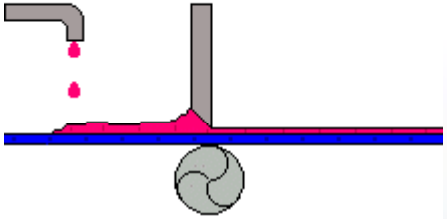
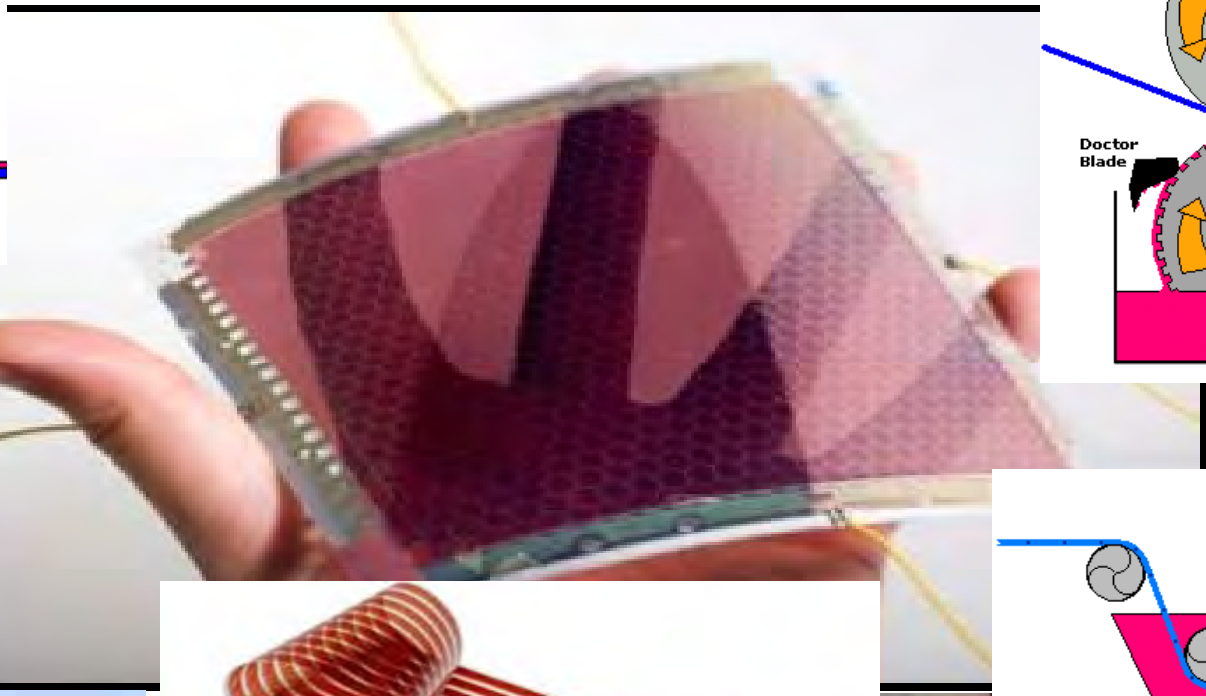
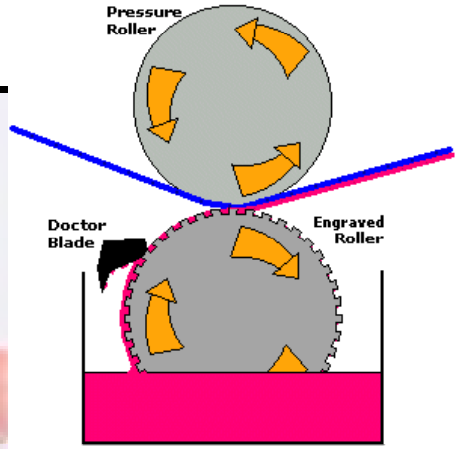
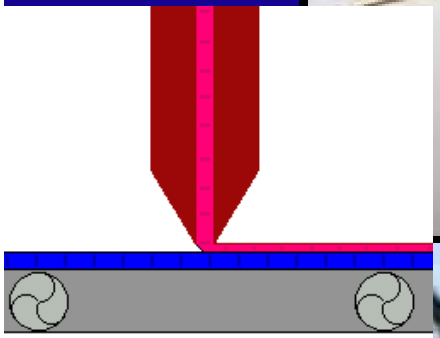
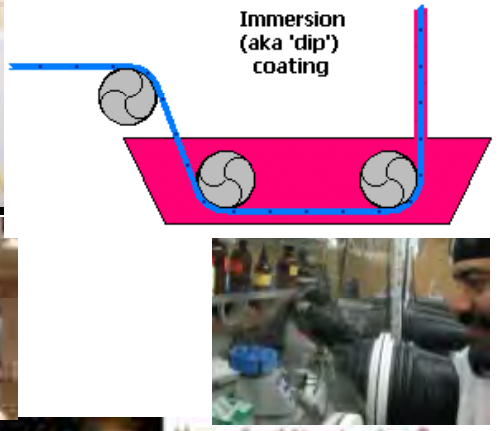
Plastic (Organic) Solar Cells: Accomplishments, Challenges, and Strategies

