Week 14

Thin Film Transistors 2

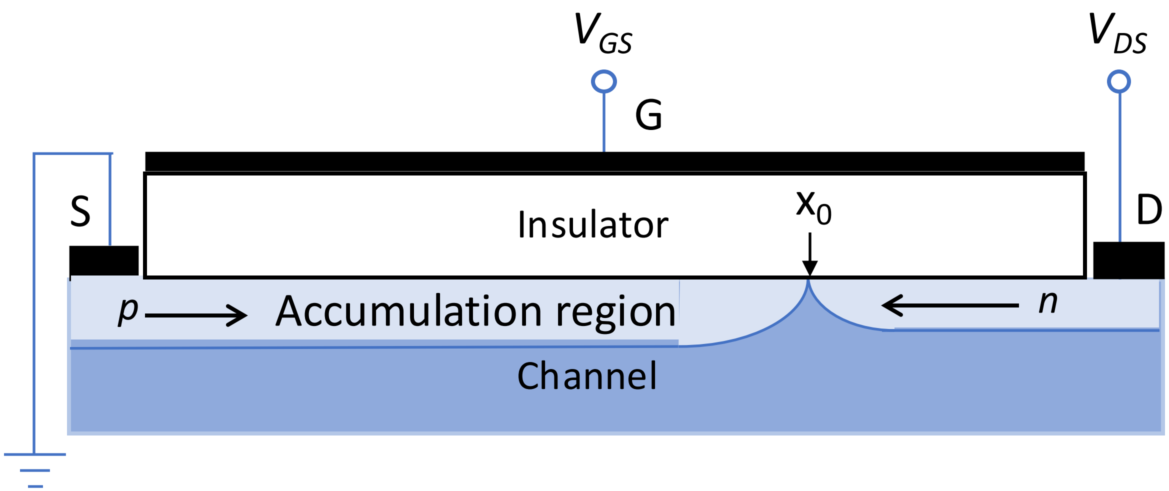
Ambipolar and Other Transistor Architectures
Materials & Morphology
Reliability
Applications

Chapter 9.2, 9.4 - 9.8

Concepts in Organic Electronics
Stephen R. Forrest

Ambipolar OTFTs

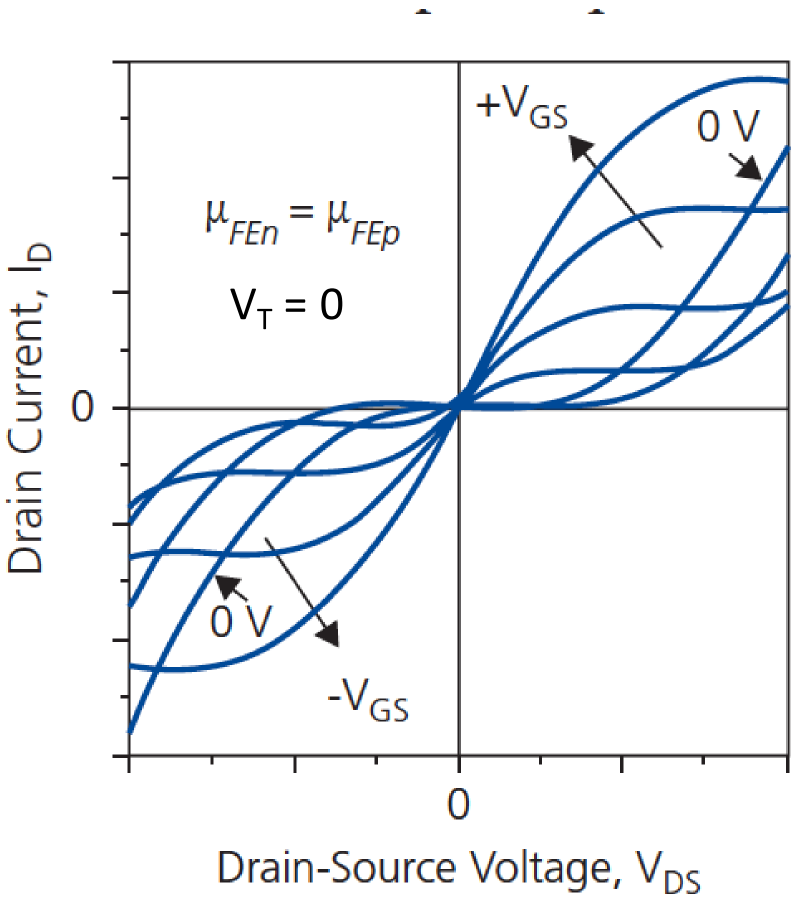
- Channel capable of supporting both electron and hole transport
- Advantage: Complementary logic possible with a single structure



Strategies for achieving bipolar action:

- Use material with both high μ_{FEn} and μ_{FEp} with contacts in the middle of the energy gap (i.e. use ambipolar conducting organics)
- Use a bilayer, one with higher electron vs. hole mobility and vice versa
- Use a blend of electron and hole transporting materials

Ambipolar transfer characteristics



Example: $V_{Tp} < V_{Tn}$

Linear regime

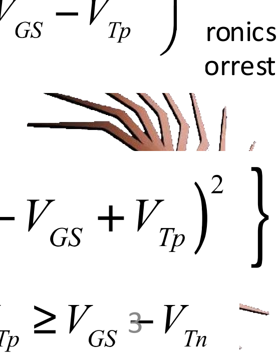
$$I_D = \frac{WC_i}{L}\mu_{FEn}\left(V_{GS} - V_{Tn} - \frac{V_{DS}}{2}\right)V_{DS}$$

$$\begin{pmatrix} 0 \le V_{DS} \le V_{DSsat} \\ V_{GS} > V_{Tn} \end{pmatrix}$$

Saturation regime

$$I_D = \frac{WC_i}{2L}\mu_{FEn}\left(V_{GS} - V_{Tn}\right)^2$$

$$\begin{pmatrix} V_{DS} \ge V_{GS} - V_{Tn} \\ V_{DS} \le V_{GS} - V_{Tp} \end{pmatrix}$$

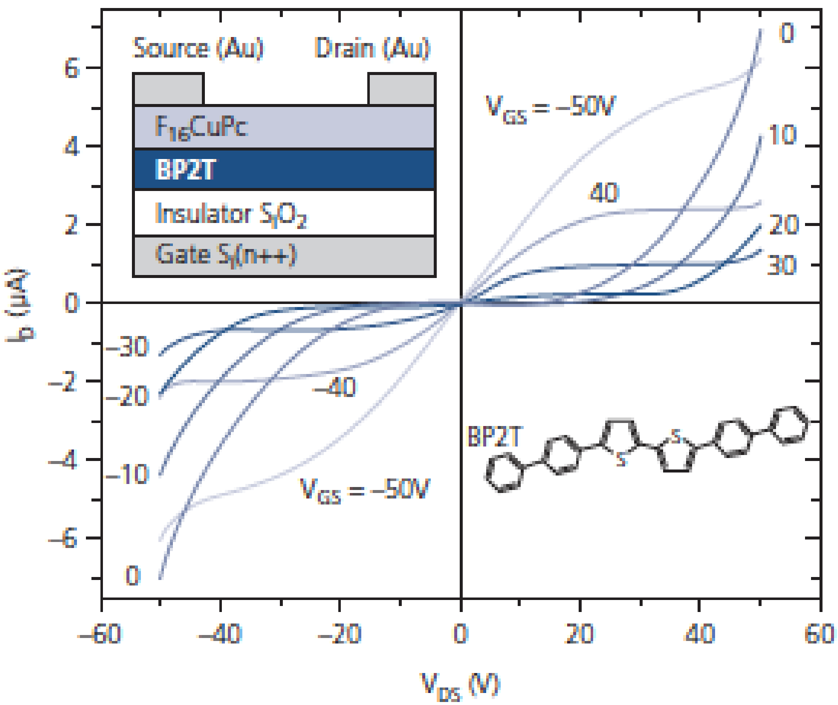


Ambipolar (quadratic) regime

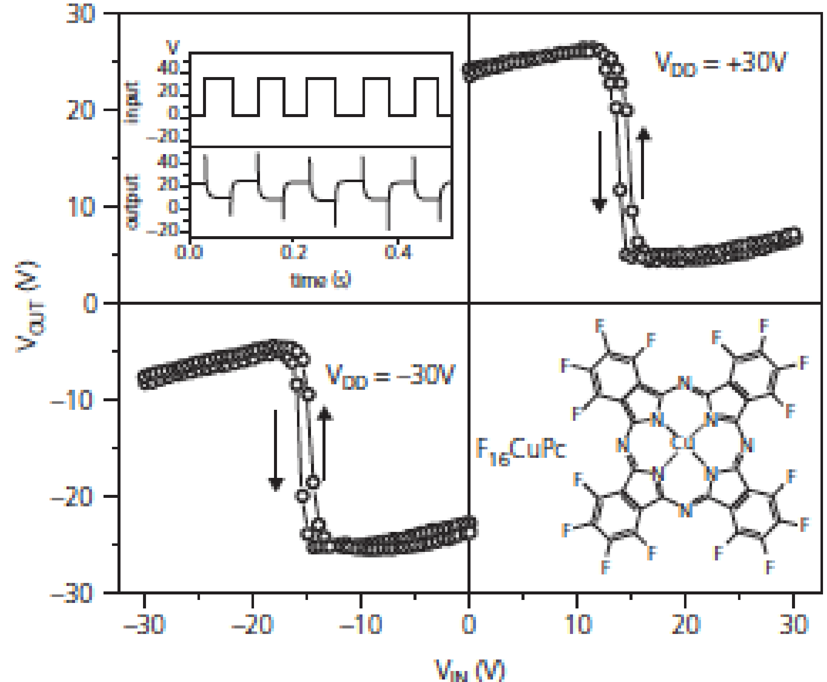
$$I_D = \frac{WC_i}{2L}\left\{\mu_{FEn}\left(V_{GS} - V_{Tn}\right)^2 + \mu_{FEp}\left(V_{DS} - V_{GS} + V_{Tp}\right)^2\right\}$$

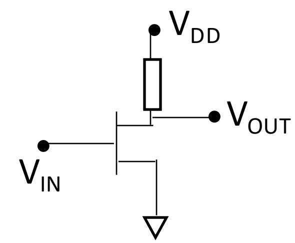
$$V_{DS} \ge V_{GS} - V_{Tp} \ge V_{GS} - V_{Tn}$$

Bilayer ambipolar OTFT



Common source amplifier response





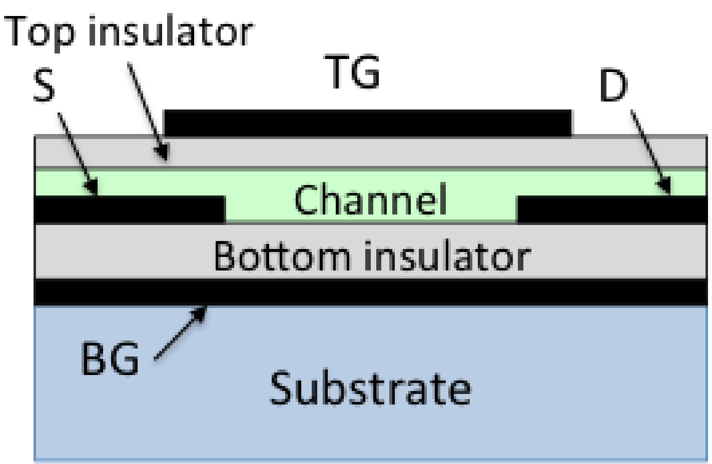
Concepts in Organic Electronics
Stephen R. Forrest

