Week 13

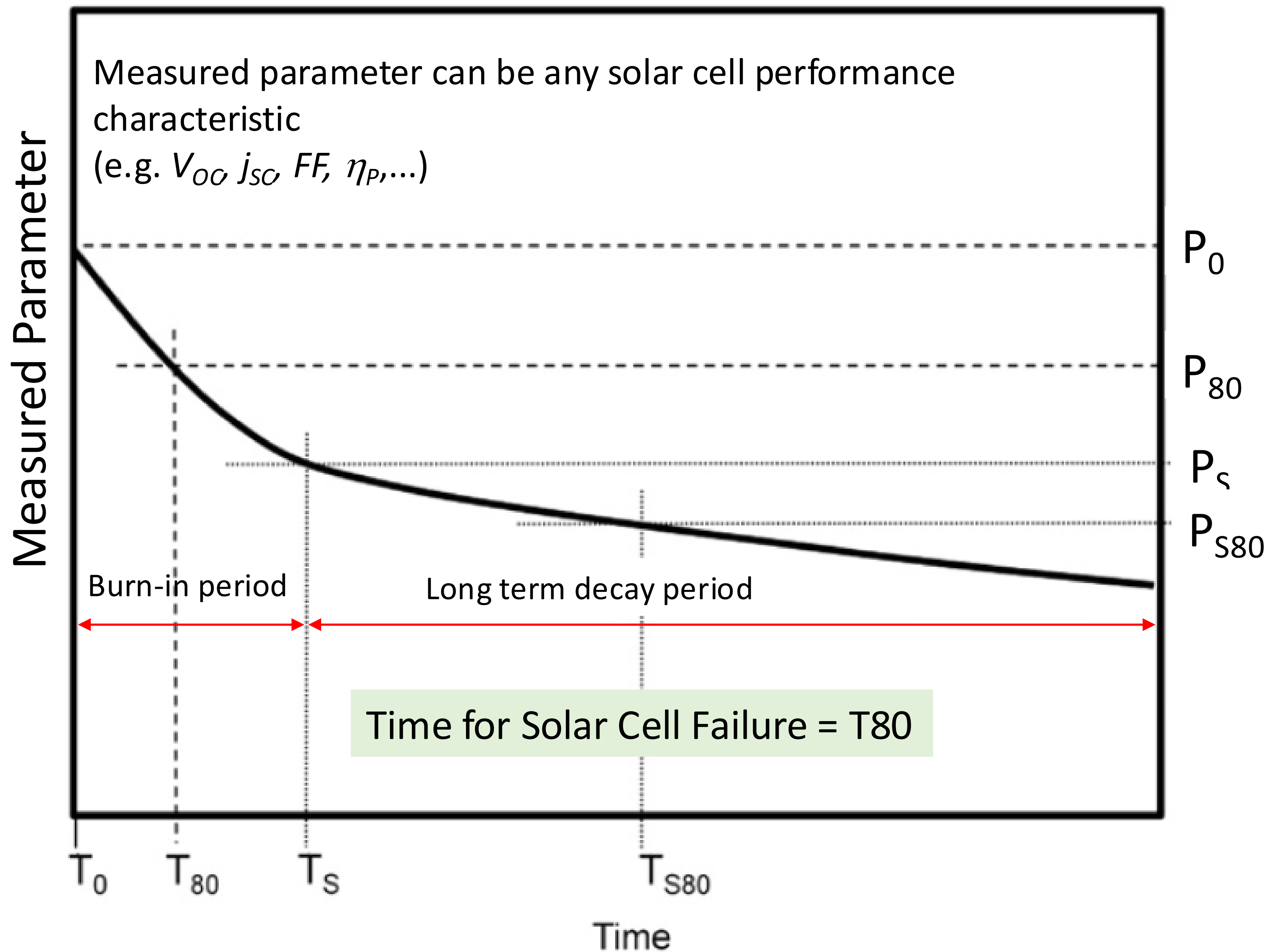
Organic Photovoltaics 2

Reliability

Modules

Chapter 8.6 – 8.7

Quantifying OPV Lifetimes



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Analytical Approaches to Failure

(see also Ch. 6.7)

Burn in   Long term loss

Sum of Exponentials: $$P(t) = P_0 \exp(-t/\tau_1) + P_{ex} \exp(-t/\tau_2)$$

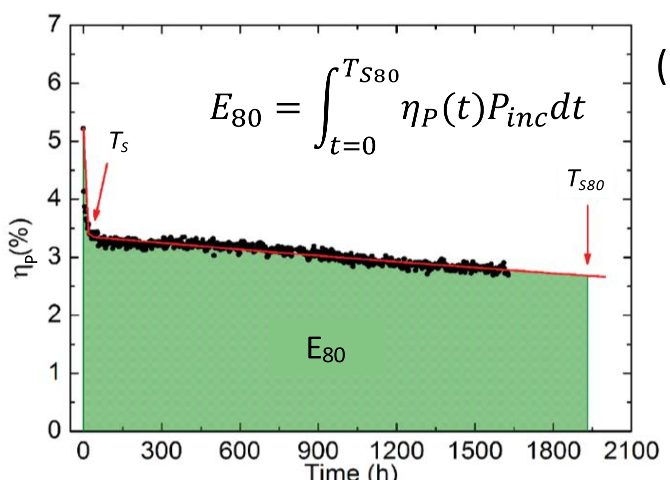
Stretched Exponential: $$P(t) = P_0 \exp\left[-(t/\tau_1)^{\beta}\right]$$

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

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

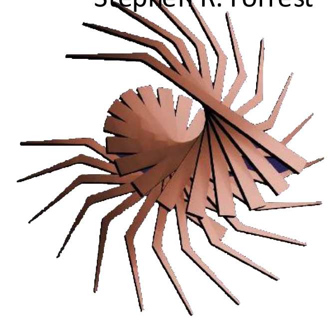
Acceleration Factor: $$\mathcal{A} = \left(\frac{P_{inc}^1}{P_{inc}^2}\right)^{\gamma} \exp\left[-\frac{E_a}{k_B}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right]$$

Total energy generated:

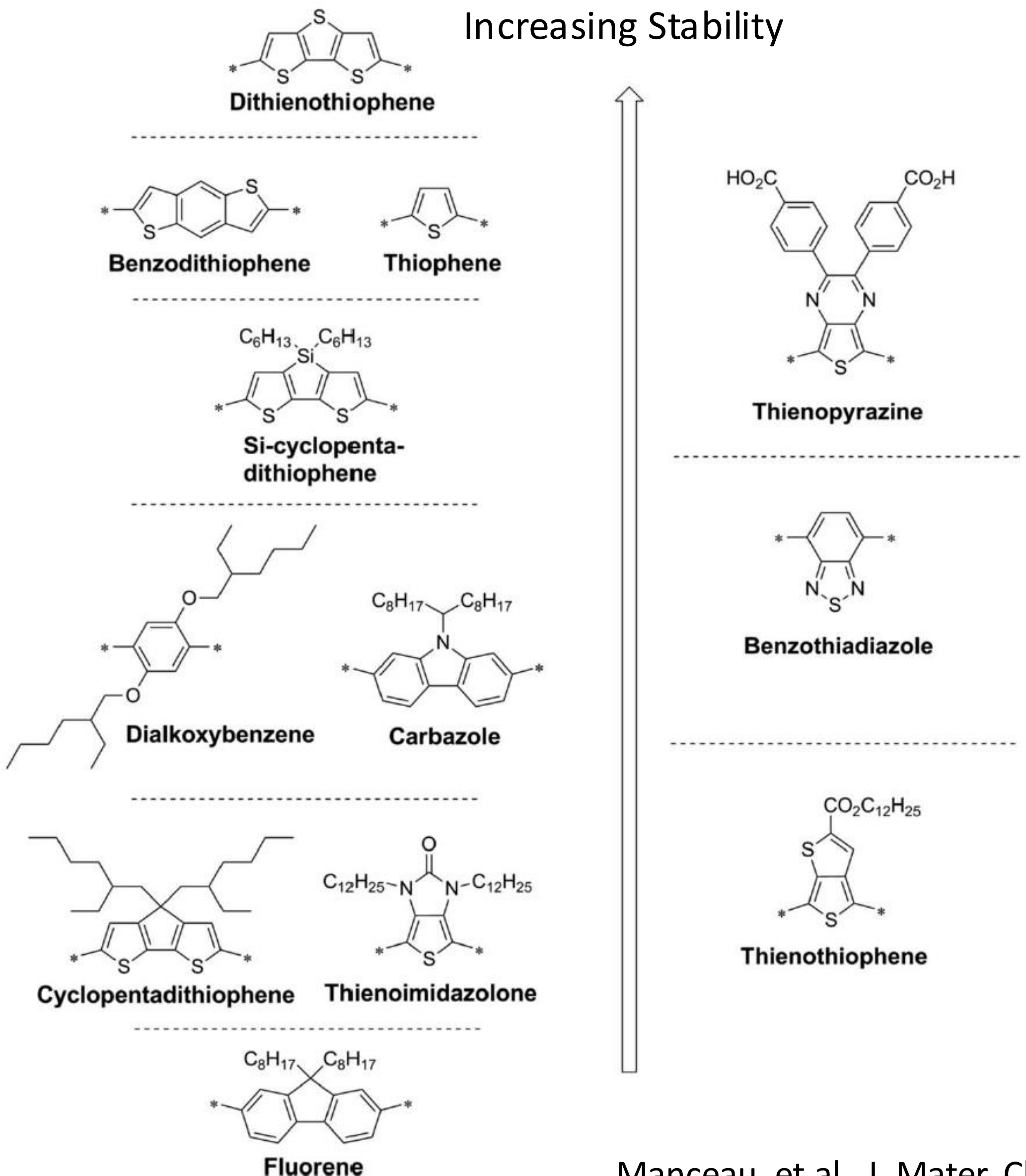


(assumes life begins after burn-in)