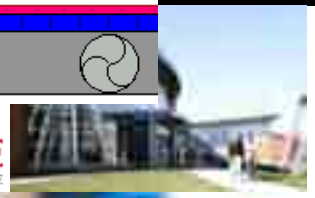












IOWA STATE
WITH PRIDE AND PURPOSE

IOWA STATE UNIVERSITY

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Organic semiconductors

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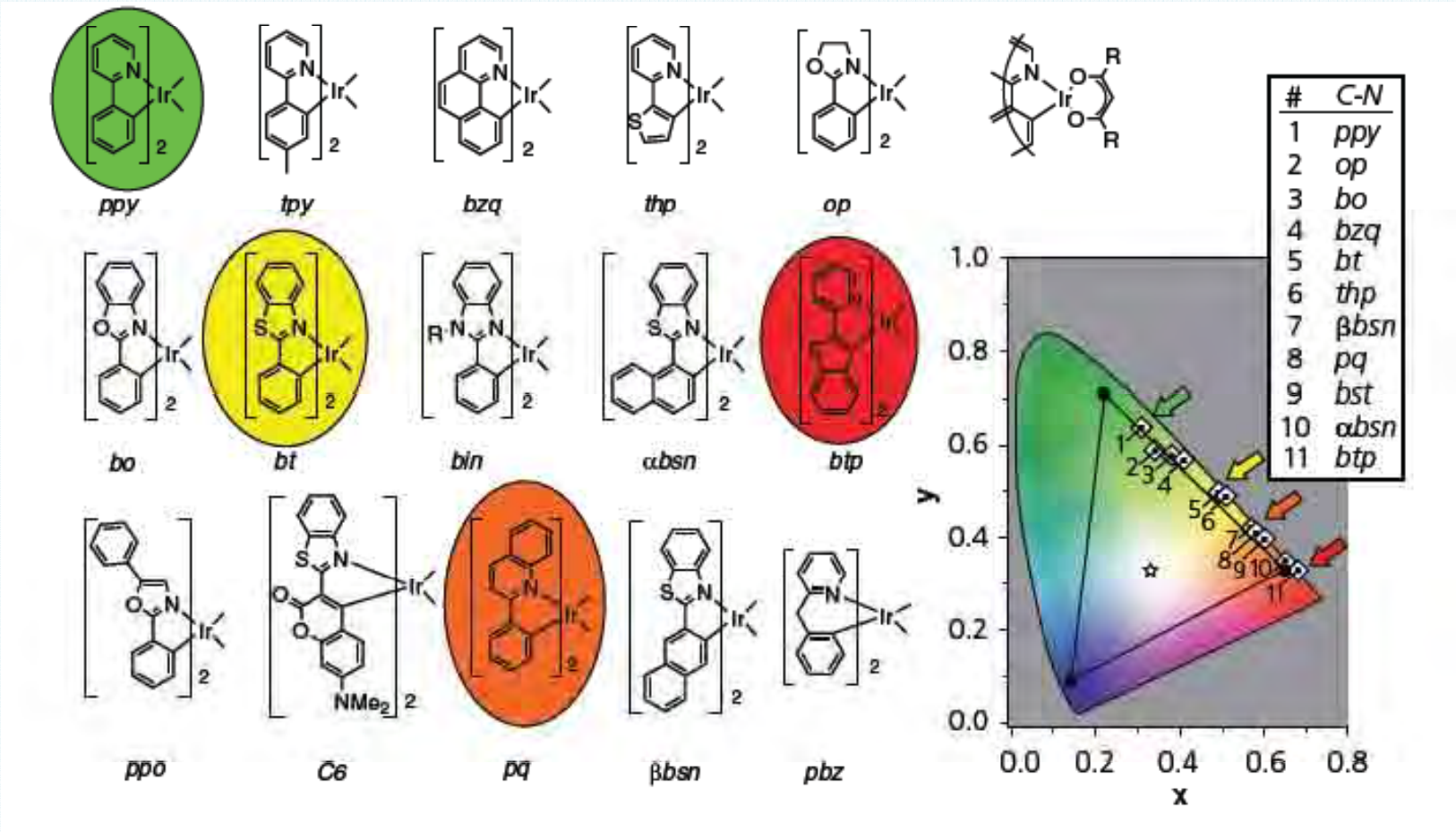
Function comes from form !



Some representative OPV materials

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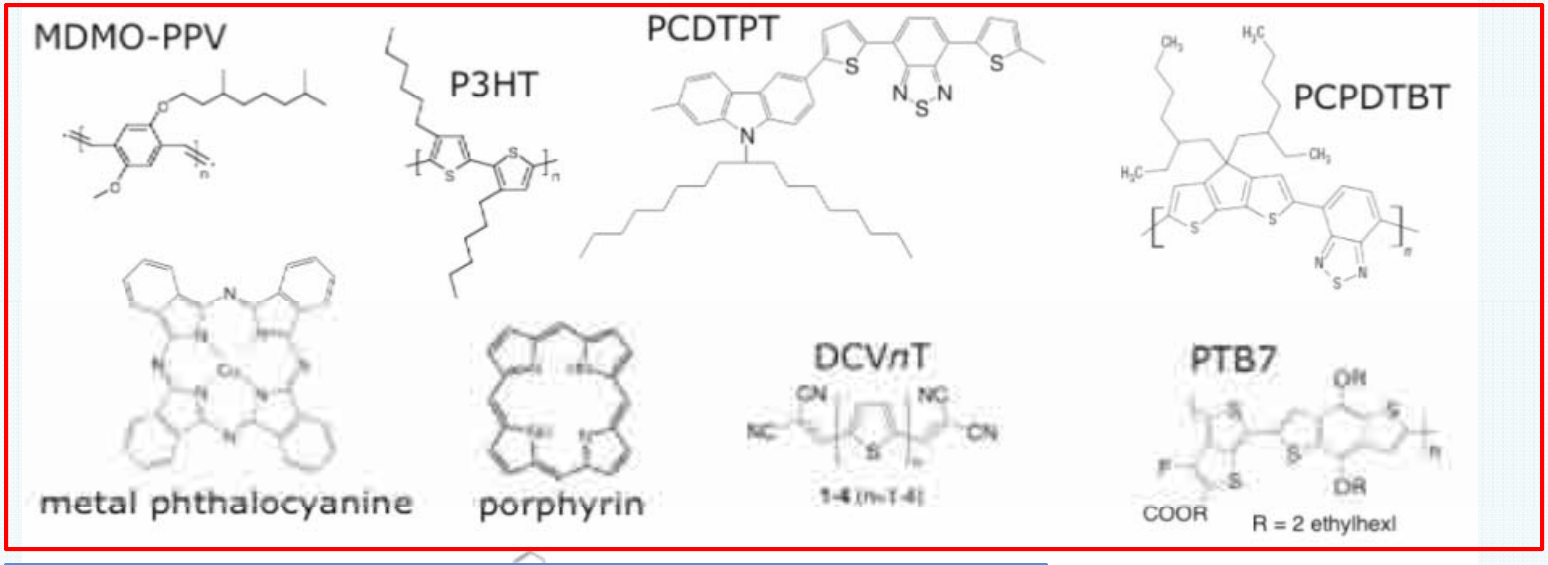
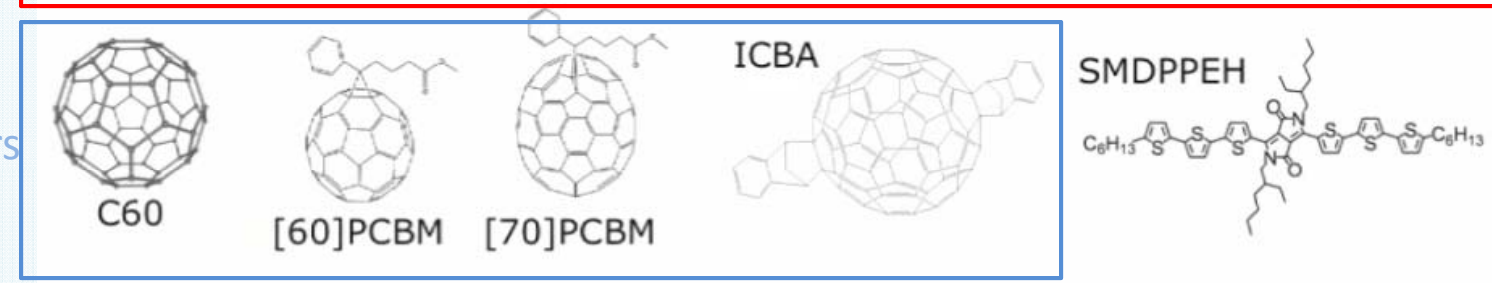
Donors