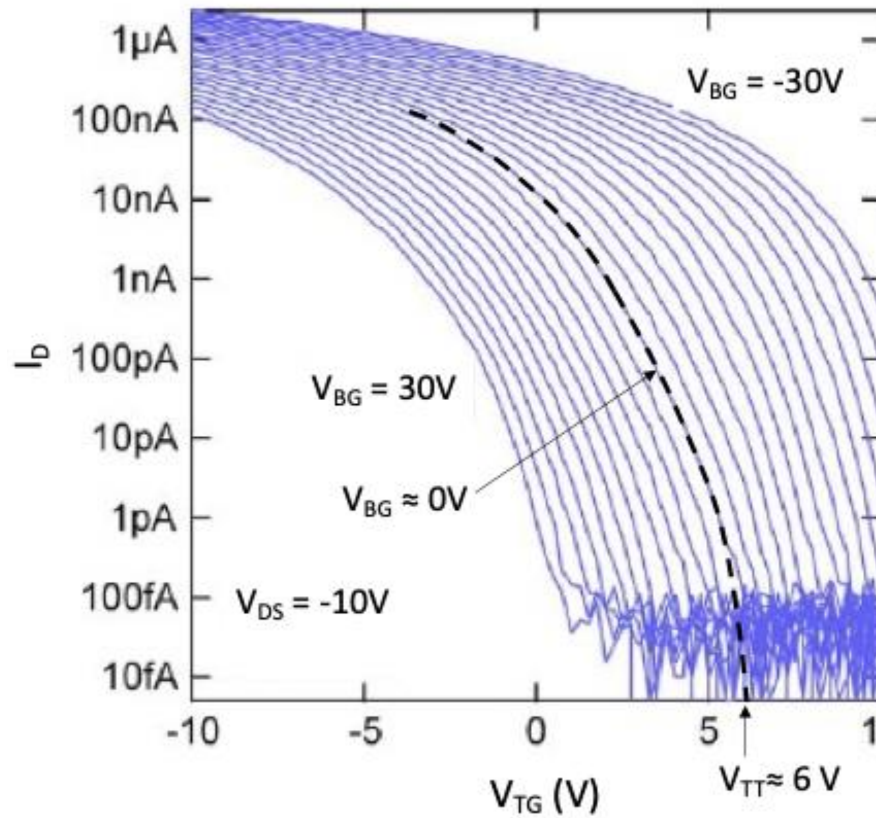
Disadvantage of the ambipolar OTFT: I_{on}/I_{off} is small since no condition where one carrier type is completely absent.

Wang et al., Appl. Phys. Lett. **88**, 133508 (2006)

Dual gate transistors

- Useful for adjusting V_T due to extra bias control of the second (bottom) gate
- In conventional CMOS technology, this is the "body potential"
- Important for controlling large ICs



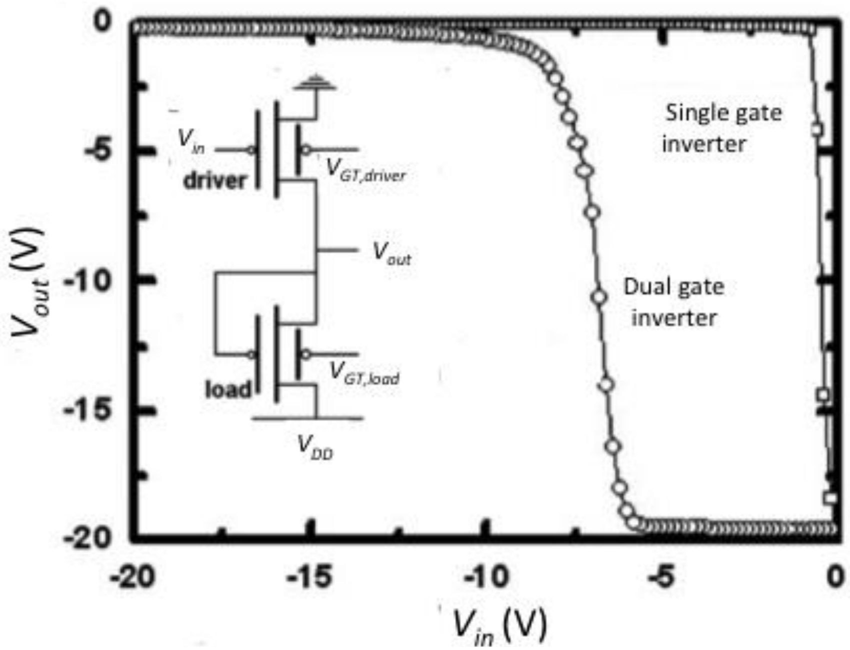


Shift in top gate threshold related to bottom gate voltage:

$$\Delta V_{TT} = \frac{C_B}{C_T} V_{GB}$$

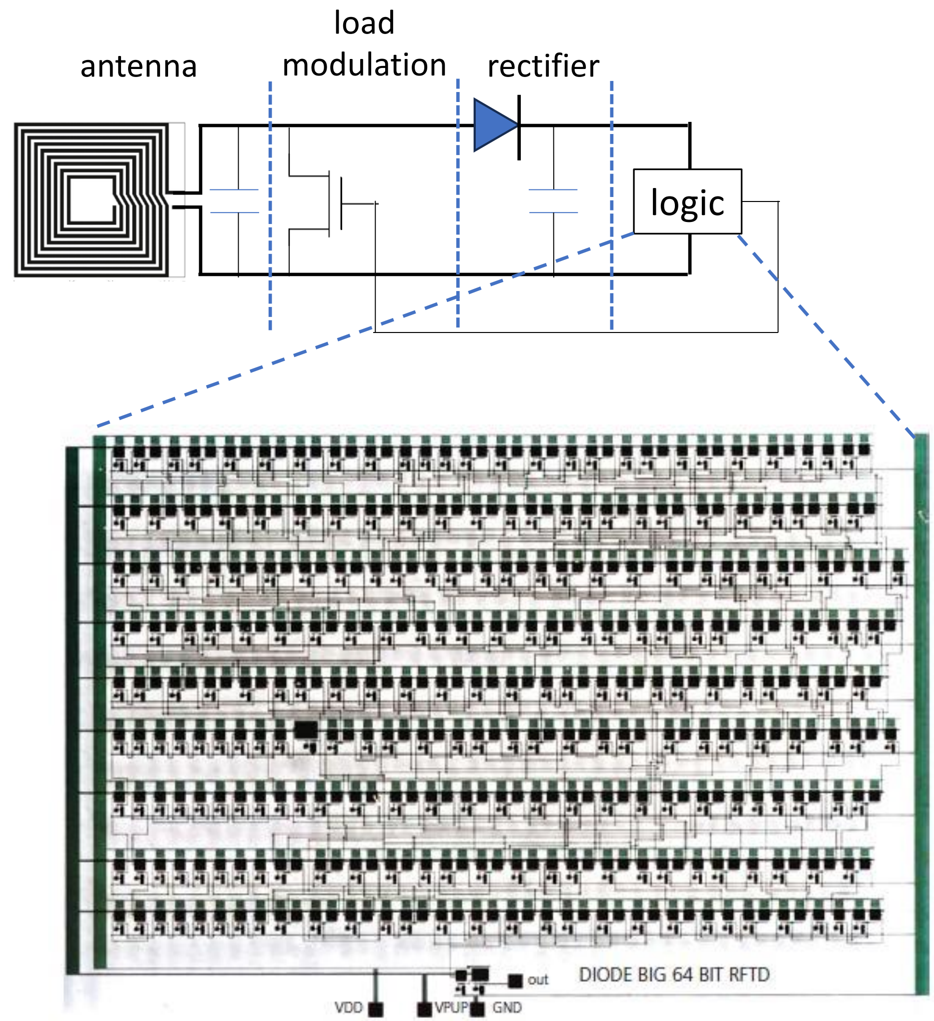
K. Myny. et al. (2011) *IEEE J. Solid-State Circuits,* 46**,** 1223-1230.

Dual gate control in an RFID transponder



Improved noise margin
Control of circuit gain

Spijkman et al. Appl. Phys. Lett., **92** 143304 (2008)

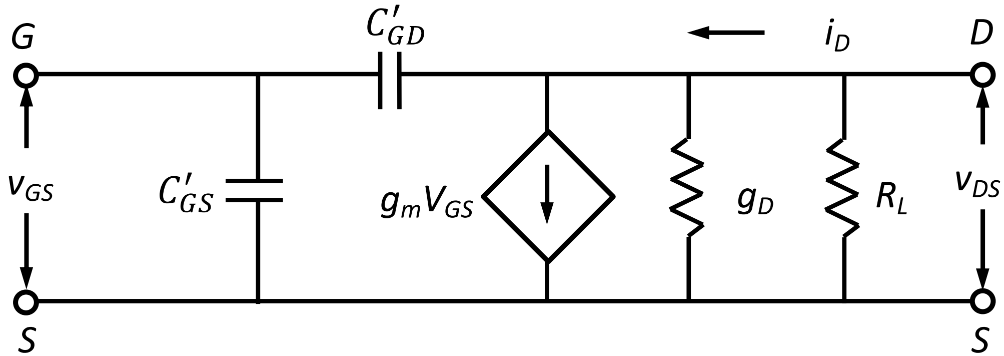


Photograph of a 64-bit RFID transponder operating at 4.3 kb/s using dual gate inverter logic.

Myny et al. IEEE J. Sol. State Circuits, **46**, 1223 (2011)

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: $i_D \simeq g_m v_{GS}$

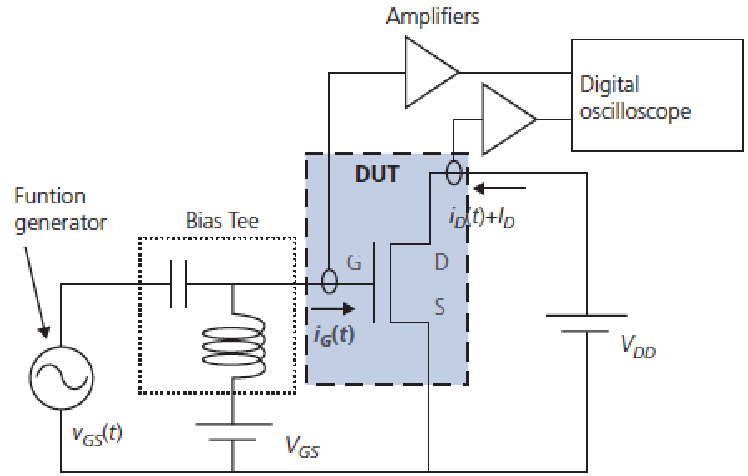
The maximum transistor bandwidth is reached when the current gain $\left|\frac{i_D}{i_G}\right| = 1$

