Week 13

Light Detectors 3

Multijunction Cells

Reliability

Solar Modules

Chapter 7.5, 7.8, 7.9

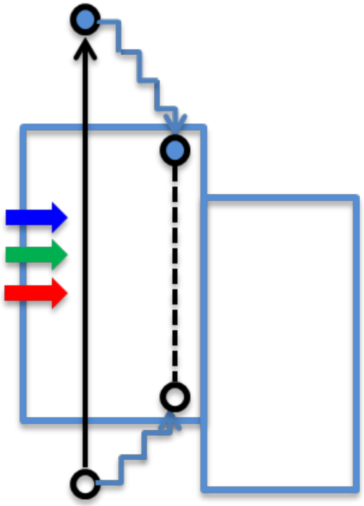
Organic Electronics
Stephen R. Forrest

Multijunction OPV cells: The Most Effective Way to Increase Efficiency

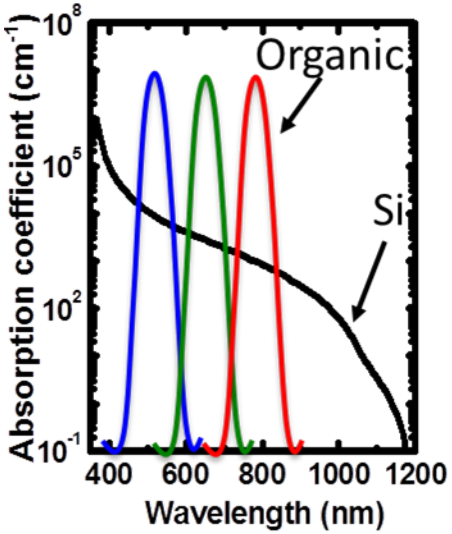
Can significantly exceed the thermodynamic limit of single junction cells

Major issues of single junction OPV:

(a) Thermalization loss

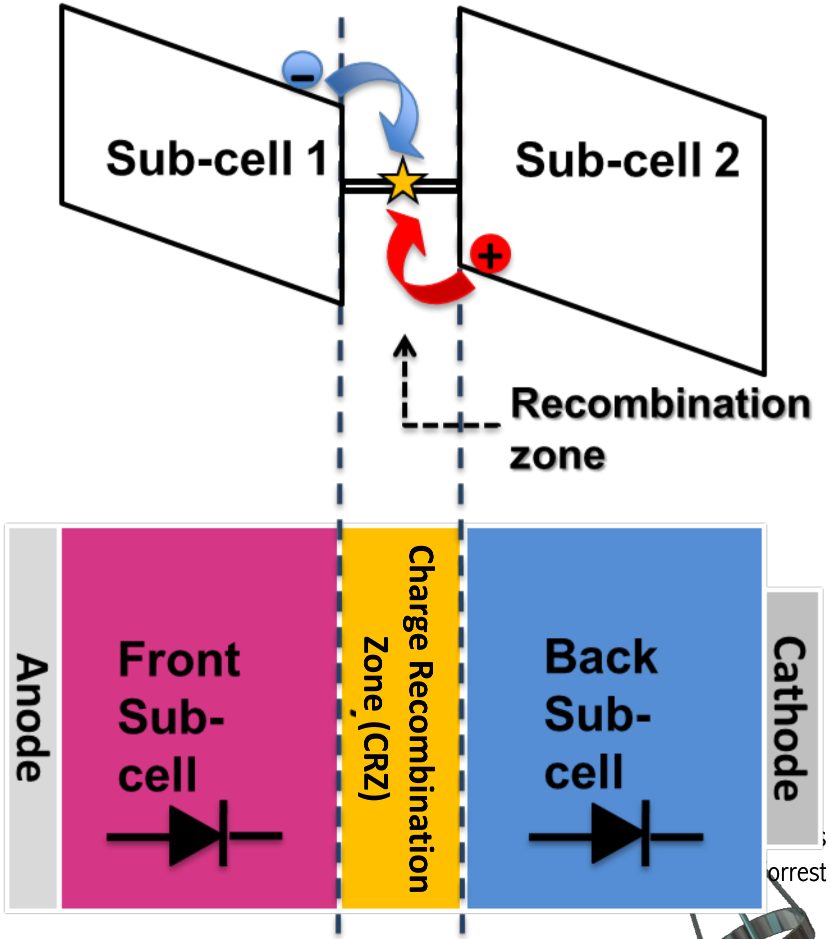


(b) Narrow absorption range

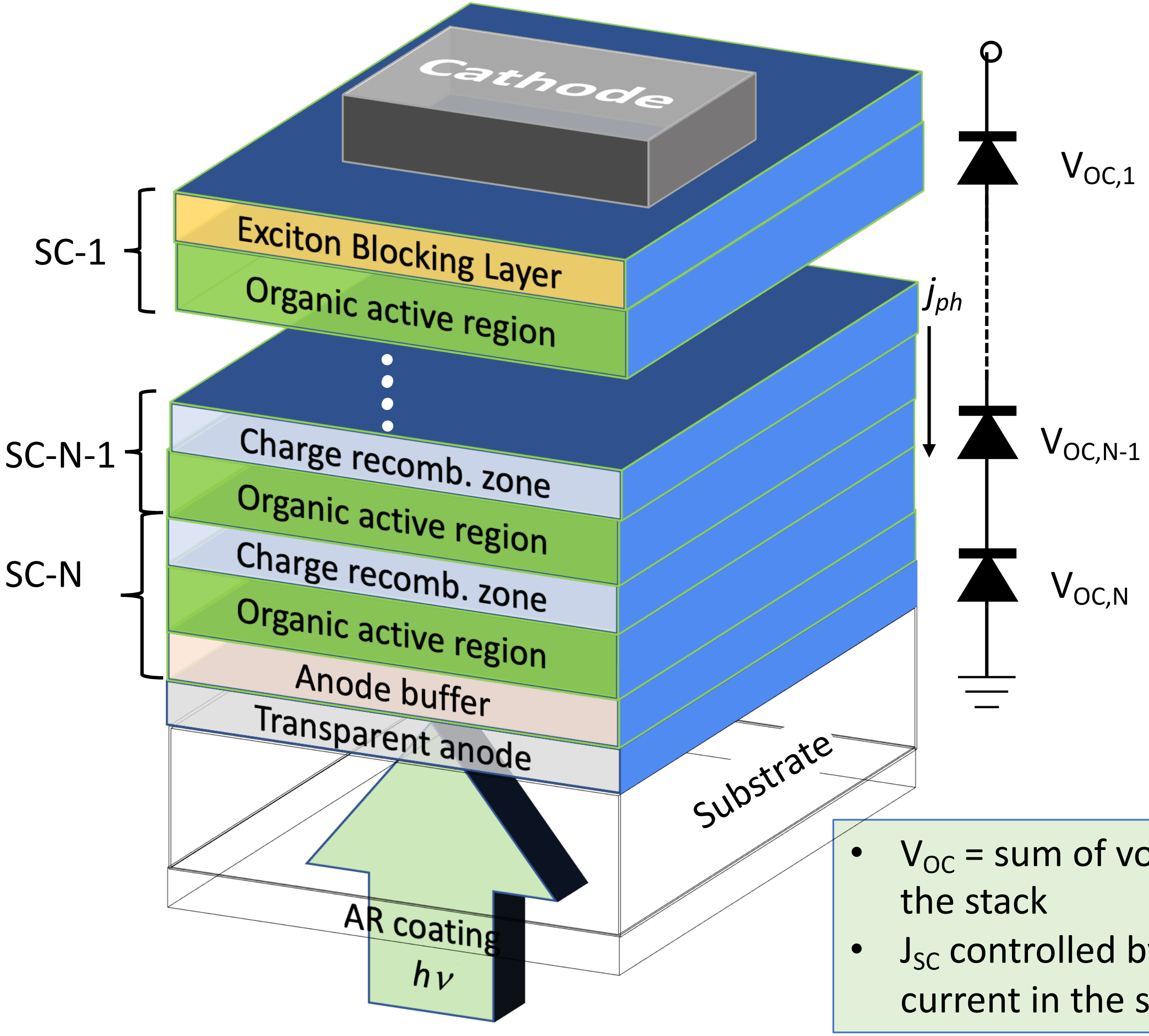


Advantages of multijunction cells:

- Decrease thermalization losses
- Cover a broad spectral range

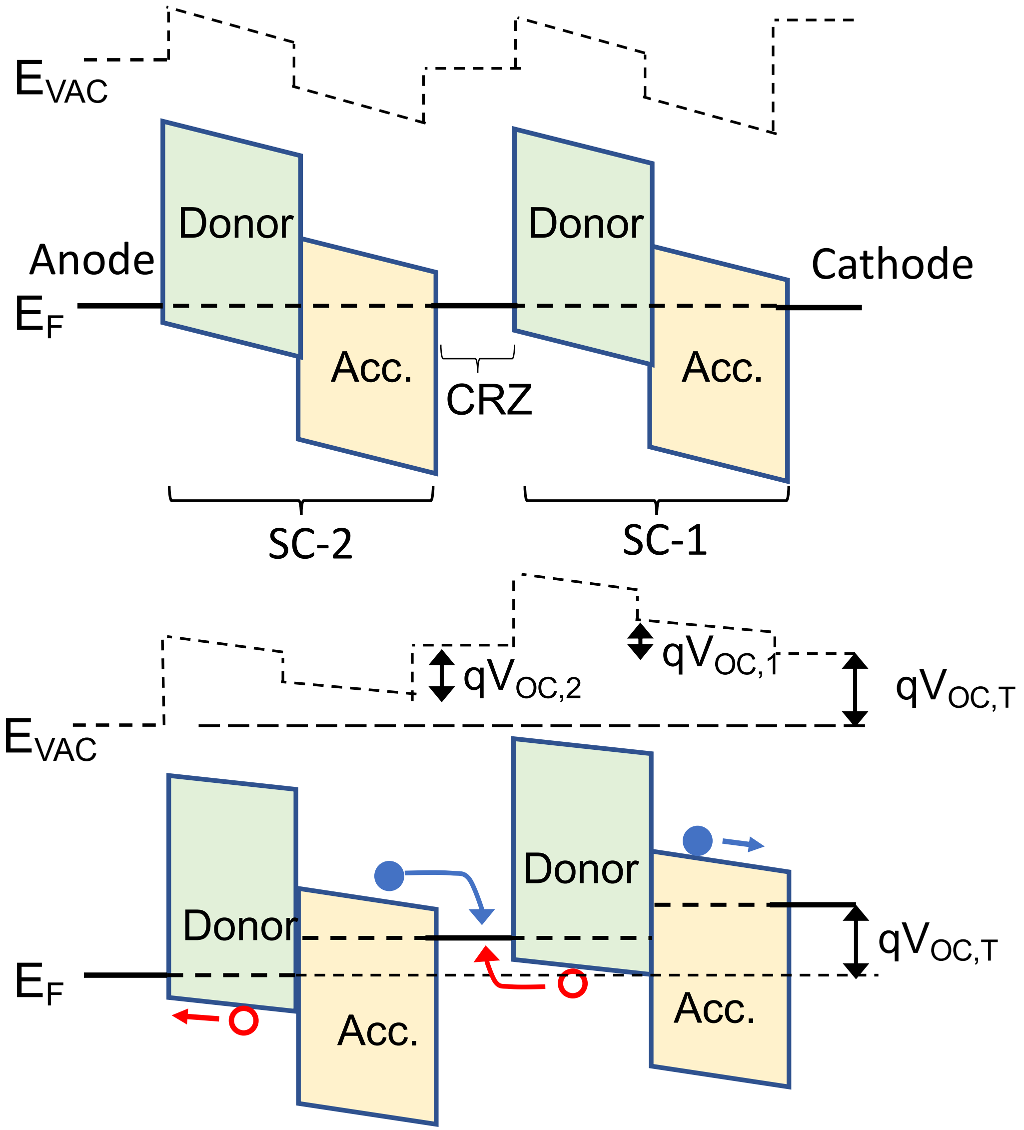


Tandem Cell Designs: Series Stacking

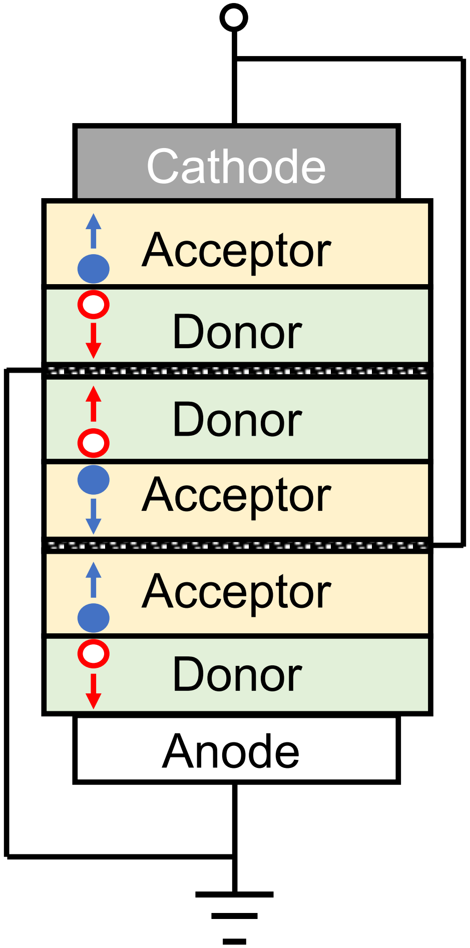


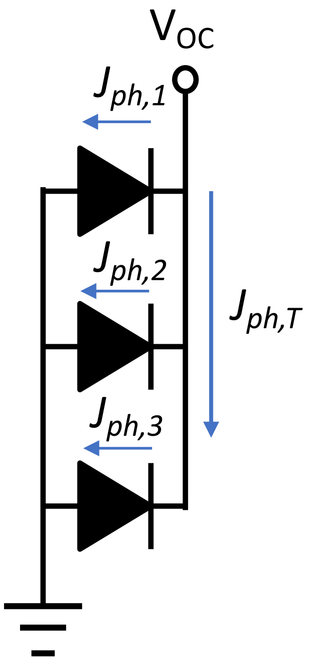
- V_{OC} = sum of voltages of the subcells in the stack
- J_{SC} controlled by the lowest subcell current in the stack

