Organic Electronic Devices

Week 4: Organic Photovoltaic Devices

Lecture 4.5: Emerging Trends in OPV Devices

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Lecture Overview and Learning Objectives

- **Concepts to be Covered in this Lecture Segment**
  - Introduction to Inverted Organic Photovoltaic Devices and Explanation of Device Operation
  - Explanation of the Benefits of Inverted Organic Photovoltaic Device Fabrication and Operation
  - Benefits of Tandem and Multi-junction Organic Photovoltaic Devices for High-Performance Devices

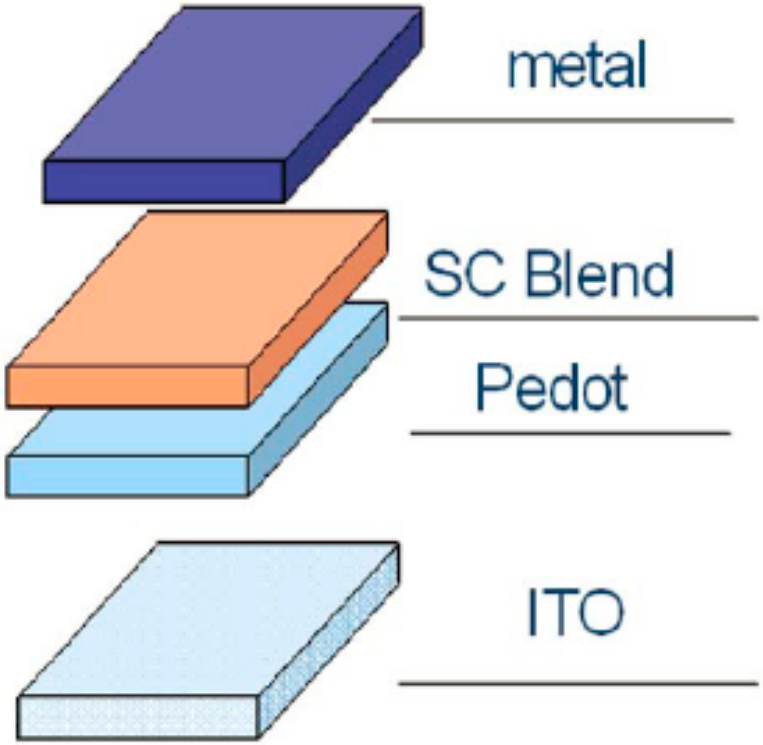
- **Learning Objectives**

  By the Conclusion of this Presentation, You Should be Able to:

  1. **Define** what is meant by an “inverted” organic photovoltaic device and **describe** how it differs from a “regular” architecture.
  2. **Discuss** potential advantages of using inverted organic photovoltaic devices related to regular architectures.
  3. **Explain** what is meant by a tandem or multi-junction solar cell and why these solar cells have very high power conversion efficiencies.

Inverted OPVs Alter the Polarity the Transparent Conductor

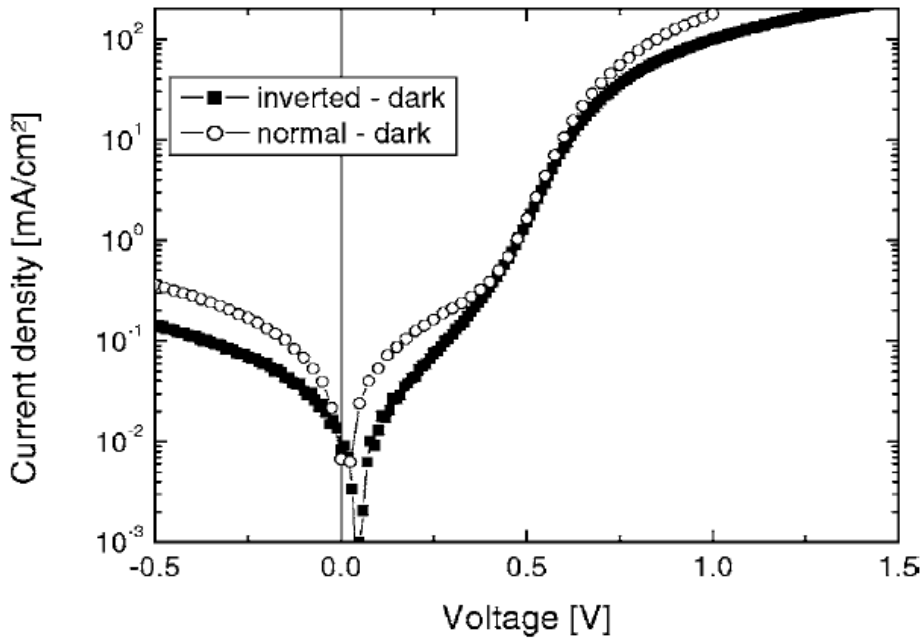
“Regular”, “Standard”, or “Normal” Device Architecture