Acceptors



Enormous variety of molecules is a great strength of organic photovoltaic

But it also brings challenges

Conventional solar cells vs. Plastic solar cells

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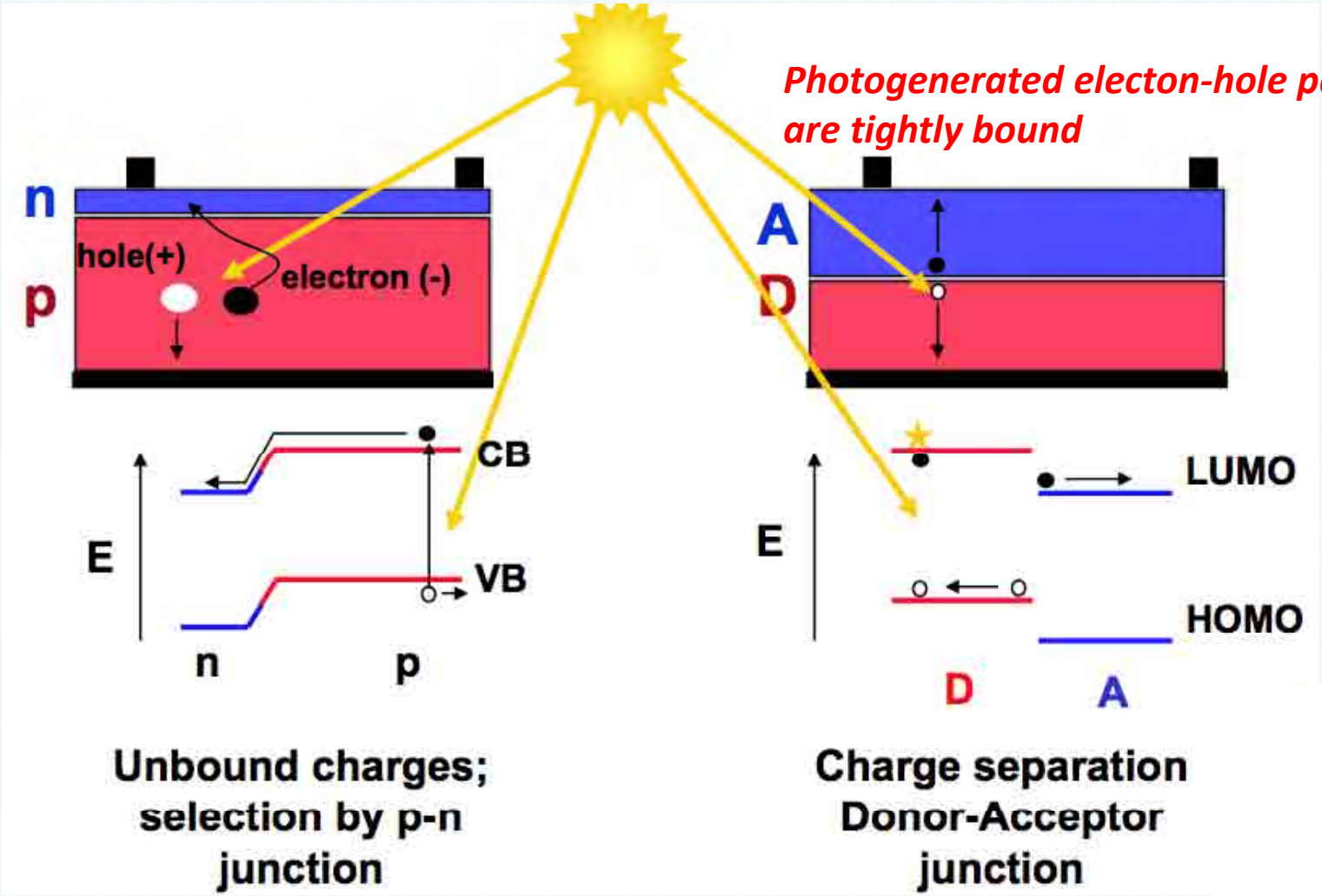

Heterojunction vs. Bulk-heterojunction

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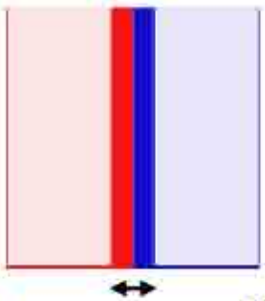
Inefficient 1990's architecture

Heterojunction

optimal light absorption $d=10^{-7}m$



efficient charge separation $d=10^{-8}m$

State-of-the-art architecture

Bulk Heterojunction

optimal light absorption $d=10^{-7}m$

efficient charge separation $d=10^{-7}m$

Progress in photovoltaic efficiencies

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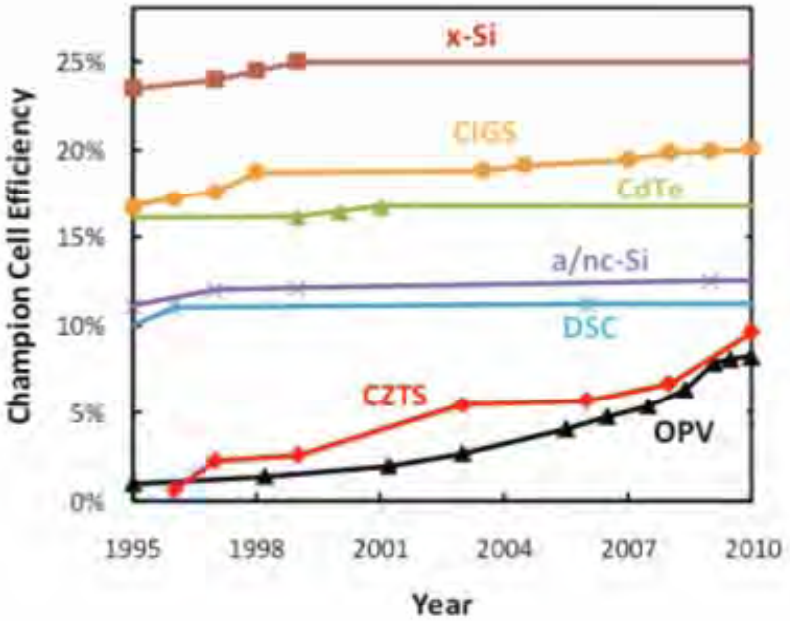
Early days of OPV
- Late 60's and early 70's: early work with tetracene, phthalocyanine, and polyvinylcarbazole
- 1986: 2-layer cell, Tang (Kodak)

The evolution of champion cell single-junction efficiency since 1995 for various PV technologies*



*C. A. Wolden, J. Kurtin, J. B. Baxter, I. Repins, S. E. Shaheen, J. T. Torvik, A. Rockett, V. Fthenakis, E. S. Aydil, "Photovoltaic Manufacturing: Present Status and Future Prospects", *Journal of Vacuum Science and Technology A*, **29** (3) 030801 (2011).

OPV reaches 10% efficiency

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...-electronics Lab

Recent results from Mitsubishi Corporation

Japan Chemical Web — Date: June 27, 2011 (Page 1 of 1)

Mitsubishi Ups Efficiency of Organic-photovoltaic Cell to Over 10%

Mitsubishi Chemical Holdings announced that it had achieved the world's first thin-film organic-photovoltaic cell with energy-conversion efficiency of over 10% and OPV-module energy-conversion efficiency of 6-7%, almost equivalent to that of thin-film amorphous-silicon photovoltaic cells and opening the door to applications in locations such as trailer roofs and building walls.

The company plans to promote its products at home and abroad, develop new applications and leverage its strength as a diversified chemical company, handling raw materials to finished products, to raise the efficiency further to 15% by 2015 and over 20% thereafter. It plans to coat polyester, polyethylene naphthalate and polyimide films with its OPV cells and distribute them in rolls by 2012.

Applications in locations such as building walls.