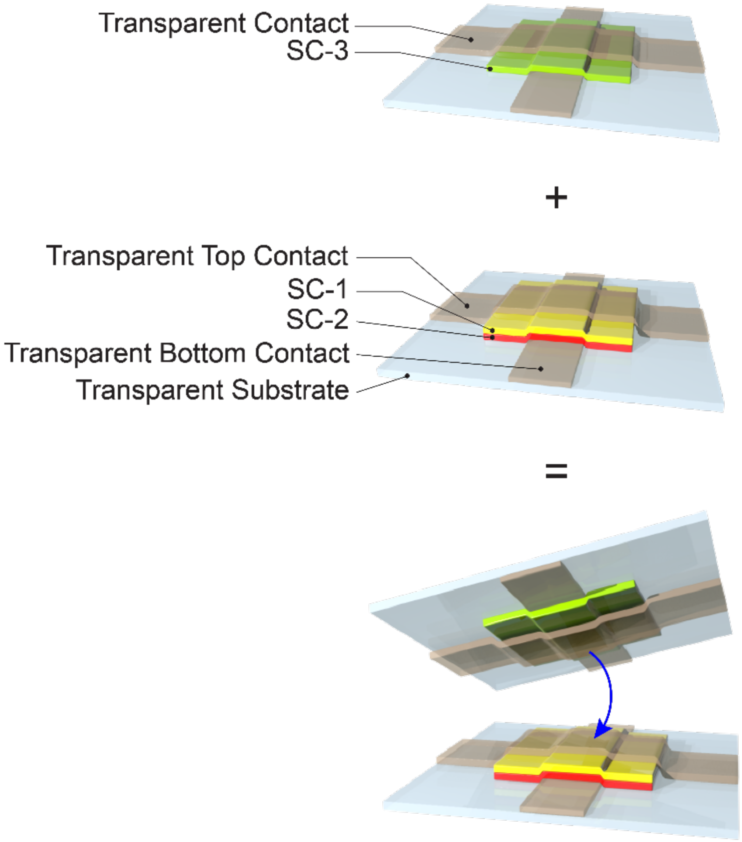
Tandem Cell Energetics

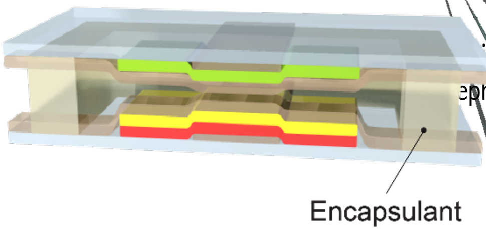


Tandem Cell Designs: Parallel Stacking



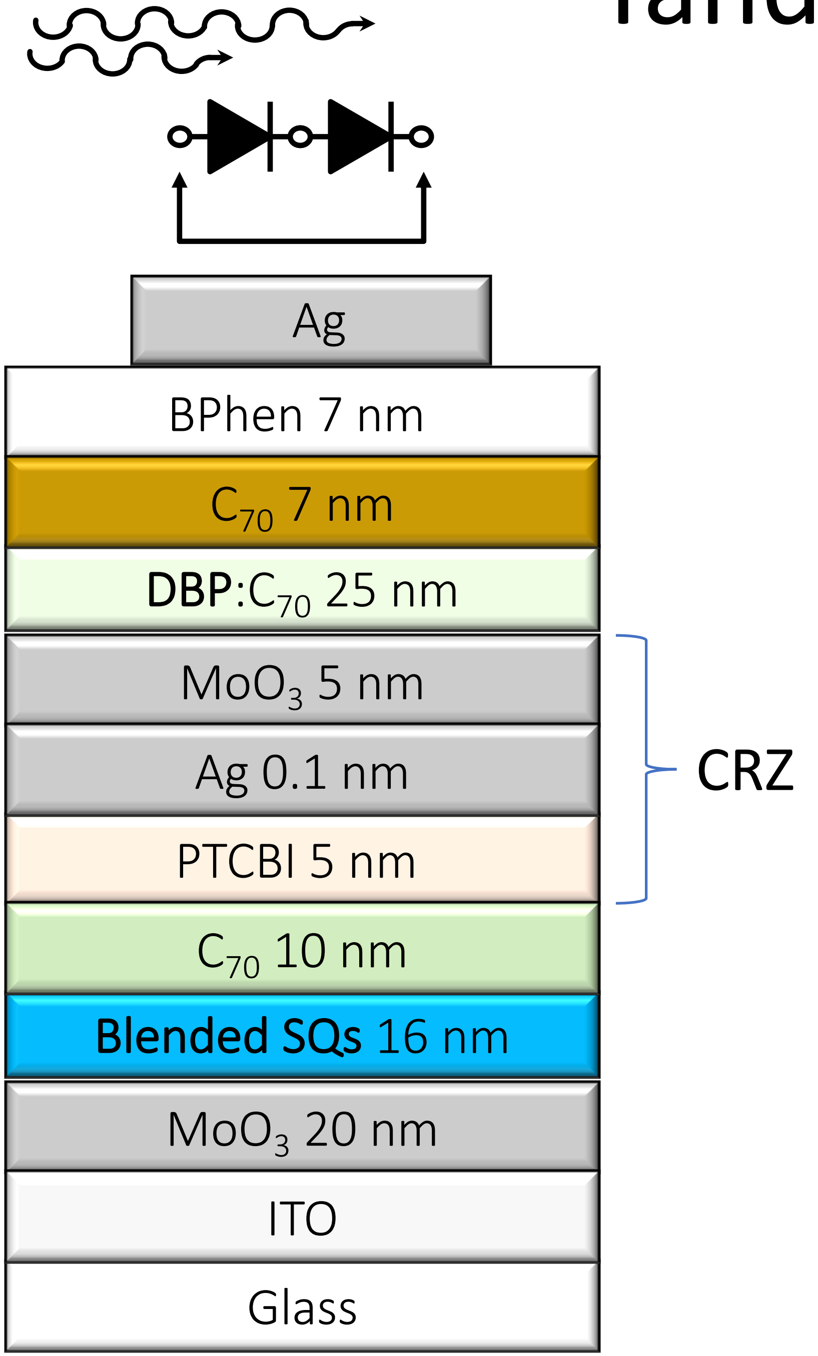






- V_{OC} controlled by the lowest voltage element in the stack
- J_{SC} = sum of individual subcell currents

Tandem Cells



Ag

BPhen 7 nm

C_{70} 7 nm

DBP:C_{70} 25 nm

MoO_3 5 nm

Ag 0.1 nm

PTCBI 5 nm

C_{70} 10 nm

Blended SQs 16 nm

MoO_3 20 nm

ITO

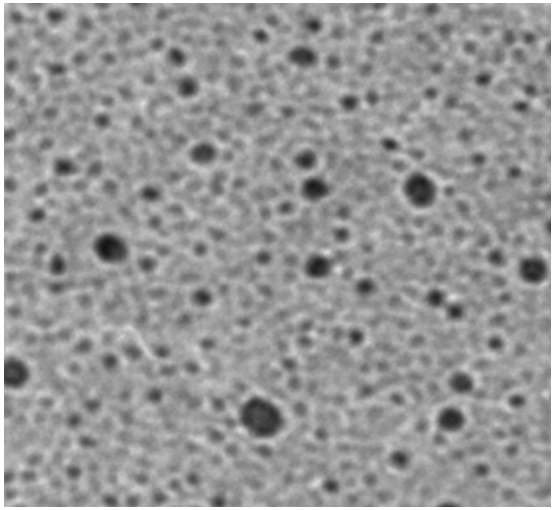
Glass

CRZ

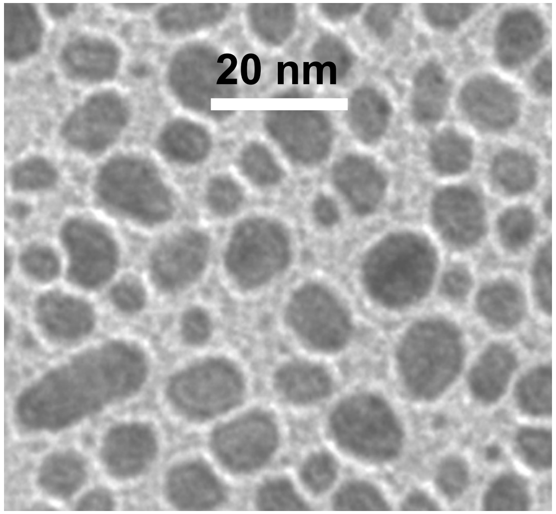
- Thinner cells have higher IQE.
- Stacking cells in series improves the total absorption.
- Addition of the photovoltage increases V_{OC}.
- Ag nanoclusters provide efficient charge recombination.

- DBP:C_{70} green absorber.
- Blended squaraine/C_{70} red/NIR absorber.

Charge Recombination Zone: Ag Nanoclusters



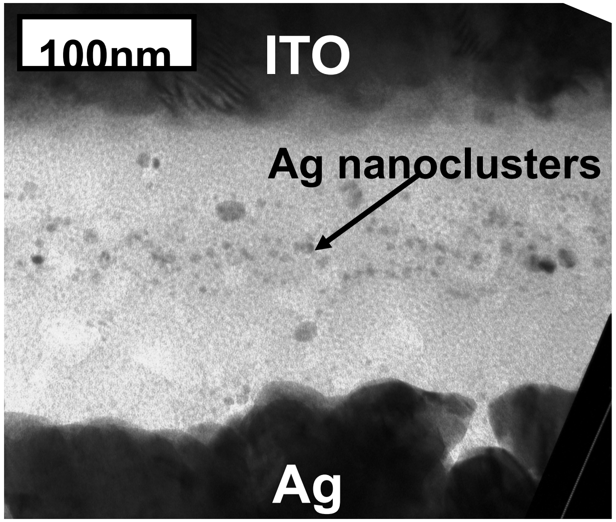
0.5 nm



45 nm

PV cell 1

PV cell 2



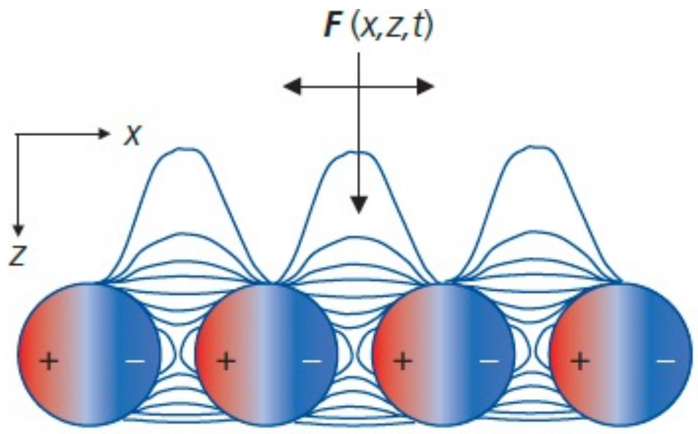
Nanoclusters give rise to surface plasmons

Plamsons reradiate field into thin active region

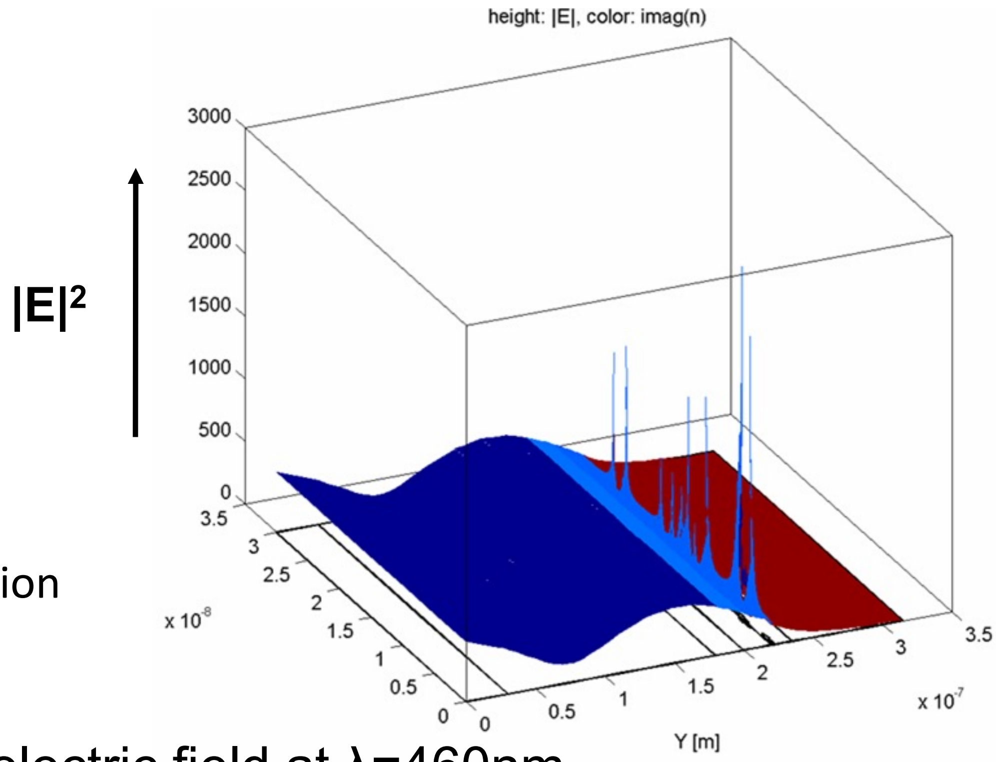
Increase in efficiency >50%

Yakimov & Forrest, *Appl. Phys. Lett.*, 80 1667 (2002)