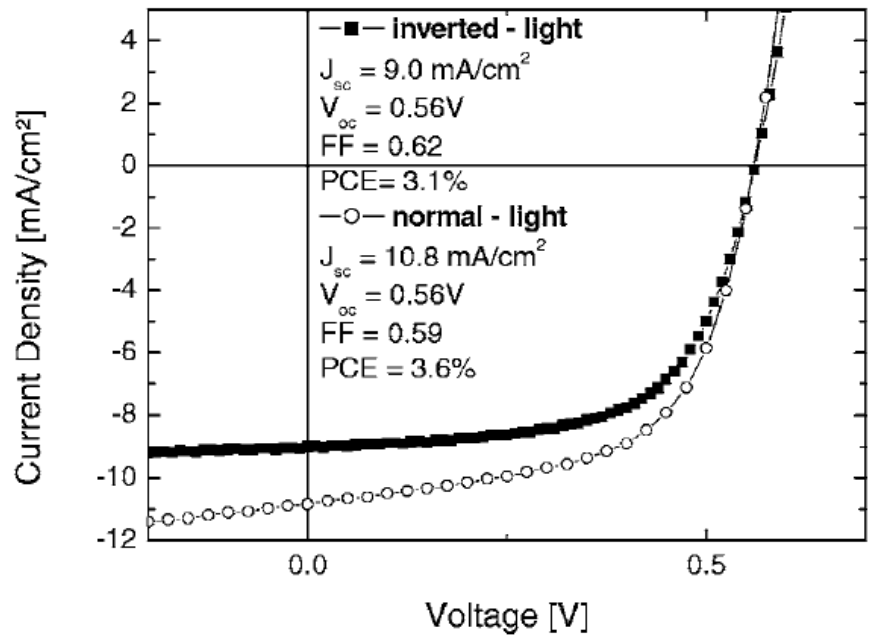
Further Reading: Waldauf, C. *et al*. *Appl. Phys. Lett.* **2006**, *89*, 233517.