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

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

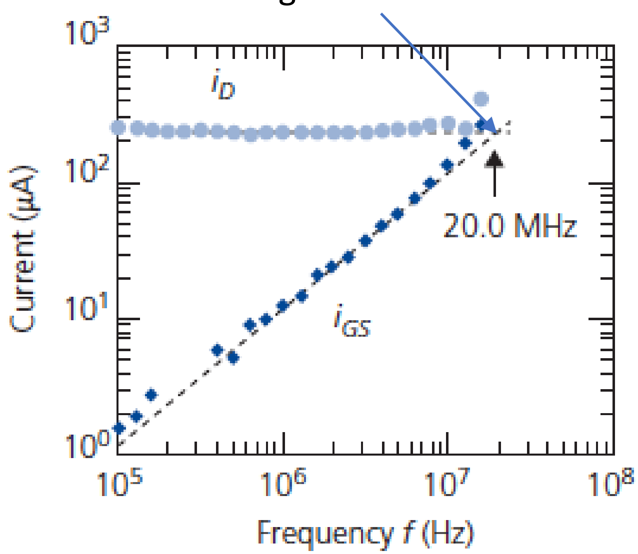
C_M = Miller capacitance

Example: High Bandwidth OTFT

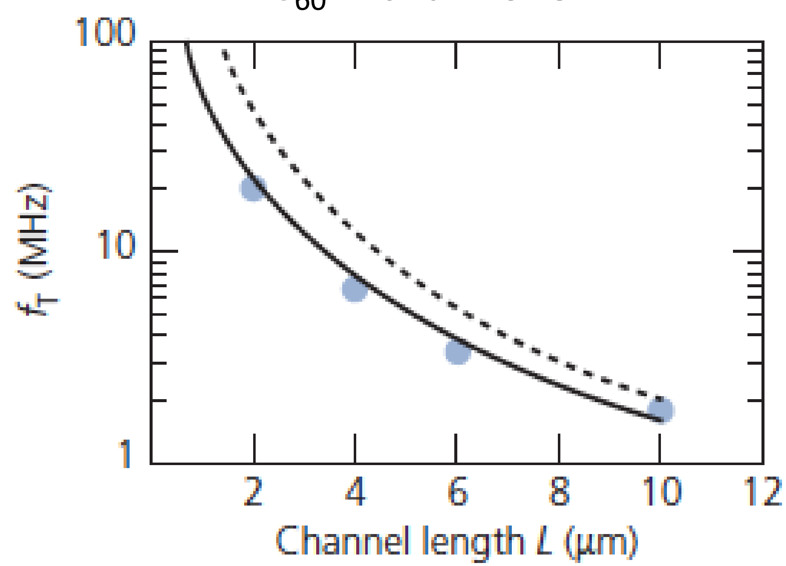


Frequency test circuit

Current gain = 1



C_{60} n-channel OTFT

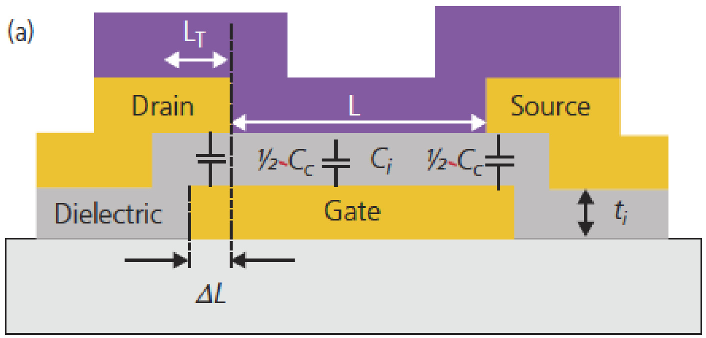


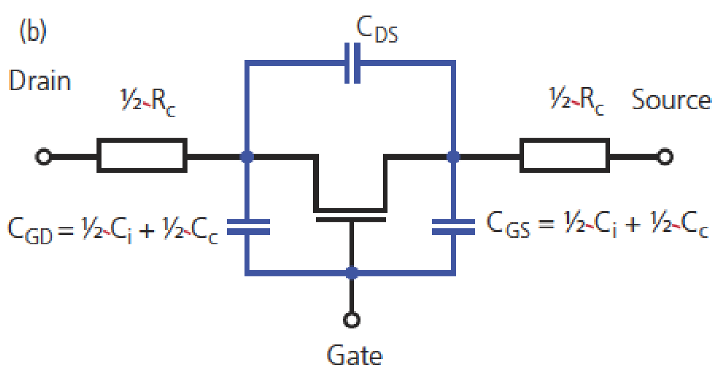
A. Yamamura, et al. 2020. *Adv. Functional Mater.,* 30**,** 1909501

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

Contact Resistance Limits OTFT Performance

Sources of Parasitic Resistance and Capacitance



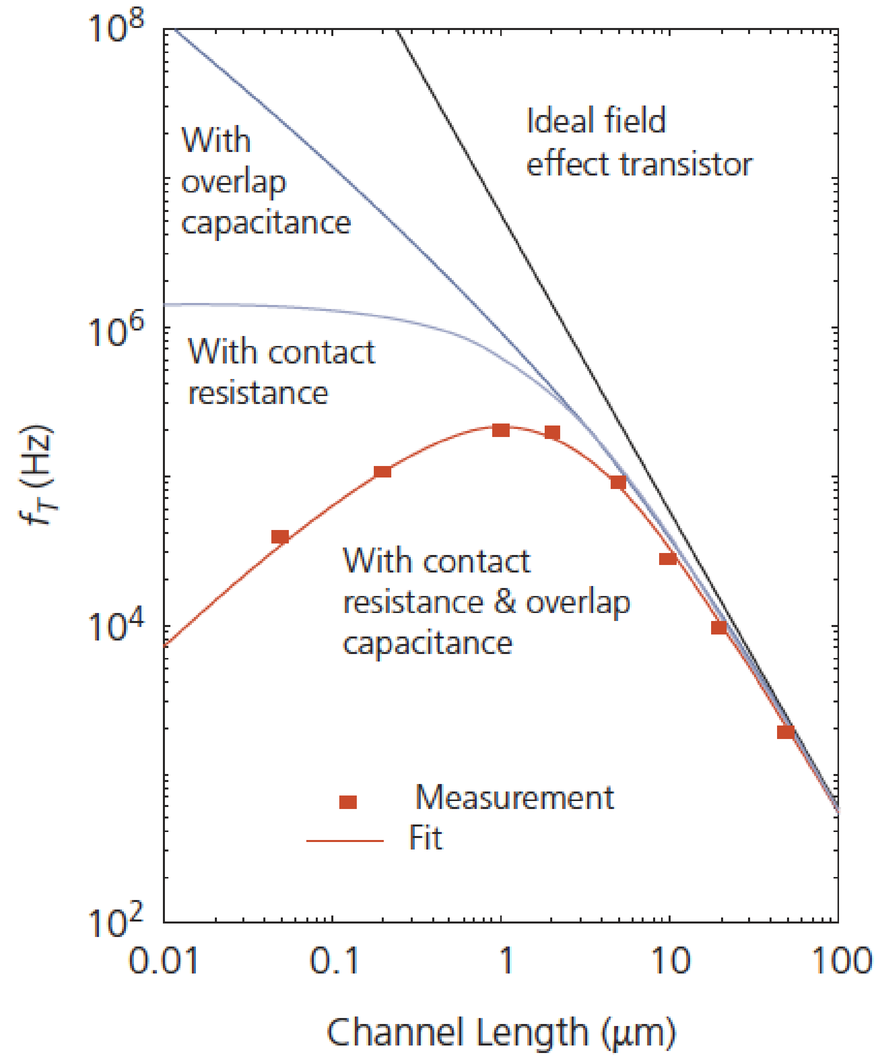


This leads to corrected transconductance and output conductance…

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

… and frequency response

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

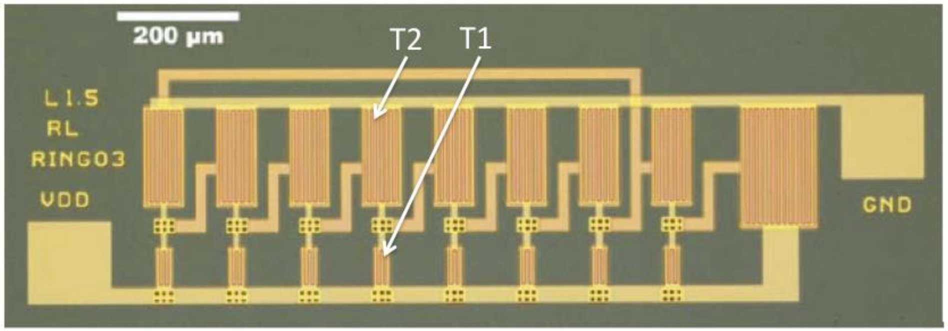


Hoppe, et al., Organic Electron., **11**, 626 (2010)

$$R_C = r_S + r_D$$

Performance has come a long way

7 stage ring oscillator

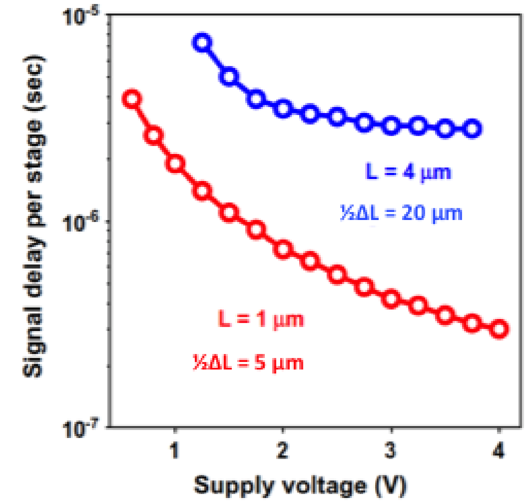


Smith et al., Appl. Phys. Lett., 93, 253301 (2008)

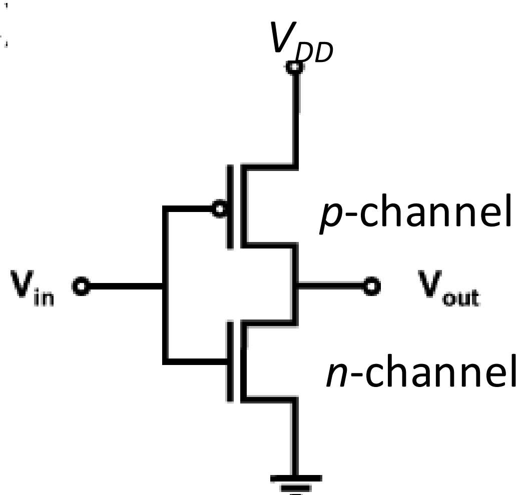
Oscillation frequency a function of the delay per gate

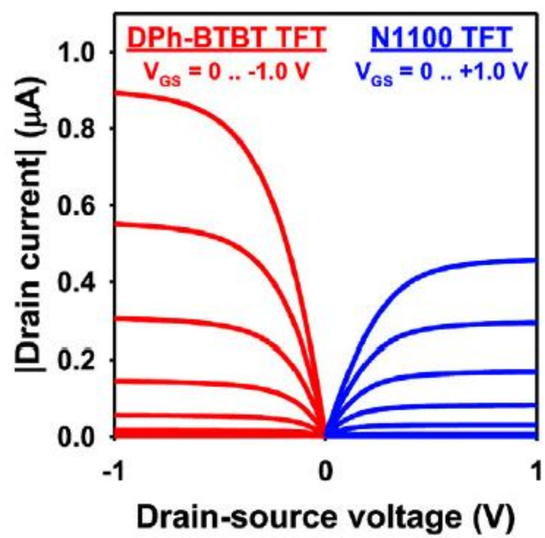
$$2 f_{osc} = 1/N\tau_{delay}$$

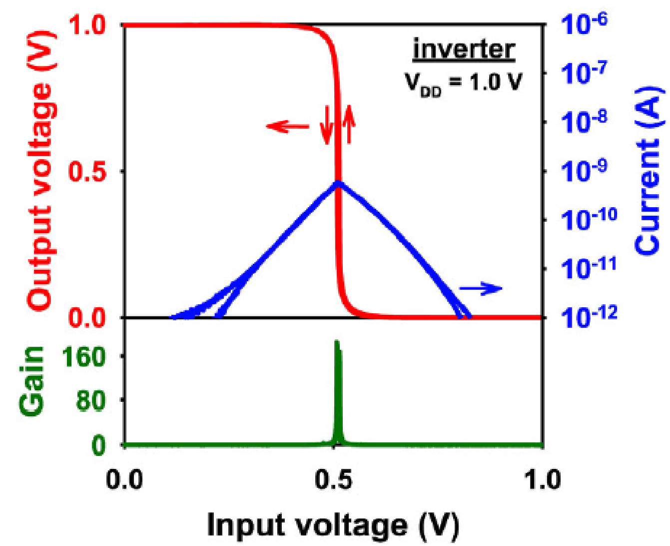
$$f_{delay} = \left(2\tau_{delay}\right)^{-1} < f_T$$



Zschieschang, et al., *Org. Electron.*, **14,** 1516 (2013).