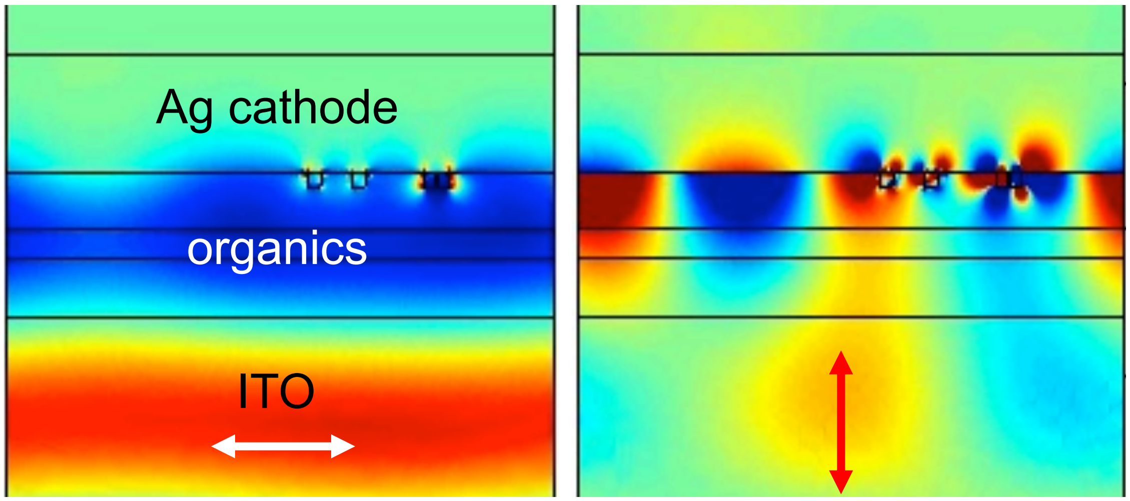
Rough interface: Surface plasmon excitation



Surface plasmons intensify near field absorption

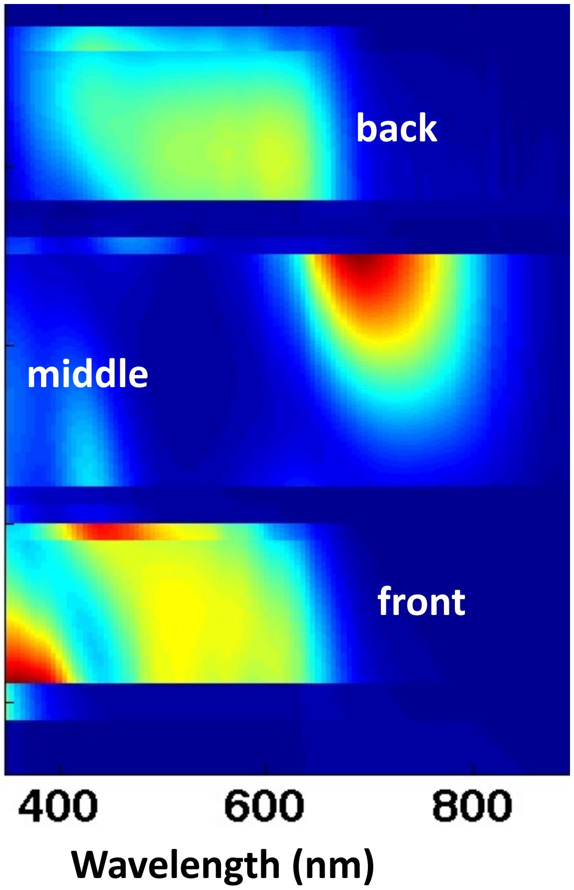


Calculation of optical electric field at λ=460nm

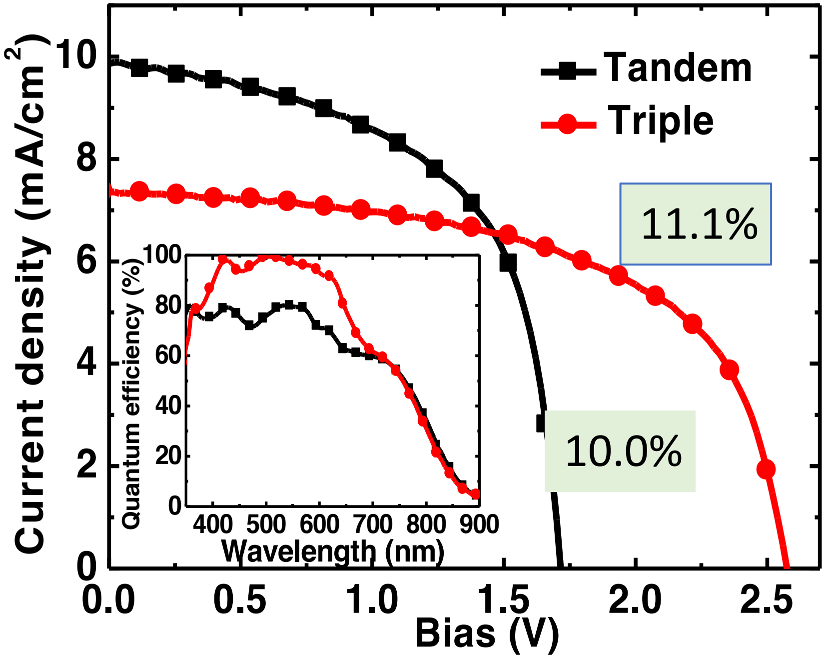


High Efficiency Triple Junction Cell

Ag (100 nm)
BPhen (7 nm)
C_{70} (7 nm)
DBP:C_{70} 1:10 (40 nm)
MoO_3 (5 nm)
Ag (0.1 nm)
Bphen:C_{60} (5 nm)
C_{60} (5 nm)
DTDCTB:C_{60} 1:1 (65 nm)
MoO_3 (5 nm)
Ag (0.1 nm)
Bphen:C_{60} (5 nm)
C_{70} (5 nm)
DBP:C_{70} 1:10 (40 nm)
MoO_3 (10 nm)
ITO



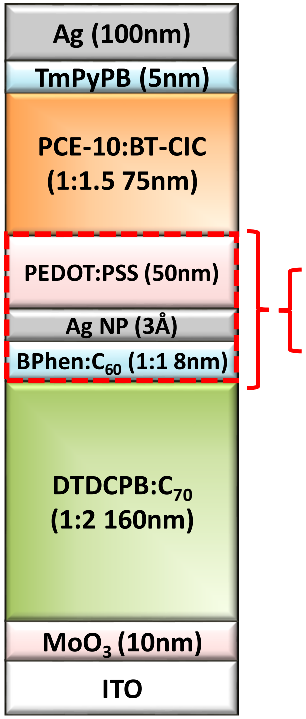
Optical field distribution

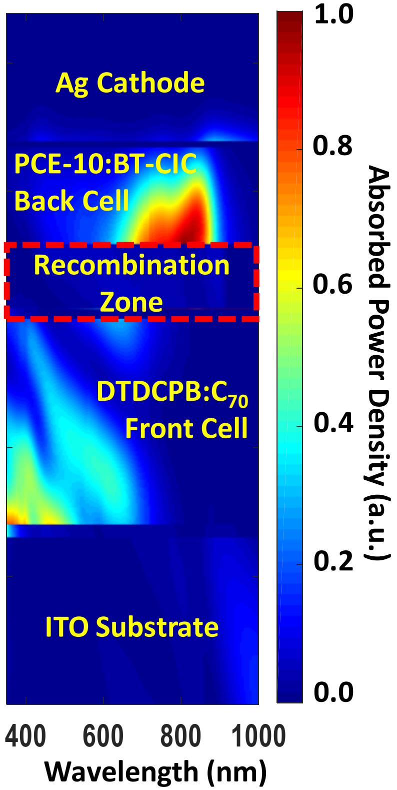


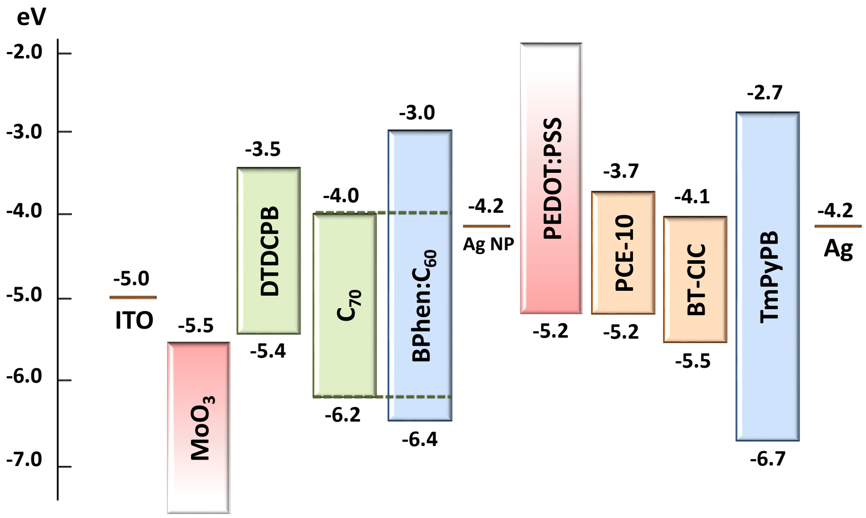
Transfer matrix calculations of optical field required to ensure current generated in every subcell is equal

X. Che, et al. Adv. Energy Mater., 4, 568 (2014)

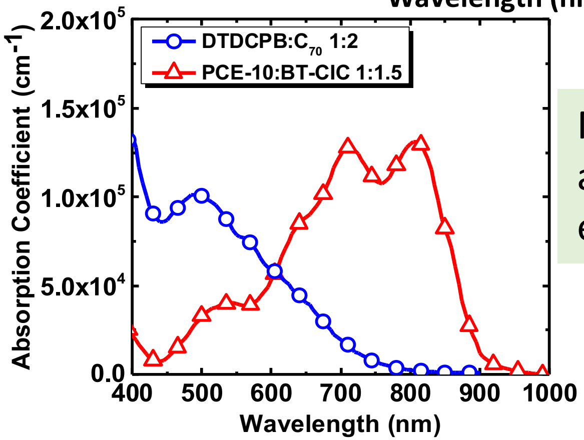
Combining Solution Processed Back Cell with Vapor Deposited Front Cell



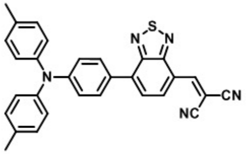




CRZ must be lossless, but also must protect front cell from damage due to deposition of back cell

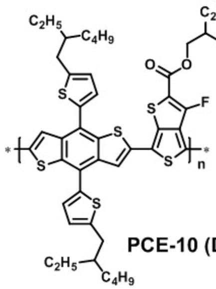


Minimal overlap of front and back spectra ensures current balance

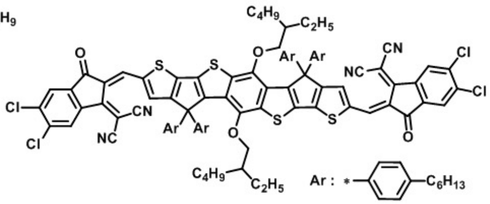


DTDCPB (Donor)

C_{70} (Acceptor)



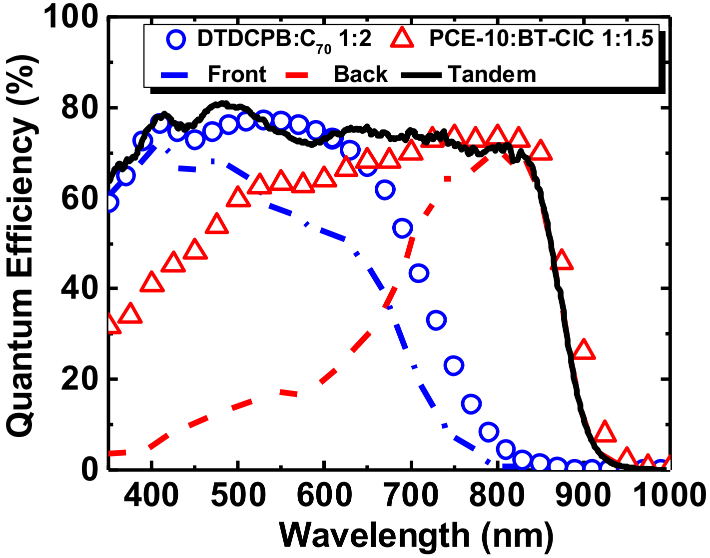
PCE-10 (Donor)

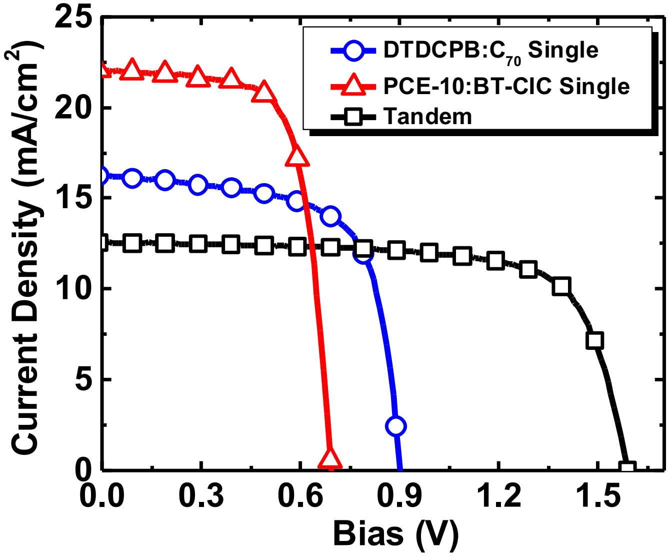


BT-CIC (Acceptor)