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

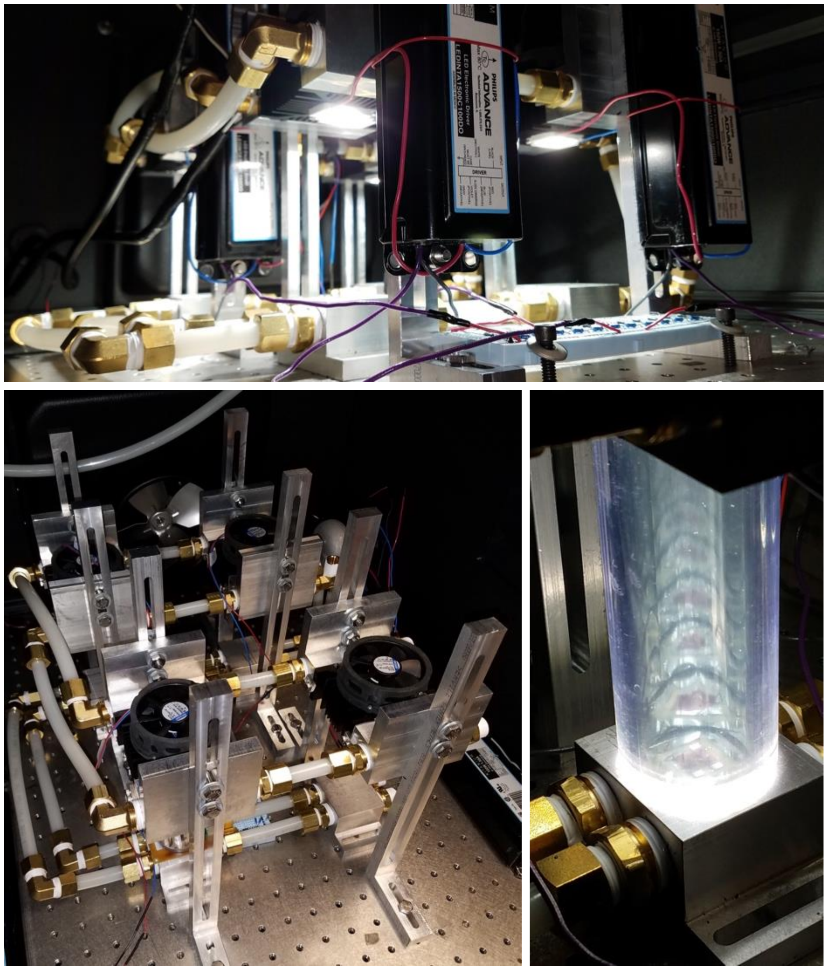


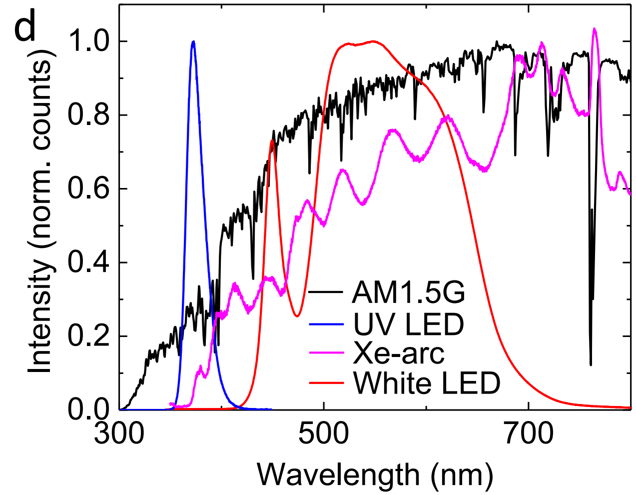
Choice of Molecules Impacts Stability

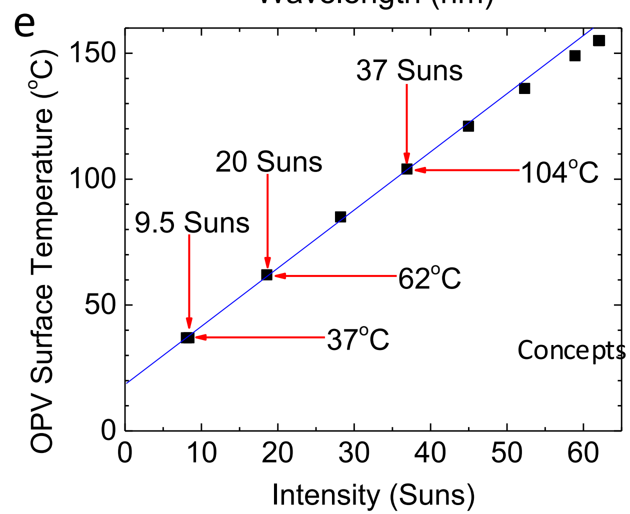


Manceau, et al., J. Mater. Chem., **21**, 4132 (2011).

Test set up for Accelerated Aging



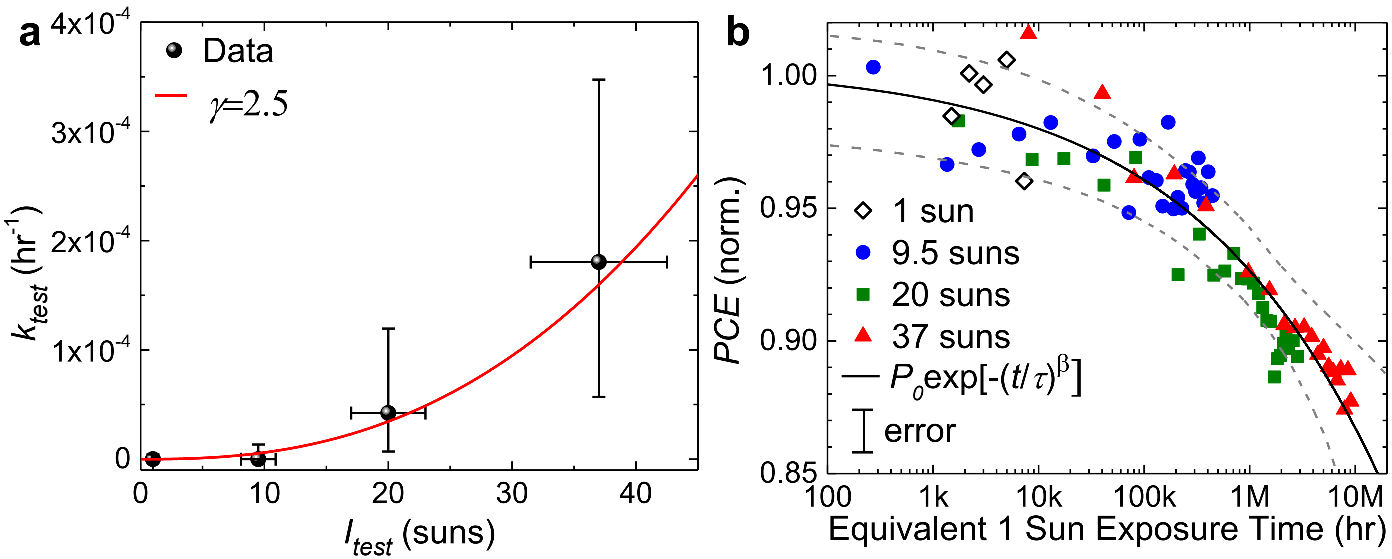




Populations of devices under very high intensity illumination using LEDs

Need to separate effects of temperature and intensity acceleration factors

Extracting Lifetime from Aging Data & Acceleration Factors



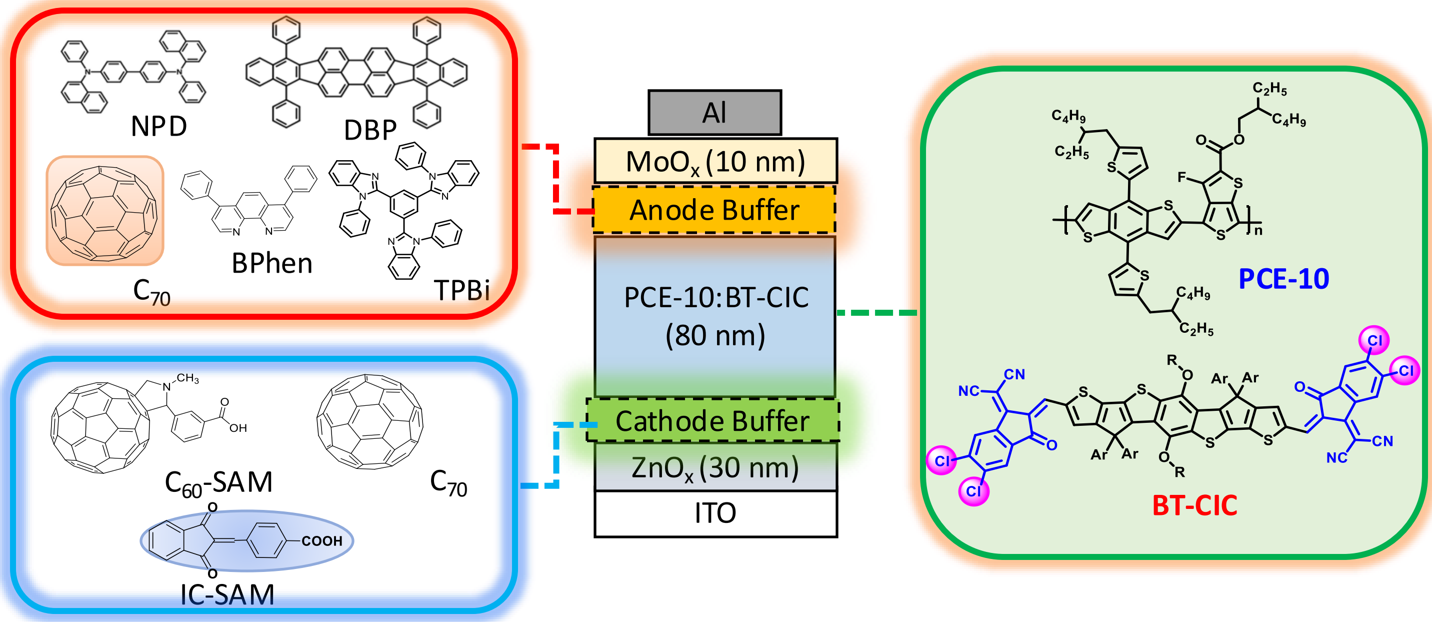
Extrapolated *intrinsic* lifetime: >10^4 years!

