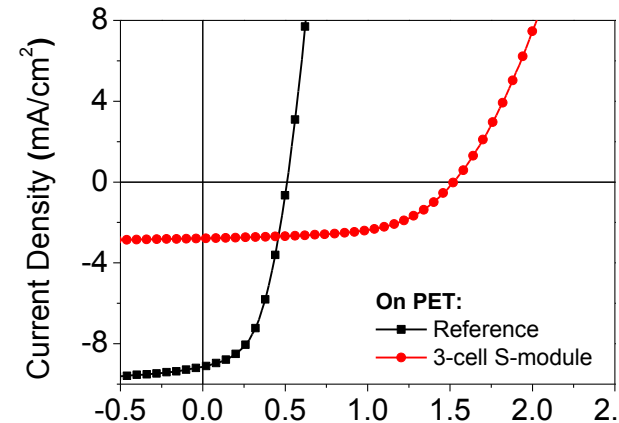
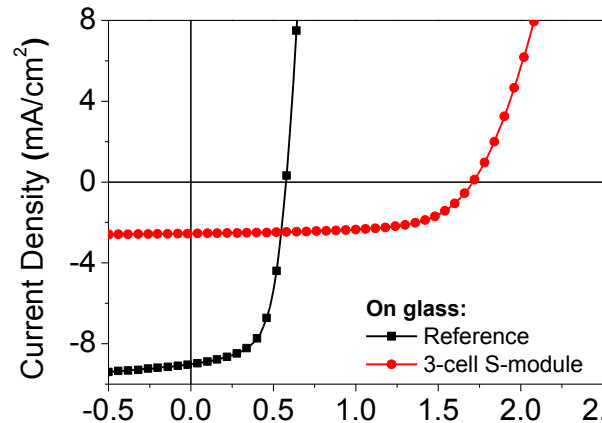
Femtosecond laser patterning allows to have a dead zone of $\sim 200\mu\text{m}$ and a high GFF of 95%

Semitransparent modules: laser structuring



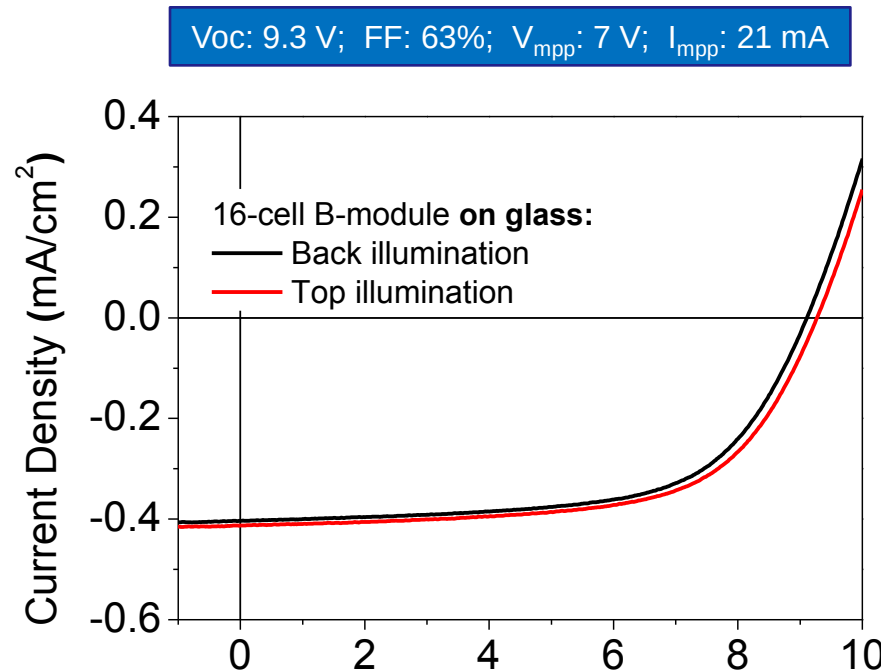
Cross-section TEM confirms the functionality of the interconnect