Inverted OPVs Perform Roughly as Well as Normal OPVs

Devices in the Dark



Devices under Illumination



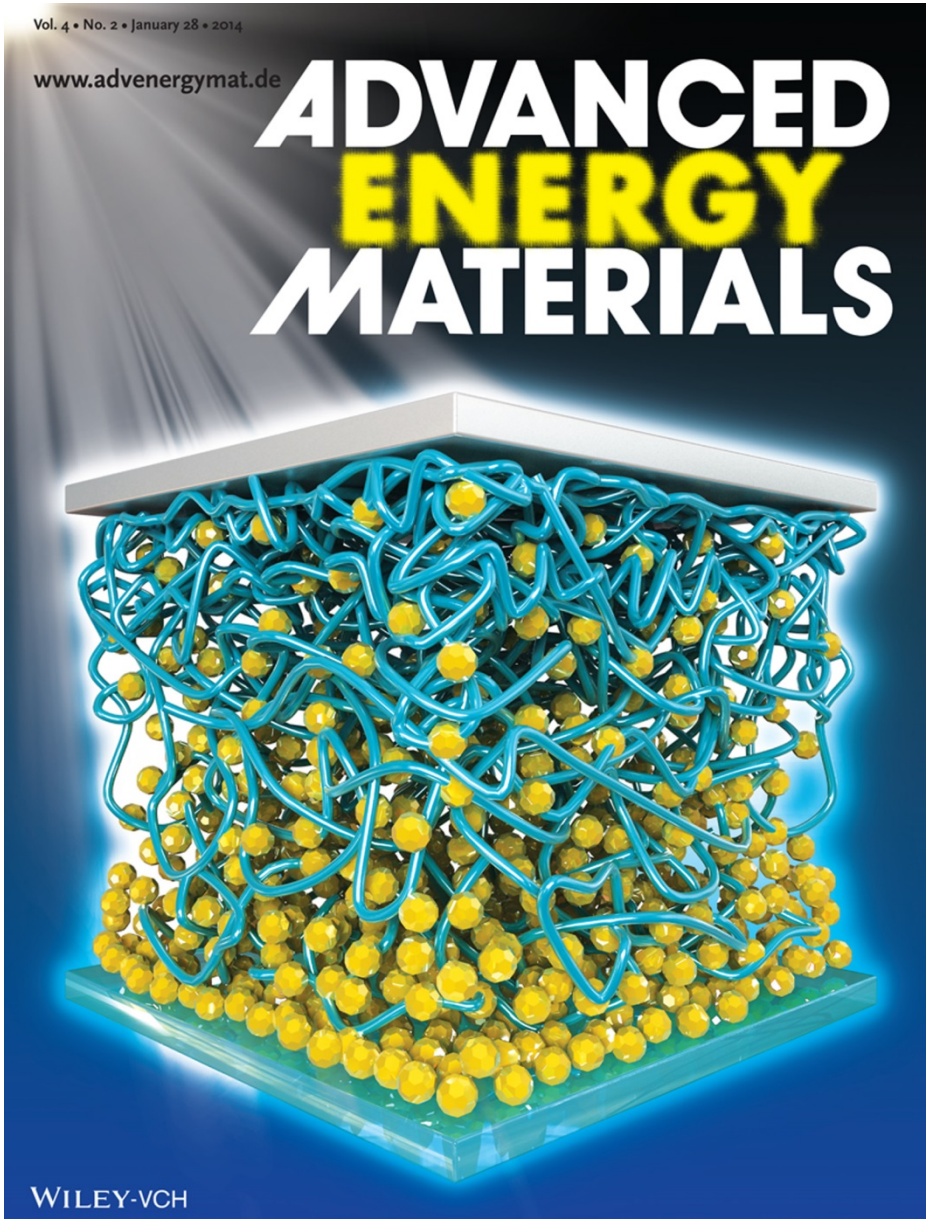
Two Primary Advantages of Inverted Organic Photovoltaic Devices

- Hole-transporting polymers (*e.g.*, P3HT) tend to phase separate away from the bottom contact (*i.e.*, to the free surface interface) during casting. This means that the nanostructure of BHJ OPVs are p-type rich near the anode in inverted devices.

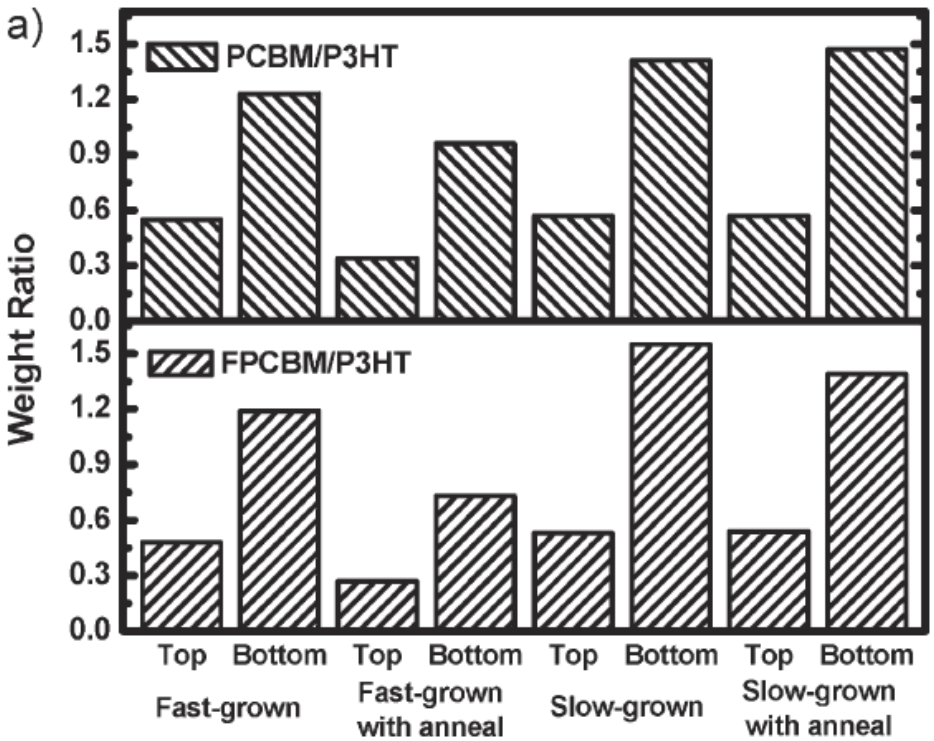
- The top contact metals (*e.g.*, Ag, Au) for inverted OPVs are much more air stable than the top contact metals (*e.g.*, Al) used for regular OPV devices.

