Week 2-10

Optical Detectors 5

OPV Modules

Ch. 7.9 – 7.10

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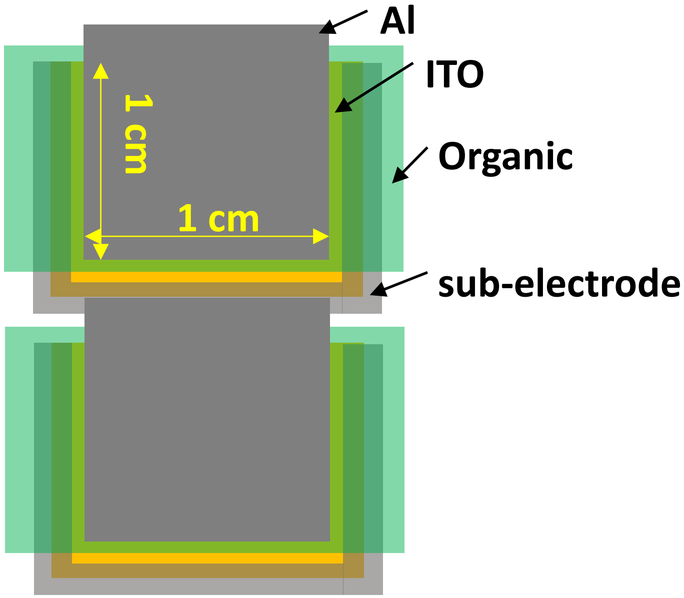
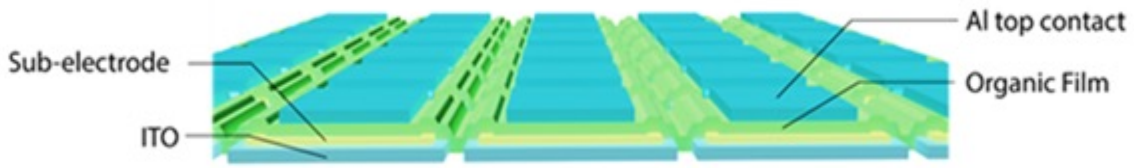
Scaling to Modules

Two tandem cells in series

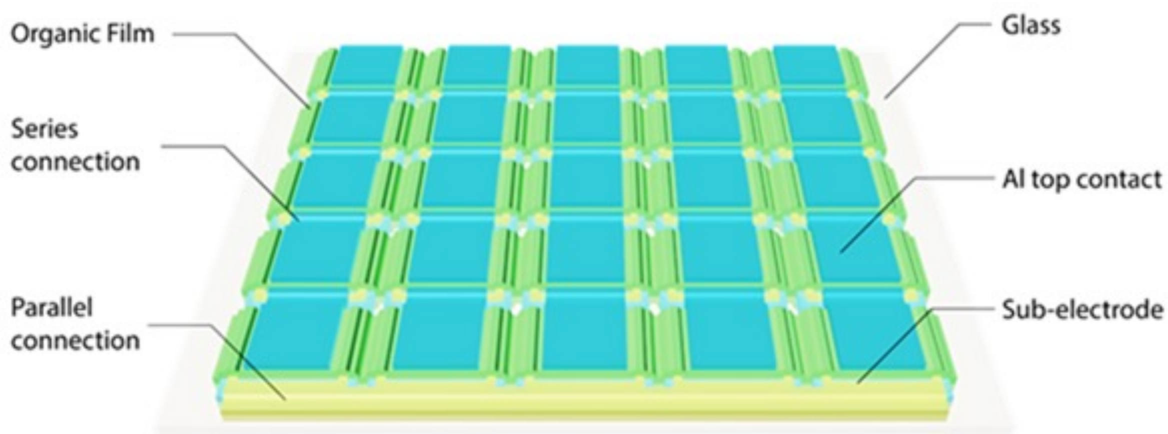


- Surrounding cell with contacts (sub electrodes) reduces resistance
- 5x5 discrete tandem cells connected in series-parallel configuration
- Active area: 1 cm^2 for discrete; 25 cm^2 for module

Front view



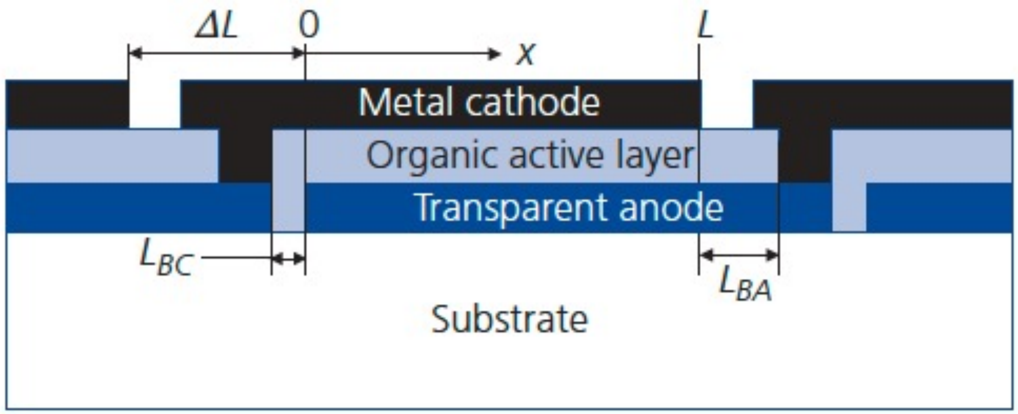
Top view



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

Power Limiting Resistances in the Module

- **Geometric fill factor** accounts for inactive regions from device interconnects: $\eta_{p,module} = GFF \cdot \eta_{P,cell}$



Material	Layer thickness	$R_{\square}$ (Ω/sq.)
Al	135	0.16
ITO on glass	150	12.5
ITO on PET	150	50
PEDOT:PSS PH1000	150	100
Material		**ρ_C with Al (mΩ cm²)**
ITO on glass		11
ITO on PET		17
PEDOT:PSS PH1000		200

Components Leading to Module Efficiency Loss

$$\Delta P_{sheet} = \frac{R_{\square}}{W}\int_0^L I(V)^2 dx = \frac{R_{\square}}{W}\int_0^L \left[j(V)Wx\right]^2 dx = I(V)^2\left[\frac{R_{\square}L}{3W}\right]$$

Power loss from contact sheet resistance, R□

$$R_{sheet} = \frac{R_{\square}L}{3W}$$

Total sheet resistance from contact of length, L, device width W

$$R_{BA,C} = R_{\square A,C}\frac{\Delta L}{3W}$$

Bridge resistance

$$R_C = \rho_C \frac{3}{W\Delta L}$$

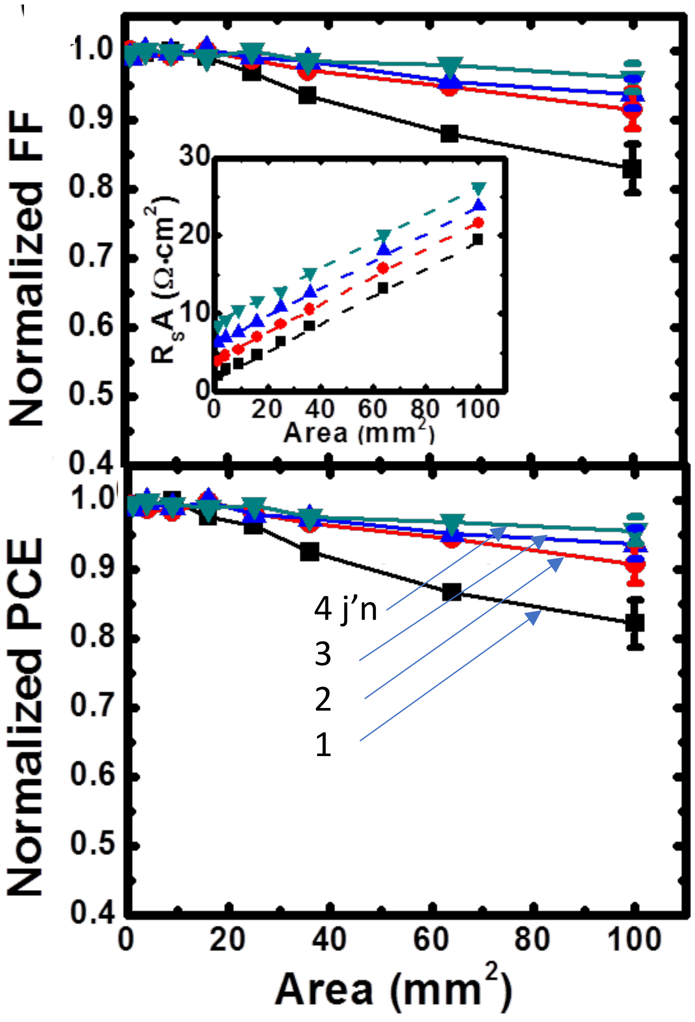
Contact resistance between cathode and anode

Hoppe et al. Solar Cell Mater. Solar Cells,97, 119 (2012)

Multijunction Cells Limit the Effects of Resistance

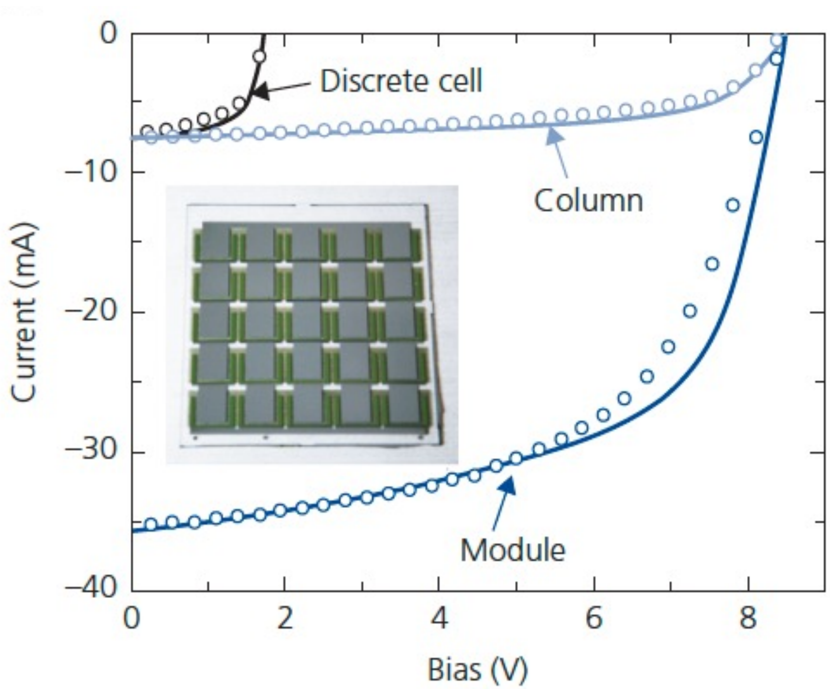
The higher the voltage,
The smaller the problem