Mitsubishi, which improved its OPV cell's elements and structure to achieve the high efficiency, expects its product's high price/performance ratio to lead to the replacement of amorphous-silicon photovoltaic cells. A target market will be China, which provides subsidies for photovoltaic cells with conversion efficiency of over 10%.

The OPV cell has coatings of tetrabenzoporphyrin to act as the p-type semiconductor and a fullerene derivative to act as the n-type semiconductor. The previous efficiency of 9.2% was already the highest in the world but still inferior to that of amorphous-silicon photovoltaic cells, limiting its application potential.

Companies working on OPV
(partial list)

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Bosch (http://www.bosch.com/content/language2/html/4942.htm)

Eight19 (http://www.eight19.com/)

Heliatek GmbH (http://www.heliatek.com/)

Konarka Technologies (http://www.konarka.com/)

Mitsubishi (http://www.mitsubishielectric.com/bu/solar/)

Ossila (http://www.ossila.com/)

Plextronics, Inc. (http://www.plextronics.com/)

Solarmer Energy, Inc. (http://www.solarmer.com/)

SolarPress (http://www.solar-press.com/)

OPV products & prototype installations

Nano Architectonics & Nano Organo-electronics Lab

http://www.energy-sunbags.de/

http://www.skyshades.de/

OPV products & prototype installations

Nano Architectonics &
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http://www.konarka.com/

Typical device: Bulk Heterojunction

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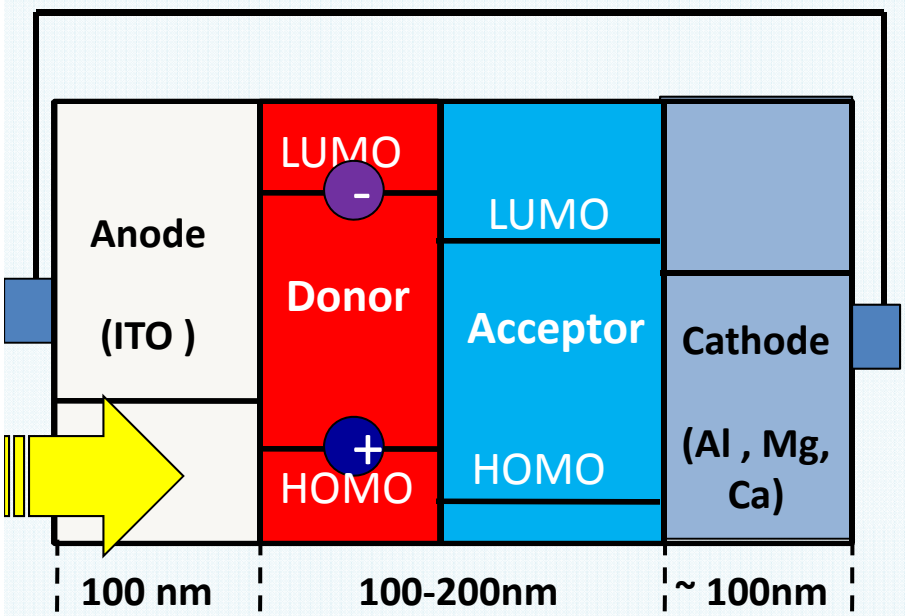
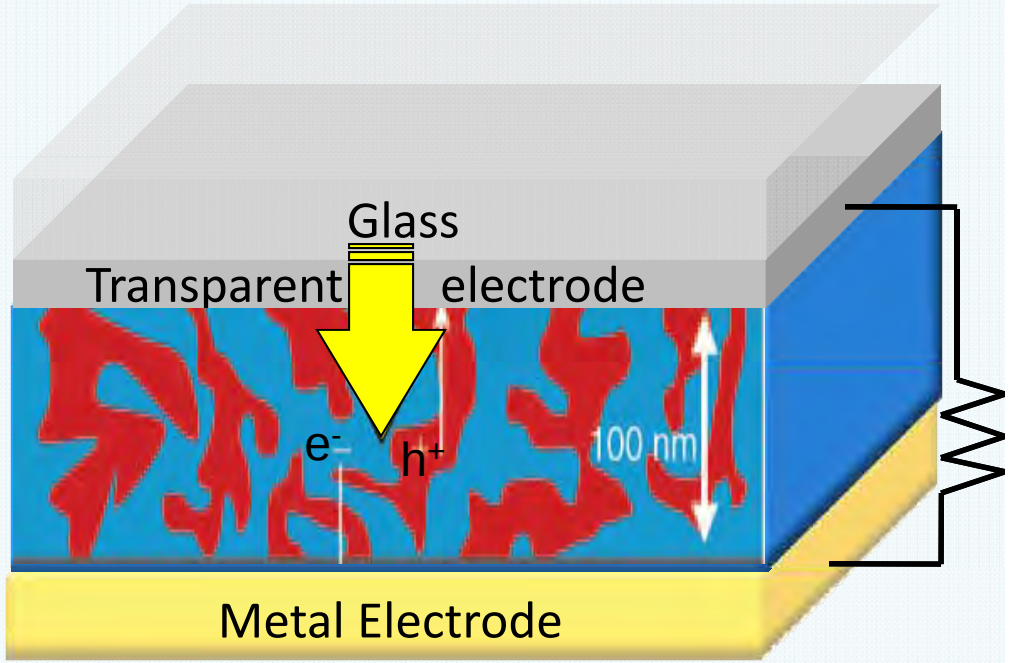
- Blend of **Donor** and **acceptor** phases
- Phase separation ~ exciton diffusion length
- Should have continuous pathways for electron and hole transport.





Hole transporting material (Donor)

Electron transporting material (Acceptor)

Major issues (losses)

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Theoretical efficiency ~ 23 %