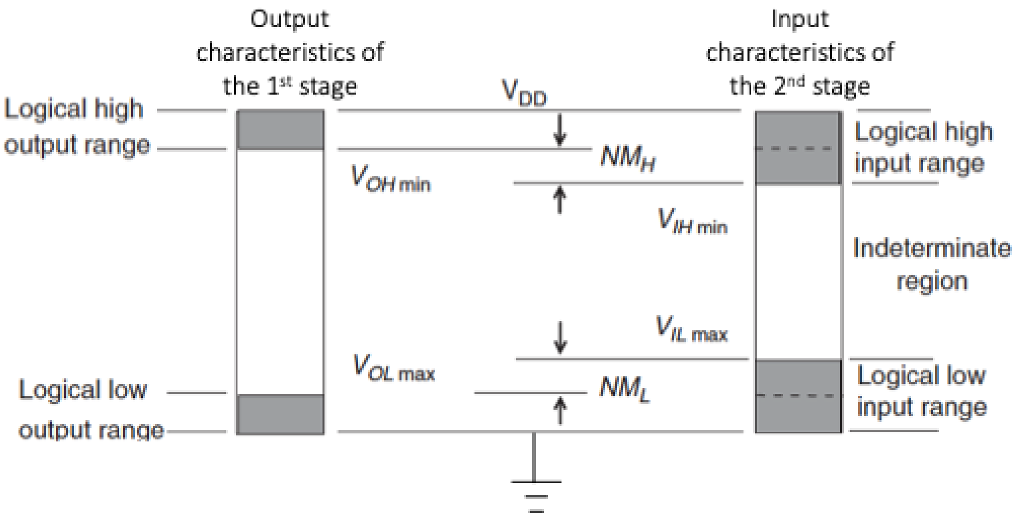


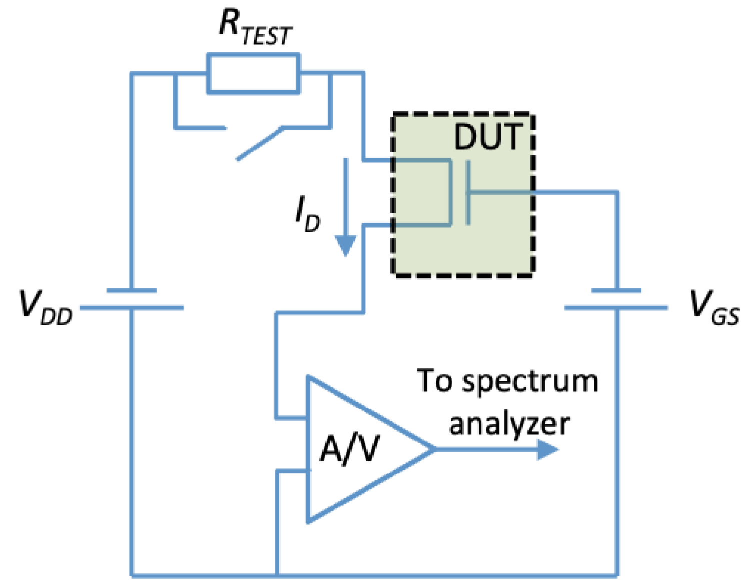




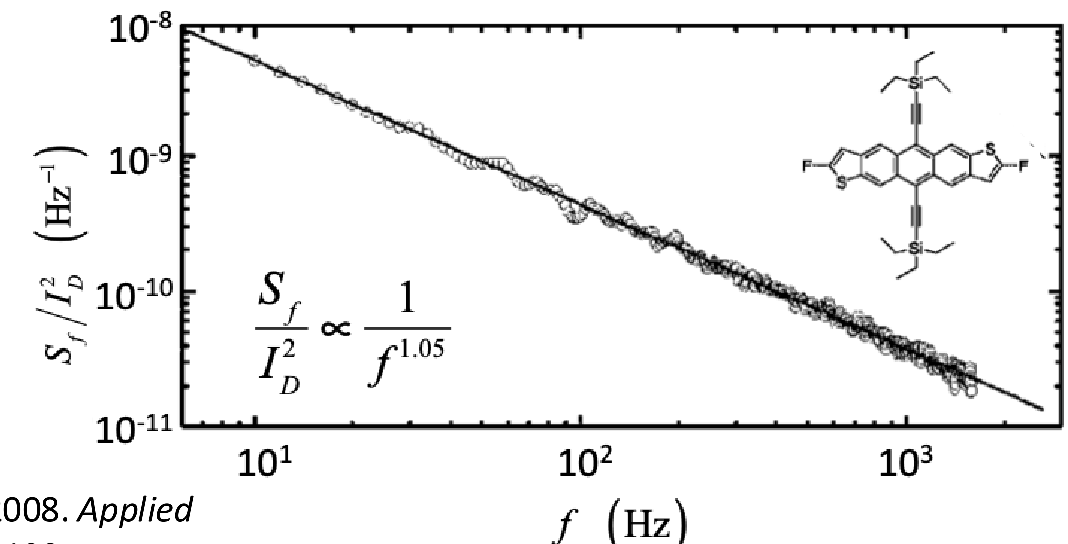
Zschieschang, et al., *Organic Electronics*, **49,** 179 (2017).

Noise measurement and margin





Measurement circuit



O. D. Jurchescu, et al. 2008. *Applied Physics Letters*, 92, 132103

Concepts in Organic Electronics
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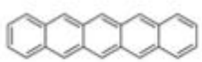
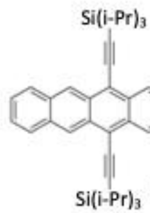
Example channel materials

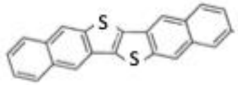
Small molecule



P1
pentacene

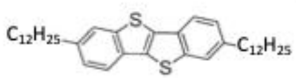


P2
TIPS-pentacene

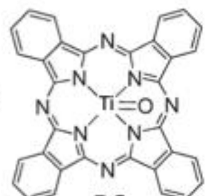


P3
DNTT

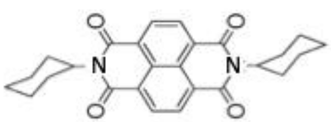
P4
Rubrene



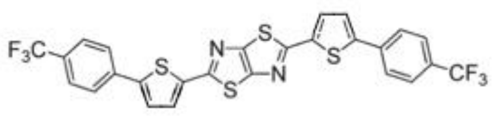
P5
C_{12}-BTBT



P6
TiOPc

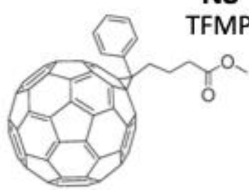


N7
NBDCI



N8
TFMPT

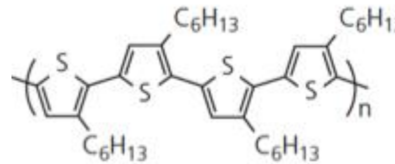
N9
C_{60}



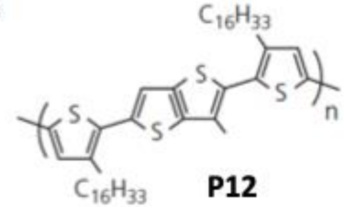
N10
$PC_{61}BM$

N = n-channel
P = p-channel

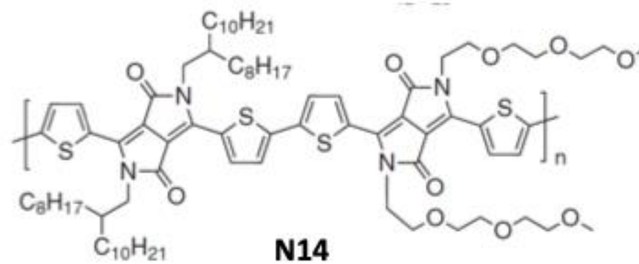
Polymer



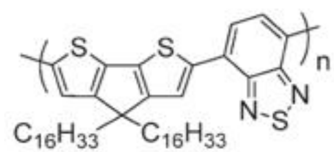
P11
rr P3HT



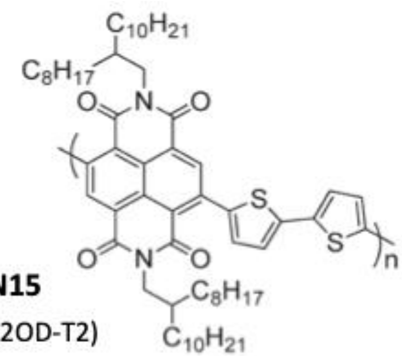
P12
pBTTT



N14
N-CS2DPP-OD-TEG

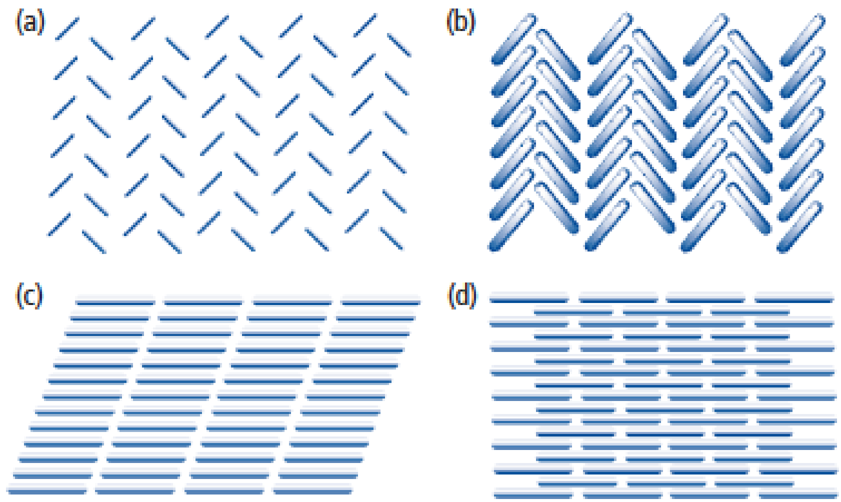


P13
CDT-BTZ

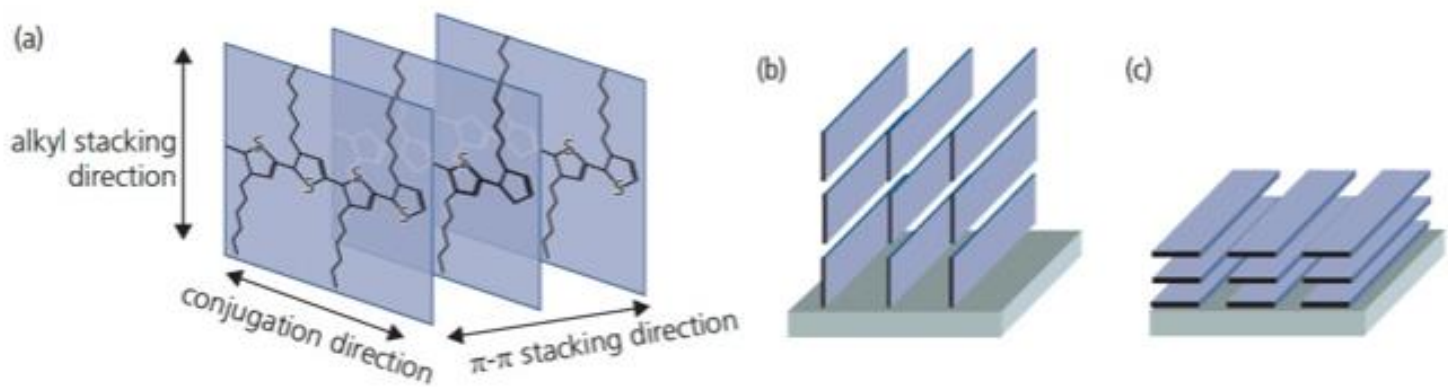


N15
DI2OD-T2)