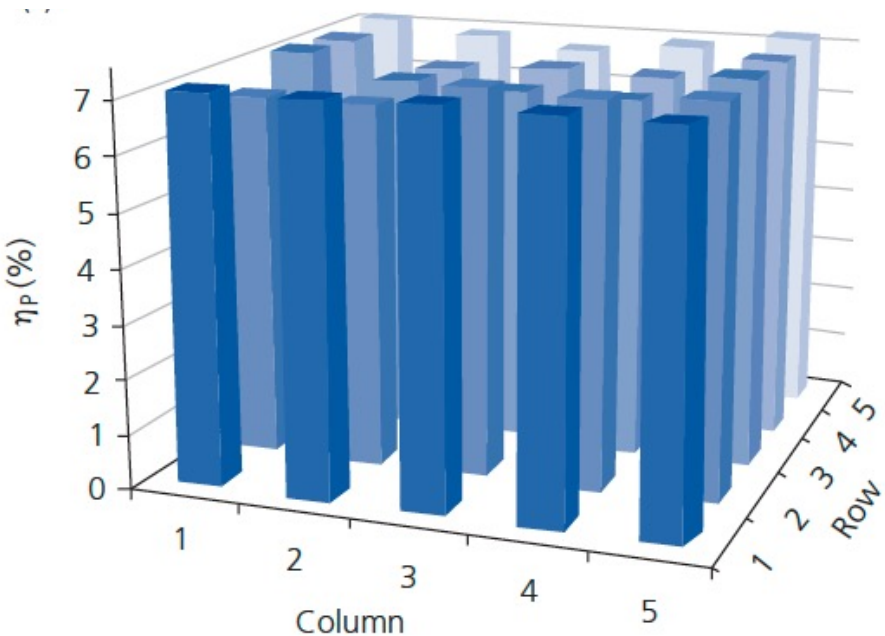
⇒ Multijunction cells



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

Efficiency of Tandem Modules in Series-Parallel Circuit





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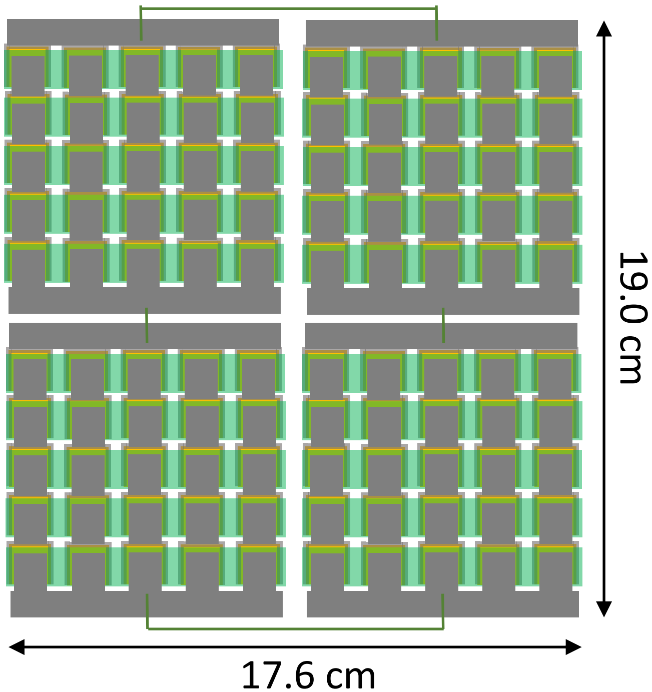
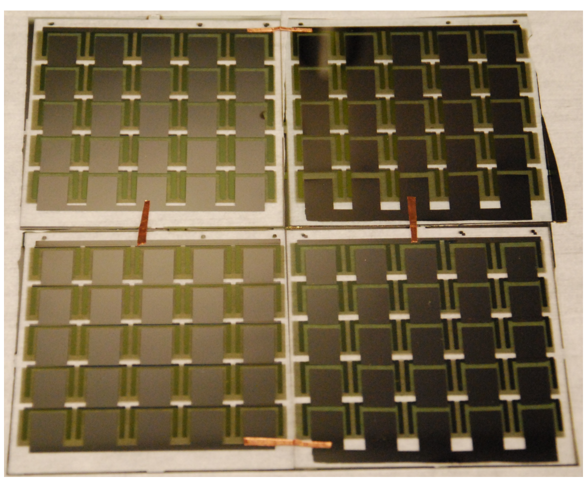
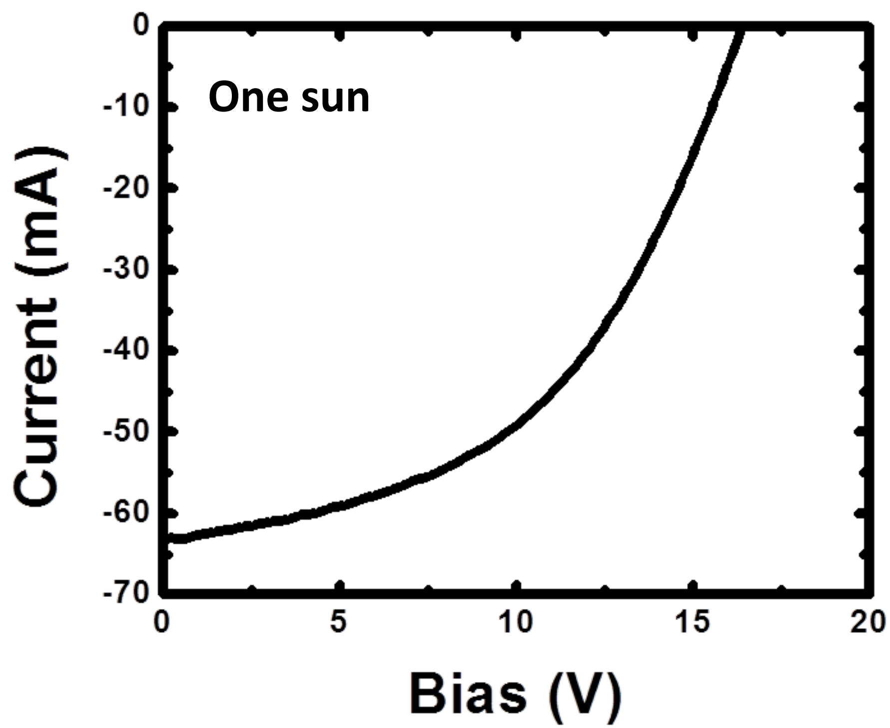
X. Xiao, et al., *Appl. Phys. Lett.*, **106**, 213301 (2015).