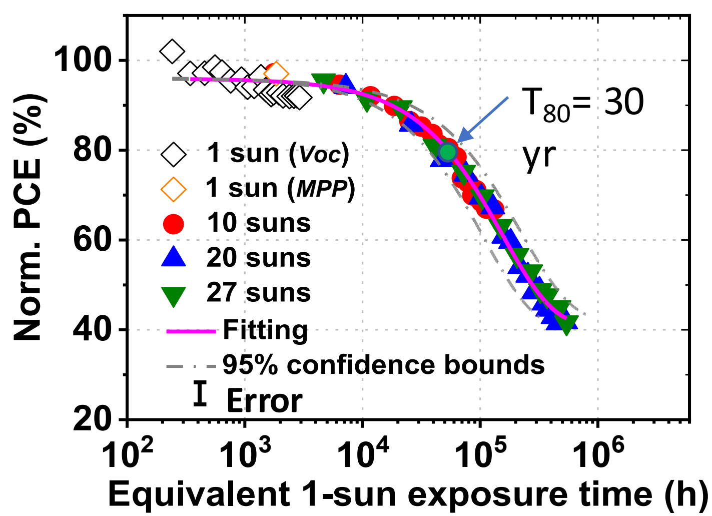
Metric for failure: T80; 5 h = 1 day solar equivalent

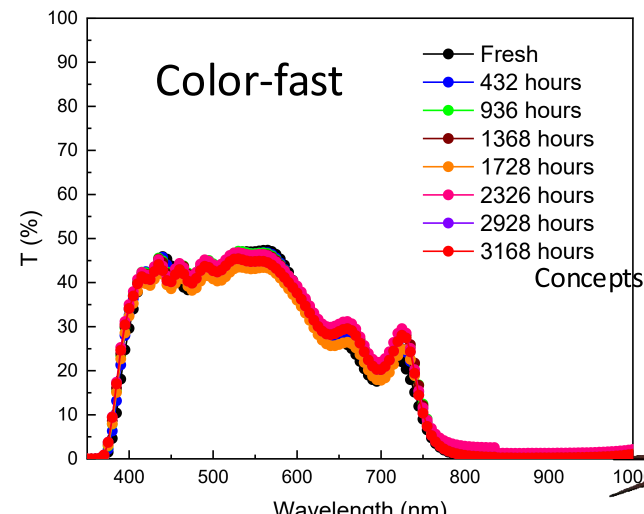
Q. Burlingame, et al., Nature, **573**, 394 (2019).

NFA OPVs Can Also Have Long Lifetimes

PCE ~ 12%







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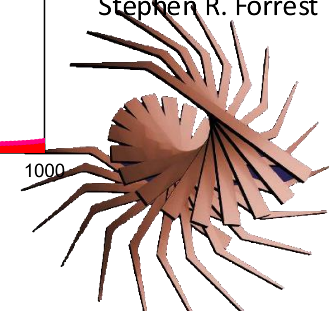
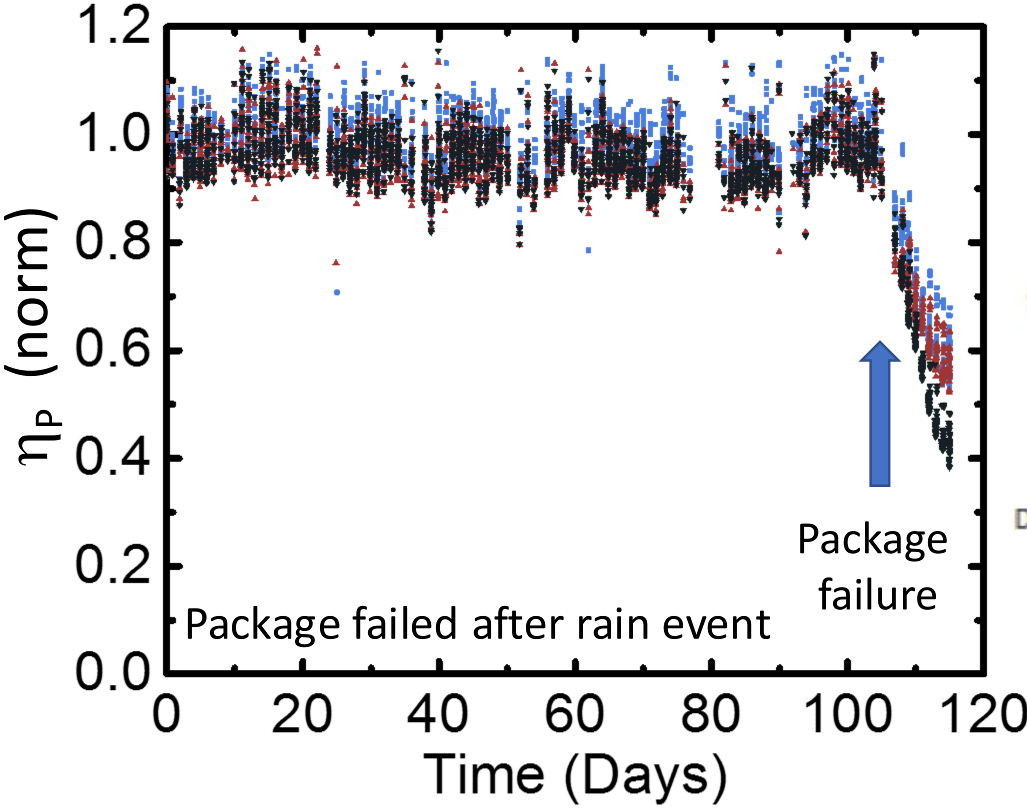


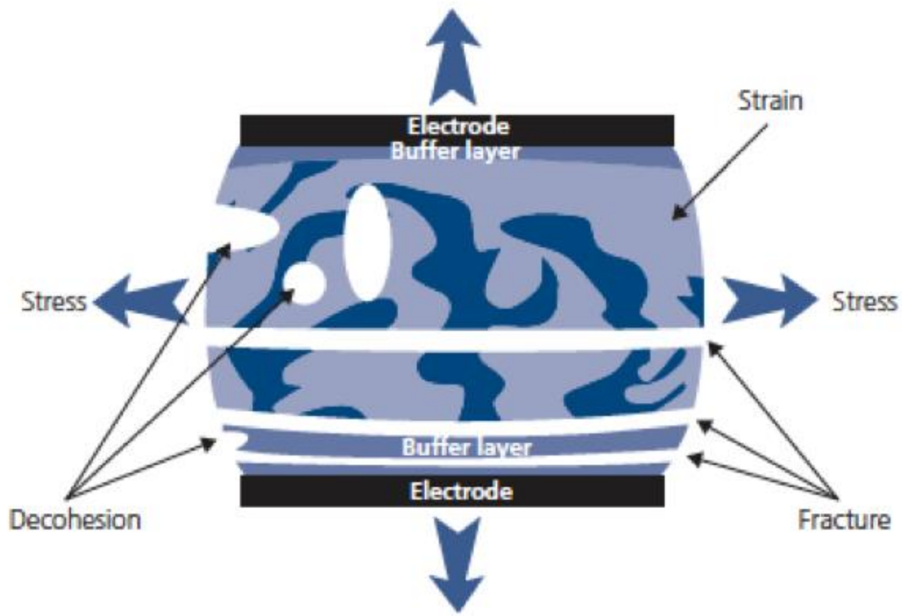
Y. Li, et al.*Nature Comm.,* **12**, 1, (2021).