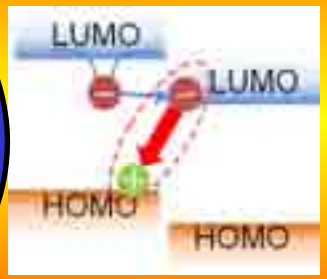
Realized efficiency ~ 8%

Efficiency Losses

Poor absorption of light

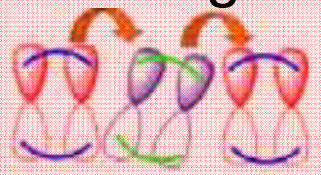
38%

Recombination losses



45%

Low charge mobility

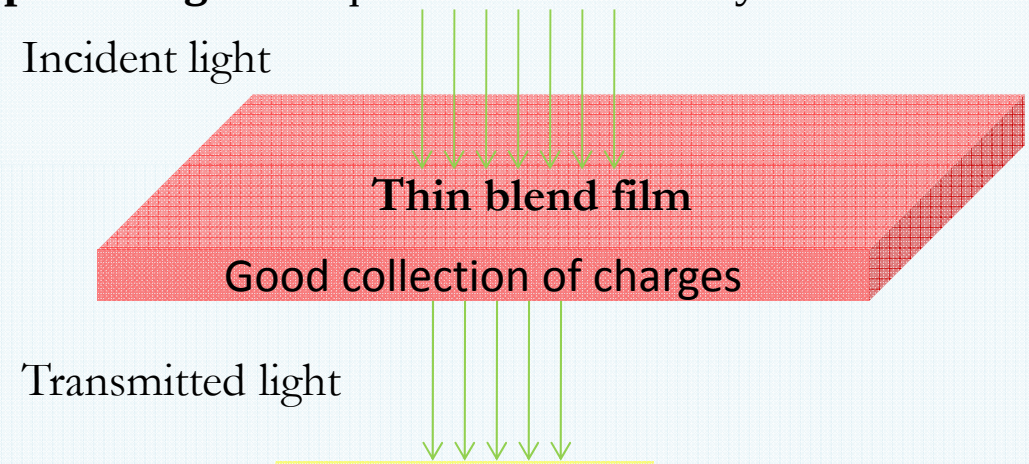


17%

Poor Absorption

Nano Architectonics & Nano Organo-electronics Lab

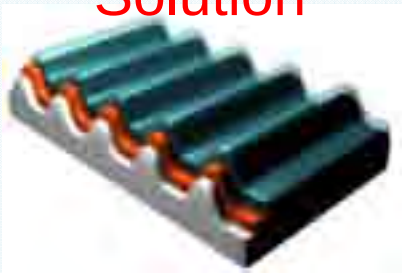
- **High band gap** of polymer – less absorption of higher wavelength photons
- **Moderate carrier mobility** –requires thin active layer
- **Absorption length** – requires thick active layer



Poor absorption !!

Solution

Requires **thin layer** for absorption due to **light trapping**

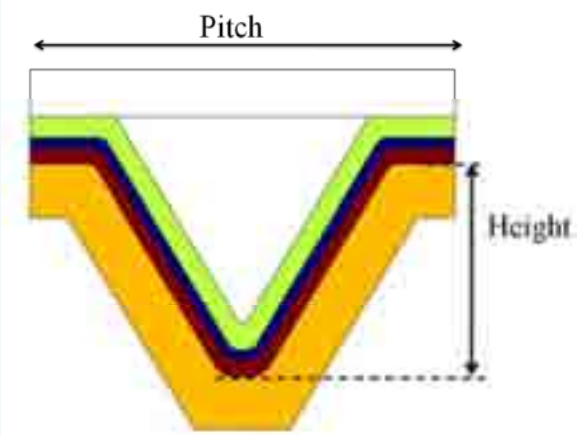


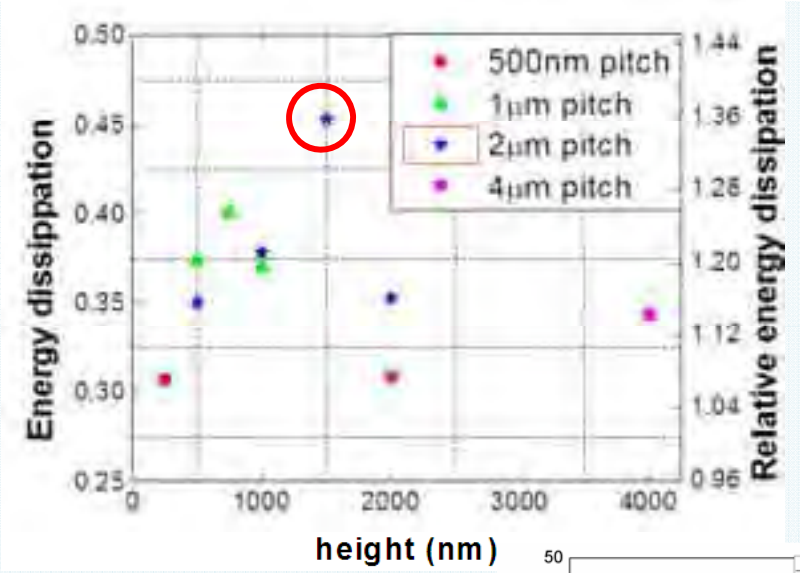
Textured substrates for Light trapping

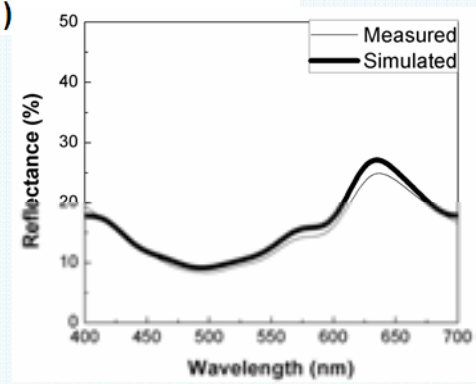
Best Photonic design

Nano Architectonics & Nano Organo-electronics Lab

(FEM) inbuilt in **COMSOL MULTIPHYSICS**







best design: 2 μm pitch-1.5 μm height
show **40%** enhancement.

Nalwa KS, Chaudhary S, "Design of light-trapping microscale-textured surfaces for efficient organic solar cells" ***Optics Express ,*** 2010, 8 (5), 5168-5178.