Tethered 10 x 10 OPV Module



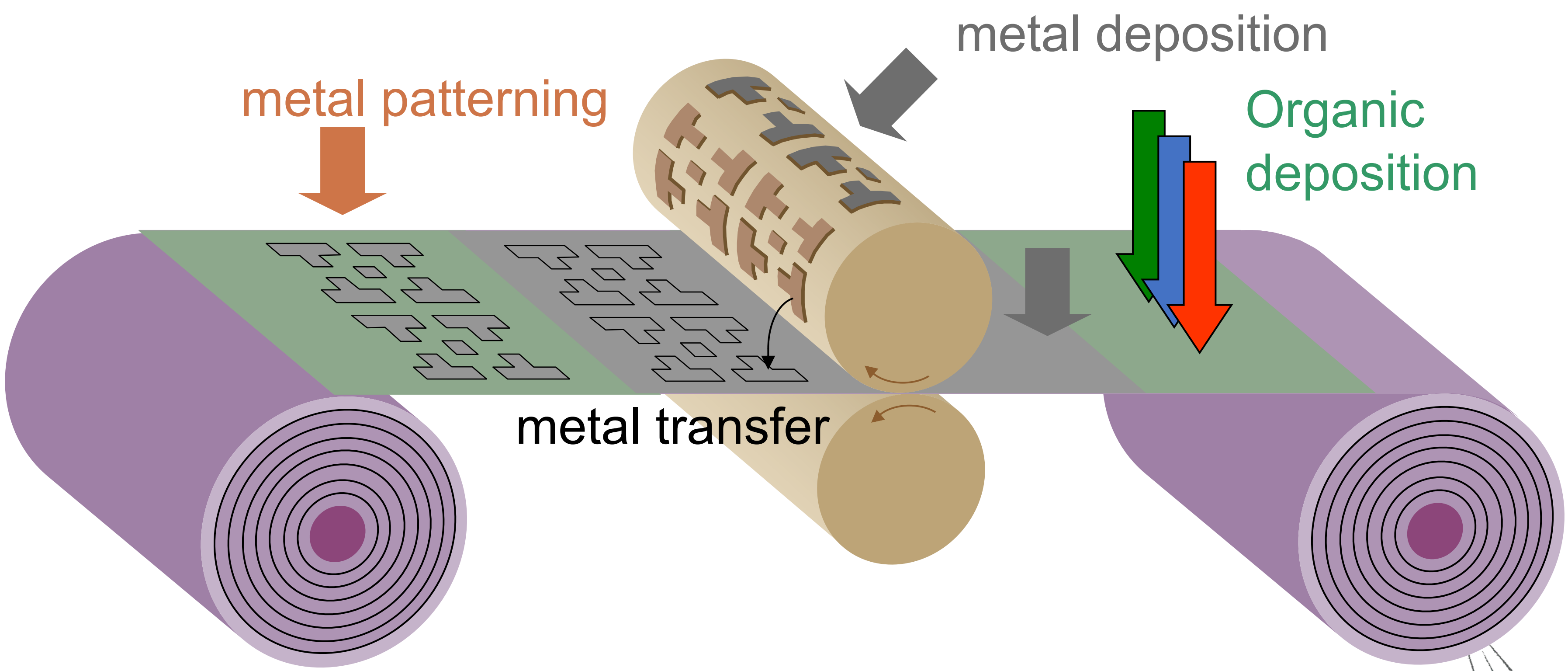




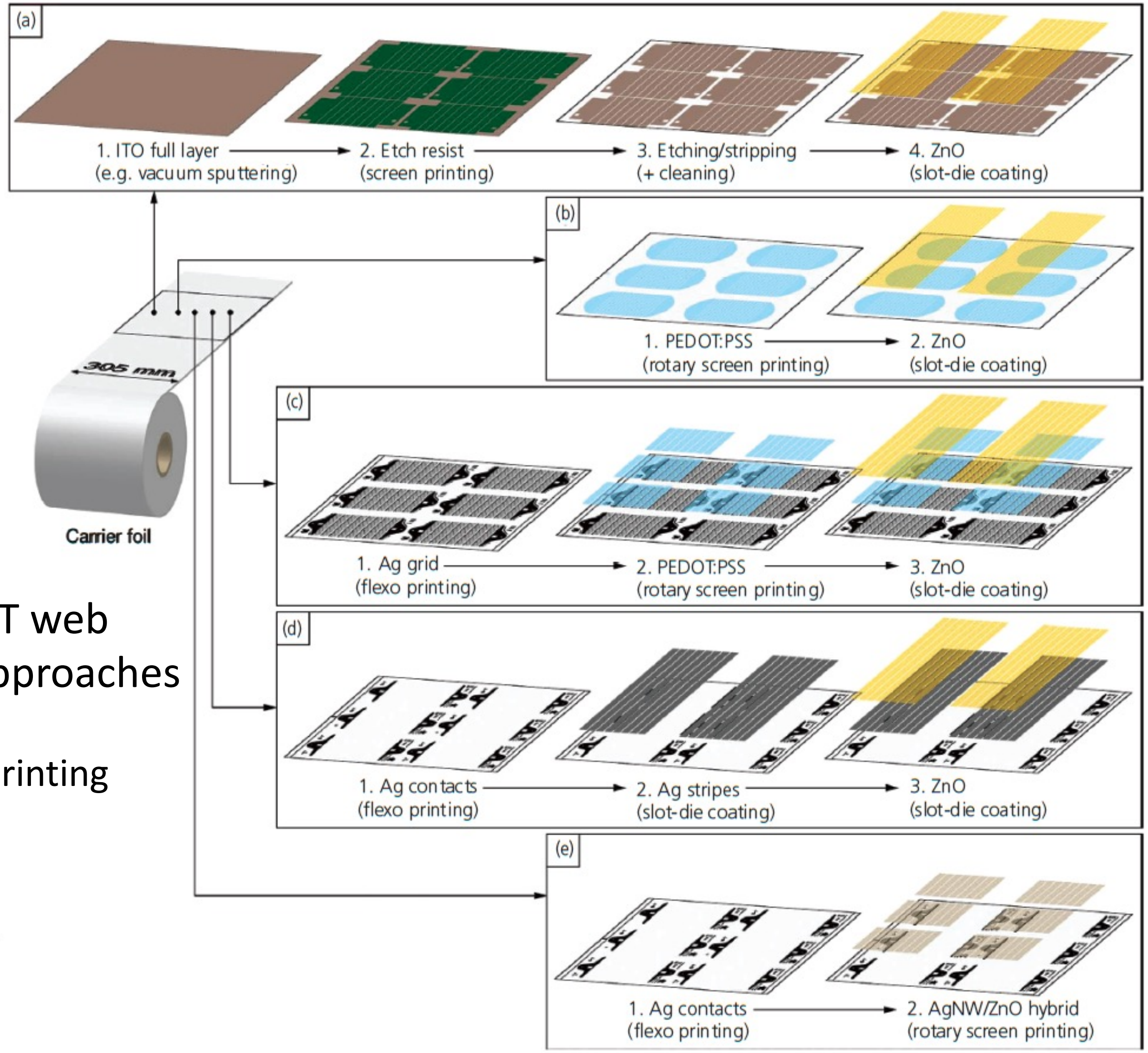
<u>Module</u>

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

Manufacturing of Solar Cells by R2R Methods



Printing Methods Used in R2R Solar Cell Production



305 mm wide PET web

Many possible approaches

- Slot-die coating
- Rotary screen printing
- Flexo printing
- Laser scribing (see Ch. 5)

Hösel et al. Adv. Sci. 1, 1400002 (2014)

What we learned

- Photoconductors, photodiodes, solar cells are three species of optical detectors
  - Detectors are fundamentally limited by a gain-bandwidth product
  - Solar cells are photodiodes operated in the 4^{th} j-V quadrant
- Photodiodes are designed for detection in narrow spectral ranges
  - OPDs have shown high bandwidth, color agility and low noise
- Solar cells have been intensively investigated due to their
  - High efficiency (now ~18% for single junction cells)
  - Transparency in the visible but >10% efficiency via absorption in the NIR
  - Efficiency is intimately linked to the morphology and chemistry of the D-A materials forming bulk HJ
  - Efficiency of OPVs paced by advances in acceptor molecules
- OPVs have demonstrated intrinsic lifetimes of thousands of years
- OPVs thermodynamically limited to <25% due to losses in forming CT states
  - The limit can be exceeded using multijunction cells, singlet fission
- Both solution and vapor deposited OPVs have been "manufactured" using high volume R2R deposition processes

Organic Thin Film Transistors

Thin Film Transistors 1

OTFT Basics
Operating Principles

Ch. 8.1 – 8.3.3

OTFT Objectives

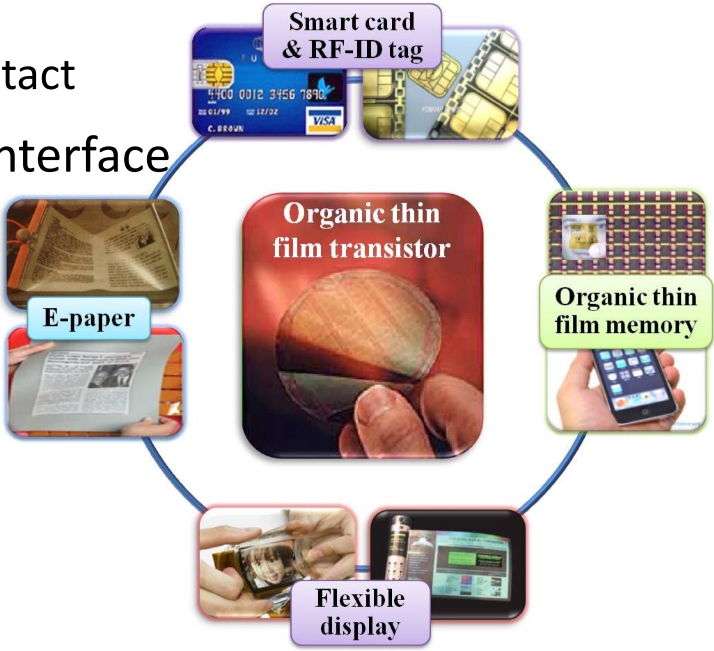
- Learn how they work
- Learn how they are made
- Learn about their operational reliability
- Learn what they are good for: Are they an answer waiting for a question?
    - Sensing
    - Medical applications

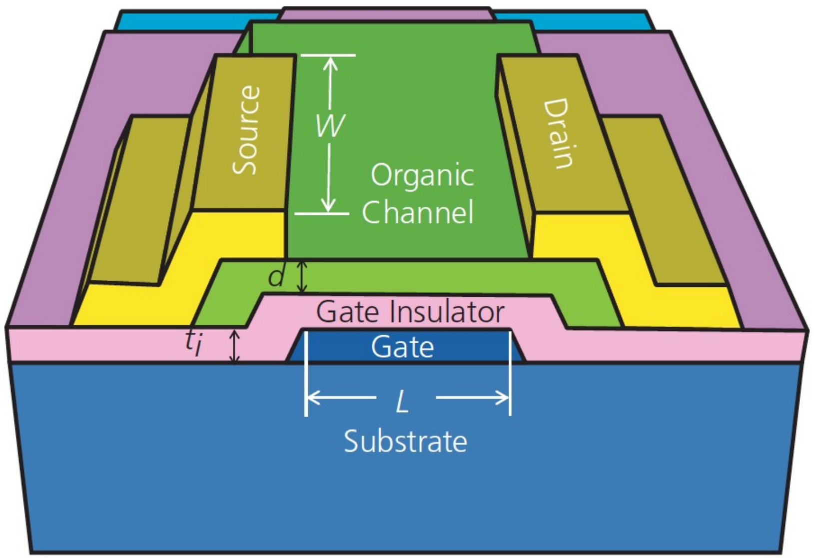
Advantages vs. Limitations of OTFTs

- 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 ($\leq$ 1 MHz in many cases)