What happens outdoors

Examining reliability in a real operating environment

1:8 DBP:C_{70} OPV





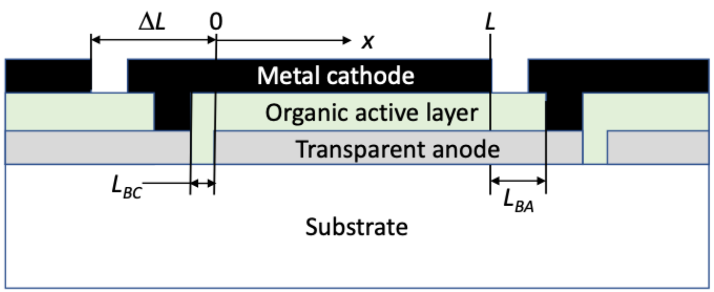
A few sources of OPV failure

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

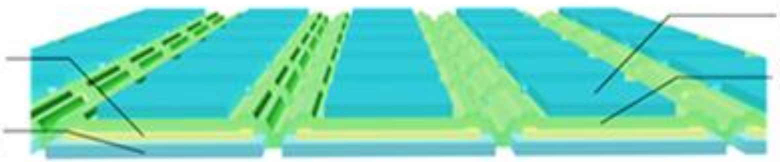
Burlingame et al. *Organic Electronics*, **41,** 274 (2016).

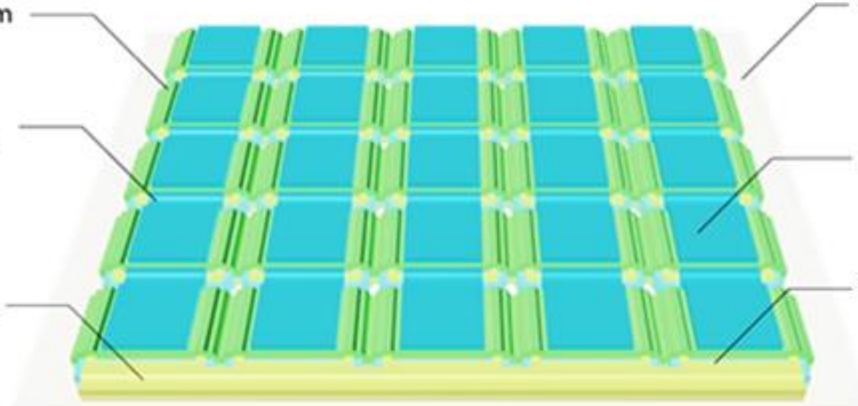
Scaling to Modules

Series connected cells

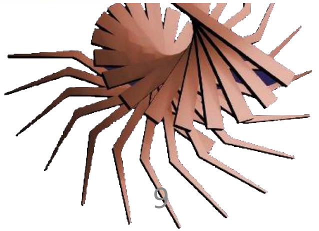


Series-parallel connected tandem OPVs





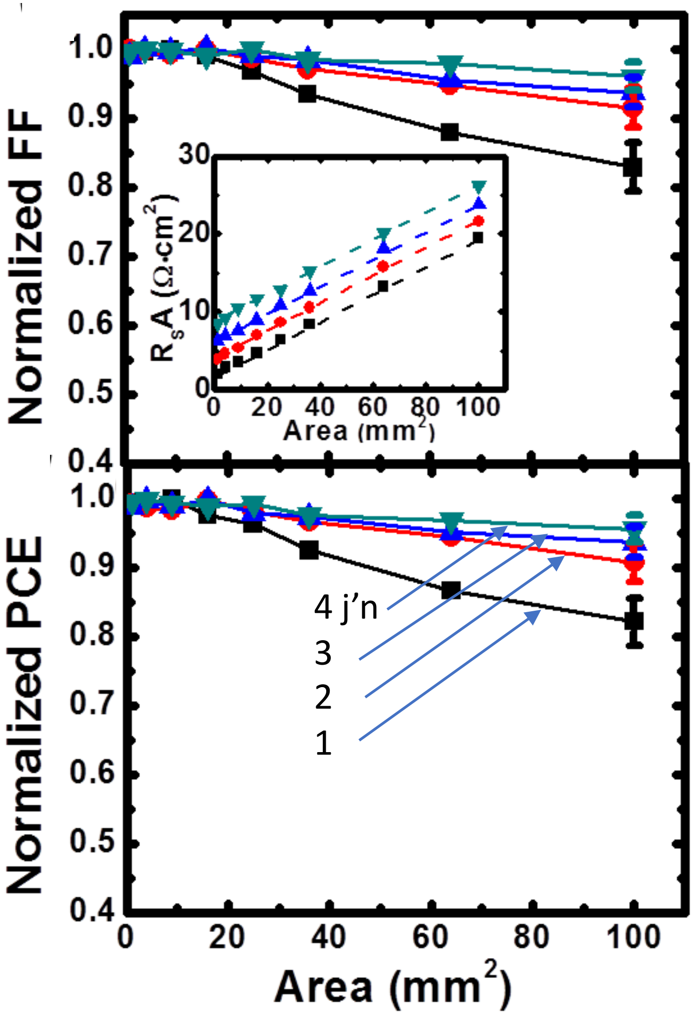
X. Xiao, et al., *Appl. Phys. Lett.*, **106**, 213301 (2015).



Multijunction Cells Limit the Effects of Resistance

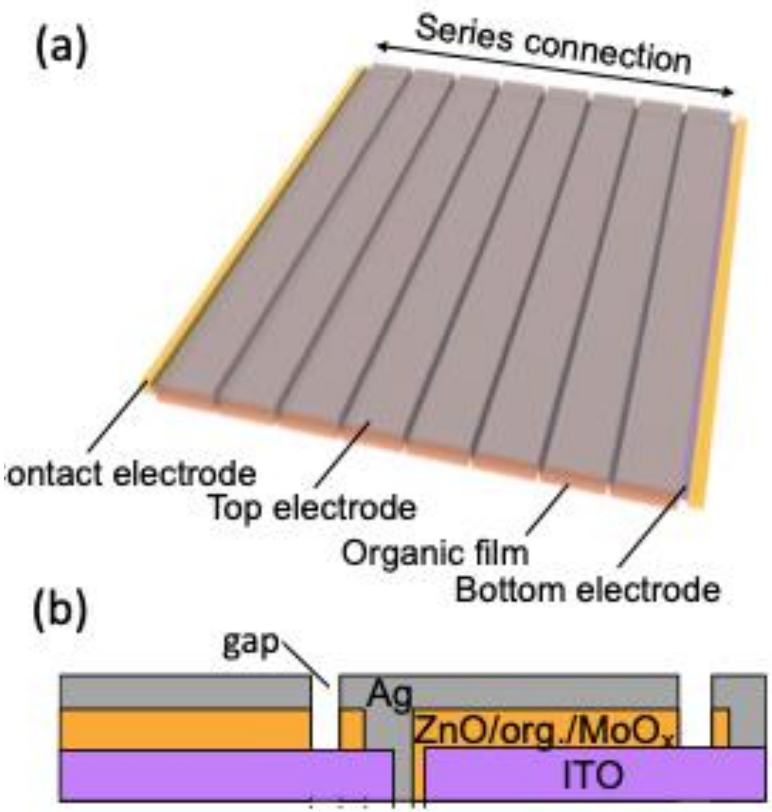
The higher the voltage,
The smaller the problem