Semitransparent modules: IV-data



Devices	Substrate	V _{oc}	FF	J _{sc}	PCE
Ref.	Glass	0.57	60.7	9.0	3.15
	PET	0.51	49.5	9.2	2.31
3-cell	Glass	1.71	63.3	2.5	2.75
	PET	1.52	57.5	2.8	2.44
5-cell	Glass	2.94	62.7	1.3	2.4

Semitransparente modules: upscaling

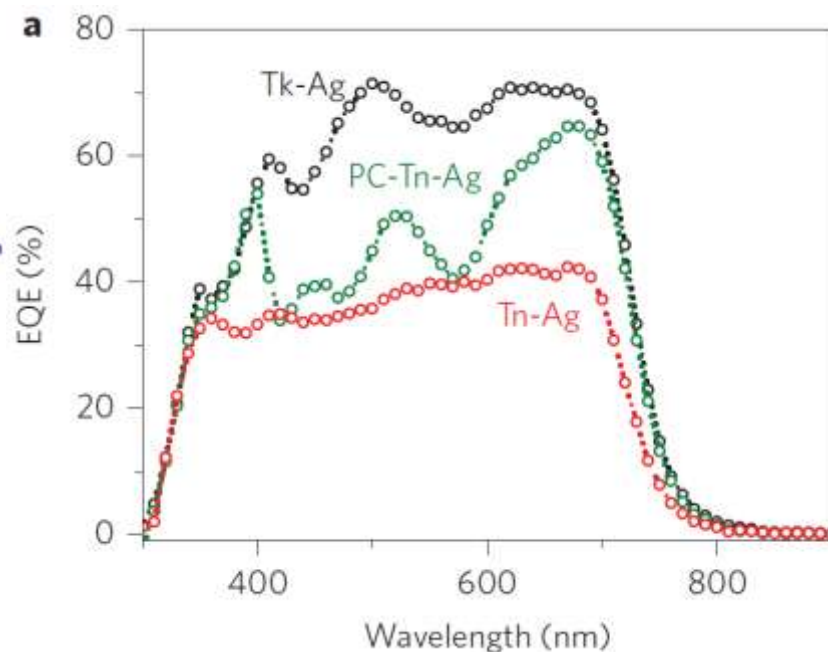
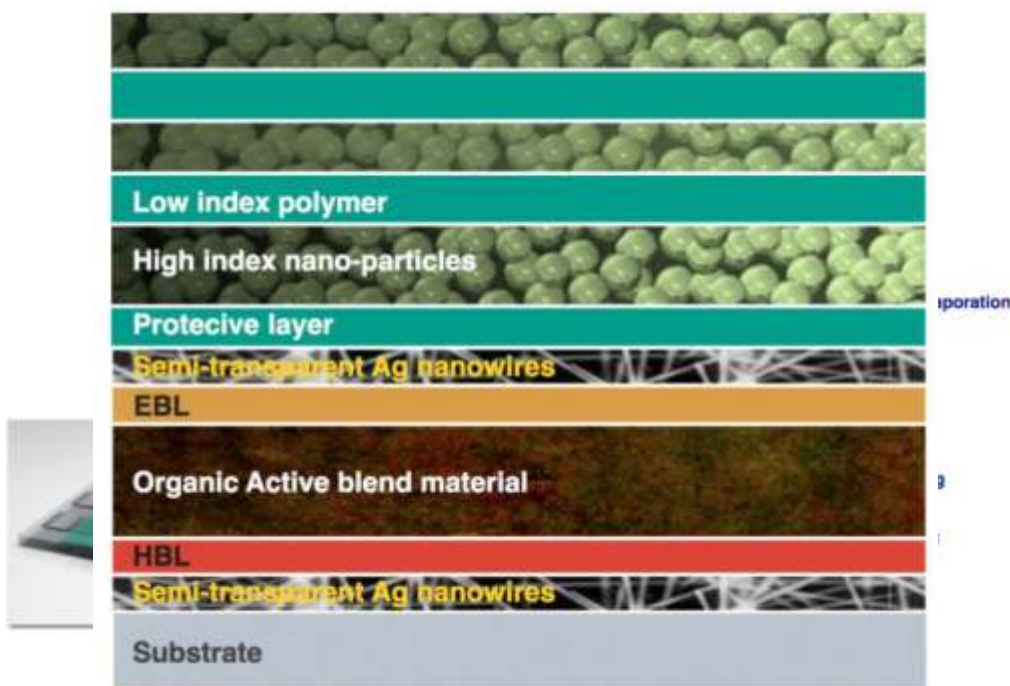