What an OTFT looks like

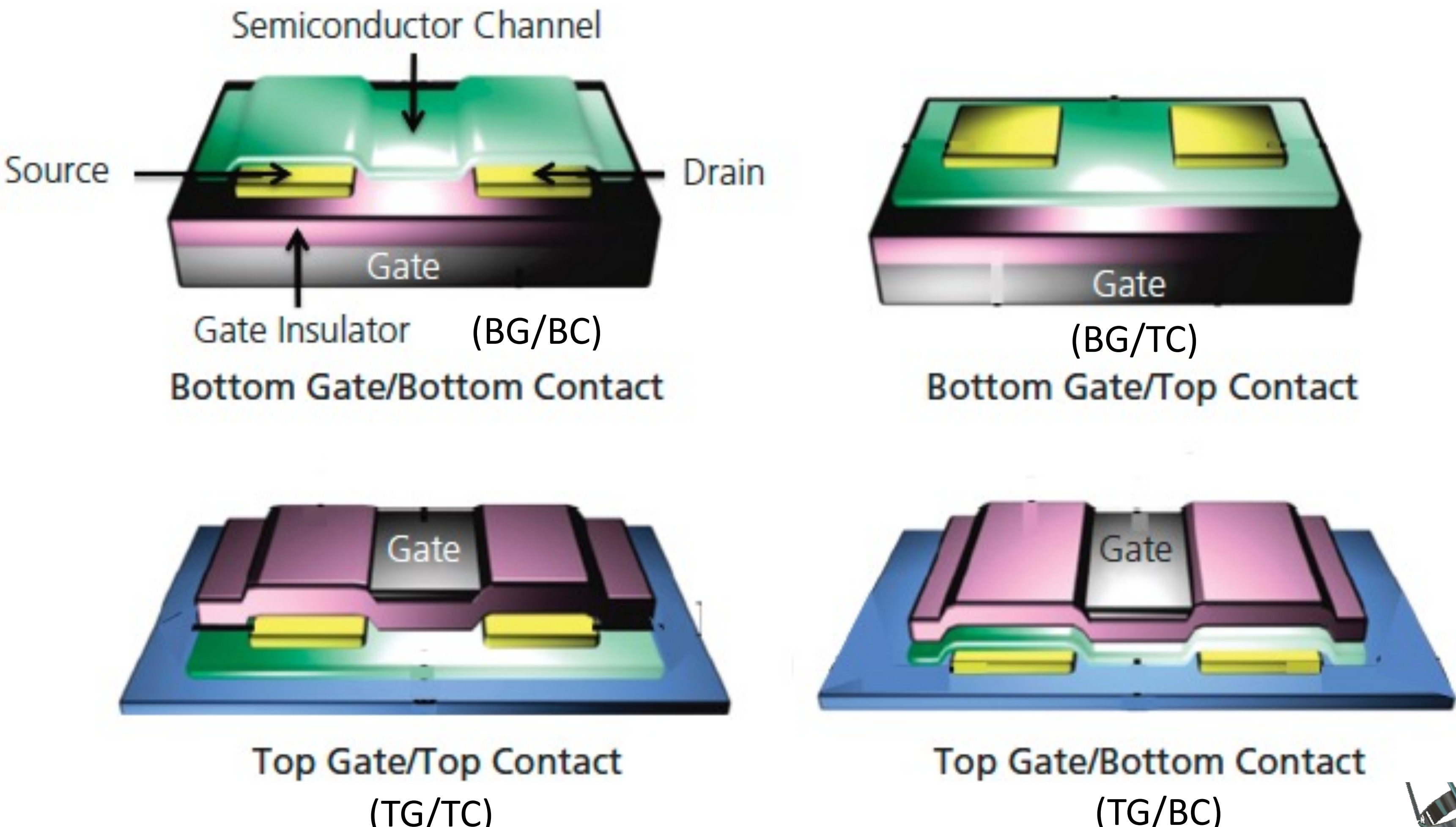
- Several different configurations
  - Bottom gate, top gate, bottom SD contact, top SD contact
- Properties strongly influenced by dielectric/organic interface
- Configuration similar to inorganic TFTs
  - Metal oxide
  - a-Si
  - Etc.