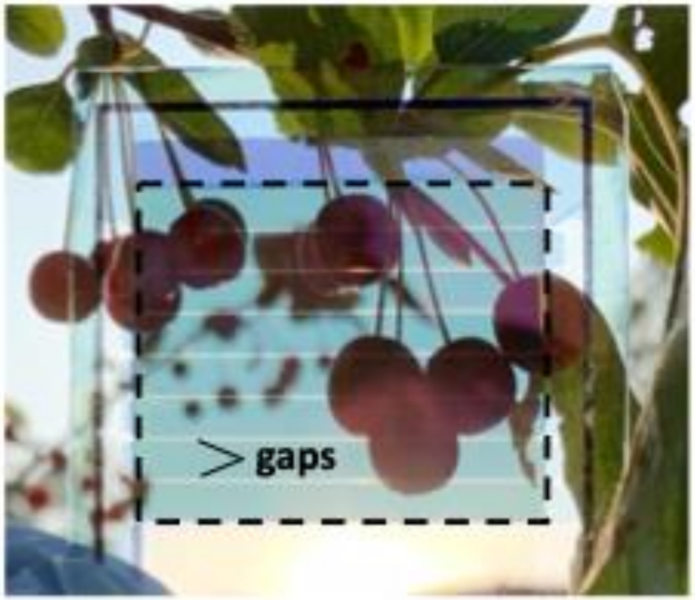
⇒ Multijunction cells



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

ST-OPV Module



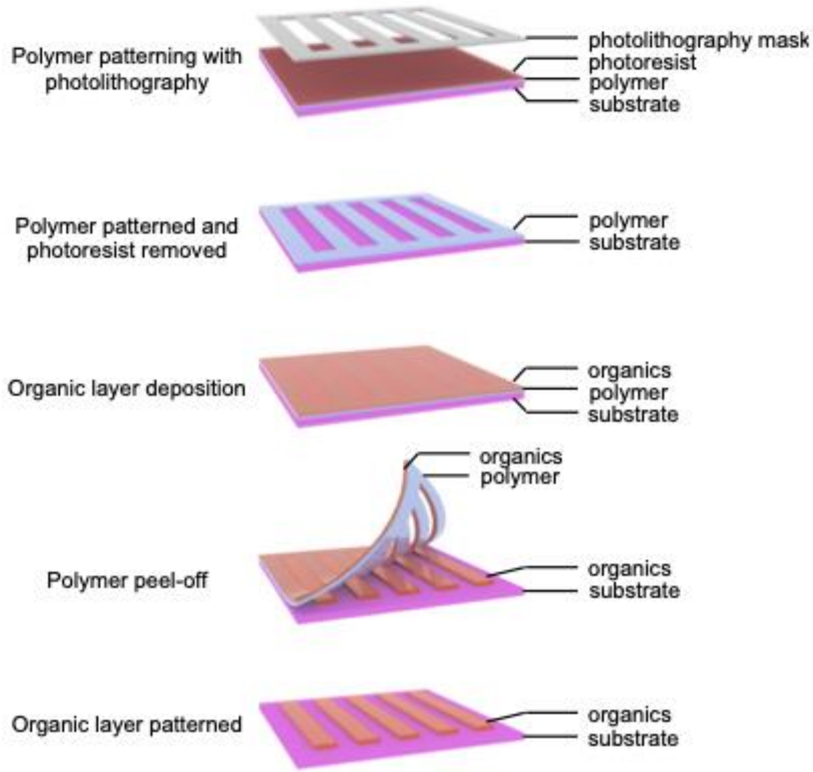


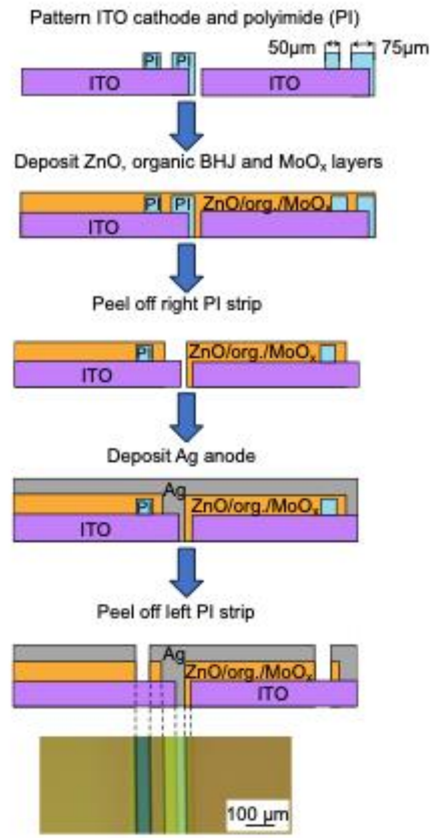
Long PV stripes equivalent to parallel connection

X. Huang, et al. (2022). Joule, **6**, 1581

Fabricating modules

- Peel off patterning





X. Huang, et al. (2022). Joule, **6**, 1581

Other methods:

Laser scribing, shadow masking, slot-dye coating, mechanical scribing…

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 cells free 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: power generating windows, agrivoltaics
- 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 9.1-9.2

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OTFT Objectives

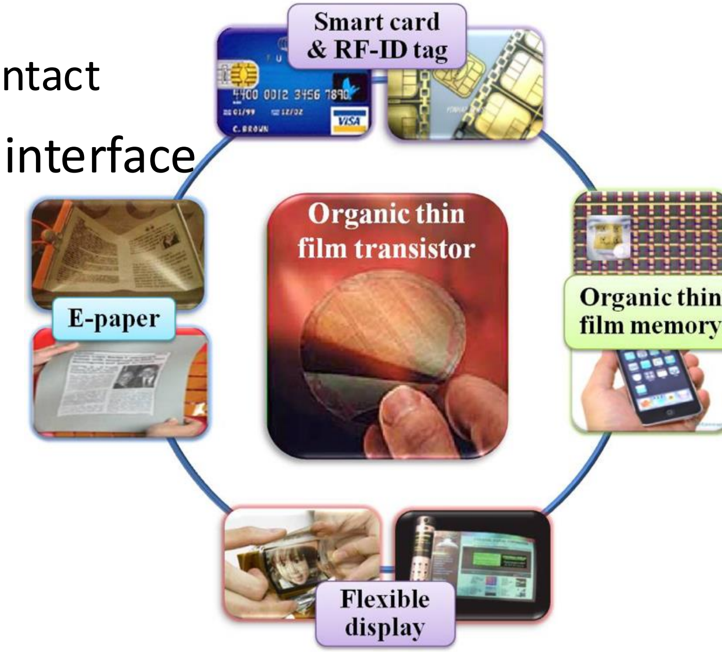
- Learn how they work
- Learn how they are made
- Learn about their operational reliability
- Learn what they are good for: Are they an answer waiting for a question?
    - Sensing
    - Medical Applications

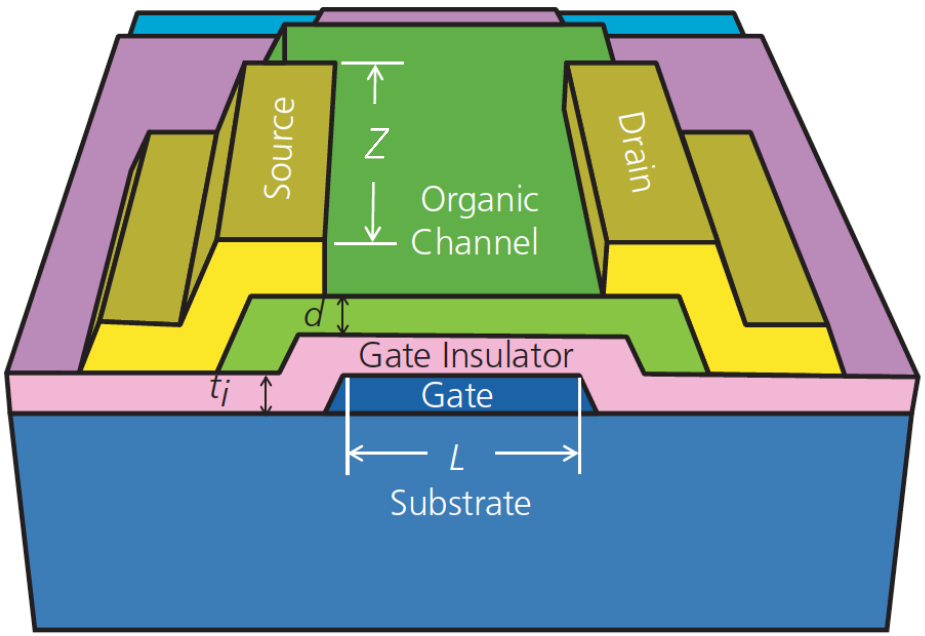
Advantages vs. Limitations of OTFTs

- 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

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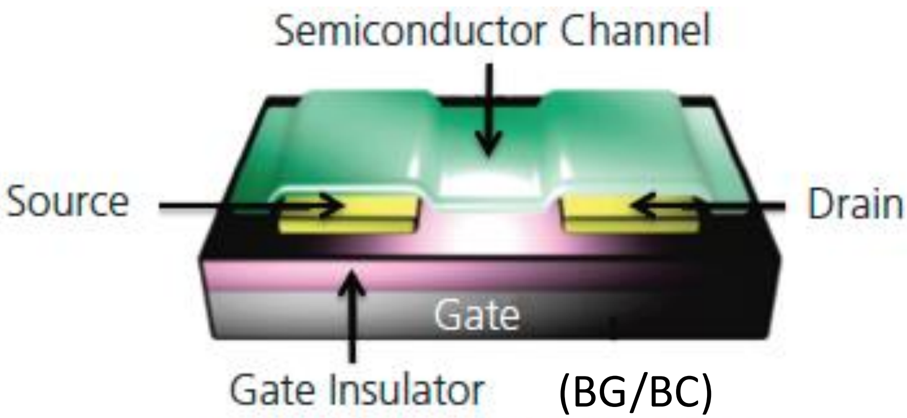
Different Contact Arrangements



(BG/BC)

Bottom Gate/Bottom Contact

(BG/TC)

Bottom Gate/Top Contact

Top Gate/Top Contact

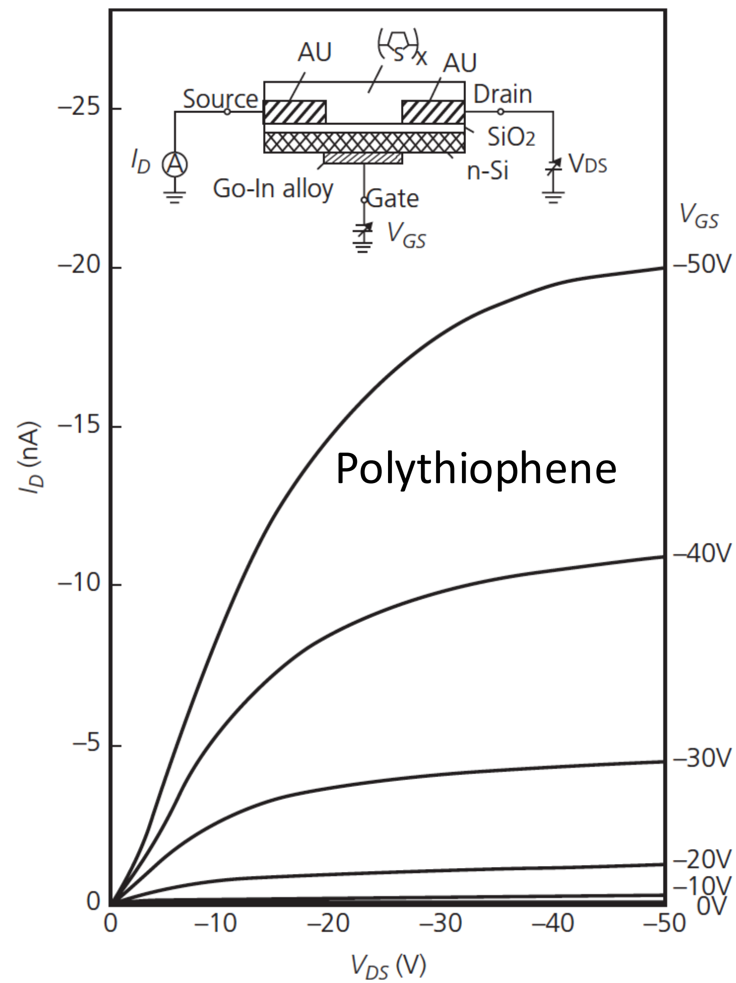
(TG/TC)