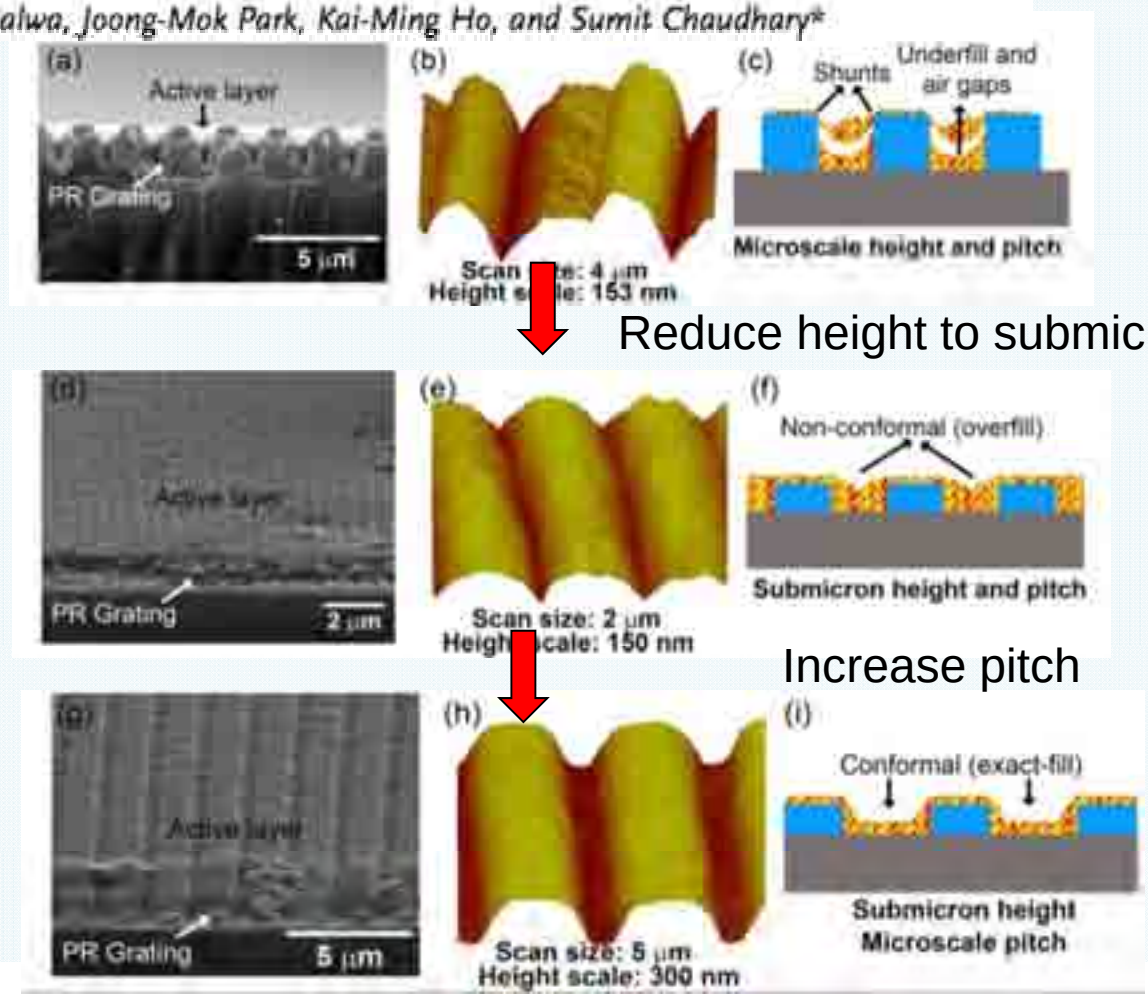
Best Practical Design

Nano Architectonics & Nano Organo-electronics Lab

ADVANCED MATERIALS
www.advmat.de
Materials Views
www.MaterialsViews.com

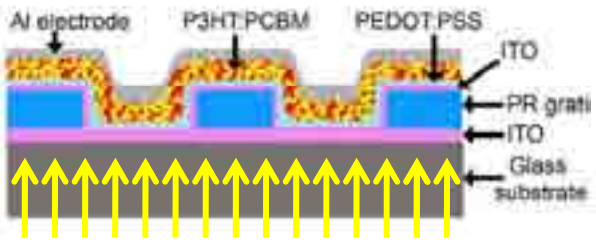
On Realizing Higher Efficiency Polymer Solar Cells Using a Textured Substrate Platform

*Kanwar S. Nalwa, Joong-Mok Park, Kai-Ming Ho, and Sumit Chaudhary**

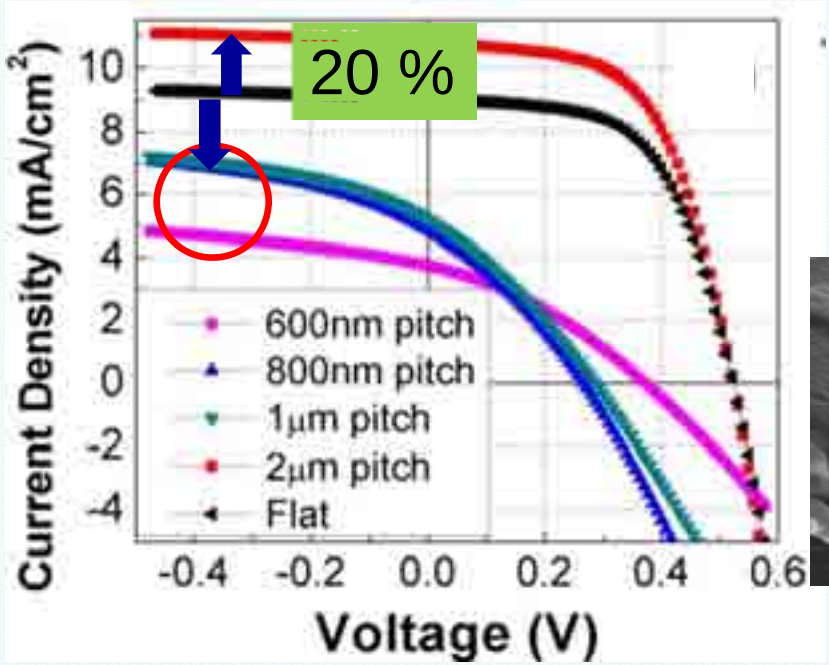


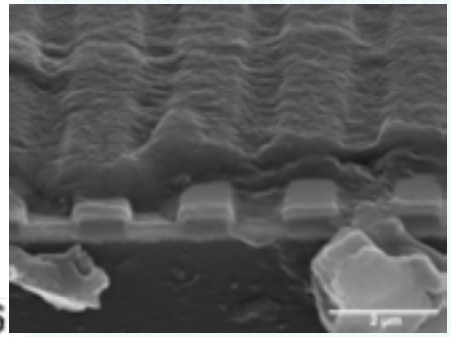
Photovoltaic characteristics

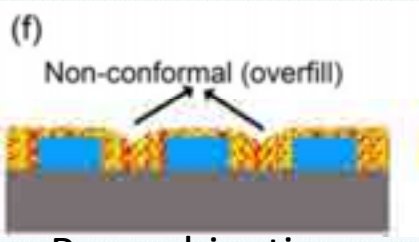
Nano Architectonics & Nano Organo-electronics Lab



Incident light







Recombination losses in valley

Micronscale pitch (2 μm) + **submicron height (300 nm)** with conformal active layer leads to **highest photocurrent.**

Nalwa KS, JM Park, KM Ho, **Chaudhary** S, "On realizing efficient polymer solar cells using a textured substrate platform" ***Advanced Materials***, 23, 112-116 (2011).

Novel transparent electrodes (metal based)

Nano Architectonics & Nano Organo-electronics Lab

Materials Views
www.MaterialsViews.com

ADVANCED MATERIALS
www.advmat.de

A New Architecture for Transparent Electrodes: Relieving the Trade-Off Between Electrical Conductivity and Optical Transmittance

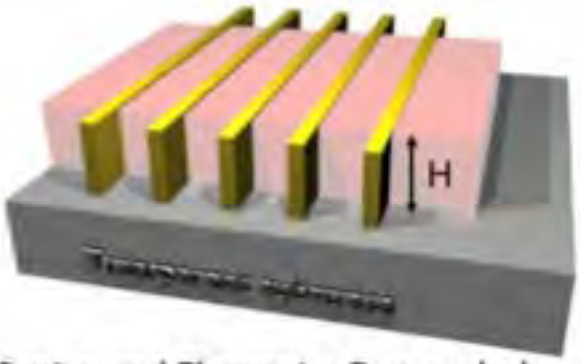
Ping Kuang, Joong-Mok Park, Wai Leung, Rakesh C. Mahadevapuram, Kanwar S. Nalwa, Tae-Geun Kim, Sumit Chaudhary, Kai-Ming Ho,* and Kristen Constant**

Nanowires or **flat lying** nanoribbons (nanoscale height and width)

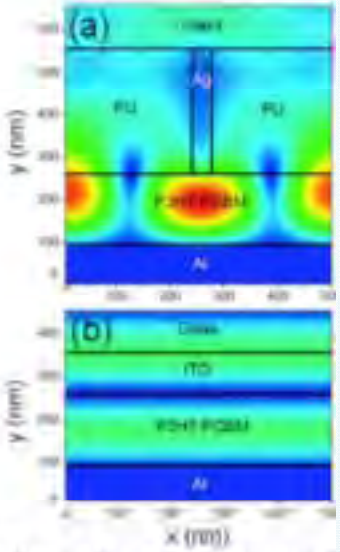
Optical/Electronic Trade-off
-- Increasing width (W) increases conductivity, but decreases transmittance

Conventional

Vertically standing nanoribbons (nanoscale width, (sub)microscale height)