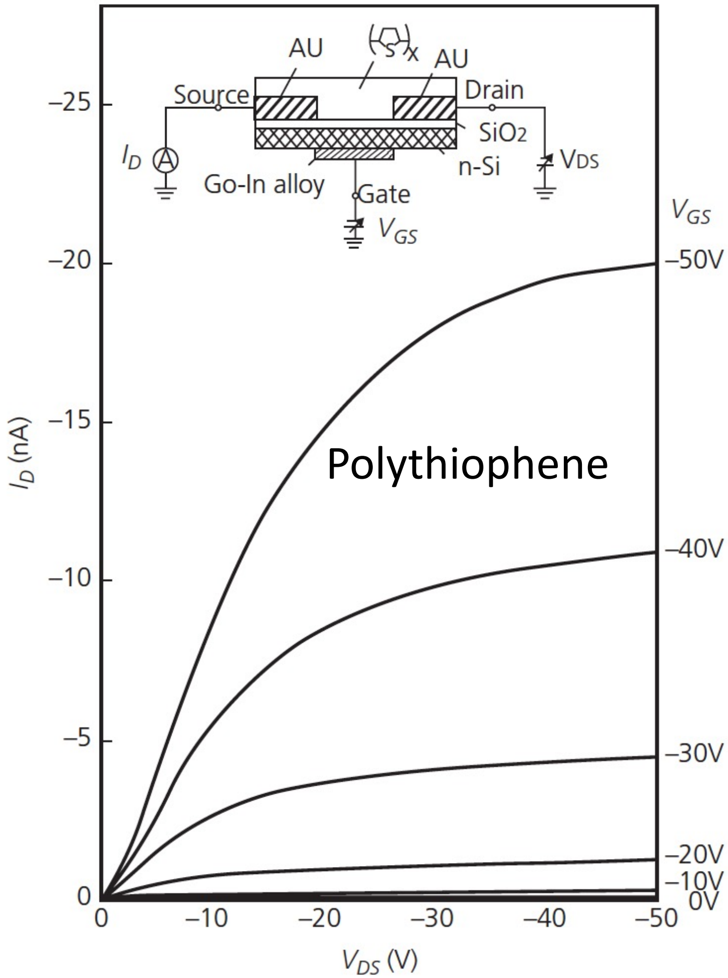
Definitions of Contacts and Dimensions

Different Contact Arrangements

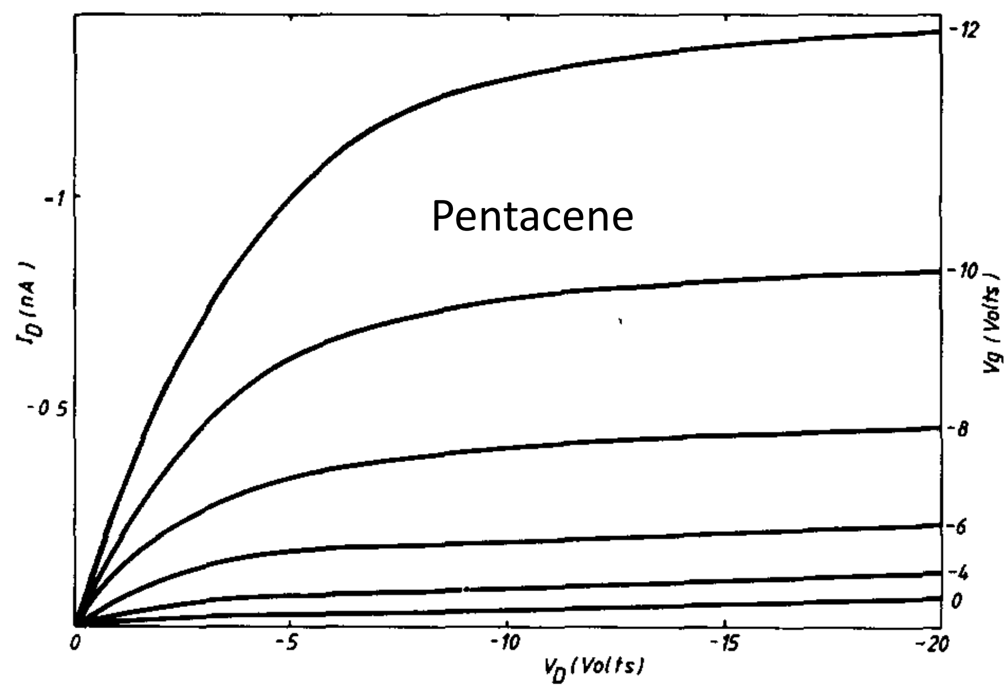


Organic Thin Film Transistors

First demonstrations



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



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

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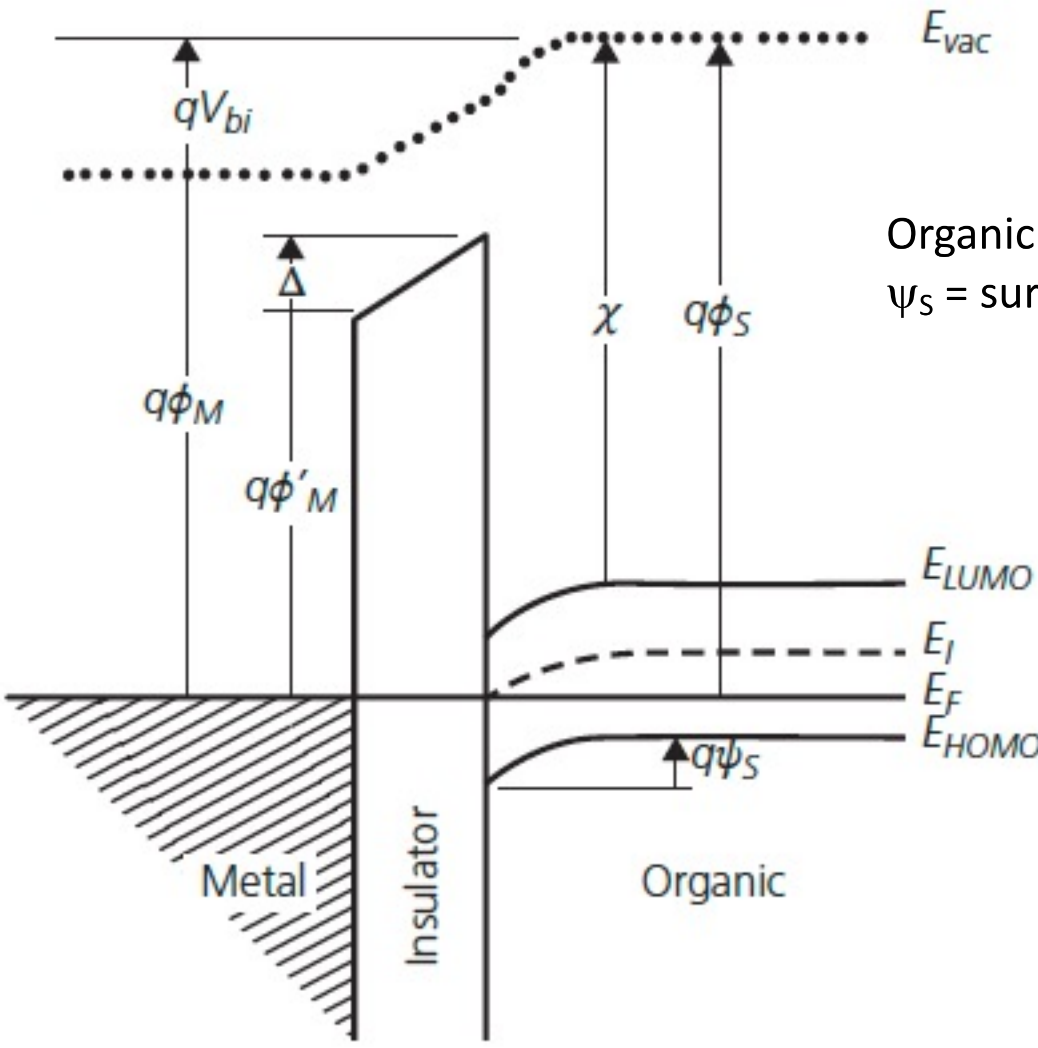
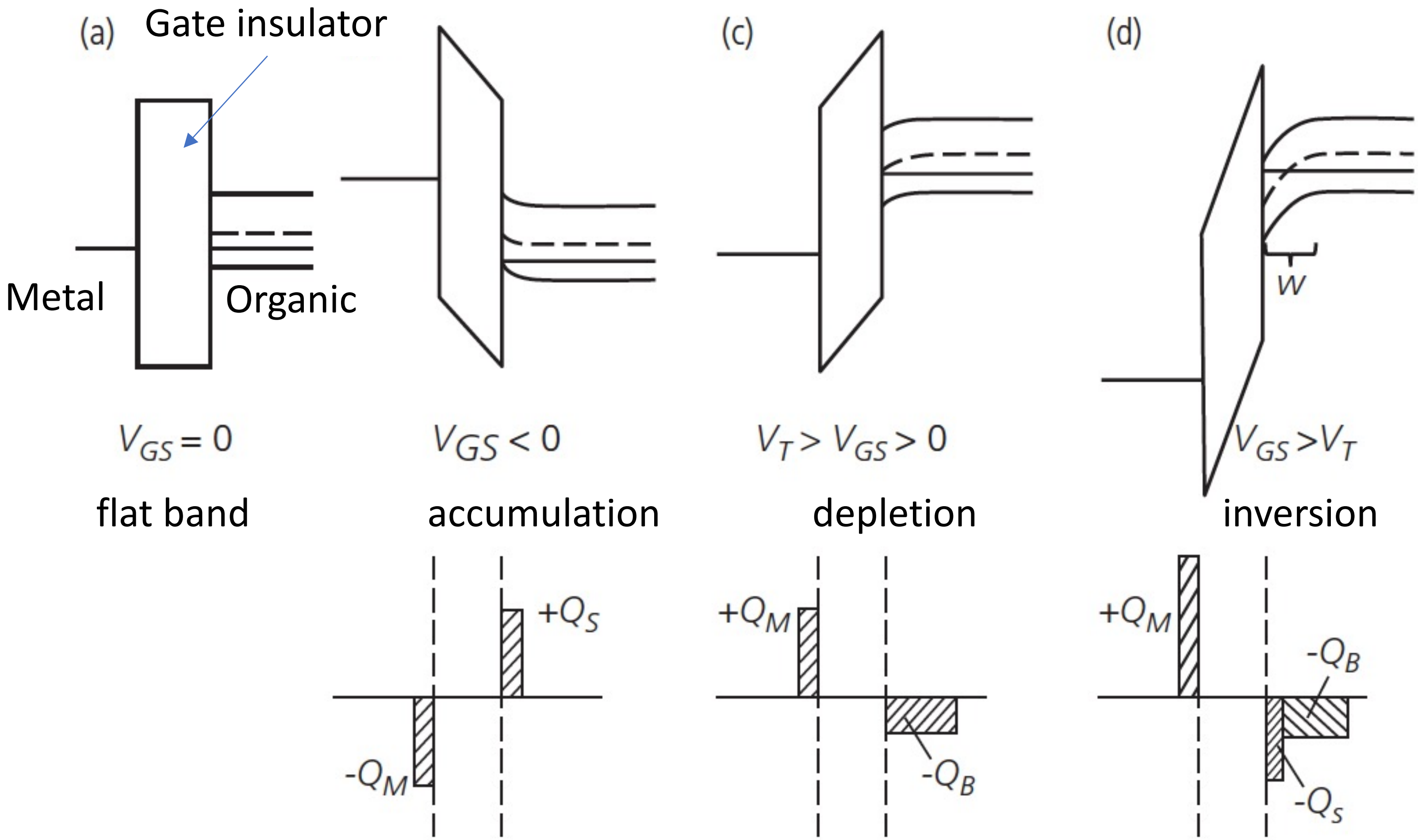
Equilibrium Energy Level Diagram at the Gate of the OTFT



Organic bulk slightly p-type

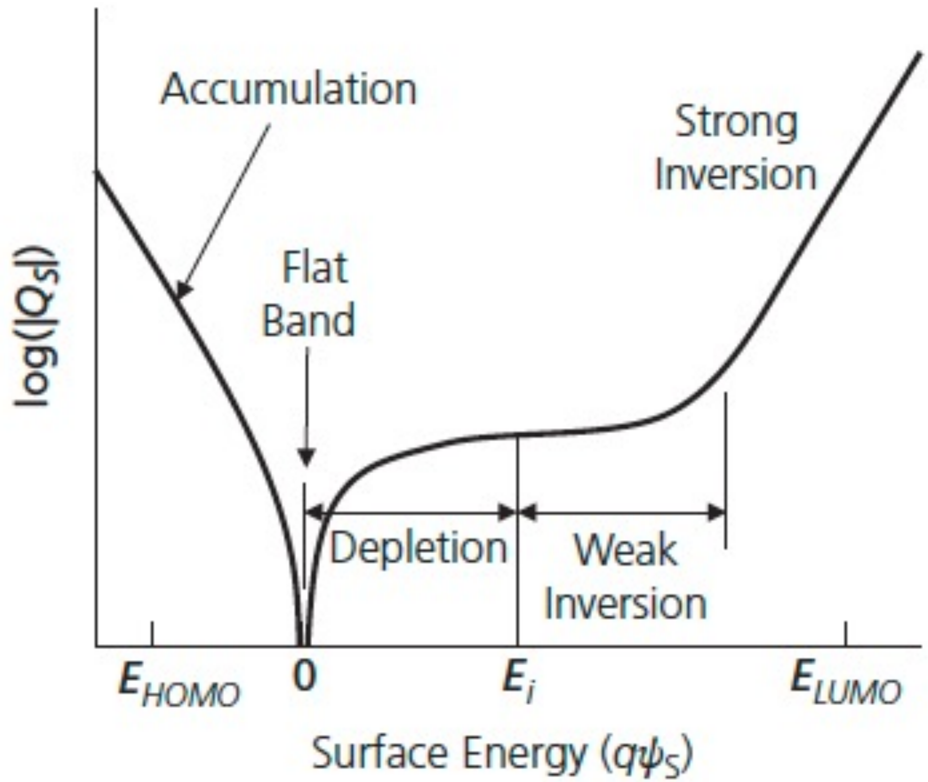
ψ_S = surface potential

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

Operating Regions of the Transistor



- Since charge is injected from the source, and the channel organic is rarely doped,
- the OTFT operates in the **accumulation regime**
- The **inversion regime** is rarely relevant in OTFTs for these reasons
- The transistor channel is normally depleted at $V_{GS} = 0$, and hence the transistors are **enhancement mode** devices

How an OTFT Works: Accumulation

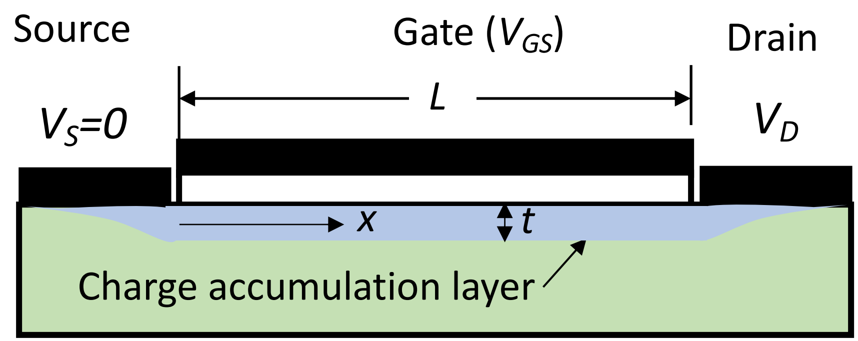
Charge injected from the source by a gate voltage, V_{GS}, at very low drain voltage, V_D, and hence low channel current (i.e. ohmic):

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

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:

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

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

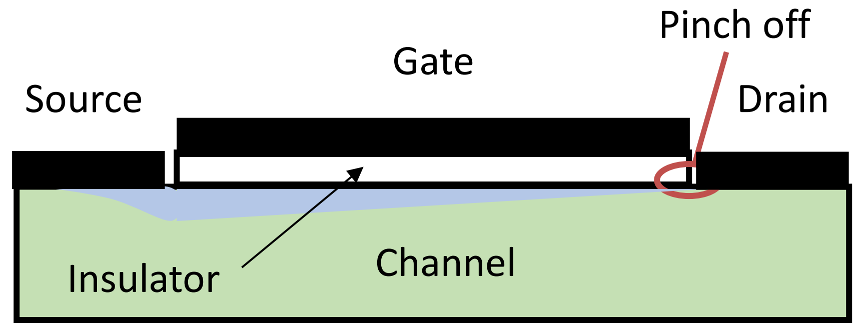
Or, in the linear regime of operation:

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

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

$\mu = \mu_{FE}$

In the Saturation Region

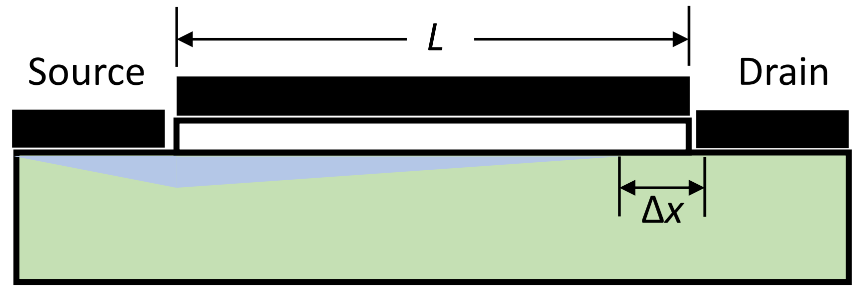


In the linear regime ($V_G - V_T >> V_D$), we calculate the transconductance:

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

And the output conductance:

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



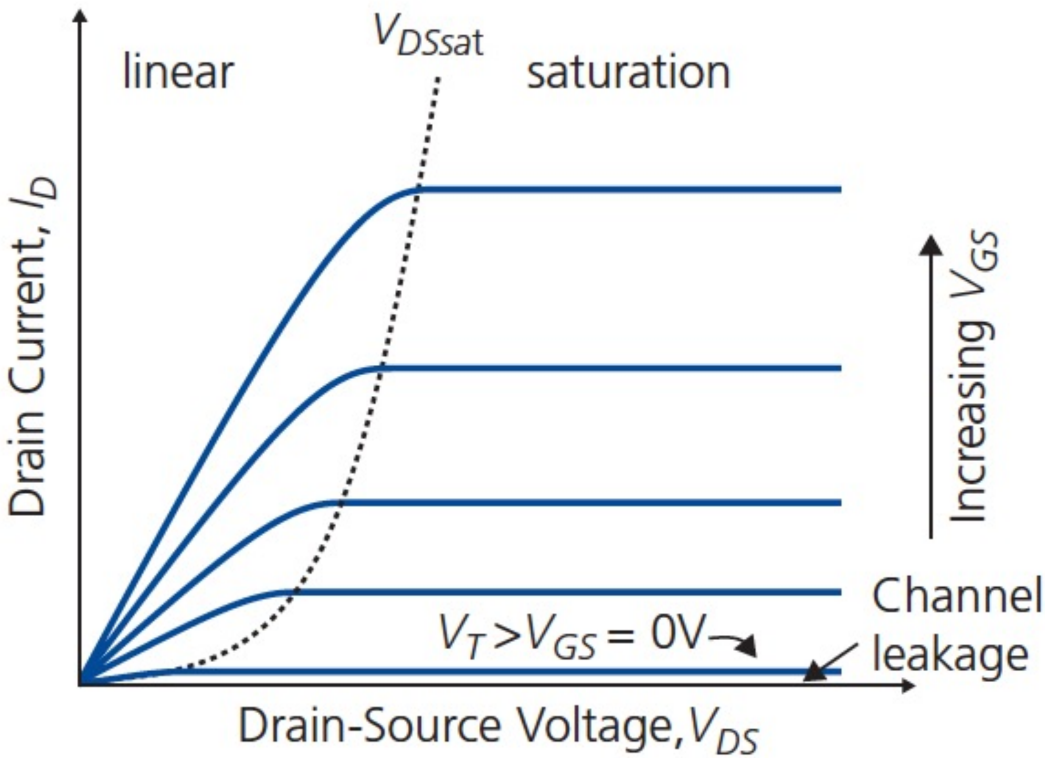
Due to contact and other parasitic resistances, μ_{lin} gives errors, so mostly use <u>saturation characteristics</u>:

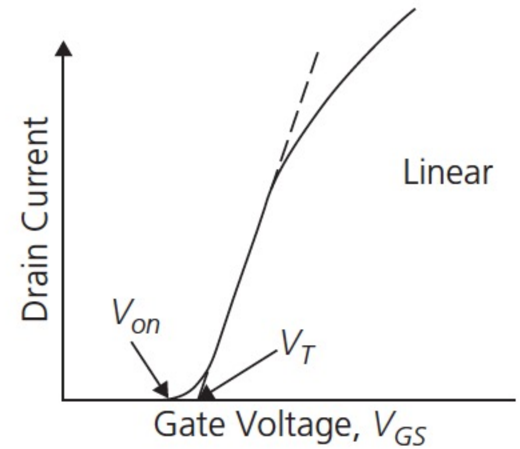
- When $V_D = V_G - V_T$, the channel **pinches off**
- Between pinchoff point and drain, $n \to 0 \Rightarrow F \to$ large to maintain current continuity ($j = nq\mu F$)
- No more current (except leakage) enters channel with increasing V_D, hence we are in the <u>saturation regime</u>.

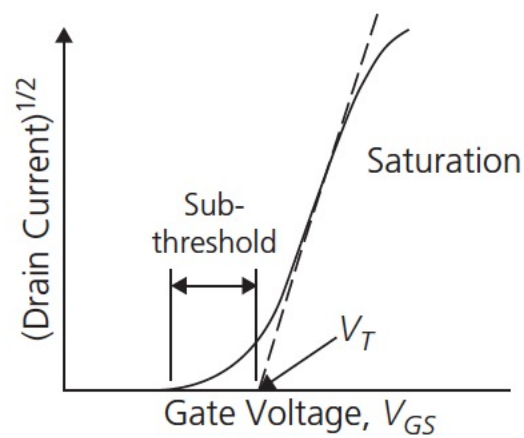
Then: $$I_D == \frac{W}{2L} C_G \mu_{sat} \left(V_G - V_T\right)^2$$

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

Ideal Unipolar OTFT Characteristics







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

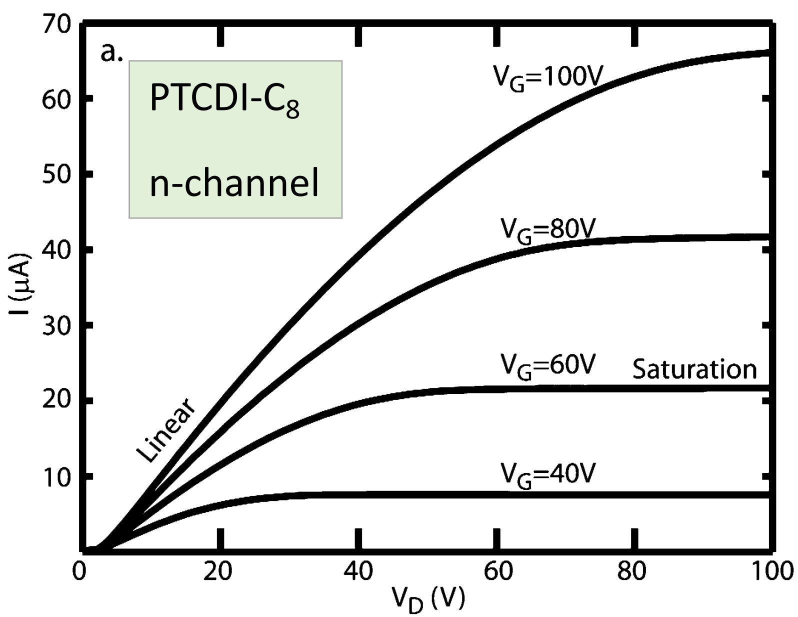
$$g_m = \left.\frac{\partial I_D}{\partial V_G}\right|_{V_D} = \frac{W}{L} C_G \mu_{lin} V_D$$

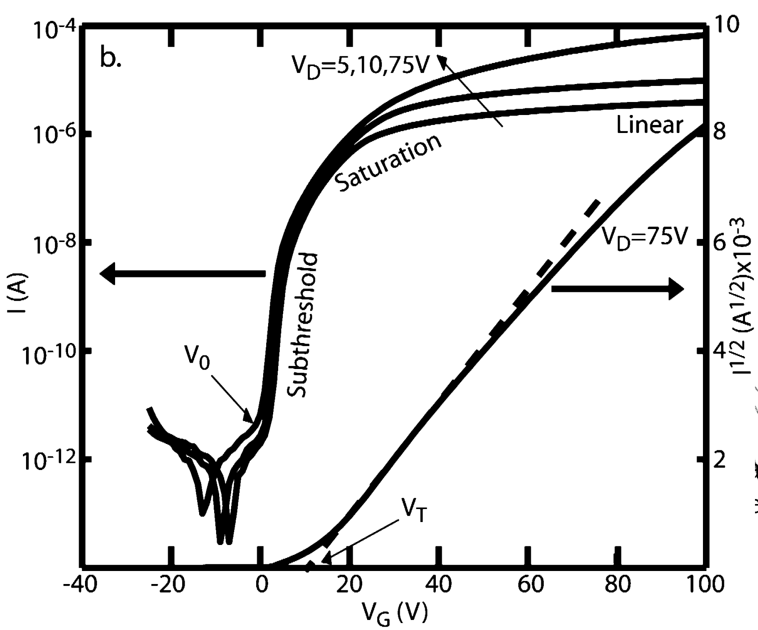
$$I_D == \frac{W}{2L} C_G \mu_{sat} \left(V_G - V_T\right)^2$$

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

DC Characteristics of an OTFT

- Pentacene most frequently employed small molecule for OTFT
- $\mu_{FE} \sim 1 - 1.5\ cm^2/V\text{-}s$
- DC mobility as high as 40 $cm^2/V\text{-}s$ 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.