Highest mobilities when π-stacking is in the transistor plane



Different, common organic stacking motifs
(see Chapter 2)

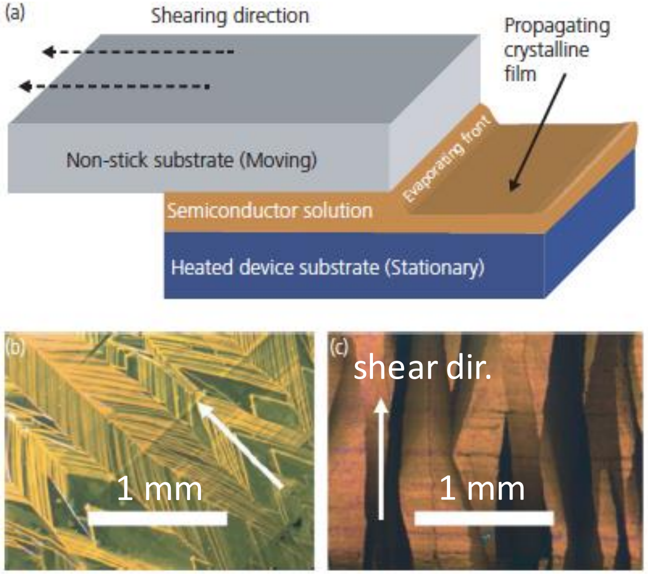


best vertical conduction

best in-plane conduction

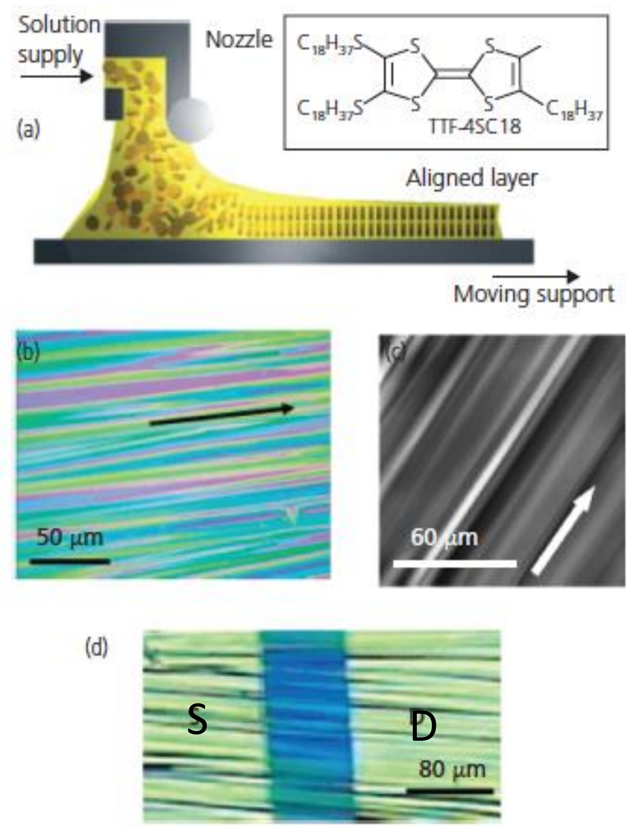
Methods for Orienting the Semiconductor

solution shearing



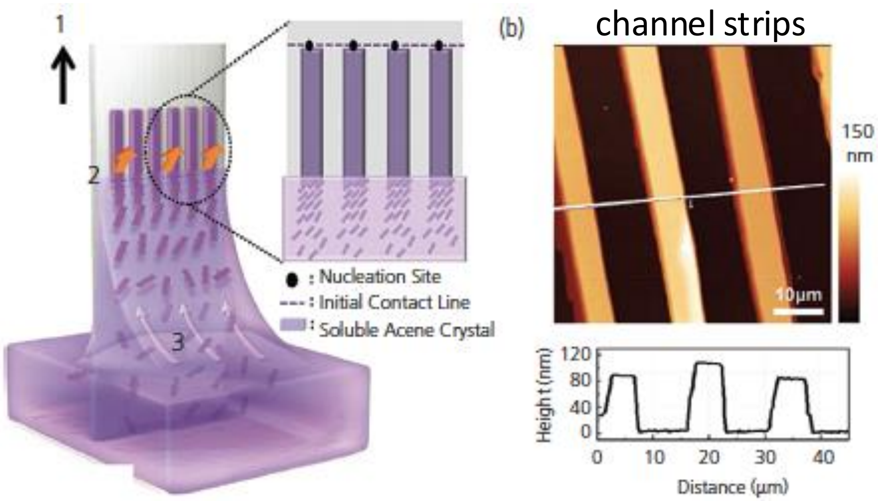
Liu, et al., Z. Adv. Materials, **21**, 1217 (2009)

zone casting

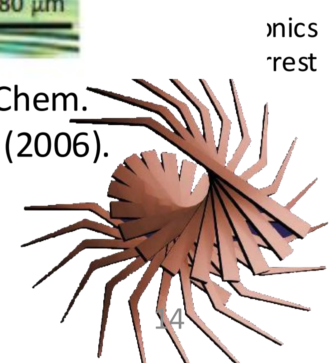


Miskiewicz, et al. Chem. Materials, **18**, 4724 (2006).

dip coating

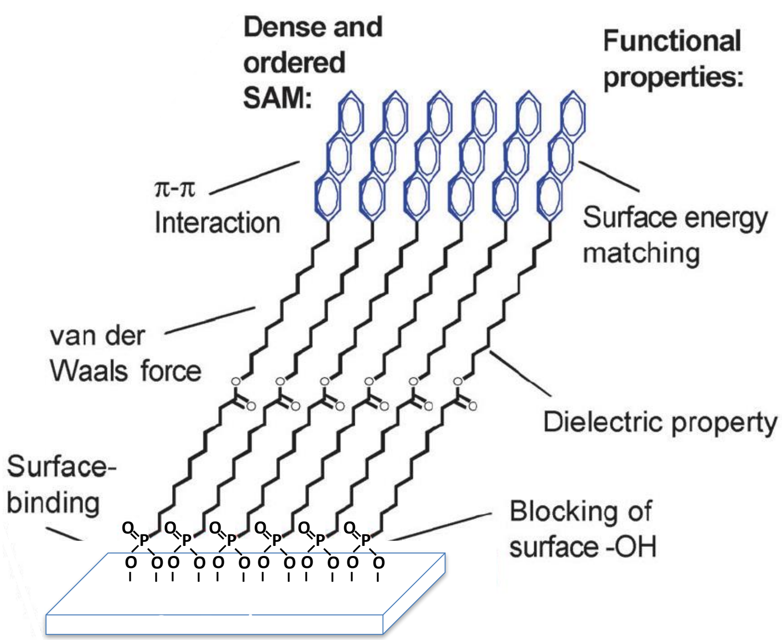


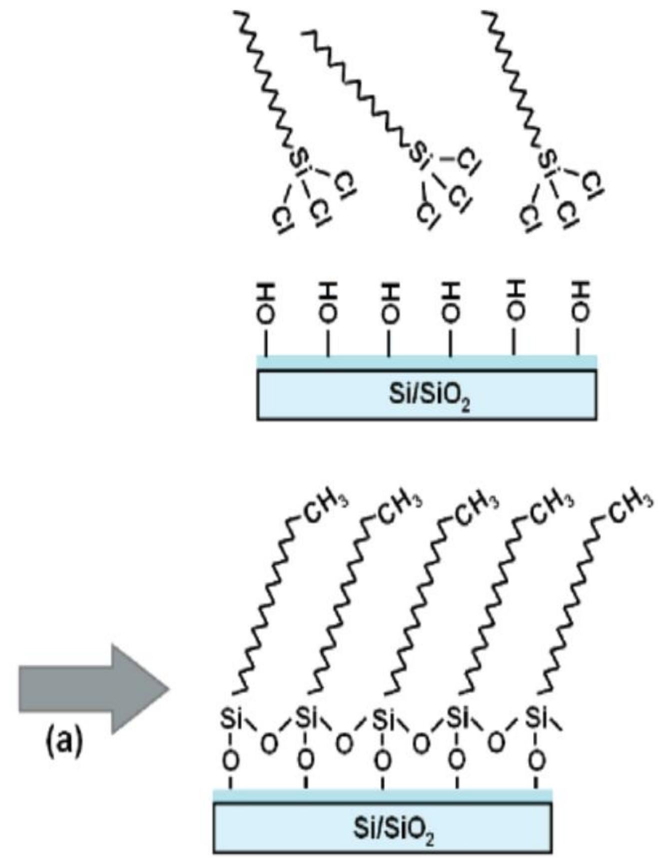
Jang et al., Adv. Functional Mater., **22**, 1005 (2012)



Achieving Optimal Morphologies

- Method 1: Control during growth by VTE, OVPD, solution
- Method 2: Use Self Assembled Monolayer (SAM) functionalization to initiate growth of desired structures by vapor or solution deposition

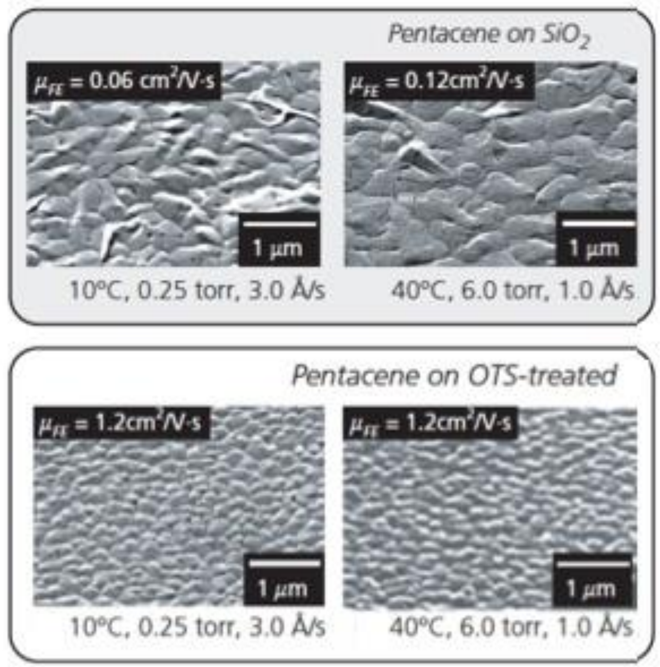




Example: Octyltrichlorosilane (OTS)

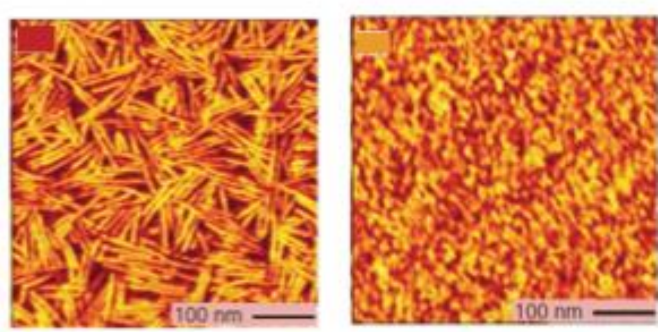
Achieving morphology through growth conditions & surface preparation