Che et al., Nature Energy, 3, 422 (2018)

High Efficiency Tandem Results

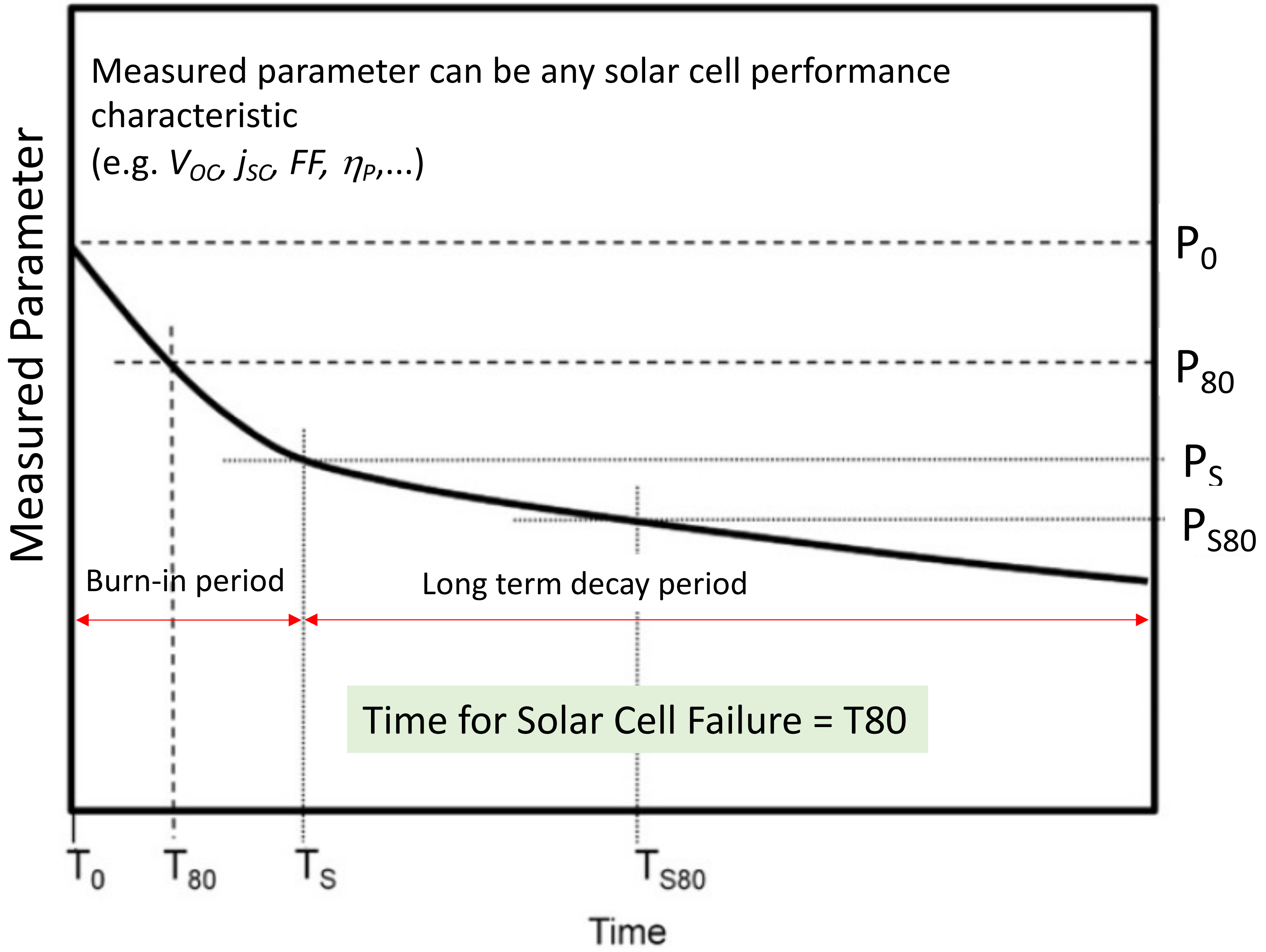




Device	J_{SC} (mA/cm²)	V_{OC} (V)	FF	η_P (%)
[Back] PCE-10:BT-CIC	22.1	0.69	0.70	10.7
[Front] DTDCPB:C_{70}	16.2	0.90	0.67	9.8
Tandem	12.7	1.59	0.71	14.3
Tandem (w/ARC)	13.3	1.59	0.71	15.0
Tandem (1 cm², w/o ARC)	12.6	1.58	0.57	11.5

Che et al., Nature Energy, 3, 422 (2018)

Quantifying OPV Lifetimes



Measured parameter can be any solar cell performance characteristic
(e.g. V_{OC}, j_{SC}, FF, η_P,...)

Time for Solar Cell Failure = T80

Analytical Approaches to Failure

(see also Ch. 6.7)

Sum of Exponentials: $$P(t) = \overbrace{P_0 \exp(-t/\tau_1)}^{\text{Burn in}} + \overbrace{P_{ex} \exp(-t/\tau_2)}^{\text{Long term loss}}$$

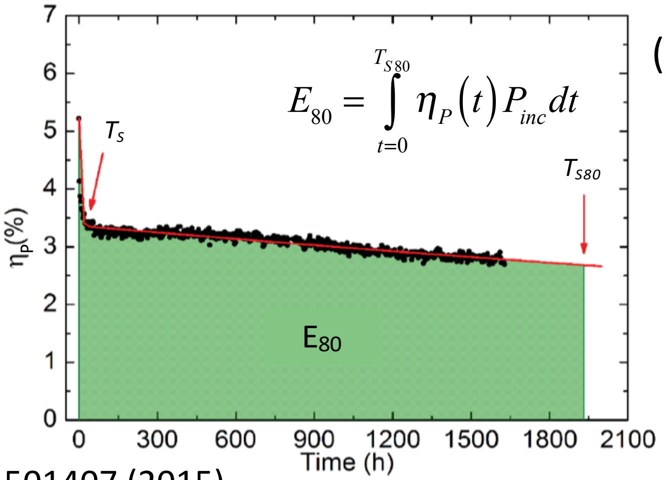
Stretched Exponential: $$P(t) = P_0 \exp\left[-(t/\tau_1)^{\beta}\right]$$

Degradation rate: $$k_{deg} = 1/\tau \;\; = k_0 \exp(-E_a/k_B T)$$

E_a = thermal activation of degradation rate, k_{deg}

Acceleration Factor: $$\mathcal{A} = \left(\frac{P_{inc}^1}{P_{inc}^2}\right)^{\gamma} \exp\left[-\frac{E_a}{k_B}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

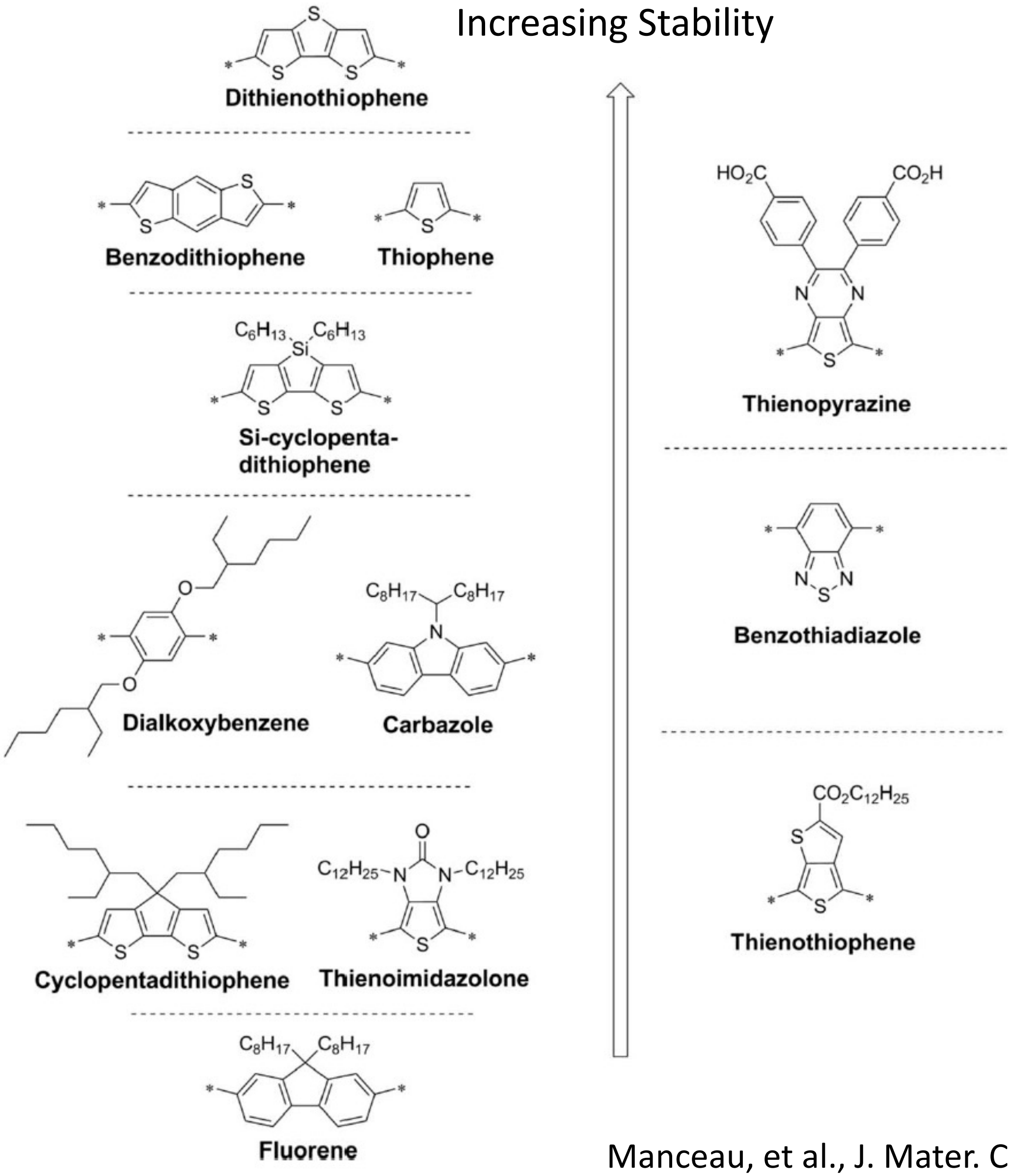
Total energy generated:



(assumes life begins after burn-in)

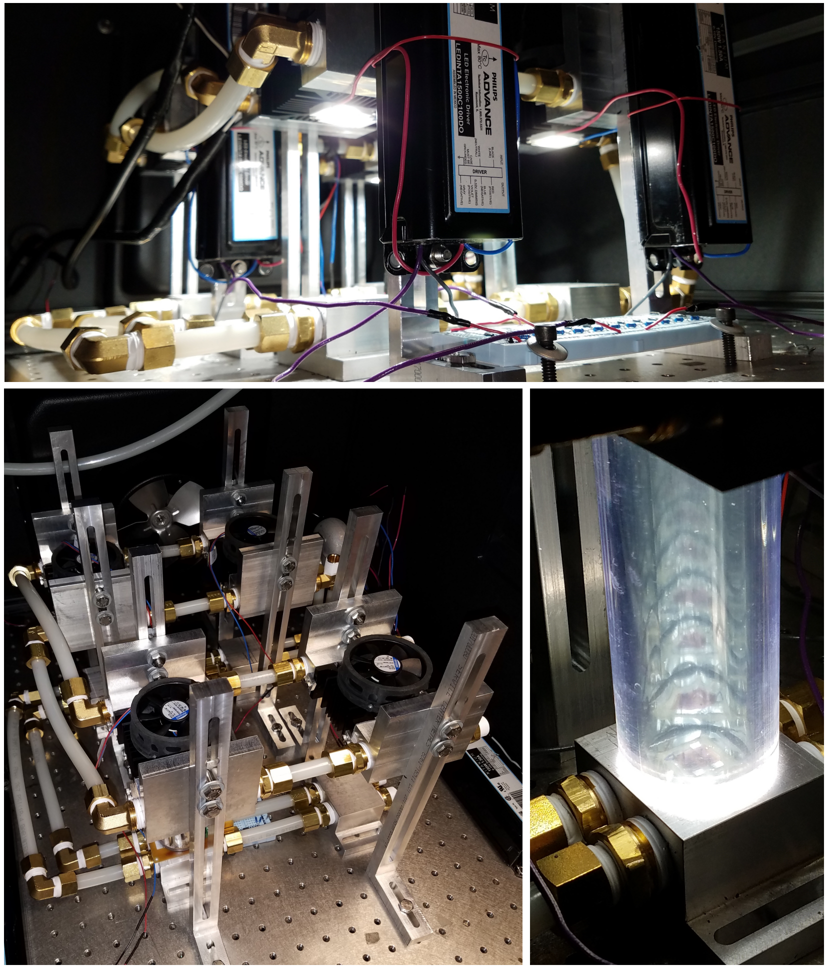
Roesch et al. Adv. Energy Mater. 5, 1501407 (2015)