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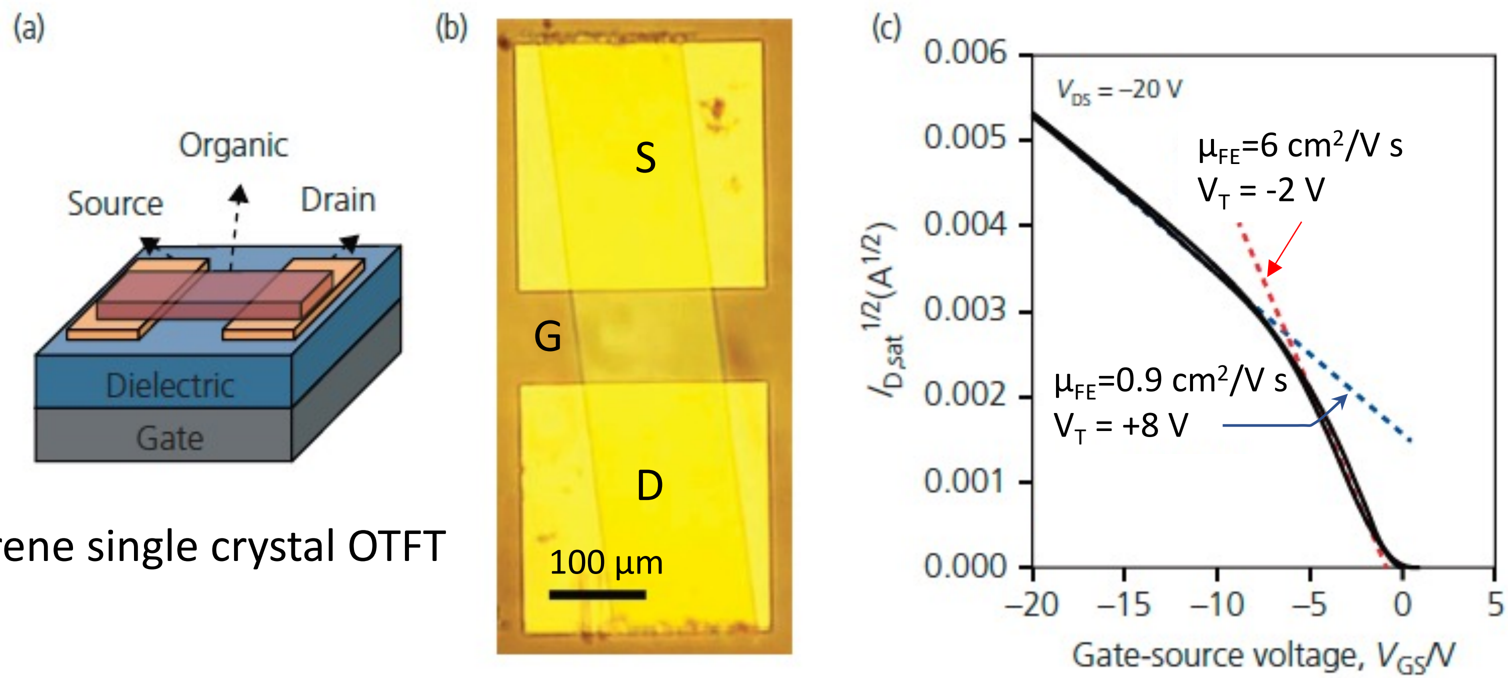
Equating Field Effect With Bulk Mobilities

- What could go wrong?

Two μ_{FE} and V_T extracted from I_D-V_{GS} characteristics: Which is right?
⇒OTFT does not follow conventional theory due to exponential distribution of states near conduction level edge



rubrene single crystal OTFT

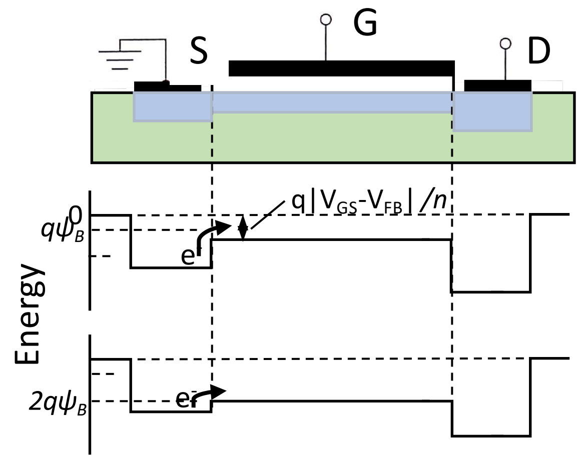
Bittle et al., Nat. Commun. 7, 10908 (2016)

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

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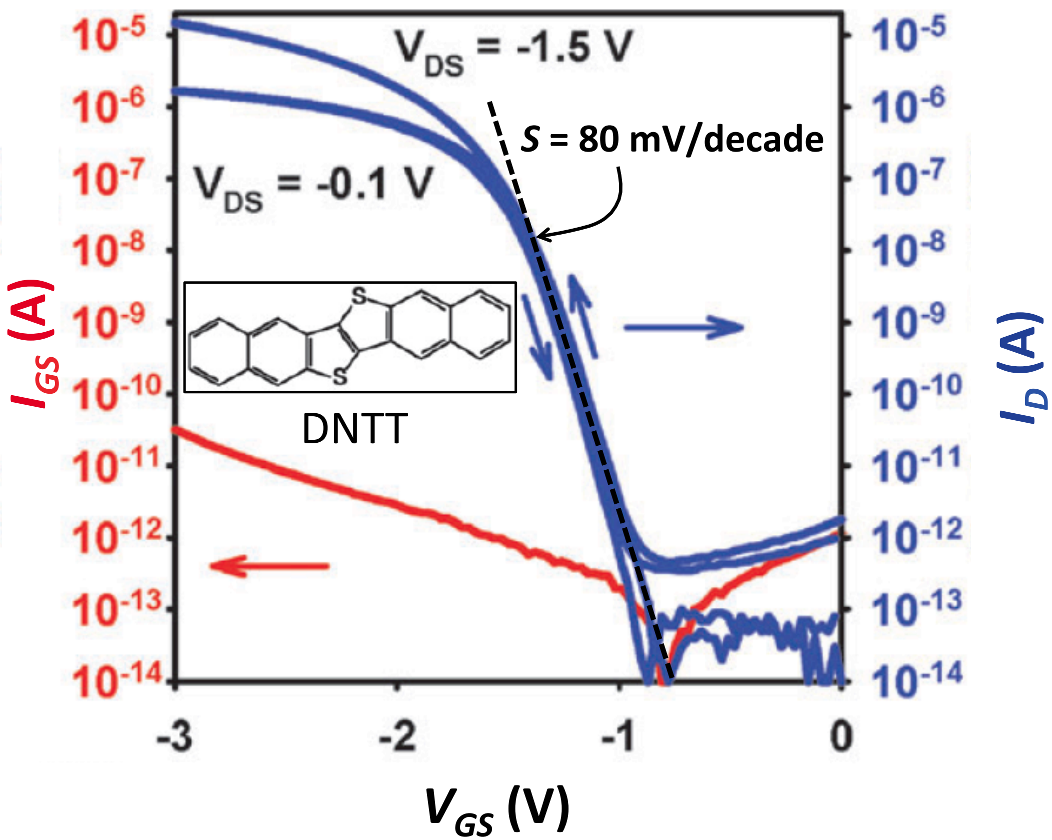
A high performance OTFT

BG/TC

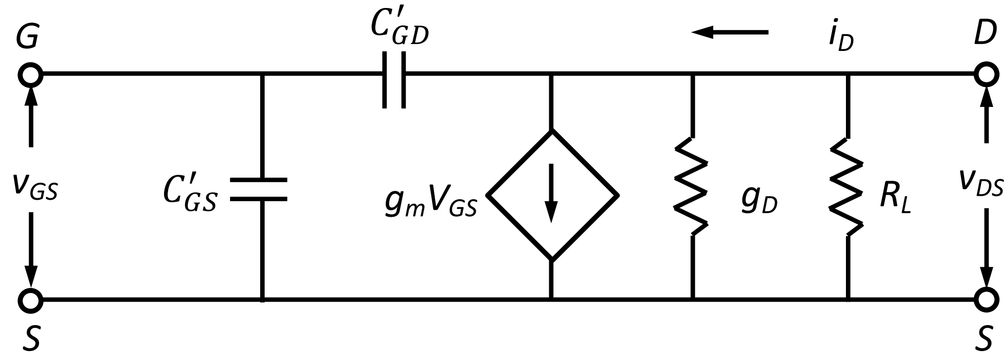


- *p* or *n* channel?
- L/W = 10 µm/100 µm
- Al gate
- AlO_x gate insulator, 3.6 nm thick, PVD grown coated with alkylphosphonic acid SAM

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

OTFT Bandwidth

Small signal equivalent circuit



C_{GS}'=total gate-source capacitance (including parasitics)
C_{GD}'=total gate-drain capacitance
R_L = external load resistance

Small signal input (gate) current: $i_{GS} = WLC_G \left.\frac{\partial v_{GS}}{\partial t}\right|_{V_{DS}} = j\omega\left(WLC_G\right)v_{GS} = j2\pi f\left(WLC_G\right)v_{GS}$

Small signal output (drain) current: $i_D = g_D v_{DS} + g_m v_{GS} \Rightarrow i_D \simeq g_m v_{GS}$ since $g_D \to 0$

The maximum transistor bandwidth is reached when the current gain $\left|\frac{i_D}{i_G}\right| = 1$

Miller Capacitance and Gain

The capacitance is equal to the input (C_{GS}) in parallel with the output capacitance (C_{GD}) "amplified" by the circuit gain, A_v, that is:

$$C_G = C_{GS} + C_{GD}\left(1 + A_v\right)$$

where $$A_v = \frac{\partial v_{DS}}{\partial v_{GS}} = \frac{\partial v_{DS}}{\partial i_D}\frac{\partial i_D}{\partial v_{GS}} = \left(R_L \,||\, \frac{1}{g_D'}\right) g_m$$

$$C_M = C_{GD}\left(1 + A_v\right)$$

This amplified output capacitance is called the "Miller capacitance" or the "Miller effect"