Laser patterning leads to a homogeneous appearance

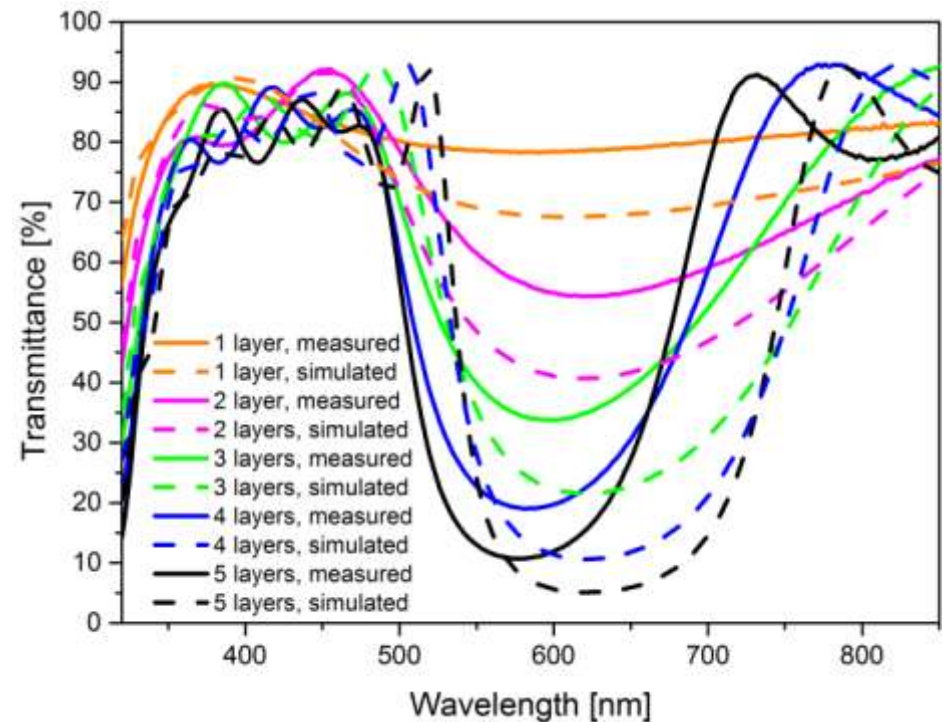
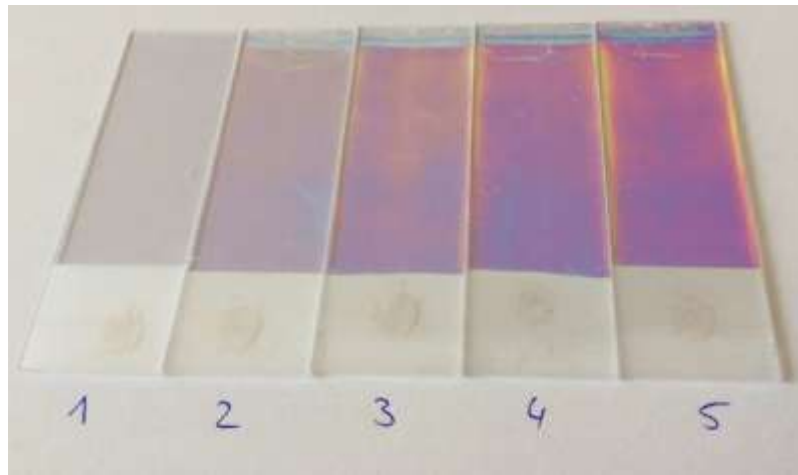
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Semitransparent solar cells with wavelength selective mirrors



Semitransparent solar cells with wavelength selective mirrors



Printed mirrors show tunable transmittance spectra and can be integrated into a roll-to-roll production process

Thank you for your attention!