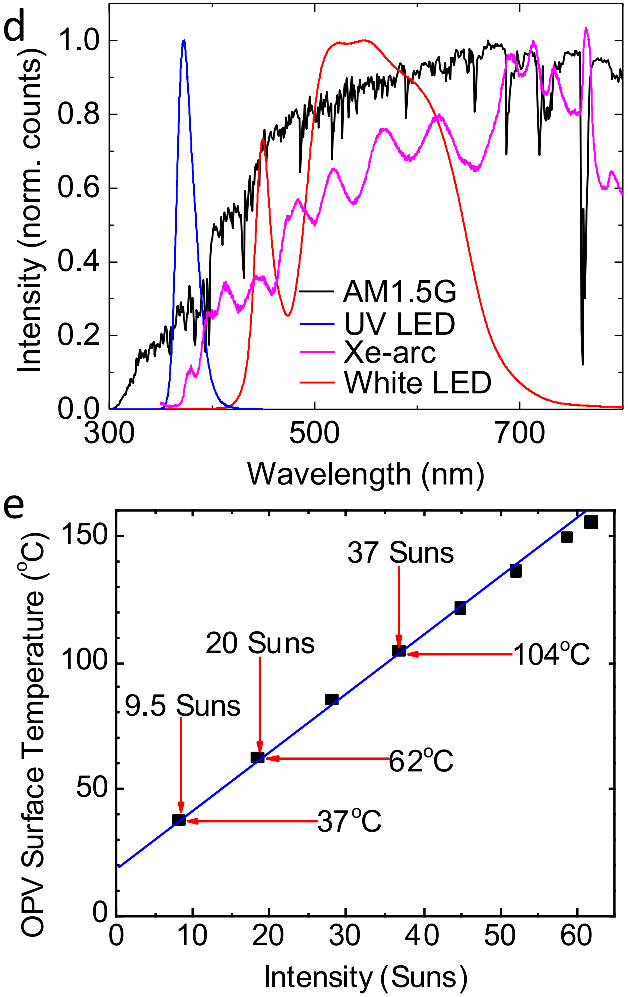
Choice of Molecules Impacts Stability



Manceau, et al., J. Mater. Chem., 21, 4132 (2011).

Test set up for Accelerated Aging

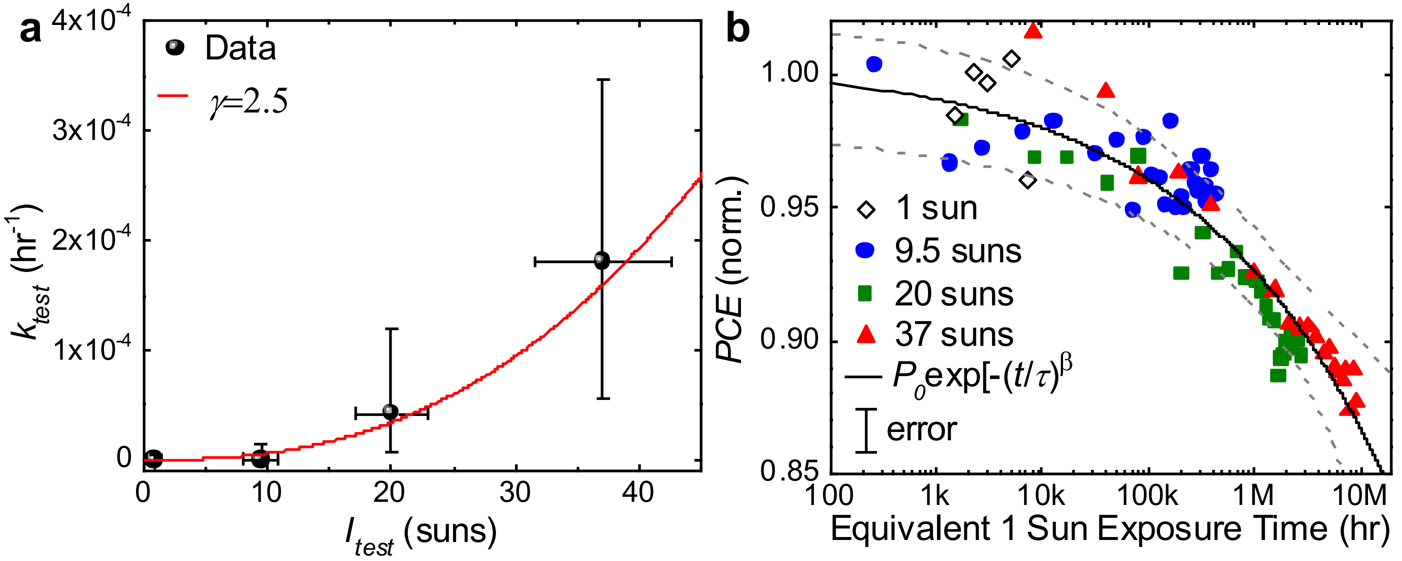




Populations of devices under very high intensity illumination using LEDs

Need to separate effects of temperature and intensity acceleration factors

Extracting Lifetime from Aging Data & Acceleration Factors



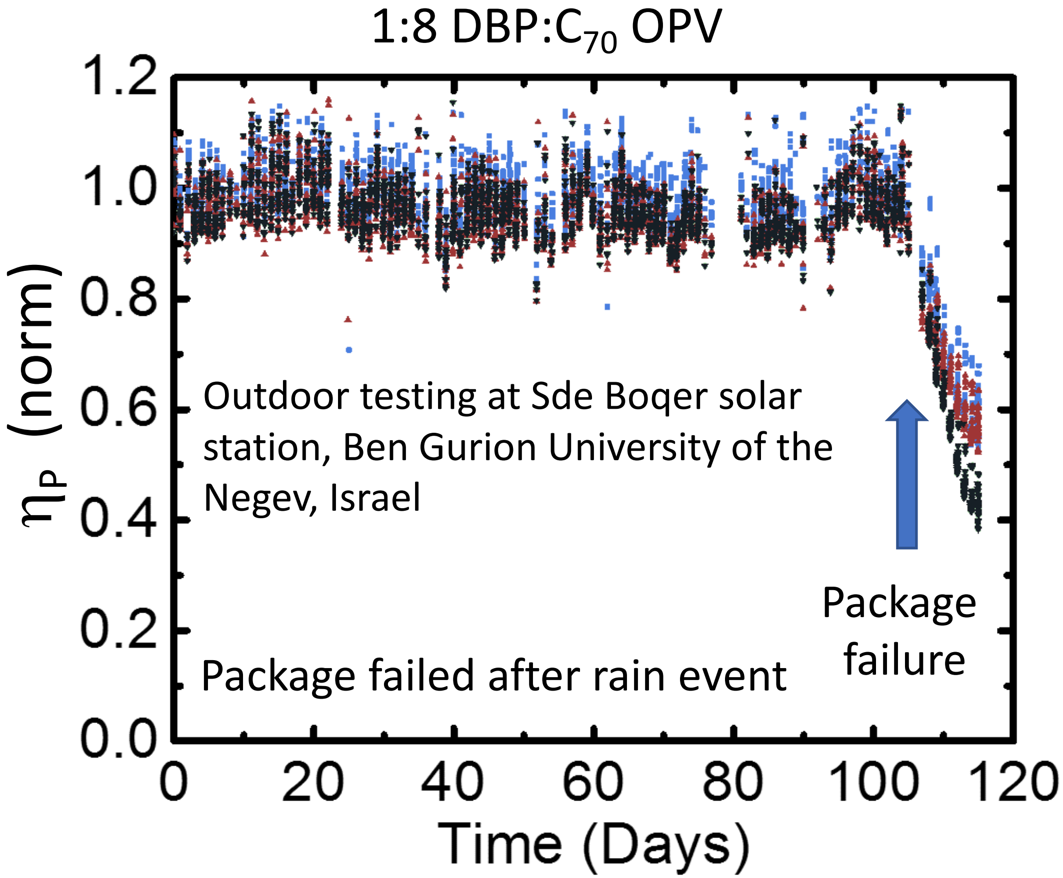
Extrapolated *intrinsic* lifetime: >10^4 years!

Metric for failure: T80; 5 h = 1 day solar equivalent

Q. Burlingame, et al., (2019),Nature, 573, 394.

What happens outdoors

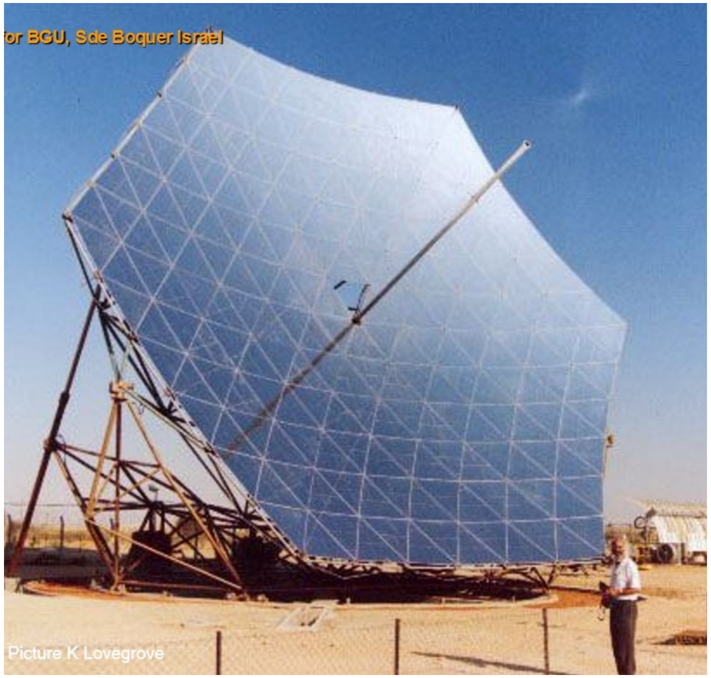
Examining reliability in a real operating environment



Outdoor testing at Sde Boqer solar station, Ben Gurion University of the Negev, Israel

Package failure

Package failed after rain event



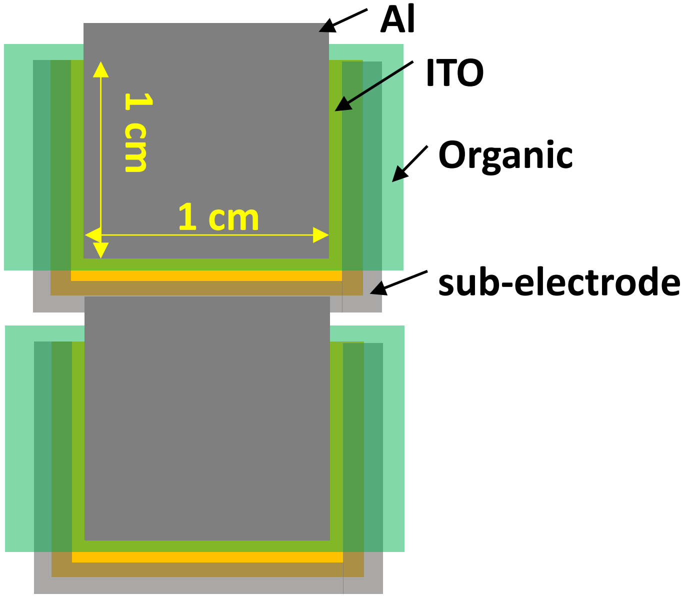
Solar concentrator system

Ultimately, solar cell reliability depends on materials, morphologies and test conditions in actual environments

Burlingame et al. *Organic Electronics,* 41, 274 (2016).

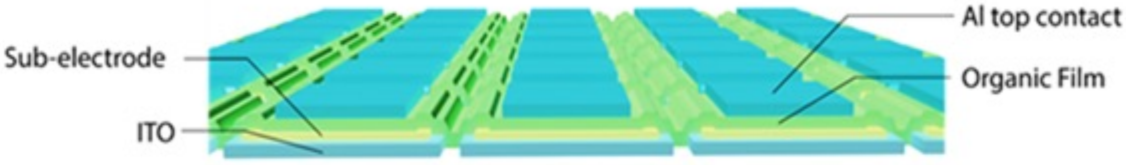
Scaling to Modules

Two tandem cells in series

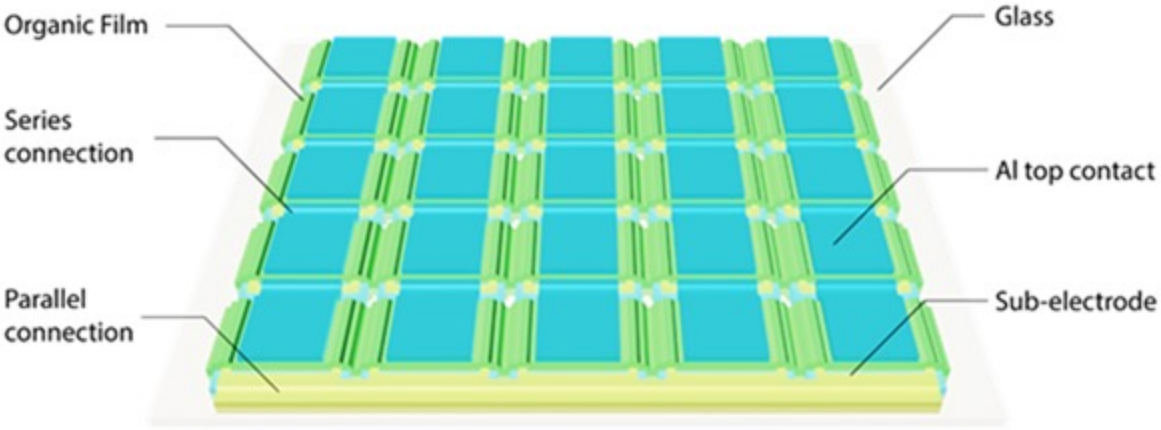


- Surrounding cell with contacts (sub electrodes) reduces resistance
- 5x5 discrete tandem cells connected in series-parallel configuration
- Active area: 1 cm^2 for discrete; 25 cm^2 for module