Top Gate/Bottom Contact

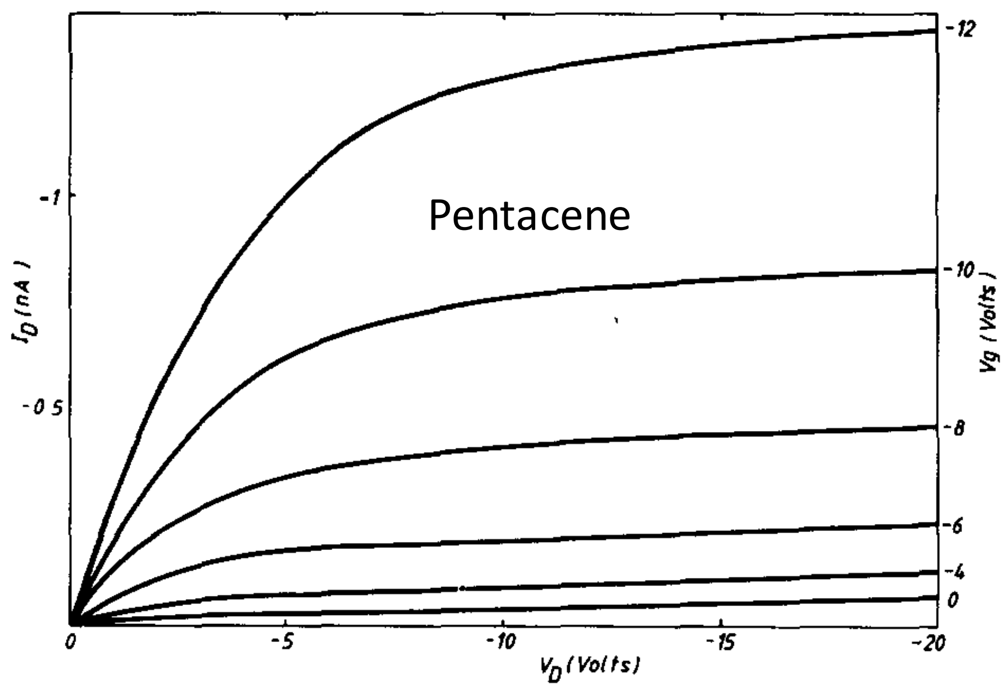
(TG/BC)

Organic Thin Film Transistors

First demonstrations



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



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

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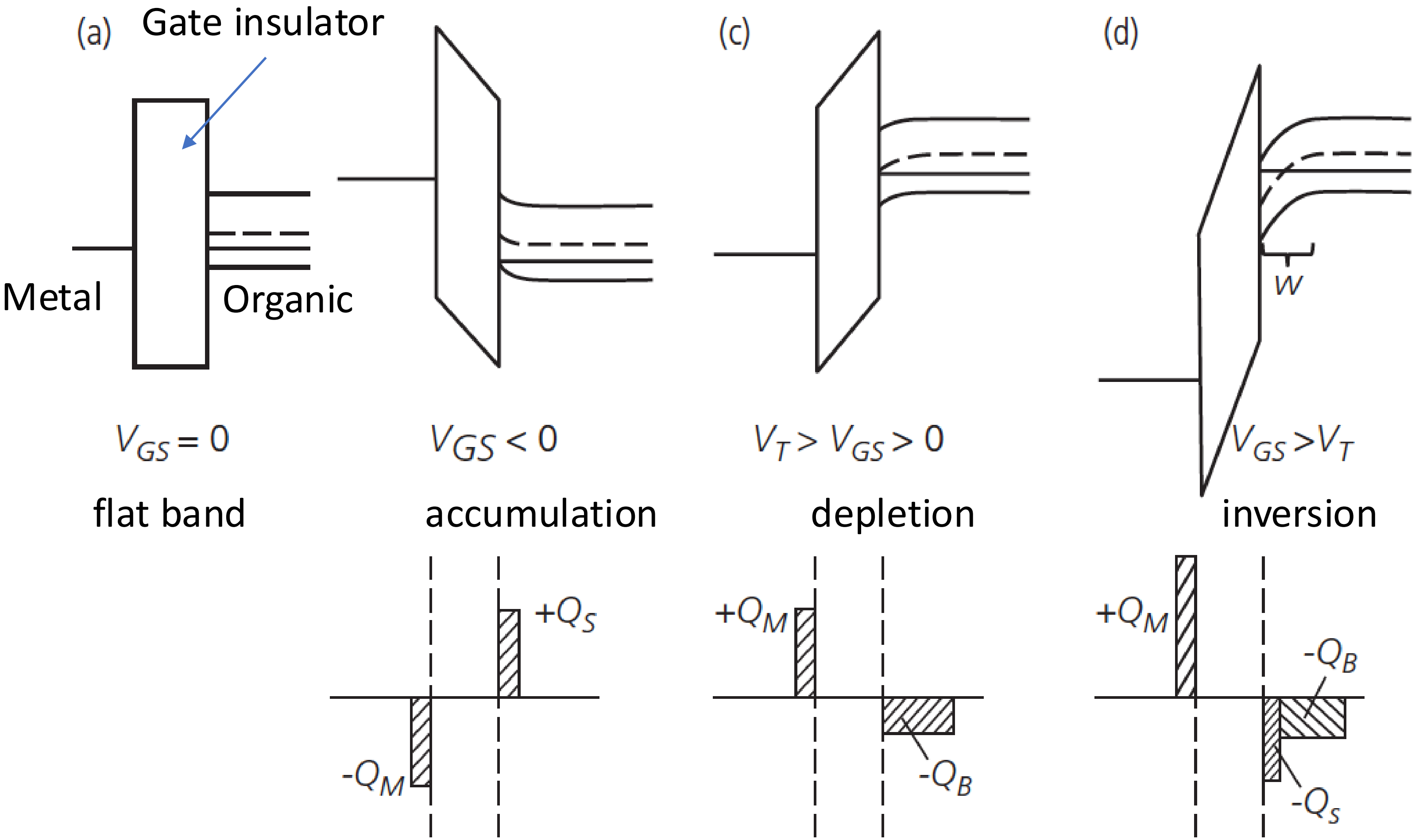
The MIS Capacitor: OTFT Building Block



tronics
Forrest

- 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):

$$Q(x) = qn(x)t = C_G(V_{GS} - V(x))$$

Charge layer thickness

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

$$Q(x) = qn(x)t = C_G(V_{GS} - V_T - V(x))$$

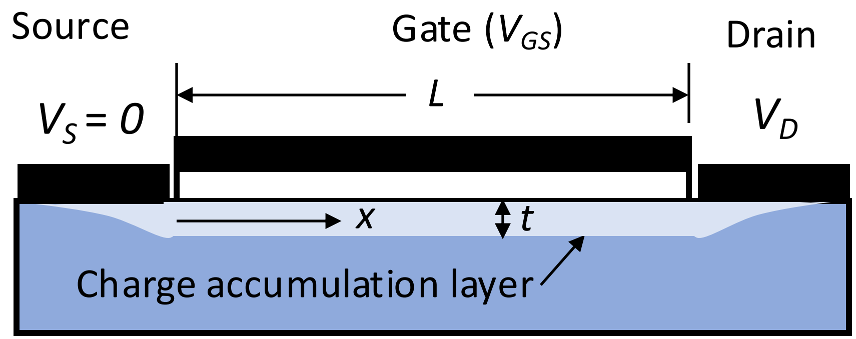
Following Ohm's Law:

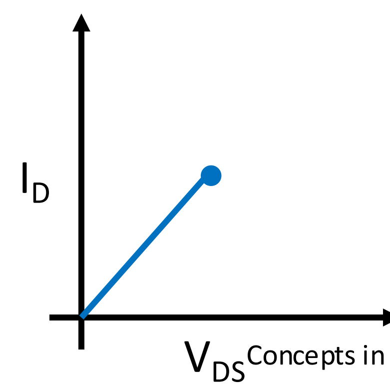
$$I_D = A\sigma F = W\overbrace{(n_{ave}qt)}^{Q_{ave}}\mu\frac{V_D}{L}$$

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

Or, in the <u>linear regime of operation</u>:

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





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:

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

And the output conductance:

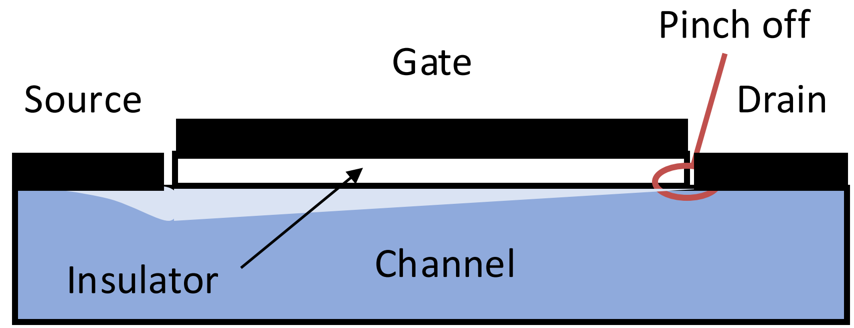
$$g_D = \left.\frac{\partial I_D}{\partial V_{DS}}\right|_{V_G} = \frac{W}{L} C_G \mu_{lin} \left(V_G - V_T\right)$$