Further Reading: Waldauf, C. *et al*. *Appl. Phys. Lett.* **2006**, *89*, 233517.

Vertical Phase Separation in Polymer:Fullerene Solar Cells



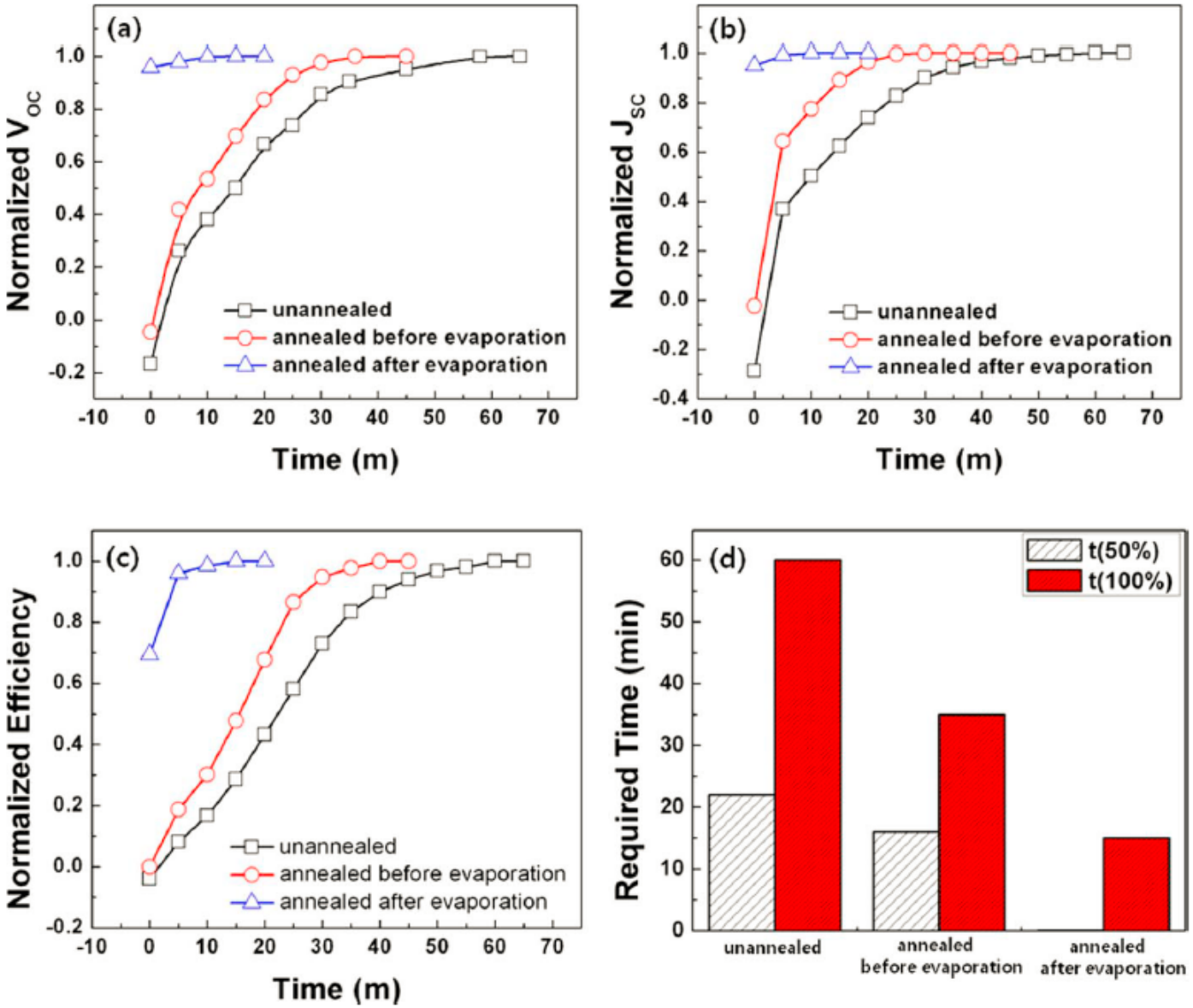
Measuring the Vertical Phase in Bulk Heterojunctions with XPS