Front view



Top view

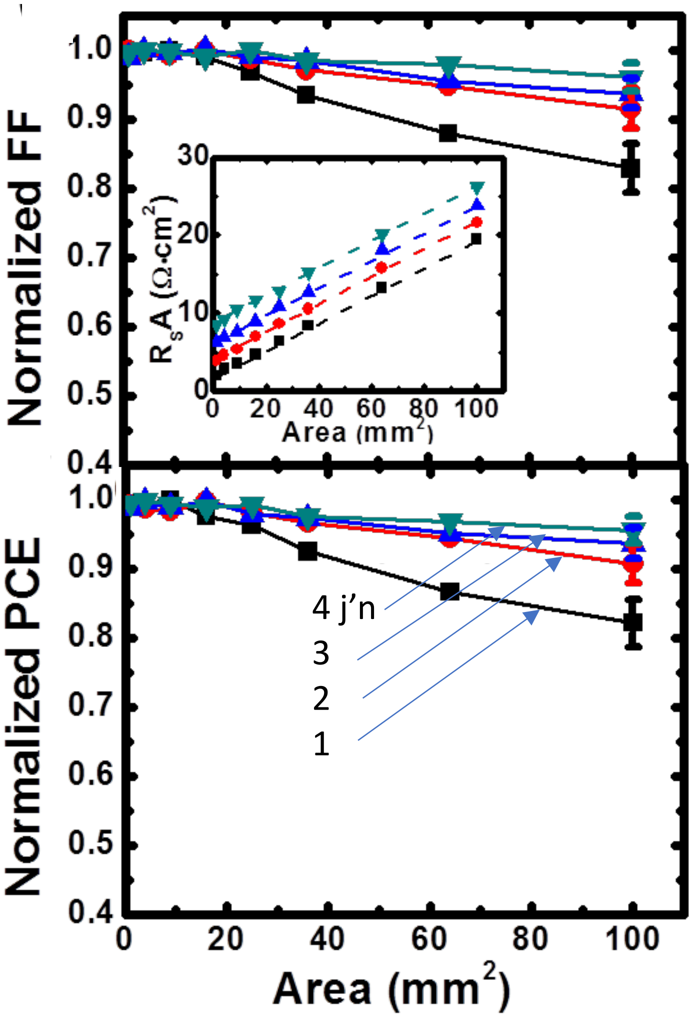


X. Xiao, et al., *Appl. Phys. Lett.*, **106**, 213301 (2015).

Multijunction Cells Limit the Effects of Resistance

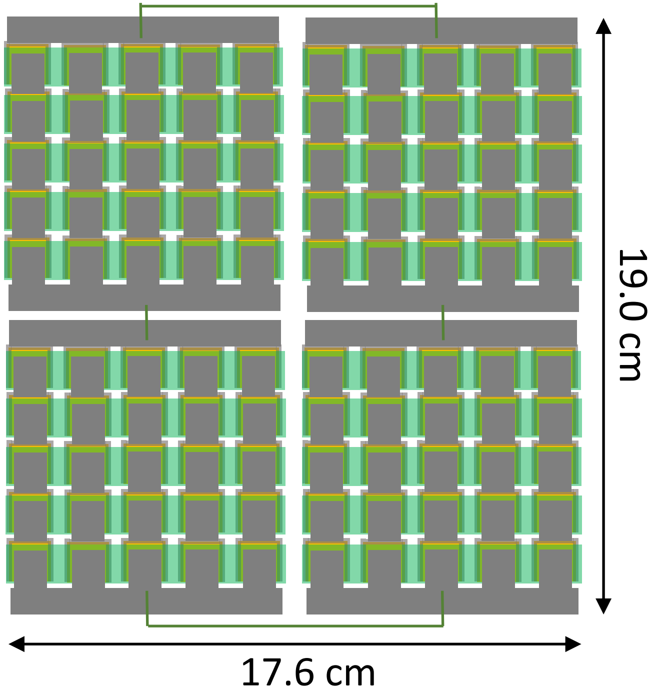
The higher the voltage,
The smaller the problem

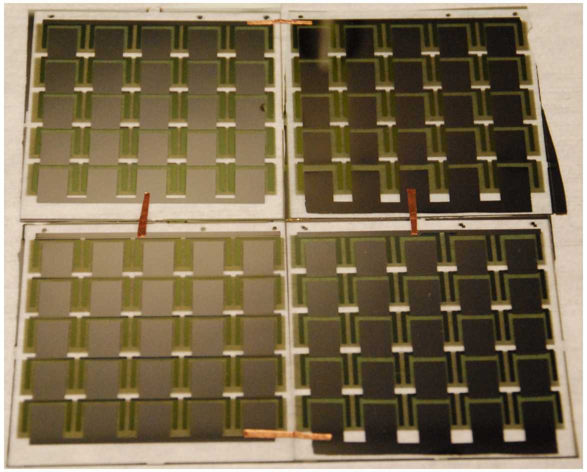
⇒ Multijunction cells

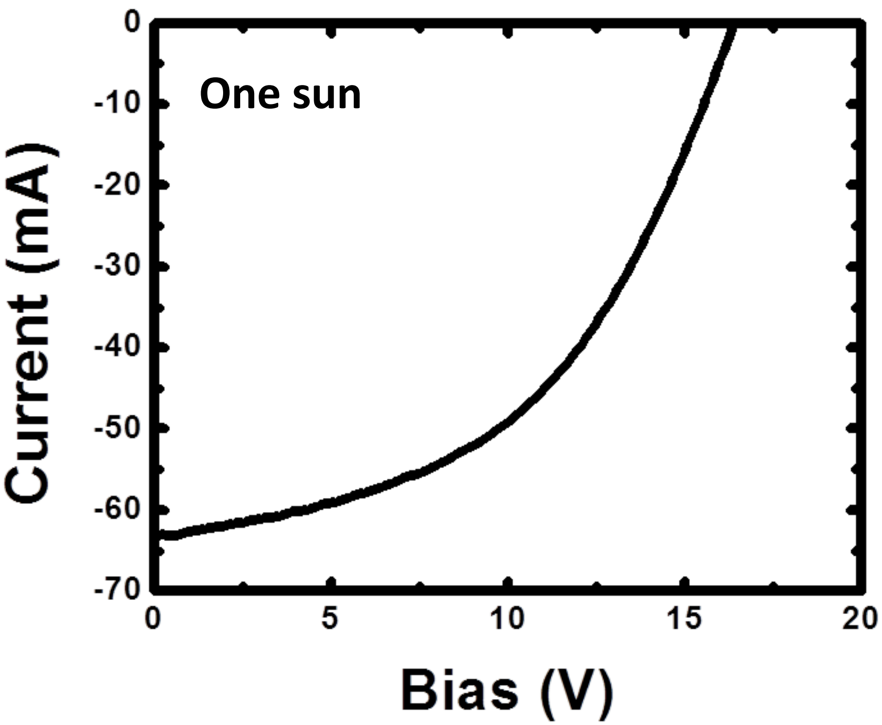


X. Xiao, et al., *Appl. Phys. Lett.*, **106**, 213301 (2015).

Tethered 10 x 10 OPV Module







<u>Module</u>

I_{SC} = 63 mA, V_{OC} = 16.4 V, FF= 50%,
Output power = 519 mW, PCE = 5.2%

What we learned about OPDs and OPVs

- Photogeneration in OPDs and OPVs mediated by charge transfer at D-A HJs
- Bulk heterojunctions break the tradeoff between a ”long” optical absorption length and and short exciton diffusion length.
  - Morphology control essential to high device performance
  - Multijunction cell frees efficiency from the single junction thermodynamic limit
- OPDs generally operated in the 3rd quadrant to minimize dark current, and hence noise. OPVs operated in the 4th, power-generating quadrant.
- Visible-transparent, NIR absorbing cells the most promising application for OPVs
- Cell reliability can extend to $\gg$ 50 years in some cases.
- Modules primarily limited by series resistance

Organic Thin Film Transistors

Thin Film Transistors 1

Transistor Basics
Conventional Transistor Architectures
Operating Characteristics
Chapter 8.1-8.3.2

OTFT Objectives

- Learn how they work
- Learn how they are made
- Learn about their operational reliability
- Learn what they are good for: Are they an answer waiting for a question?
    - Sensing
    - Medical Applications

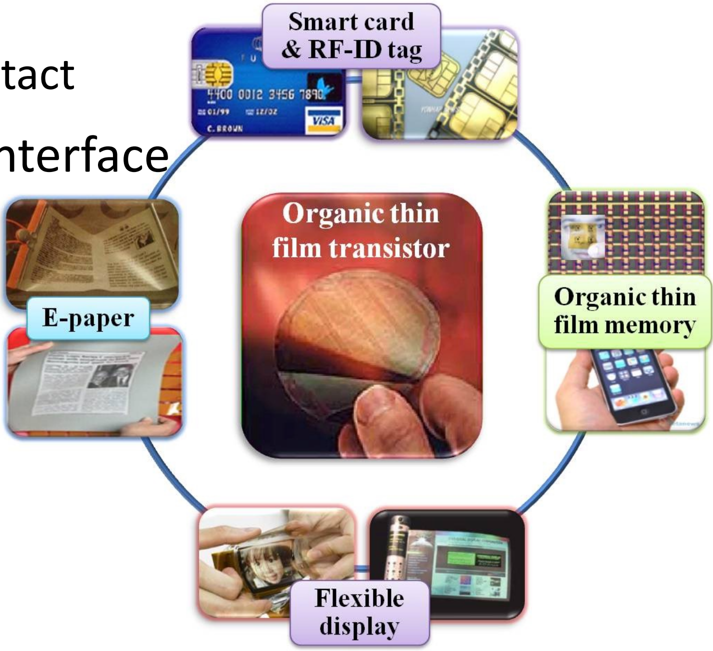
Advantages vs. Limitations of OTFTs

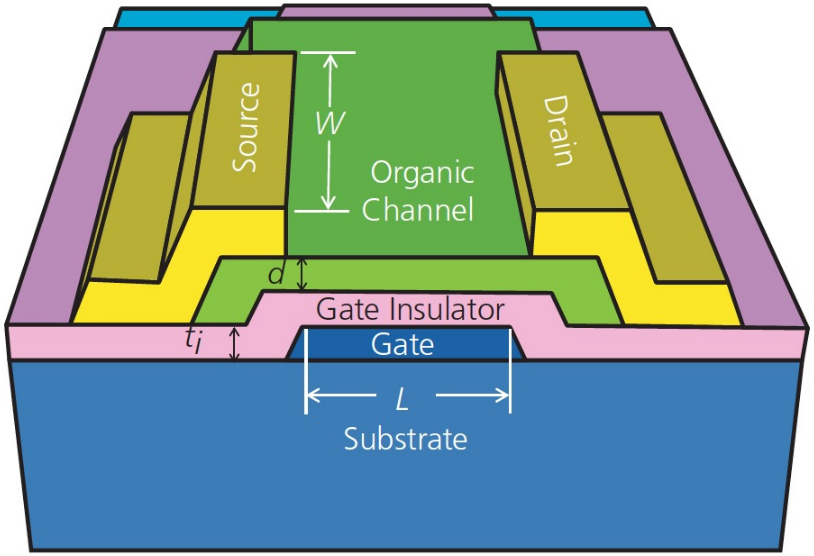
- PROs
  - Flexible, conformable, ultralight
  - Can be made over very large areas
  - Suitable for large scale R2R manufacture

- CONs
  - Cannot source large currents
  - Characteristics drift over long periods in operation
  - Limited bandwidth (≤ 1 MHz in many cases)

What an OTFT looks like

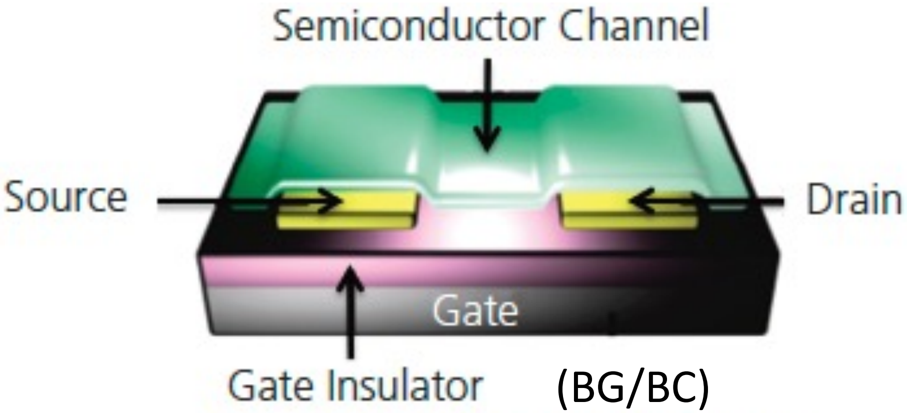
- Several different configurations
    - Bottom gate, top gate, bottom SD contact, top SD contact
- Properties strongly influenced by dielectric/organic interface
- Configuration similar to inorganic TFTs
    - Metal oxide
    - a-Si
    - Etc.