OVPD growth of pentacene



M. Shtein, et al. 2002. *App. Physics Letters,* **81,** 268-270.

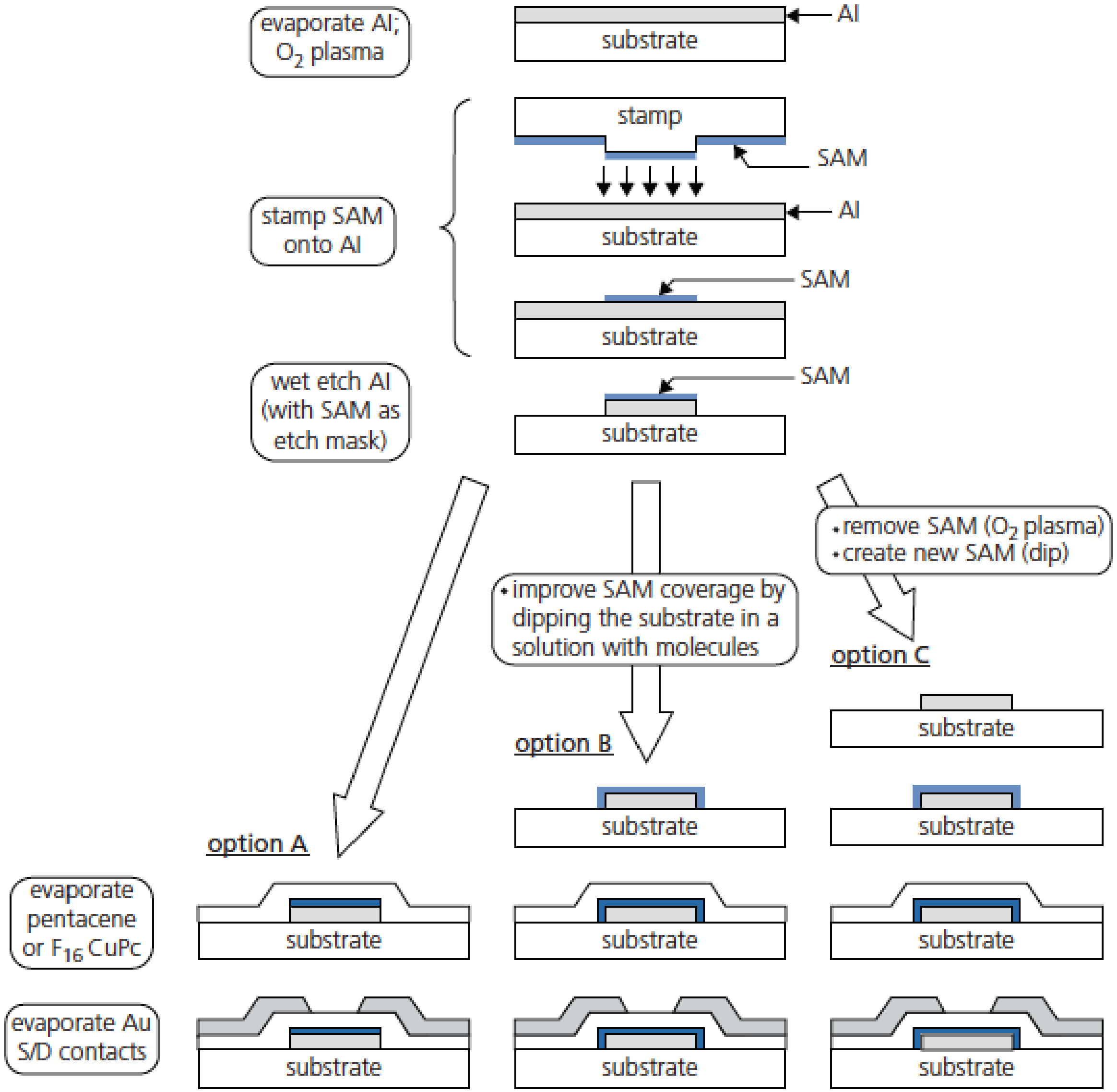
Solution growth of P3HT on HDMS-functionalized SiO_2

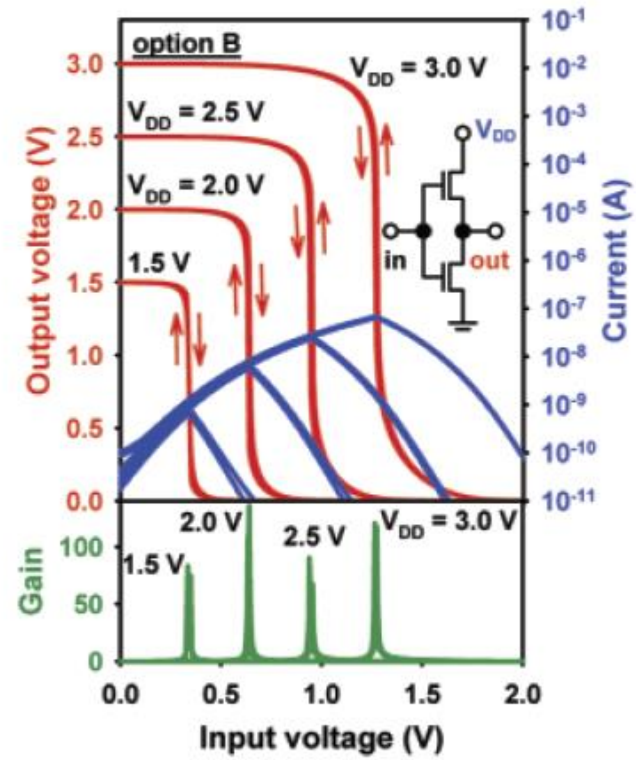


MW = 3.2 kDa 31.1 kDa

R. J. Kline, et al. 2003. *Adv. Materials*, 15, 1519-1522

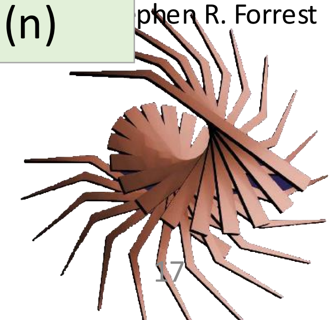
Contact Printing Initiated by SAM





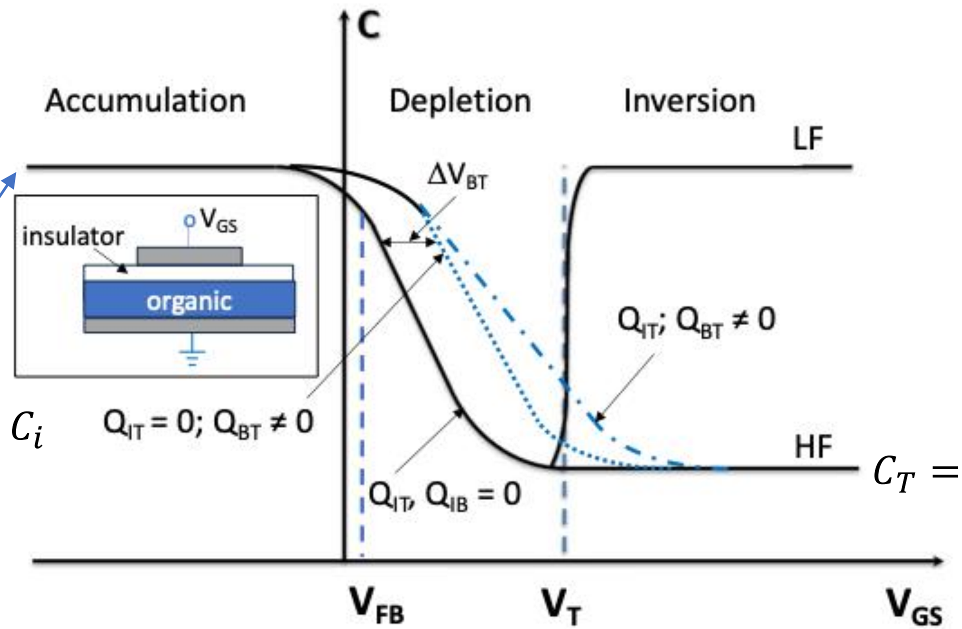
Pentacene (p)
F_{16}CuPc (n)

Zschieschang, et al., *Langmuir,* **24** 1665 (2008).

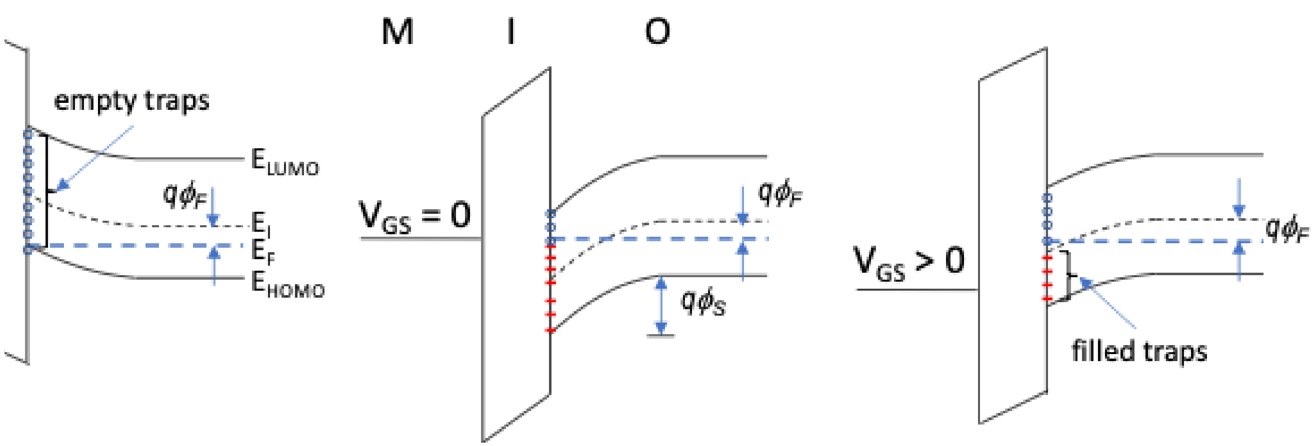


Interpreting gate C-V characteristics

$$C_T = \frac{C_S C_i}{C_S + C_i} \rightarrow C_i$$

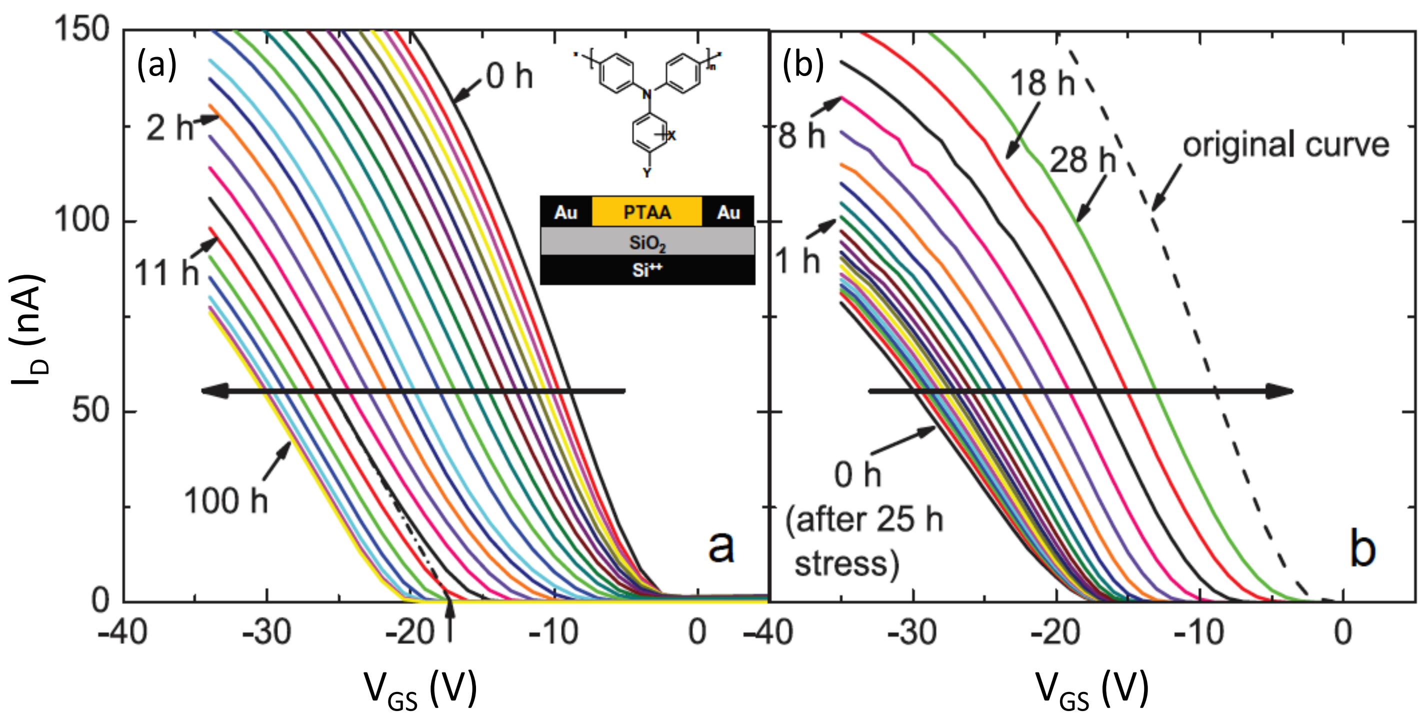


$$C_T = \frac{C_S C_i}{C_S + C_i}$$



OTFT Stability

- Threshold voltage drift the primary source of circuit failure
  - Decreasing noise margin
  - Increasing leakage



Drift $\left\{ \begin{array}{l} V_{DS} = -3V \\ V_{GS} = -20V \end{array} \right.$ Recovery

Original transfer characteristics (and V_T) partially recovered following stress

Sharma, et al. Phys. Rev. B, **82** 075322 (2010).