The thin films are fullerene-rich at the organic-substrate interface

Further Reading: Xu, Z. *et al*. *Adv. Funct. Mater.* **2009**, *19*, 1227.

Device Stability with P3HT:PCBM Inverted Solar Cells



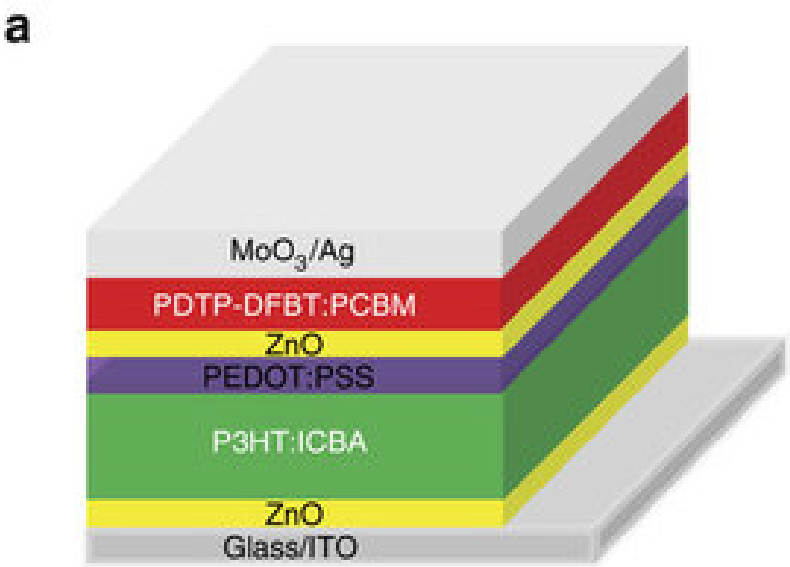
Further Reading: Kim, J. B. *et al*. *Appl. Phys. Lett.* **2009**, *95*,183301.

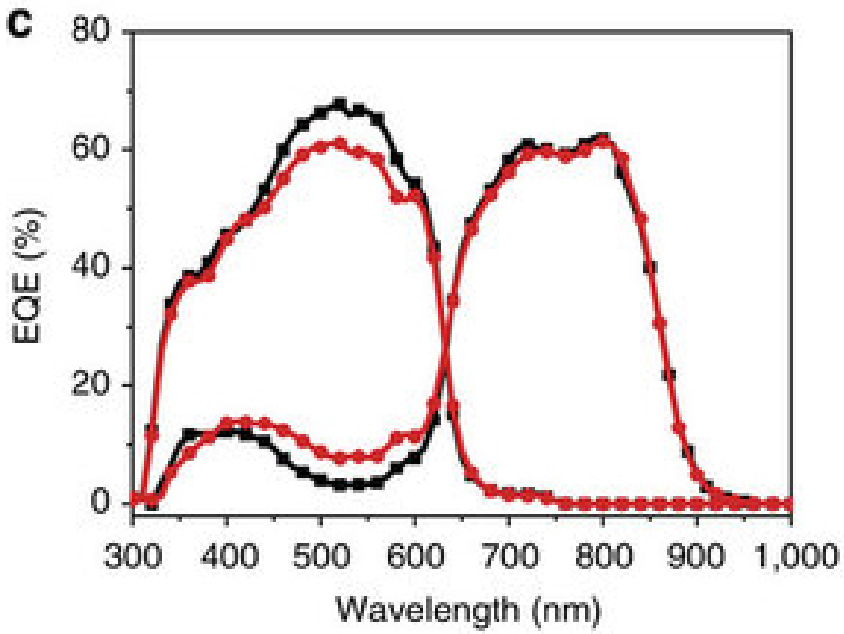
Tandem Solar Cells Allow for the Absorption of More Light