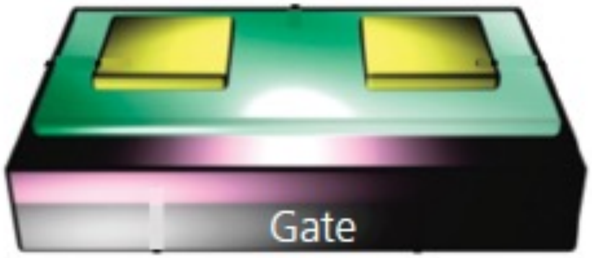
Definitions of Contacts and Dimensions

Different Contact Arrangements



(BG/BC)

Bottom Gate/Bottom Contact



(BG/TC)

Bottom Gate/Top Contact

Top Gate/Top Contact

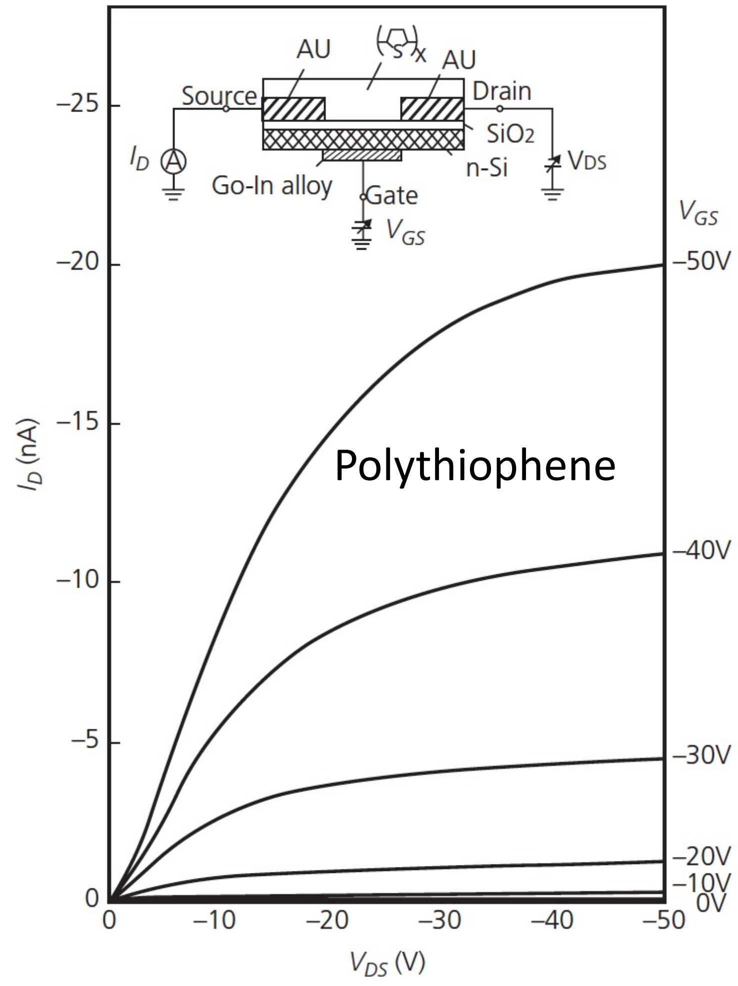
(TG/TC)

Top Gate/Bottom Contact

(TG/BC)

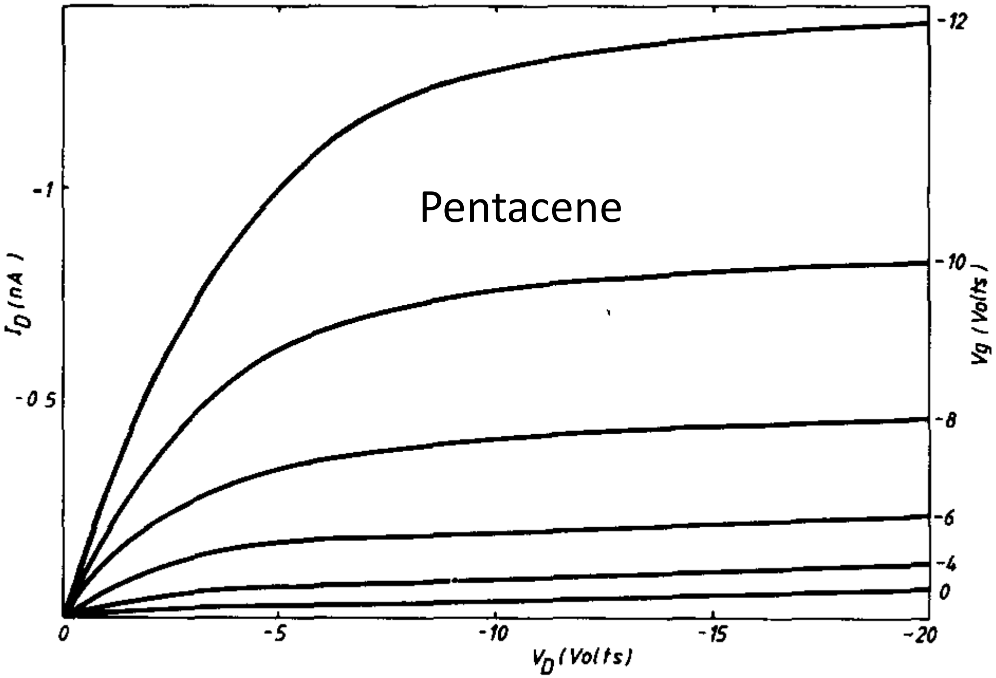
Organic Thin Film Transistors

First demonstrations



Polythiophene

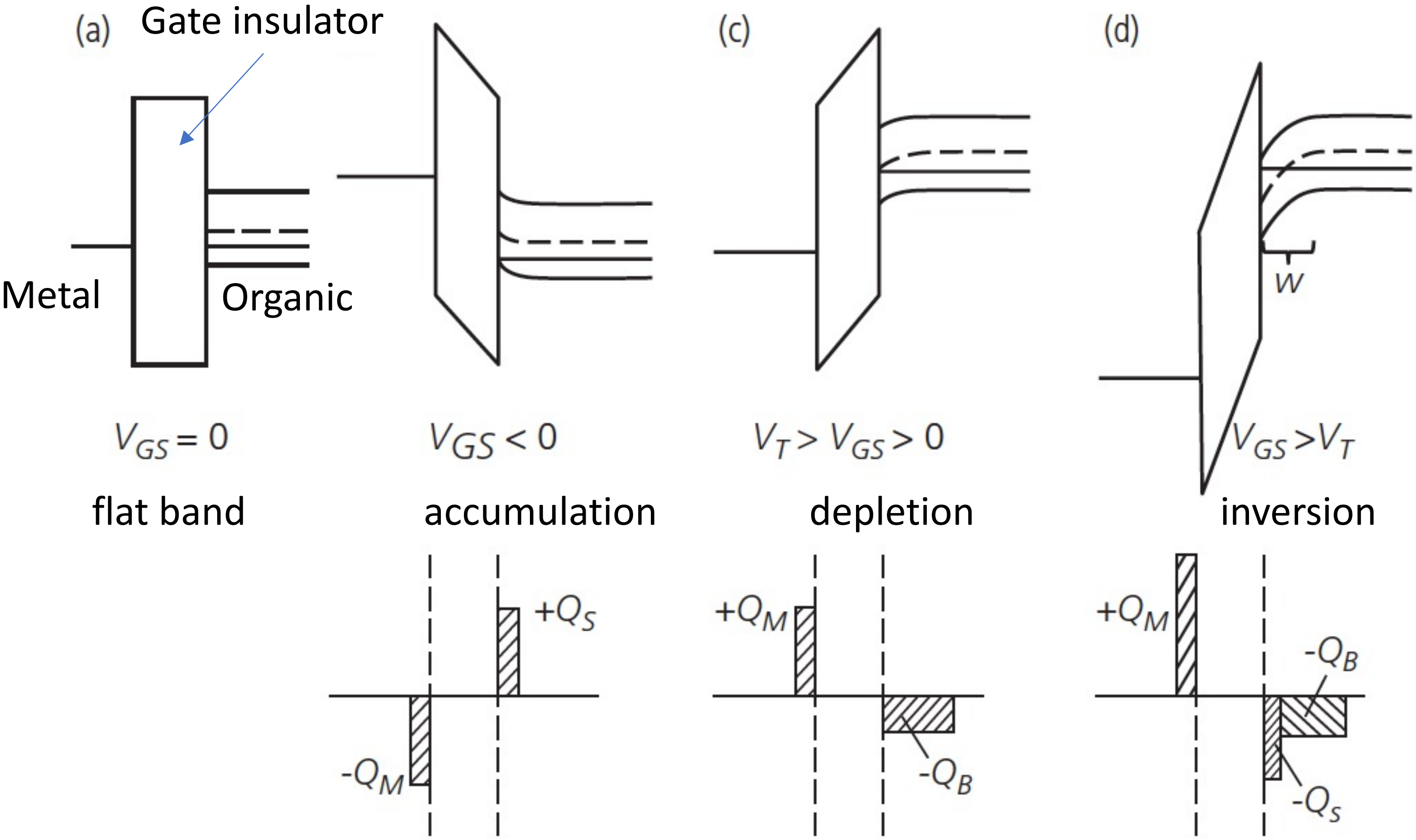
A. Tsumura, et al., Appl. Phys. Lett., (1986) 1210,**49**



Pentacene

G. Horowitz, et al., Solid State Commun., 72 381 (1989)

The MIS Capacitor: Building Block of the OTFT



- Organics often have little charge in the bulk of the semiconductor ⇒ no band bending
- Charge drawn into channel from source to allow conduction at the insulator/org. interface

How an OTFT Works: Accumulation

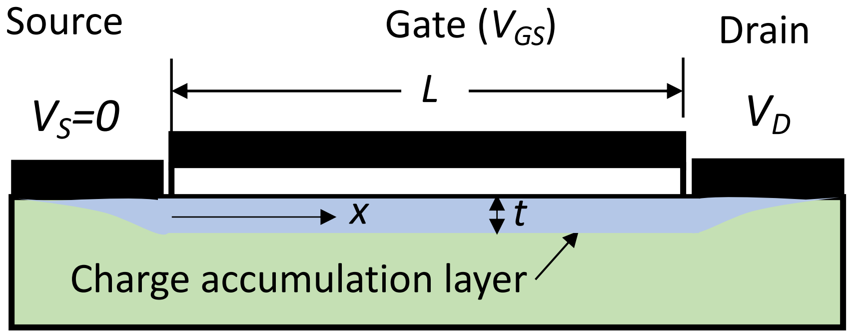
Charge injected from the source by a gate voltage, V_{GS}, at very low drain voltage, V_D, and hence low channel current (i.e. ohmic):

$$Q(x) = n(x)qt = C_G\left(V_G - V(x)\right)$$

Charge layer thickness

But contact resistance and potential, charge trapping, grain boundaries, etc. prevent channel conduction until a threshold voltage V_T is reached:

$$Q(x) = n(x)qt = C_G\left(V_G - V_T - V(x)\right)$$



Following Ohm's Law:

$$I_D = A\sigma F = W\overbrace{(n_{ave}qt)}^{Q_{ave}}\mu\frac{V_D}{L}$$

At low voltage, conduction is ohmic ⇒we can use the average channel voltage drop $V_D/2$.

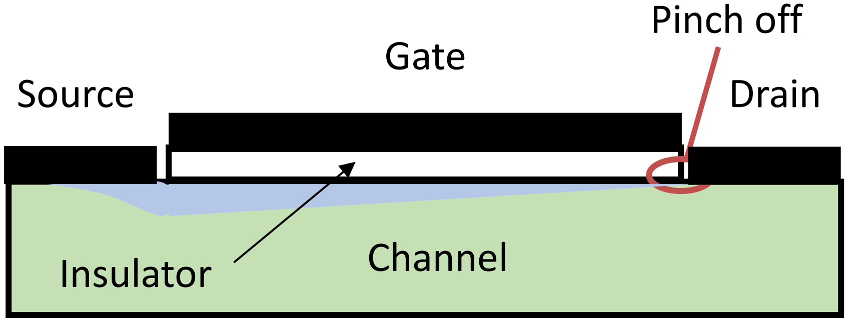
Or, in the linear regime of operation:

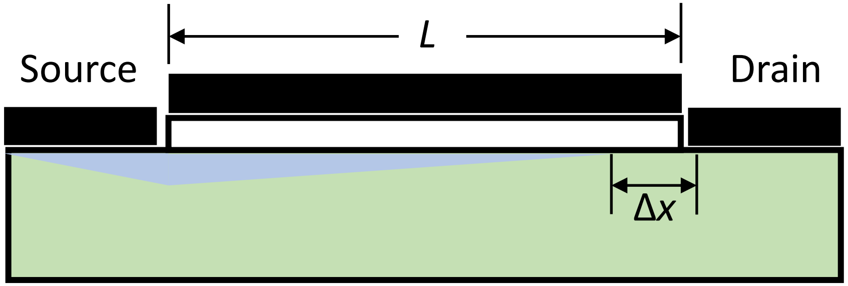
$$\boxed{I_D = \frac{W}{L}C_G\mu\left(V_G - V_T - \frac{V_D}{2}\right)V_D = \frac{W}{L}C_G\mu\left((V_G - V_T)V_D - \frac{V_D^2}{2}\right)}$$

Field-effect mobility is **not** bulk mobility

$$\mu = \mu_{FE}$$

In the Saturation Region





In the linear regime ($V_G - V_T >> V_D$), we calculate the transconductance:

$$g_m = \left.\frac{\partial I_D}{\partial V_G}\right|_{V_D} = \frac{W}{L} C_G \mu_{lin} V_D$$

And the output conductance:

$$g_o = \left.\frac{\partial I_D}{\partial V_D}\right|_{V_G} = \frac{W}{L} C_G \mu_{lin} \left(V_G - V_T\right)$$