Optics and Elecronics Decoupled
-- Increasing height (H) increases conductivity, without affecting transmittance



Broadband enhancement

Our structure

Issues

Nano Architectonics & Nano Organo-electronics Lab

Theoretical efficiency ~ 23 %

Realized efficiency ~ 8%

Efficiency Losses

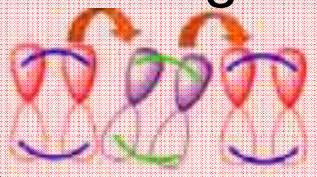
Poor absorption of light

38%

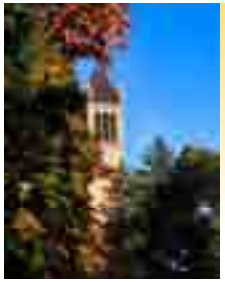
Recombination losses

45%

Low charge mobility



17%



A Solution to enhance exciton dissociation

Nano Architectonics & Nano Organo-electronics Lab

Addition of **ferroelectric polymer**

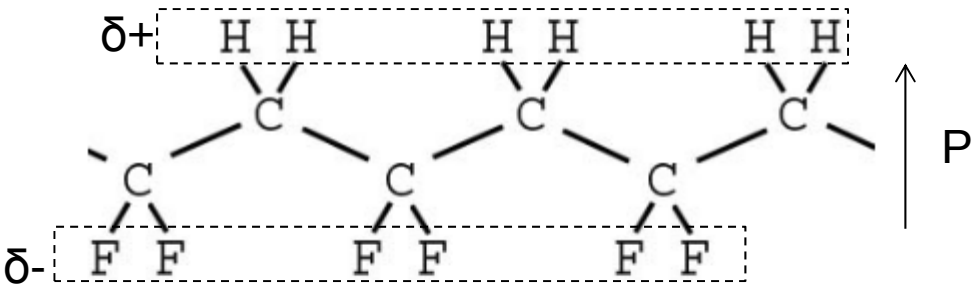
For 3% volume fraction (*f*) addition

$$E = \frac{4\pi}{\varepsilon}\sigma f \quad \rightarrow \quad E \sim 240\ \text{V/}\mu\text{m}$$

~5 times the required field for 100% CTE dissociation

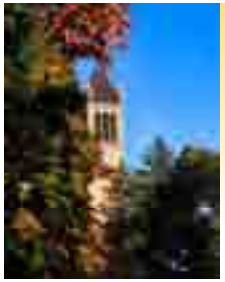
f, volume fraction of PVDF
σ, surface charge density = 6μC/cm²
ε, dielectric constant of =11

poly(vinylidenefluoride) **PVDF**



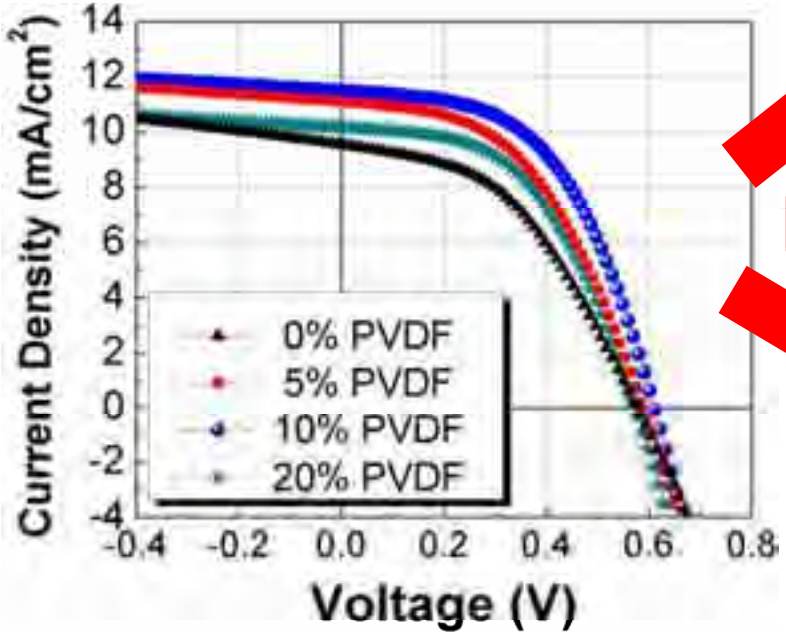
Why PVDF-TrFE copolymer ?

- Solution processibility
- High dielectric constant (~10)
- Existence in ferroelectric β-phase at room temperature.

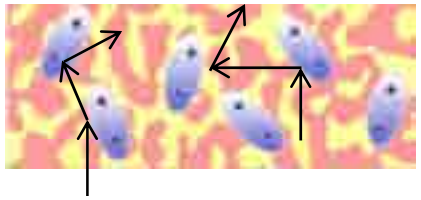


Photovoltaic performance and cause

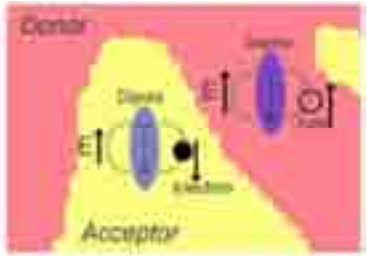
Nano Architectonics & Nano Organo-electronics Lab



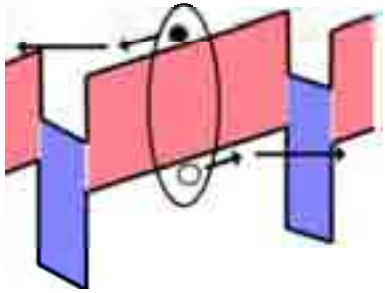
Light scattering by PVDF (n = 10)