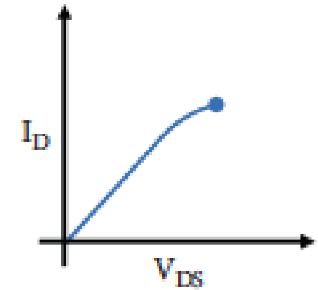
Due to contact & other parasitic resistances, μ_{lin} gives errors, so mostly use <u>saturation characteristics</u>:

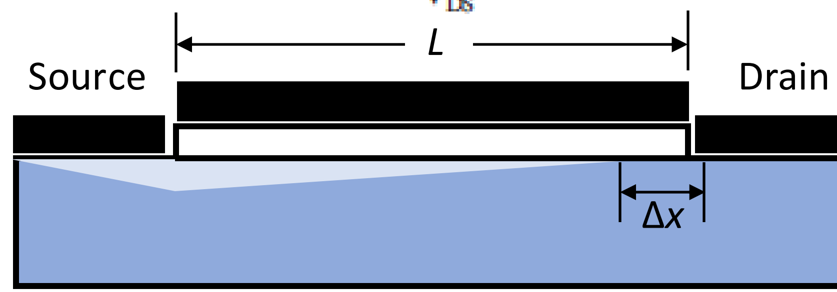
- When $V_D = V_G - V_T$, the channel **pinches off**
- Between pinchoff point and drain, $n \to 0 \Rightarrow F \to$ large to maintain current continuity ($j = nq\mu F$)
- No more current (except leakage) enters channel with increasing V_D, hence we are in the <u>saturation regime</u>.

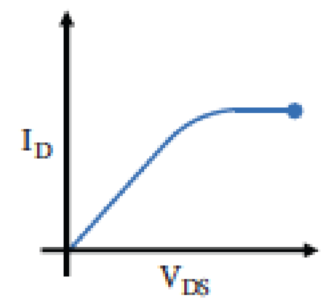
Then: $$I_D == \frac{W}{2L} C_G \mu_{sat} \left(V_G - V_T\right)^2$$

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



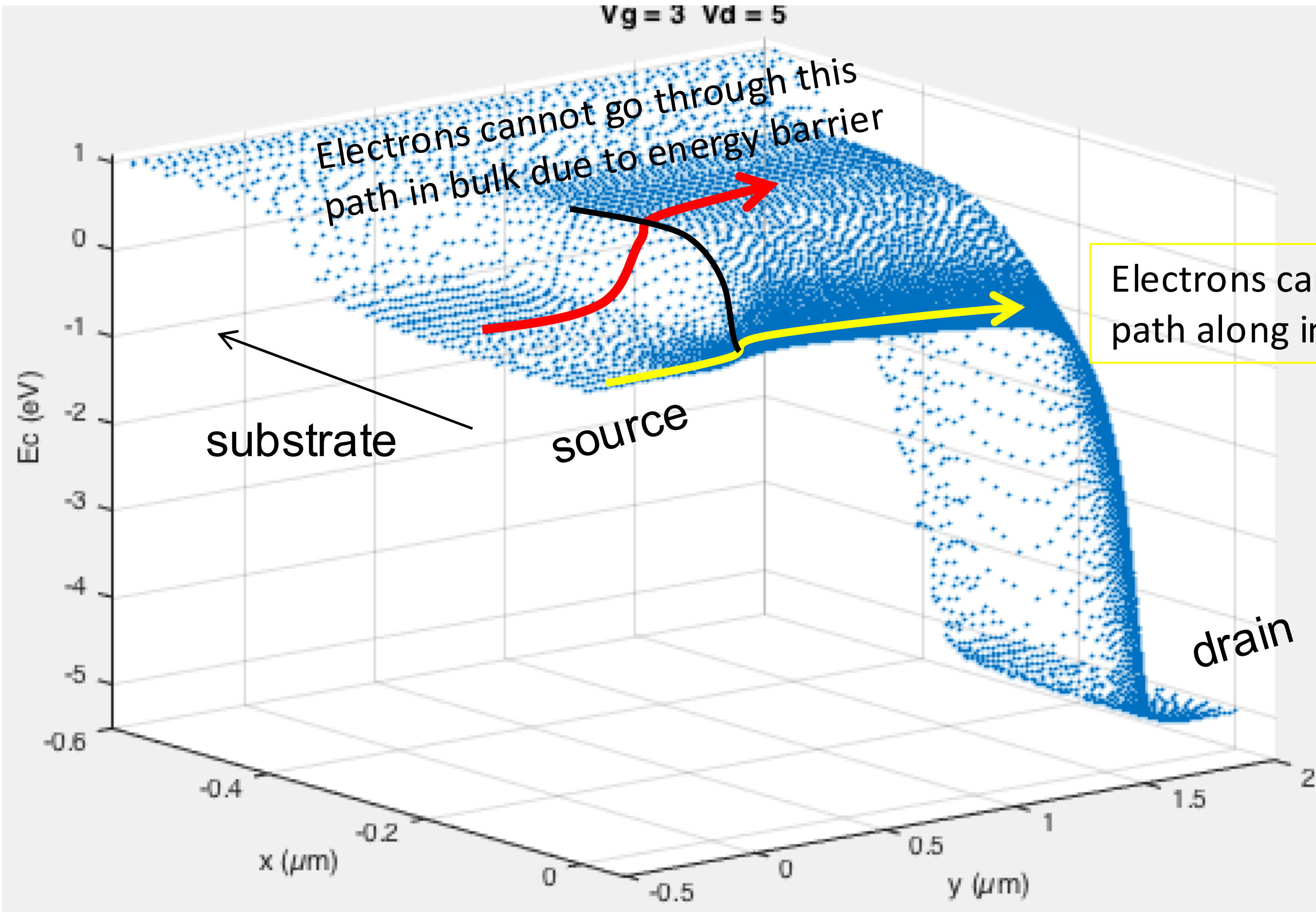






Above threshold

- Source electrons can enter the channel at will.
- Channel is converted to n-type to conduct electrons that have entered the channel.



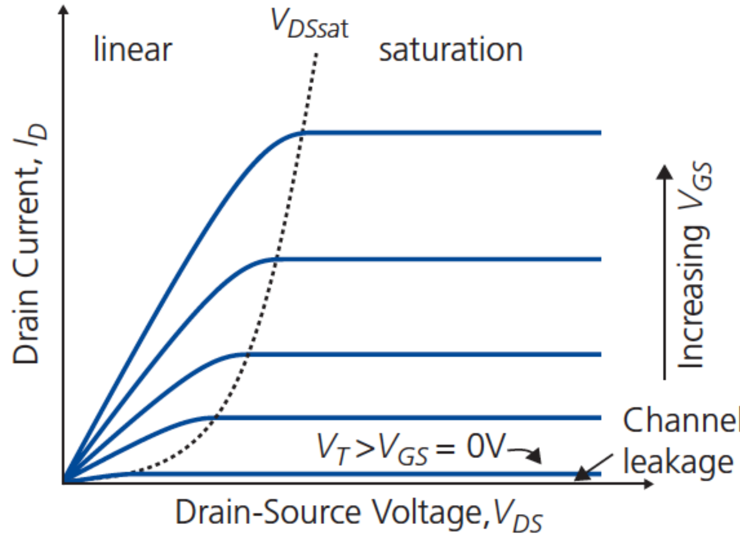
Ideal Unipolar OTFT Characteristics

$$\boxed{I_{DS} = \frac{Z}{L}\mu_n C_{ox}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS}}$$

$$|V_{DS}| < |V_{GS} - V_T|$$

$$\boxed{I_{DS} = \frac{Z}{2L}\mu_n C_{ox}\left(V_{GS} - V_T\right)^2}$$

$$|V_{DS}| > |V_{GS} - V_T| = V_{Dsat}$$

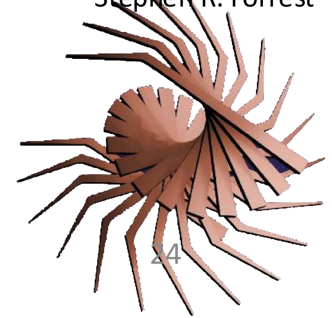


Output conductance (slope of the output characteristics)

$$g_D = \left.\frac{\partial I_{DS}}{\partial V_{DS}}\right|_{V_G=\text{constant}} = \begin{cases} \frac{Z}{L}\mu_n C_{ox}\left(V_{GS} - V_T - V_{DS}\right) & \text{Below } V_{Dsat} \text{ (pinch –off)} \\ 0 & \text{Above } V_{Dsat} \end{cases}$$

Transconductance (rapidity of change of drain current with input voltage = "gain")

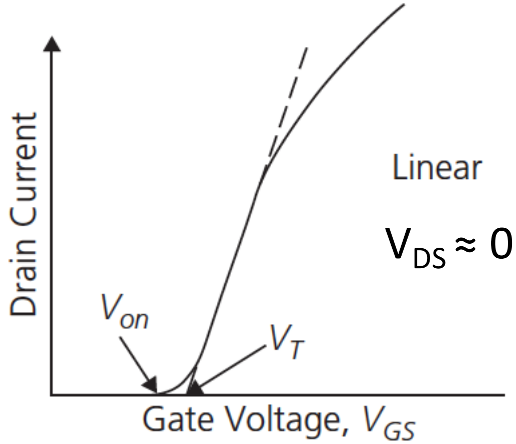
$$g_m = \left.\frac{\partial I_{DS}}{\partial V_{GS}}\right|_{V_{DS}=\text{constant}} = \begin{cases} \frac{Z}{L}\mu_n C_{ox} V_{DS} & \text{Below } V_{dsat} \\ \frac{Z}{L}\mu_n C_{ox}\left(V_{GS} - V_T\right) & \text{Above } V_{Dsat} \end{cases}$$