<u>In Order to Absorb More Light, There Generally Are Two Different Stratagies</u>

1. Create a polymer capable of absorbing across a wide range of wavelengths in the visible and infrared spectrum. This is possible, but can be difficult due to the stringent design demands of such a polymer.

2. Use a combination of solar cells with active layer polymer materials that absorb in complementary portions of the spectrum. This is easy to achieve from a materials perspective, but can does have device fabrication concerns.





Further Reading: You, J.; Dou, L. *et al*. *Nat. Commun.* **2013**, *4*, 1446.

Tandem Solar Cells Have a Tradeoff Between J_{sc} and V_{oc}

ARTICLE

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OPEN

A polymer tandem solar cell with 10.6% power conversion efficiency

Jingbi You[1,*], Letian Dou[1,*], Ken Yoshimura[2], Takehito Kato[2,†], Kenichiro Ohya[2], Tom Moriarty[3], Keith Emery[3], Chun-Chao Chen[1], Jing Gao[1], Gang Li[1] & Yang Yang[1,4]

Table 2 | P3HT and PDTP-DFBT single junction cell and tandem solar cell performance.

Devices	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF (%)	PCE (%)
P3HT:ICBA	0.84	10.3	71.1	6.1
PDTP-DFBT:$PC_{61}BM$	0.70	15.4	66.2	7.1
PDTP-DFBT:$PC_{71}BM$	0.68	17.8	65.0	7.9
P3HT:ICBA/PDTP-DFBT:$PC_{61}BM$ (Tandem 1)	1.53	10.1	68.5	**10.6***
P3HT:ICBA/PDTP-DFBT:$PC_{71}BM$ (Tandem 2)	1.51	9.8	69.2	10.2

DFBT, difluorobenzothiadiazole; FF, fill factor; ICBA, Indene-C_{60}Bisadduct; P3HT, poly-(3-hexylthiophene); PCE, power conversion efficiency.
*Values are measured and certified by National Renewable Energy Laboratory.

There is a trade-off between the short-circuit current density and the open-circuit voltage that can be pulled from the tandem cells relative to the individual sub-cells.

Further Reading: You, J.; Dou, L. *et al*. *Nat. Commun.* **2013**, *4*, 1446.

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- If the fill factor of the first sub-cell (FF_1) is similar to the fill factor of the second sub-cell (FF_2) then the short-circuit current density of the tandem cell will be limited by the short-circuit current density of the lower-performing cell.

- The open-circuit voltage of the tandem cell can be as high as the summation of the open-circuit voltage values of the two individual sub-cells.