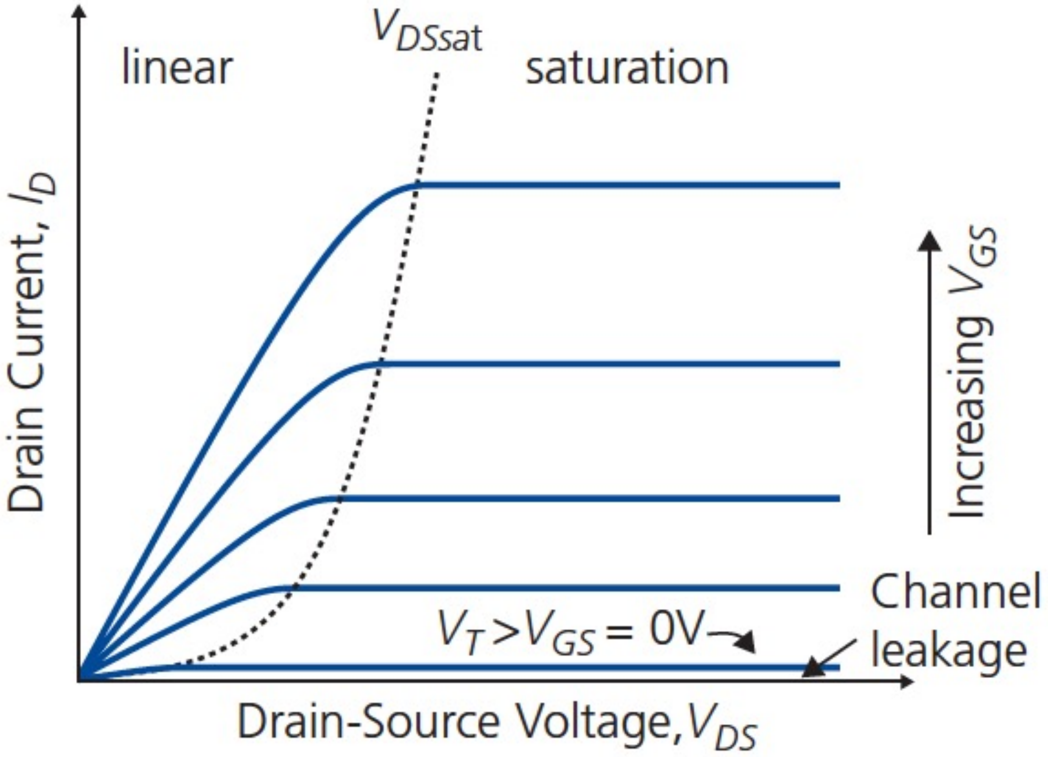
Due to contact and other parasitic resistances, μ_{lin} gives errors, so mostly use saturation characteristics:

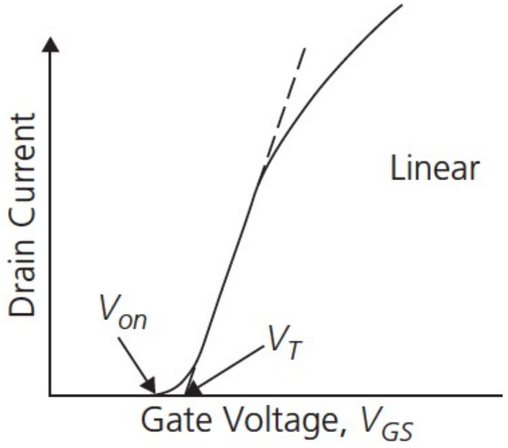
- When $V_D = V_G - V_T$, the channel **pinches off**
- Between pinchoff point and drain, $n \to 0 \Rightarrow F \to$ large to maintain current continuity ($j = nq\mu F$)
- No more current (except leakage) enters channel with increasing V_D, hence we are in the saturation regime.

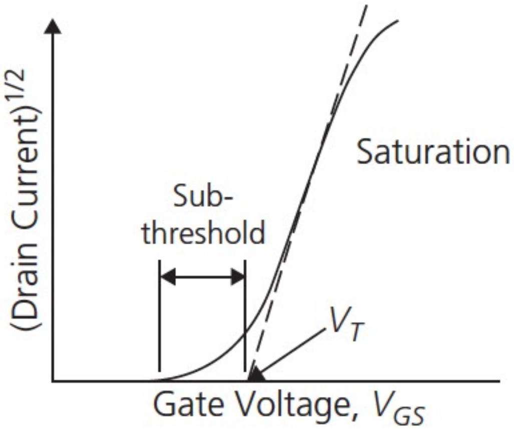
Then: $$I_D == \frac{W}{2L} C_G \mu_{sat} \left(V_G - V_T\right)^2$$

Plot of $I_D^{1/2}$ vs. V_G gives both μ_{sat} and V_T

Ideal Unipolar OTFT Characteristics







$$I_D = \mu \frac{W}{L} C_G\left((V_G - V_T)V_D - \frac{V_D^2}{2}\right)$$

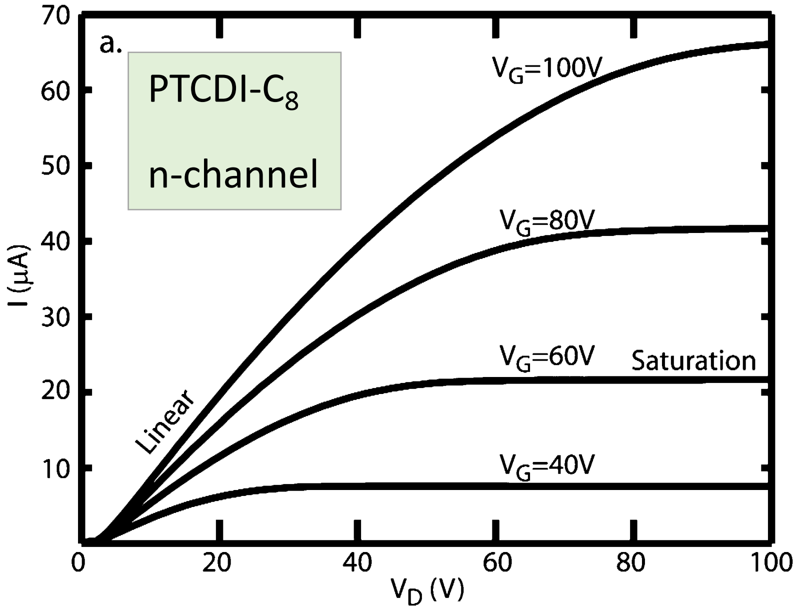
$$g_m = \left.\frac{\partial I_D}{\partial V_G}\right|_{V_D} = \frac{W}{L} C_G \mu_{lin} V_D$$

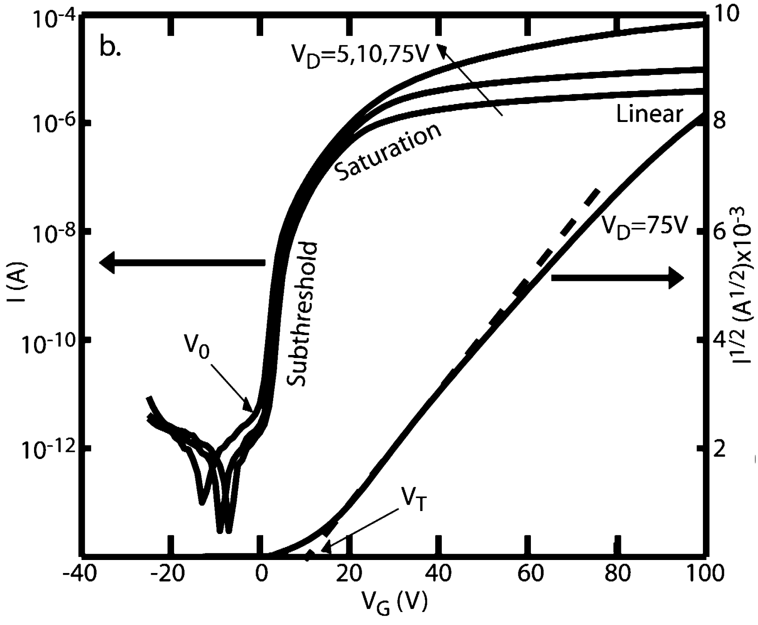
$$I_D == \frac{W}{2L} C_G \mu_{sat} \left(V_G - V_T\right)^2$$

$$g_o = \left.\frac{\partial I_D}{\partial V_D}\right|_{V_G} = \frac{W}{L} C_G \mu_{lin} \left(V_G - V_T\right)$$

DC Characteristics of an OTFT

- Pentacene most frequently employed small molecule for OTFT
- μ_{FE} ~ 1 - 1.5 cm^2/V-s
- DC mobility as high as 40 cm^2/V-s measured in rubrene using OTFTs: is it reliable? (Takeya, et al. Appl. Phys. Lett. **90** 102120 (2007))
- OTFTs measure <u>interface conductance</u>, not mobility.



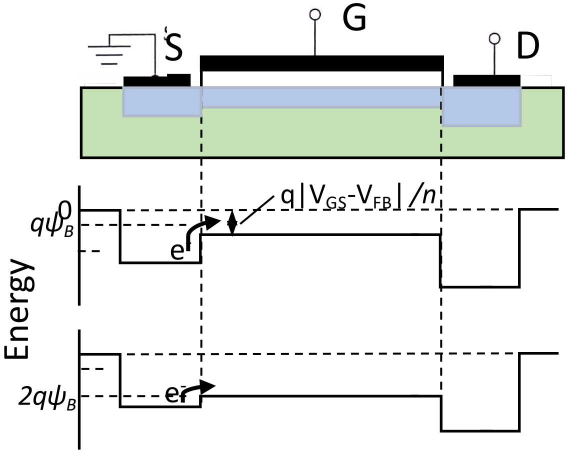


Subthreshold slope

- Measure of how small a voltage swing needed to turn on a transistor
- Determines noise margin of a circuit (i.e. how easy is it for a "1" to be mistaken for a "0")

Definition: $$S = \frac{\partial V_{GS}}{\partial\left(\log_{10} I_D\right)}$$

@ $V_{on} < V_{GS} < V_T$



Leakage due to thermionic emission from contact regions

Imperfect contacts, traps lead to injection barrier at source:

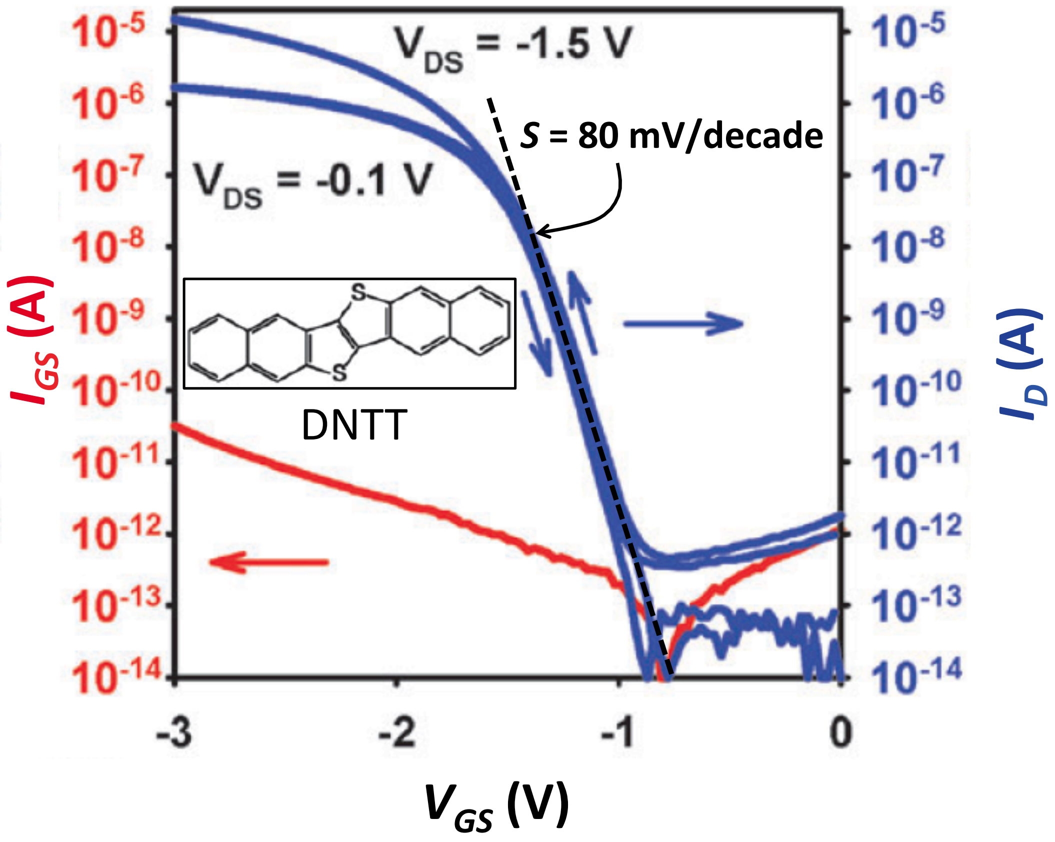
$$I_D = I_{D0}\exp\left(q\left|V_{GS} - V_{FB}\right| / nk_BT\right) = I'_{D0}\exp\left(qV_{GS} / nk_BT\right)$$

$$\Rightarrow\ S = 2.3\frac{nk_BT}{q}$$ $n = 1 \Rightarrow S = 60$ mV/decade

Theoretical minimum slope

A high performance OTFT

BG/TC



- *p* or *n* channel?
- L/W = 10 µm/100 µm
- Al gate
- AlO_x gate insulator, 3.6 nm thick, PVD grown coated with alkylphosphonic acid SAM

Klauk, Chem. Soc. Rev., 39, 2643 (2010)