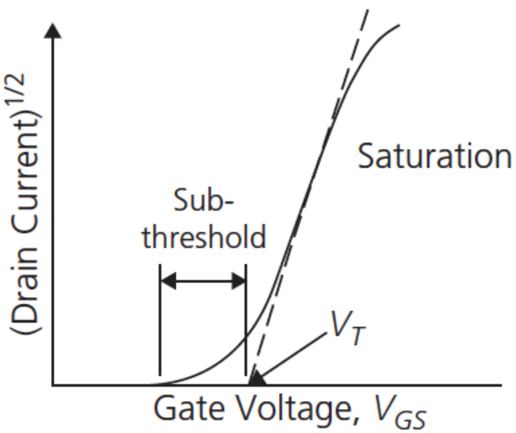


OTFT Transfer Characteristics

$$I_{DS} = \frac{Z}{L}\mu_n C_{ox}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS}$$

$$I_{DS} = \frac{Z}{2L}\mu_n C_{ox}\left(V_{GS} - V_T\right)^2$$





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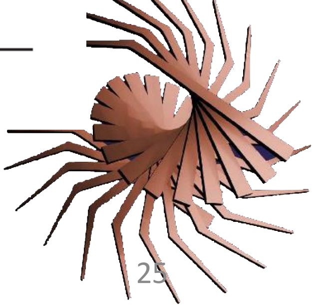
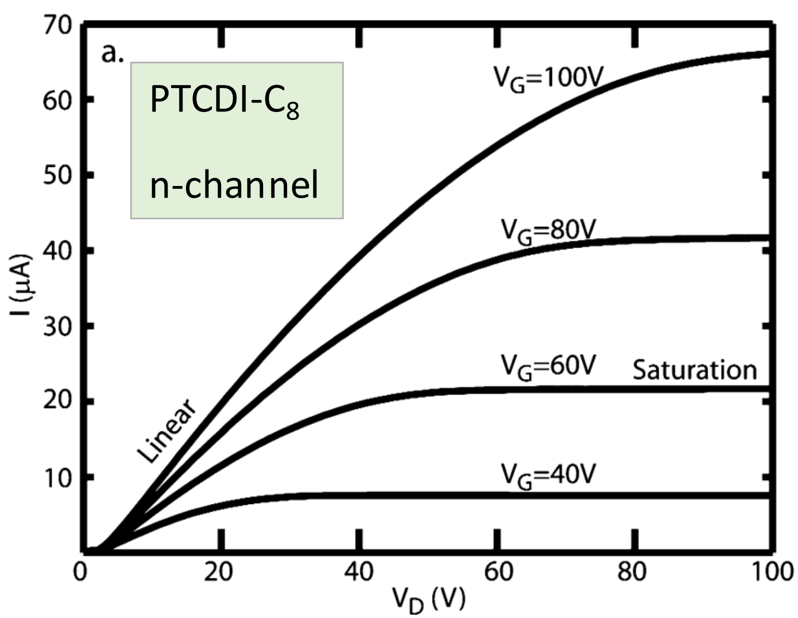
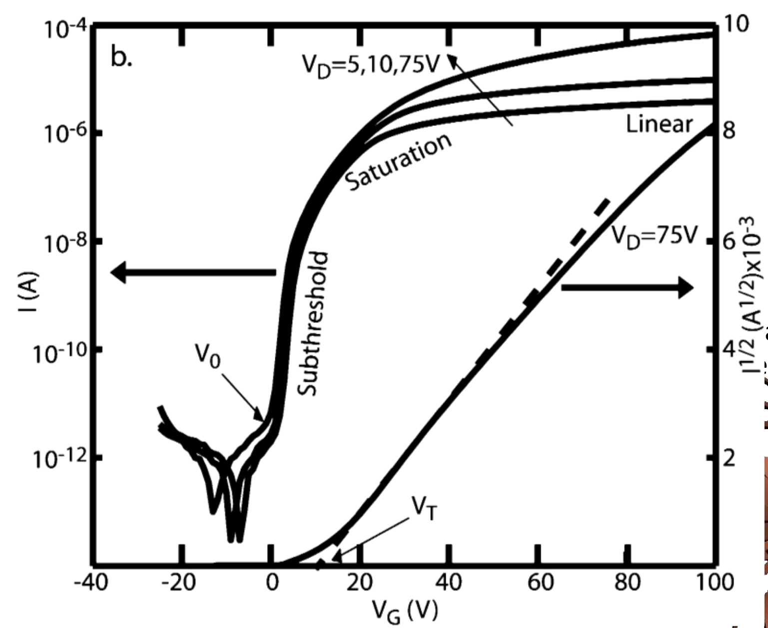


DC Characteristics of an OTFT

- Pentacene historically most frequently employed small molecule for OTFT (but not the best)
- 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.



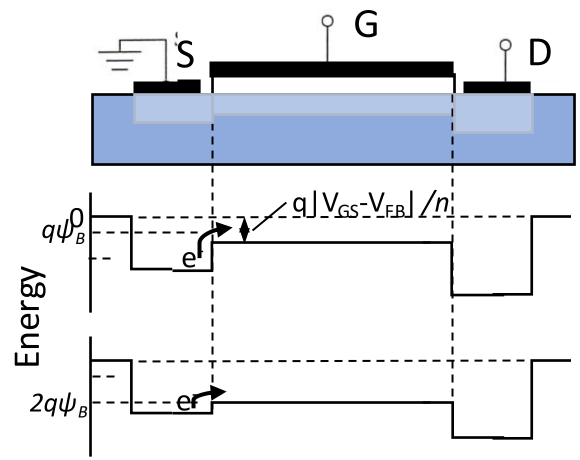


Subthreshold slope

- 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”)
- Low power digital circuits often operated in subthreshold regime

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

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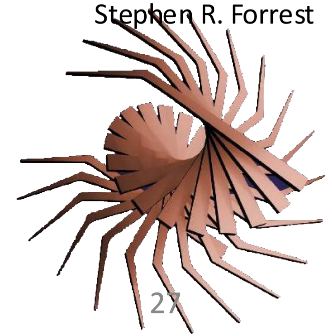
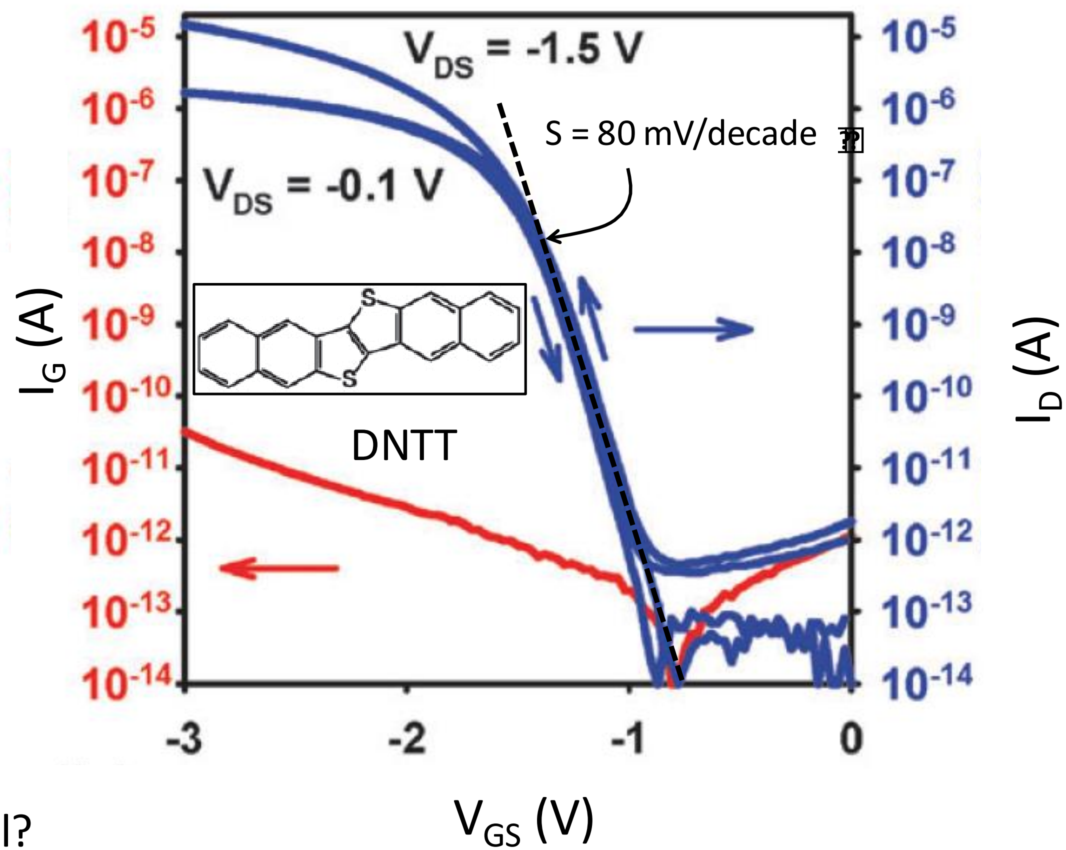


A high performance OTFT

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)