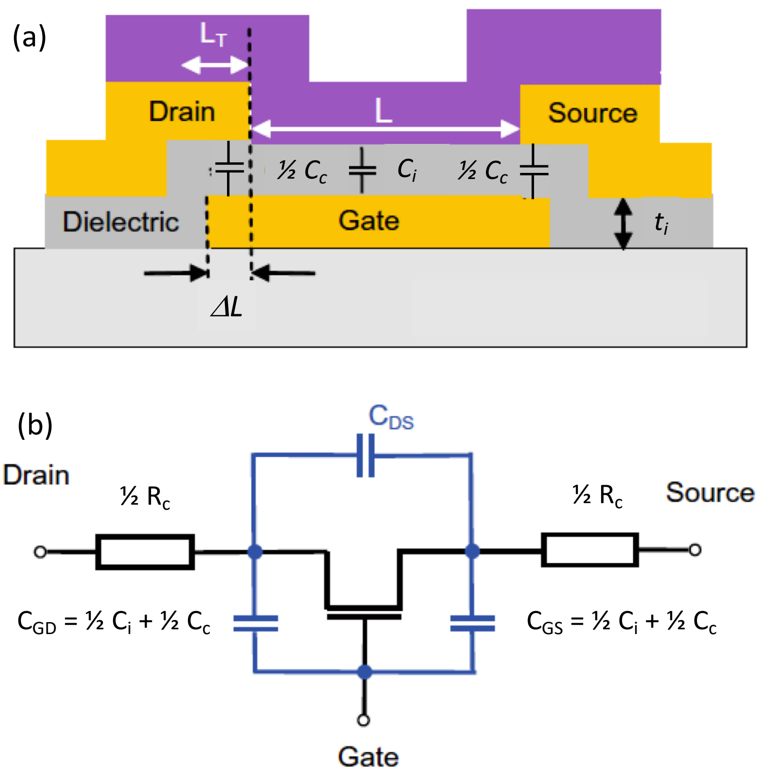
But the output conductance is small: $R_L \,||\, \dfrac{1}{g_D'} \rightarrow R_L$

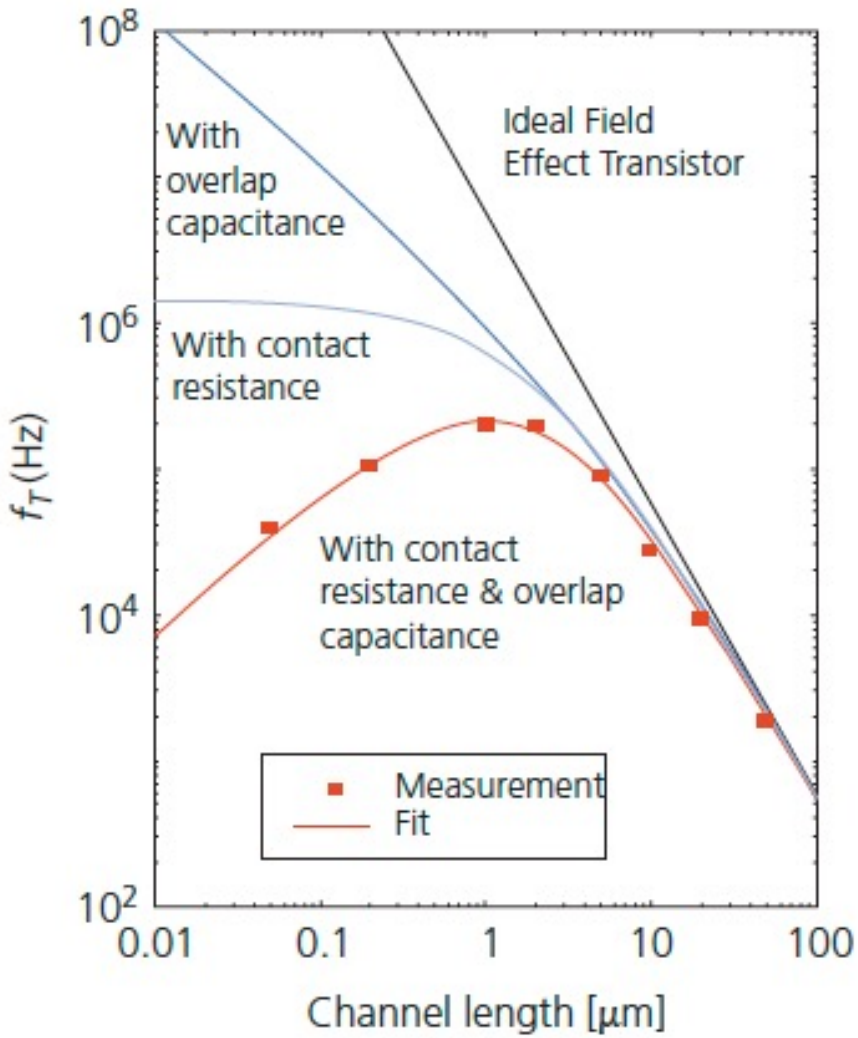
From these expressions, we get the cutoff, or transfer frequency:

$$f_T = \frac{g_m}{2\pi WLC_G} = \frac{g_m}{2\pi WL\left(C_{GS} + C_M\right)}$$

Capacitance and Frequency Response

Sources of parasitic capacitances





Hoppe et al. Org. Electron. 11, 626 (2010)

Combining Effects of Resistance and Capacitance

The transconductance and output conductances are reduced by drain and source contact resistances

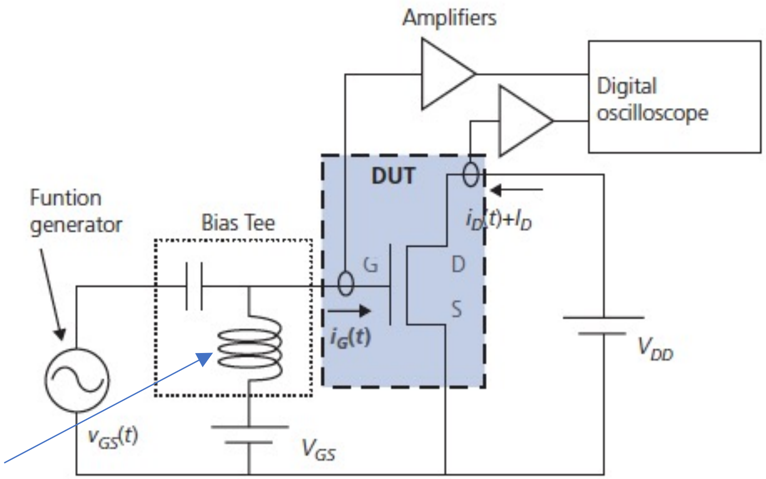
$$g'_m = \frac{g_m}{1 + r_S g_m} \qquad g'_D = \frac{g_D}{1 + \left(r_S + r_D\right) g_D}$$

As is the frequency response frequency response

$$f_T = \frac{\mu_{FE0}\left(V_{GS} - V_T\right)}{2\pi L\left(L + \Delta L\right)}\left[\frac{1}{1 + W\mu_{FE0} C_G \left(V_{GS} - V_T\right) R_C / L}\right]$$

Where the total contact resistance is the series contributions from S and D: $R_C = r_S + r_D$

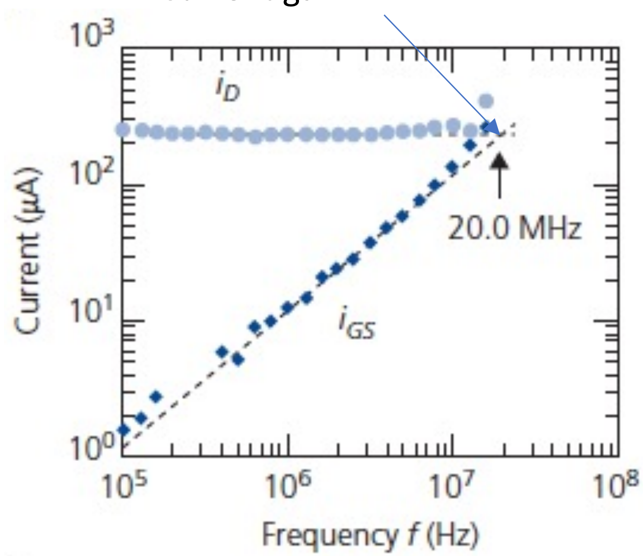
High Bandwidth OTFTs



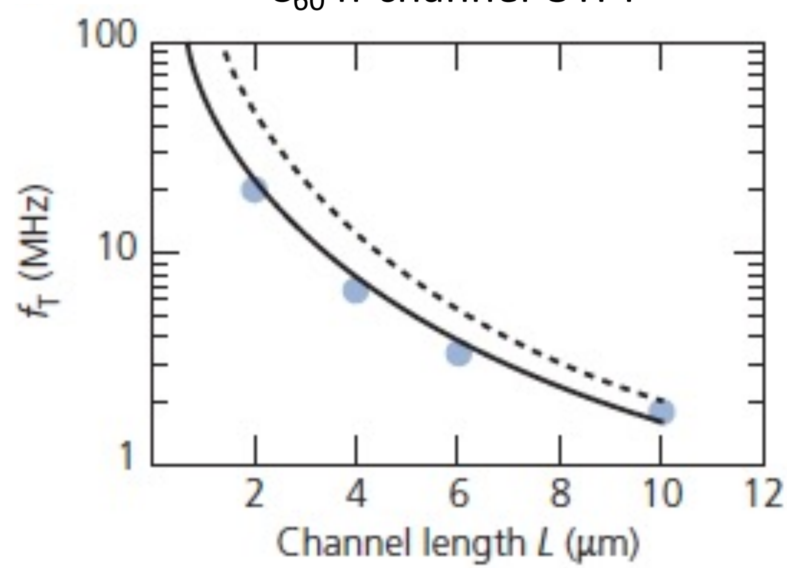
Choke prevents ac short to ground

Frequency test circuit

Current gain = 1



C_{60} n-channel OTFT



Kitamura & Arakawa 2009. *Appl. Phys. Lett.,* 95**,** 023503.