Enhanced charge transport



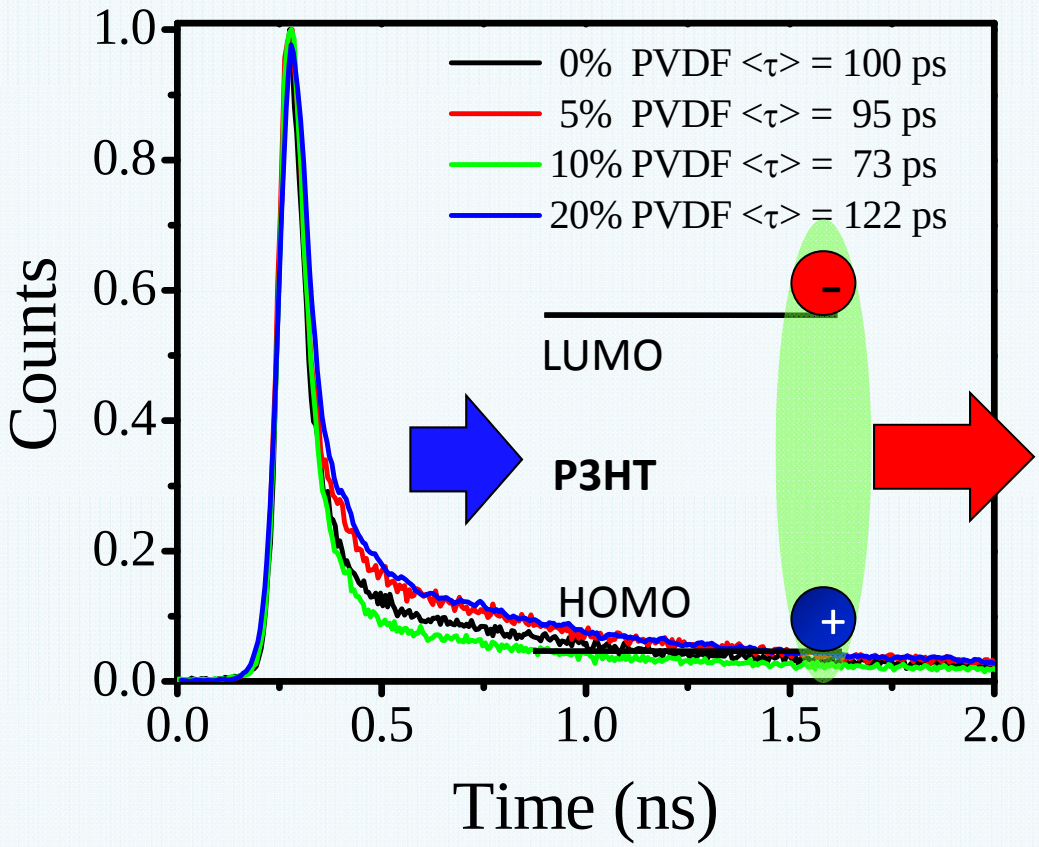
Enhanced exciton dissociation

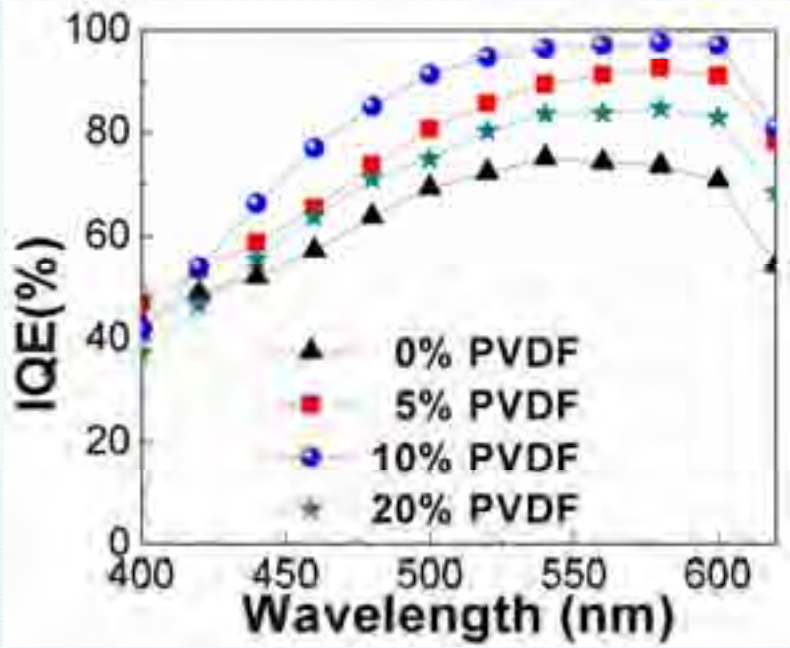


- **10 % ferroelectric** addition gives highest **efficiency**.
- **50%** improvement in **efficiency**

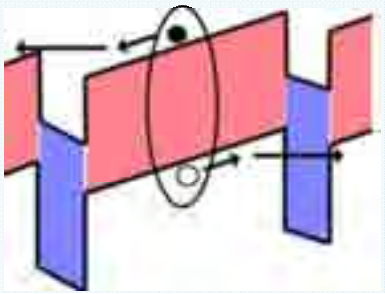
Enhanced Exciton Dissociation ?

Nano Architectonics & Nano Organo-electronics Lab





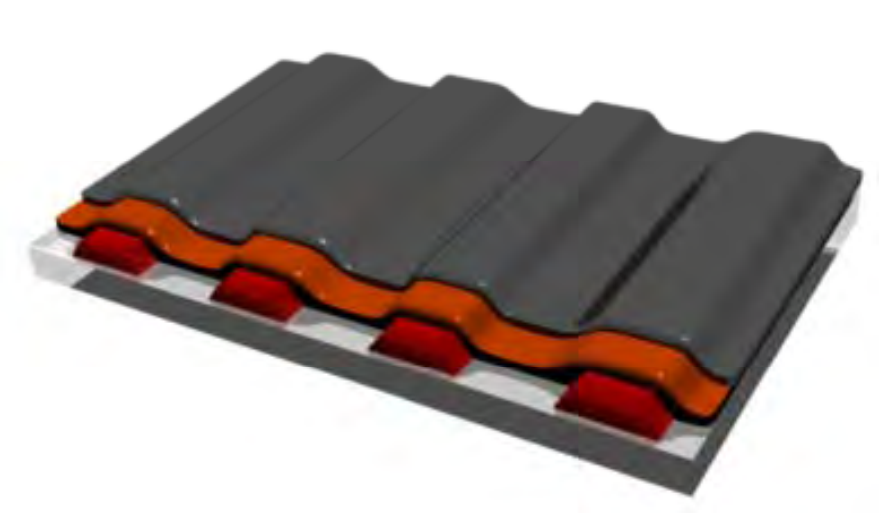
Indeed !!



In summary

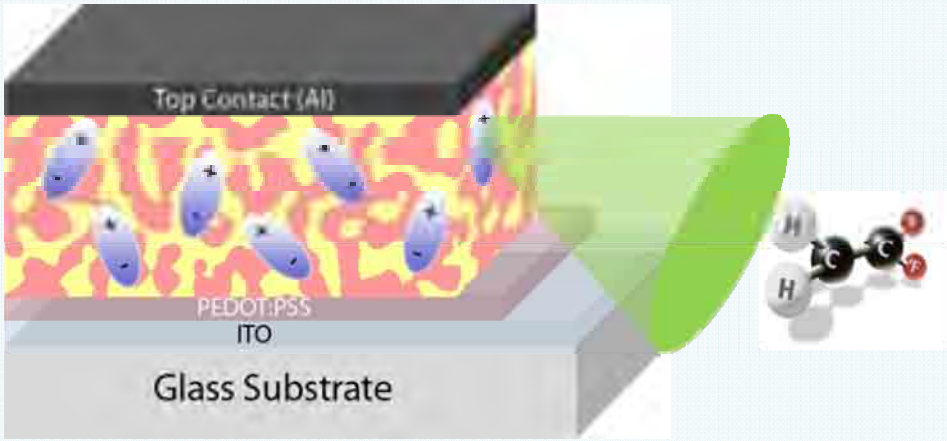
Nano Architectonics & Nano Organo-electronics Lab

- Organic photovoltaics are at an exciting stage. More challenges ahead in terms of efficiency and stability
- We realized two ways to improve efficiency of organic solar cells:



20% improvement

Solution for thin layer OPV



50% improvement

Solution for thick layer OPV

Acknowledgements

Nano Architectonics & Nano Organo-electronics Lab

STUDENTS

Kanwar Nalwa (now at Intel)

Rakesh Mahadevapuram

John Carr

Yuqing Chen

Moneim Ismail

COLLABORATORS

Kai-Ming Ho, Baskar Ganapathysubramanian, Jake Petrich

$$$$

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