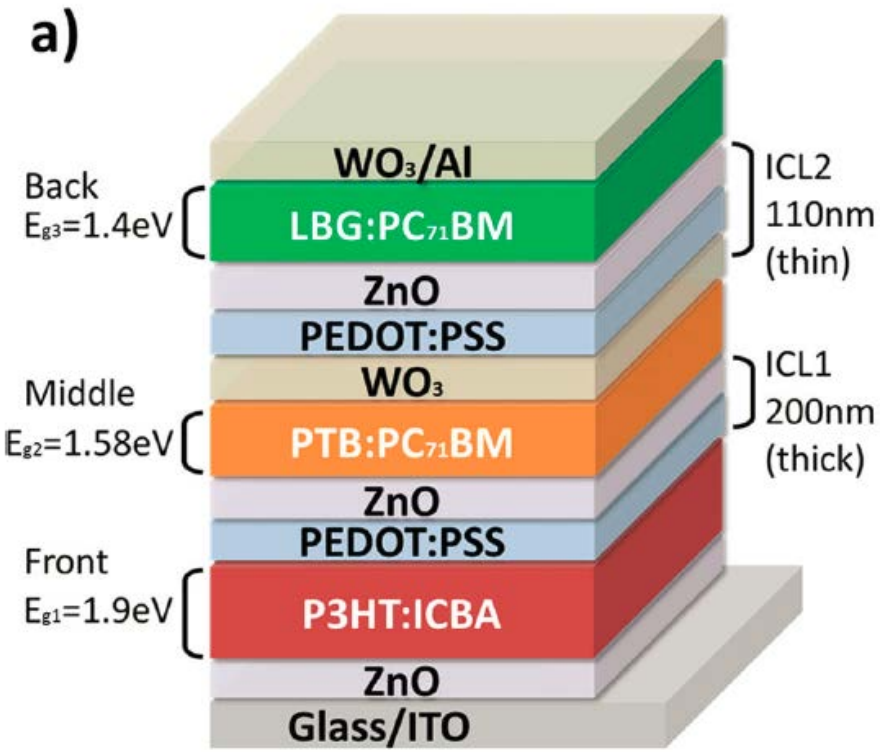
$$\therefore FF_1 \approx FF_2 = FF; \quad (J_{sc})_{\min} \approx J_{sc}; \quad V_{oc} \approx V_{oc_1} + V_{oc_2}$$

$$\eta_{Tandem} \approx \frac{(J_{sc})_{\min} \times FF \times \left[V_{oc_1} + V_{oc_2}\right]}{P_{in}}$$

Further Reading: You, J.; Dou, L. *et al*. *Nat. Commun.* **2013**, *4*, 1446.

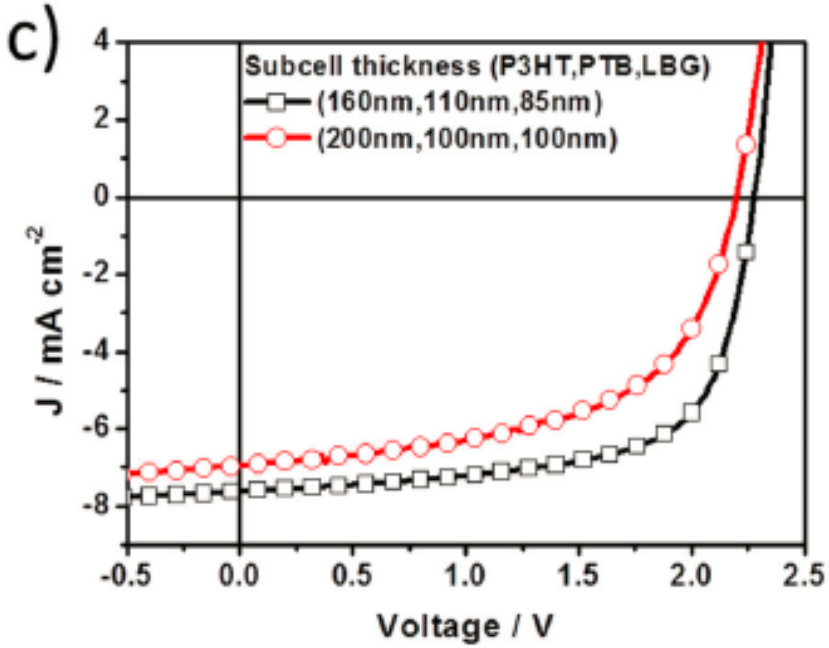
Multiple Junction Solar Cells Extend Efficiencies to 11%

Triple Junction Device Structure



Further Reading: Chen, C.-C.; *et al*. *Adv. Mater.* **2014**, *26*, 5670.