Threshold voltage drift over time

(see Ch. 6.7 & 7.8)

- Drift due to charges migrating in insulator or channel toward the interface
  - Surface traps at the channel
  - Traps within the semiconductor bulk
  - Charge (ions) drifting within the insulator

$$\boxed{\Delta V_T(t) = \Delta V_T(\infty)\left(1 - \exp\left(-\frac{t}{\tau}\right)^m\right)}$$

Empirical voltage drift expression:
Stretched exponential

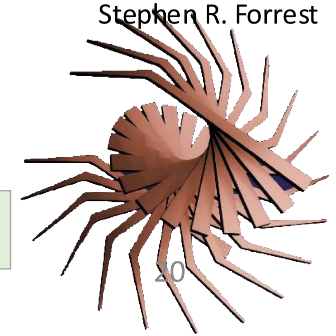
$m = T/T_0$ for exponential trap distribution given by:

$$h_{tr}(E) = h_{tr0}\exp\left(-E/E_T\right)$$

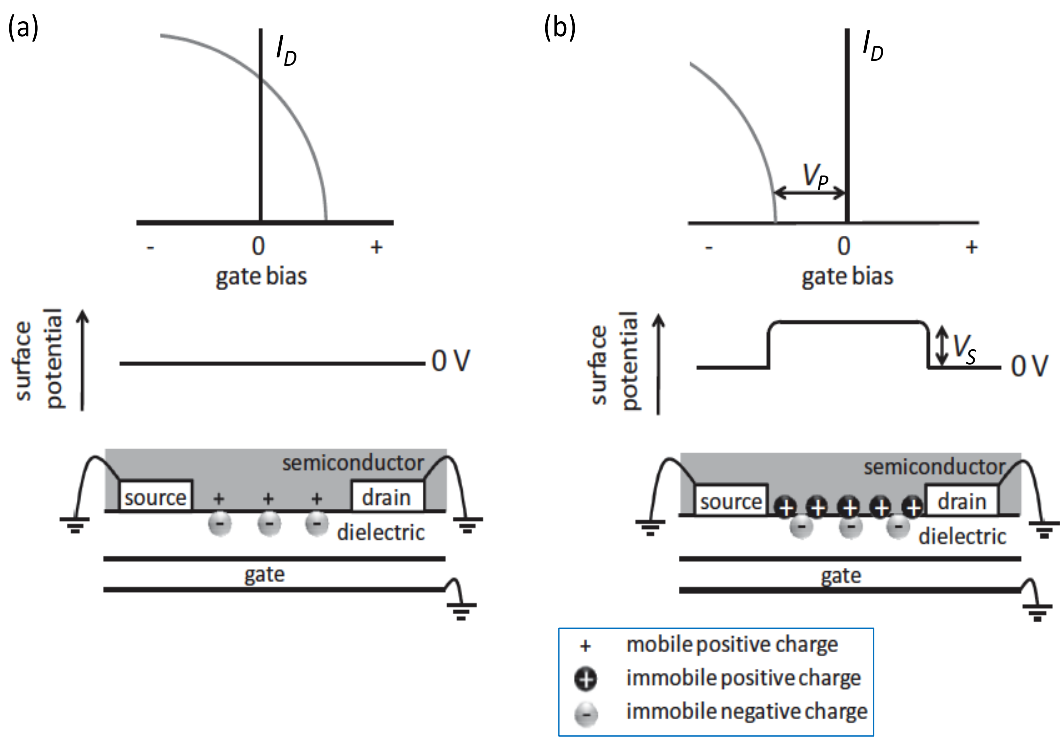
$\Rightarrow$ Time constant for drift

$$\tau = (2\pi\nu)^{-1}\exp\left(E_T/k_BT\right)$$

Drift occurs over an extended time, and is thermally activated



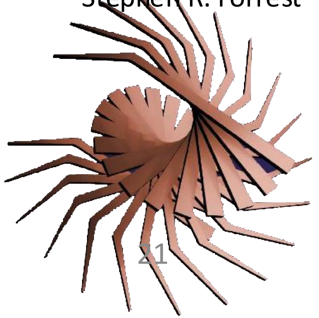
Water results in ionic charge at interface ⇒ charge trapping



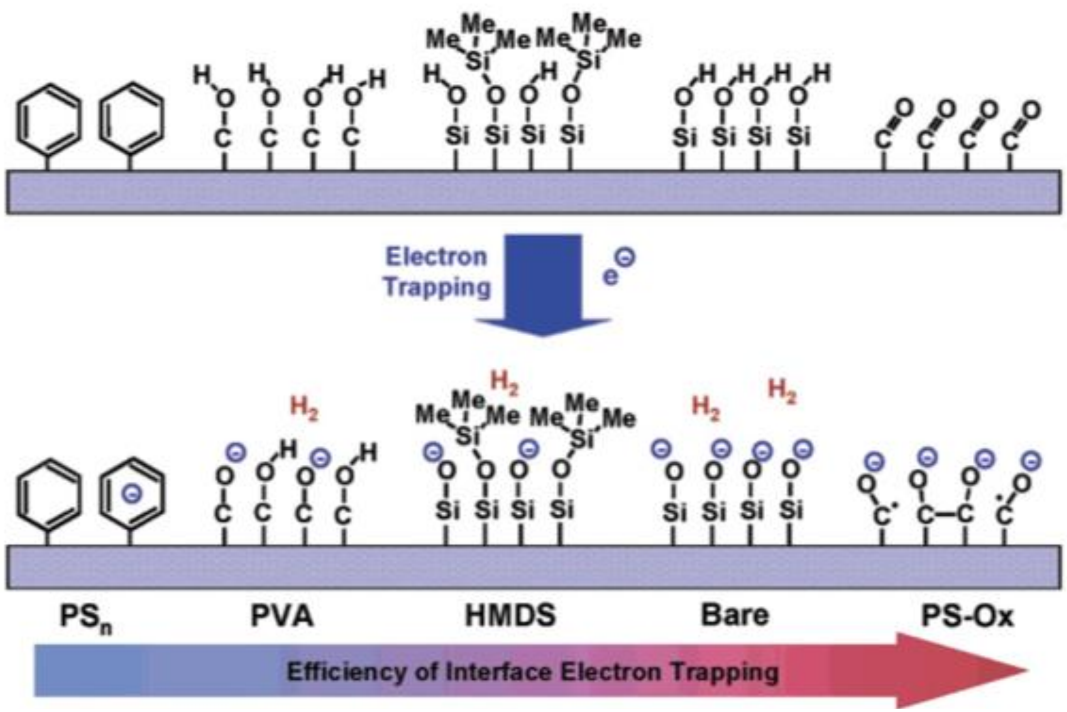
Water is the main problem: Proton generation

$$2H_2O \leftrightarrow 4H^+ + O_2 + 4e^-$$

Mathijessen et al., Adv. Mater. **22**, 5105 (2010)

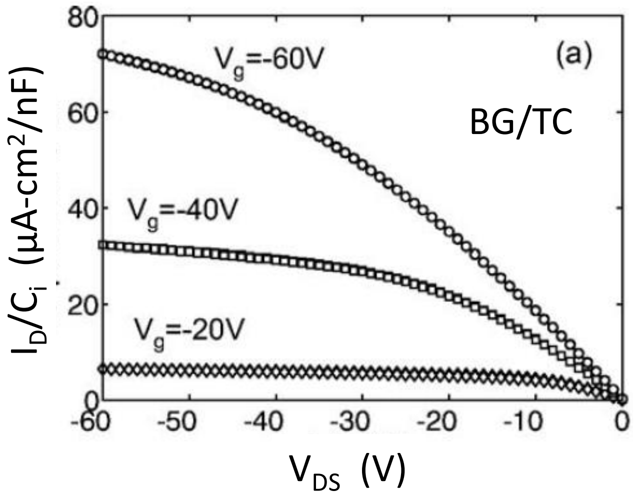


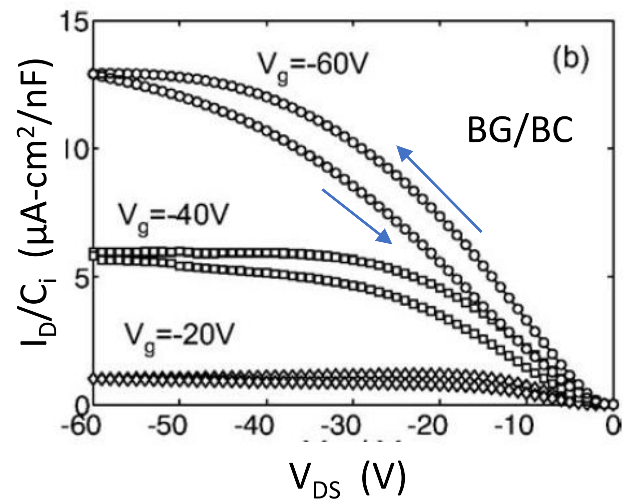
SAMs can passivate the SiO2 surface and reduce ΔV_T.