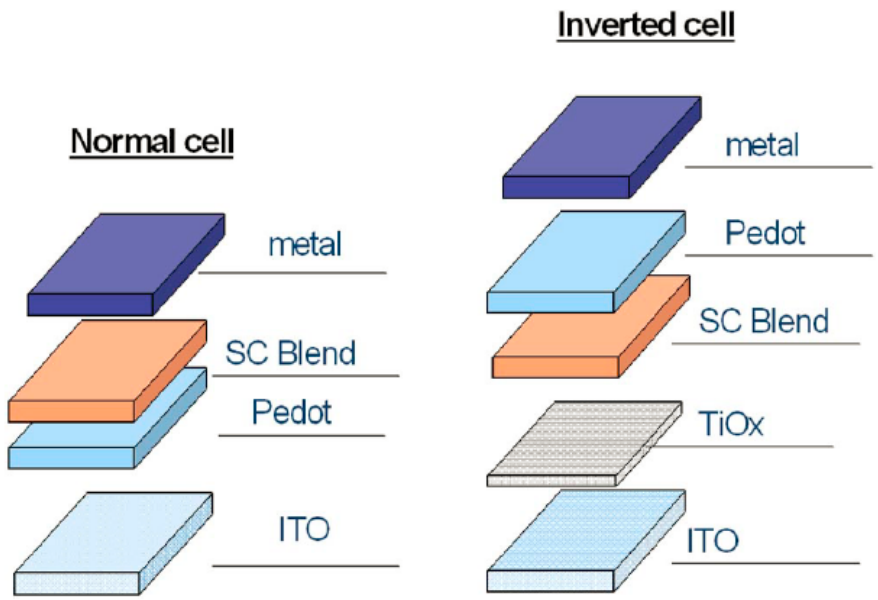
Triple Junction Device *J-V* Curves



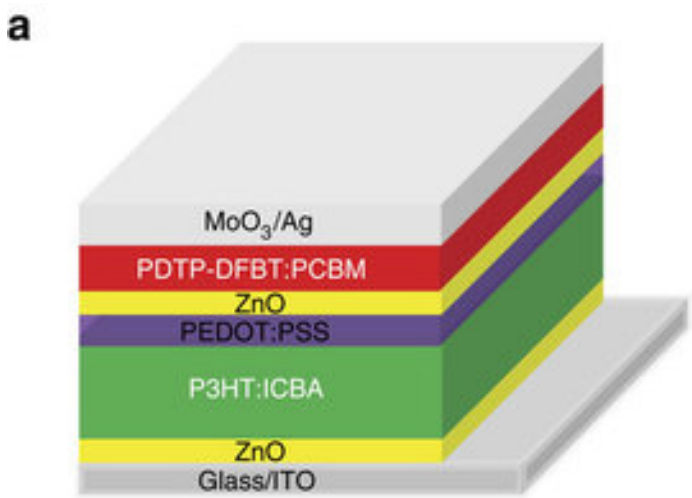
Configuration	V_{OC} [V]	J_{SC} [mA cm^{-2}]	FF	PCE [%]
Double-junction 1	1.58	8.81	68.83	9.58
Double-junction 2	1.42	11.30	66.67	10.70
Double-junction 3	1.53	9.50	67.65	9.83
Triple-junction[a)]	2.22	6.95	56.64	8.74
Triple-junction[b)]	2.28	7.63	66.39	11.55
	(2.26 ± 0.02)[c)]	(7.3 ± 0.3)[c)]	(64 ± 3)[c)]	(11.0 ± 0.5)[c)]

[a)]Unoptimized thicknesses (200, 100, 100 nm); [b)]Optimized thicknesses (160, 110, 85 nm); [c)]Average performance taken from 20 devices.

Summary and Preview of the Next Lecture



Inverted solar cells are devices that have the transparent contact serving as the cathodic layer as opposed the anodic layer, which is the case for the regular architecture. Inverted solar cells tend to have device performance values on the same scale as that of regular architecture solar cells. They have the added advantage of being more air-stable as well.



Tandem and multiple junction (or multi-junction) solar cells are a manner by which to utilize known semiconducting materials in unique geometries in order to capitalize on the addition of open-circuit voltages of the sub-cells that absorb complementary portions of the solar spectrum. In this way, researchers have been able to achieve power conversion efficiencies greater than 11%, which is approaching the levels seen typically for standard inorganic photovoltaic devices.

Next Time: Introduction to Organic Light-emitting Devices (OLEDs)