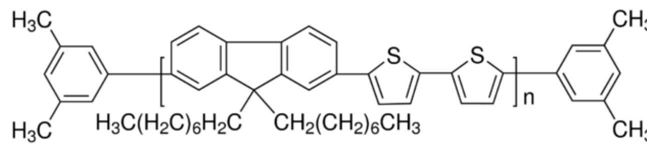
M.-H. Yoon, et al. 2006. *JACS,* 128**,** 12851-12869

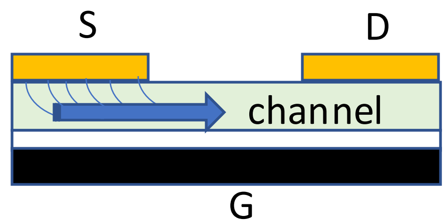
Hysteresis: Another failure mode



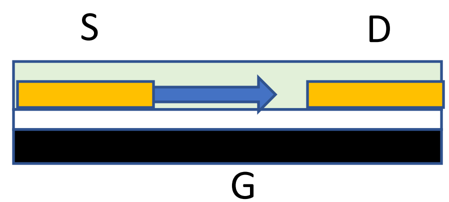


p-channel F8T2 transistors





BG/TC: Large contact area to channel
Current drawn from contact surface (arrow)



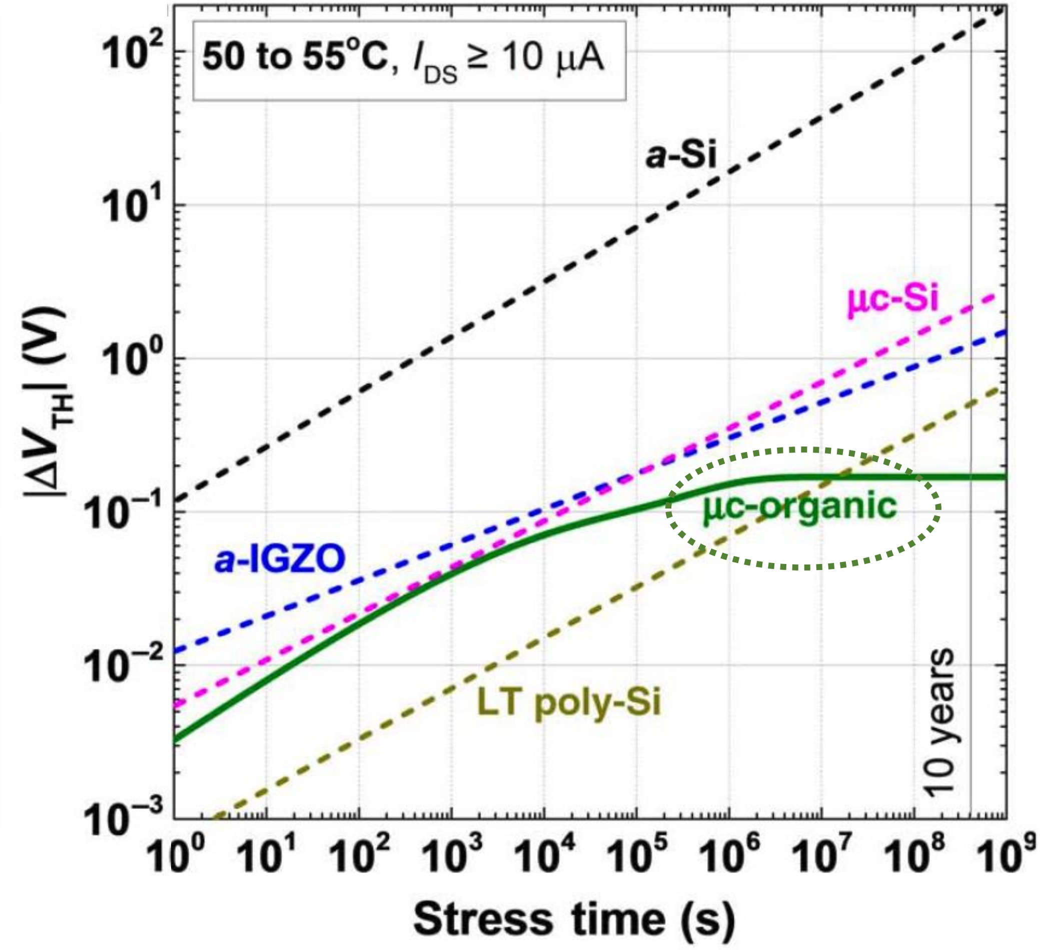
BG/BC: Small (edge) contact to channel
Current drawn from contact edge (arrow)

<u>Drain contact trapping</u>

Contact only via edge of the electrodes increases the current density, resulting in defect formation and charge trapping. This induces changes in V_T and I_{DS}, depending on sweep direction (arrows)

Richards & Sirringhaus Appl. Phys. Lett., **92**, 023512 (2008)

Comparison of TFT Reliabilities



Jia, et al. Science Adv. 4, eaao1705, (2018)

Caveats (and there are many):

- Devices from different labs may be based on different standards and conditions
- Device selection not necessarily based on same characteristics
- Performance can vary over a wide range in any technology

Applications must exploit advantages, and cannot be vulnerable to disadvantages

To review….

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

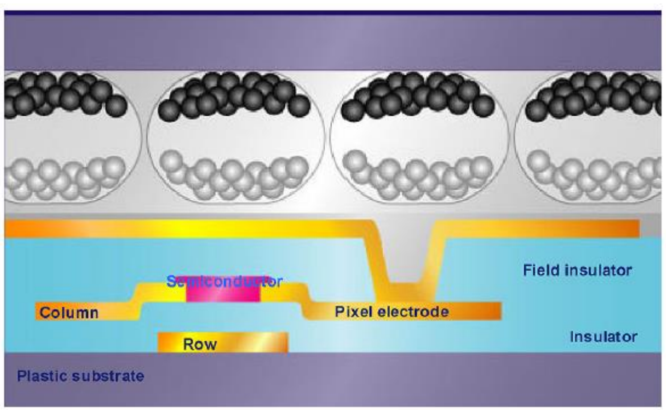
- CONs
  - ➢ Cannot source large currents
  - ➢ Characteristics drift over long periods in operation
  - ➢ Limited bandwidth (≤ 1 MHz in many cases)

Voltage driven display backplanes

- Electrophoretic displays

(a)

(b)



320 x 240 QVGA display
Display pixels are voltage (not current) driven

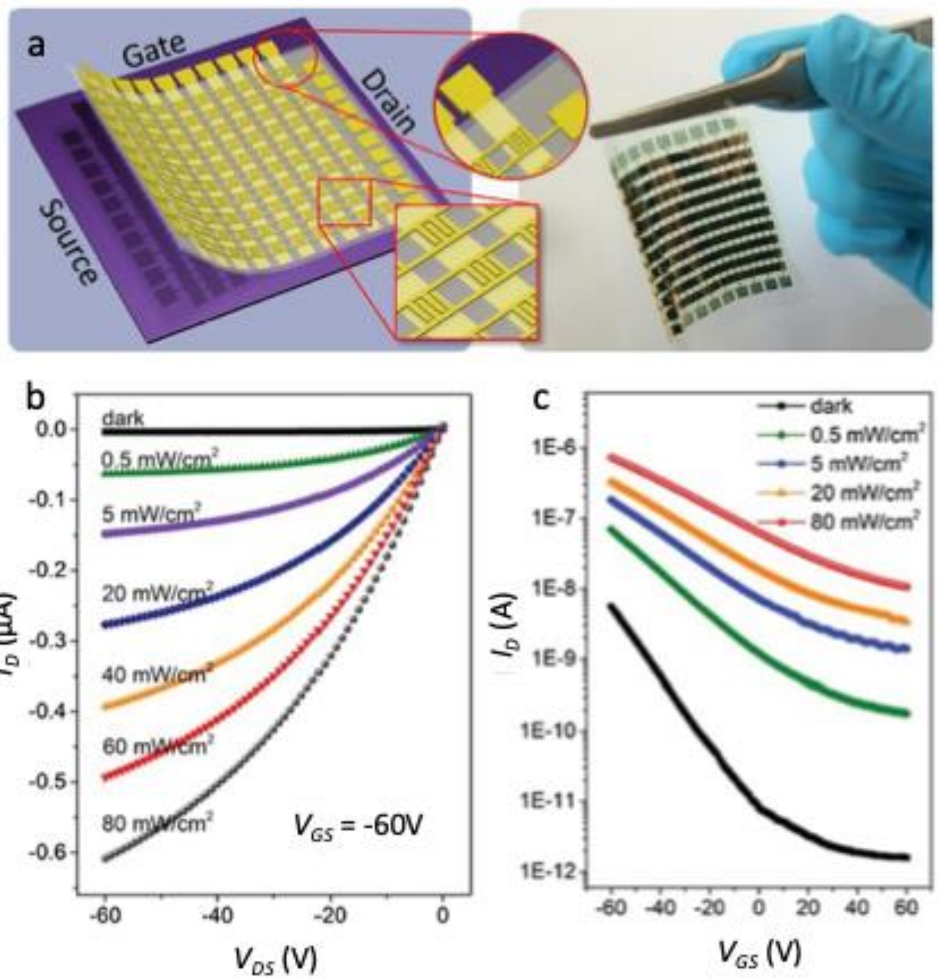
QVGA=quarter video graphics array

Concepts in Organic Electronics
Stephen R. Forrest

G. Gelinck *et al J. Soc. Info. Display,* **14**,113, (2006).

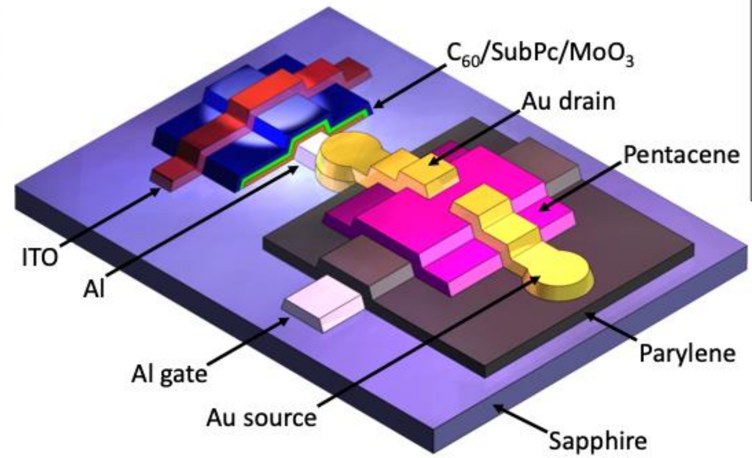
Imaging devices

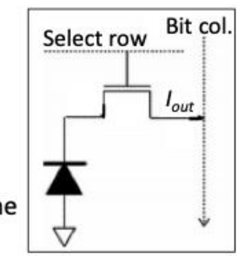
Phototransistor imaging array



Y. Chu, et al, J. 2016. *Advanced Science,* 3

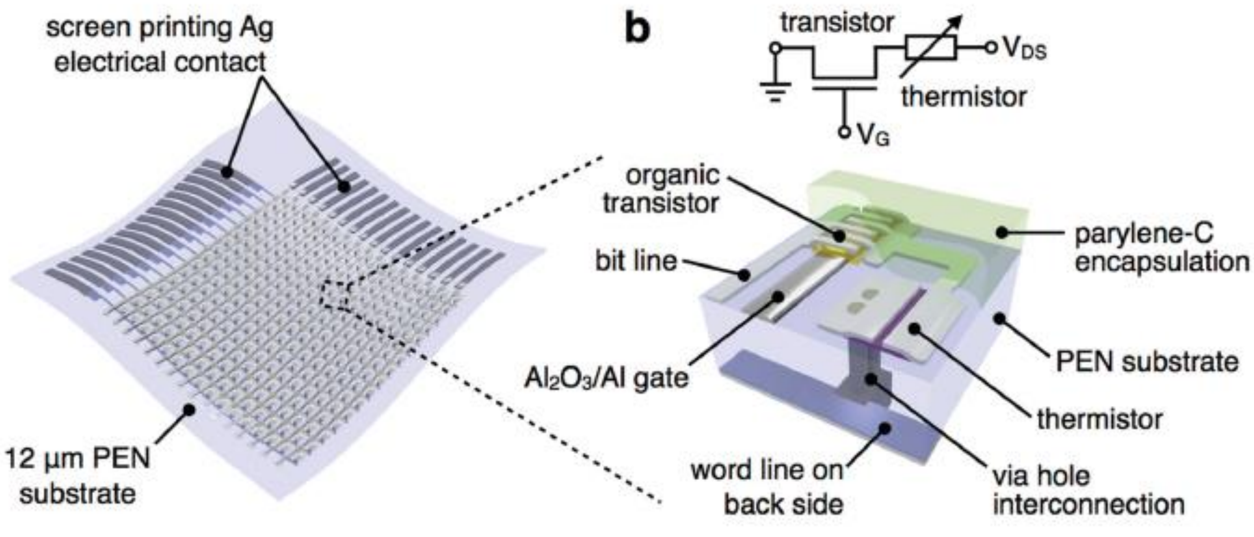
Passive pixel sensor element for detector arrays

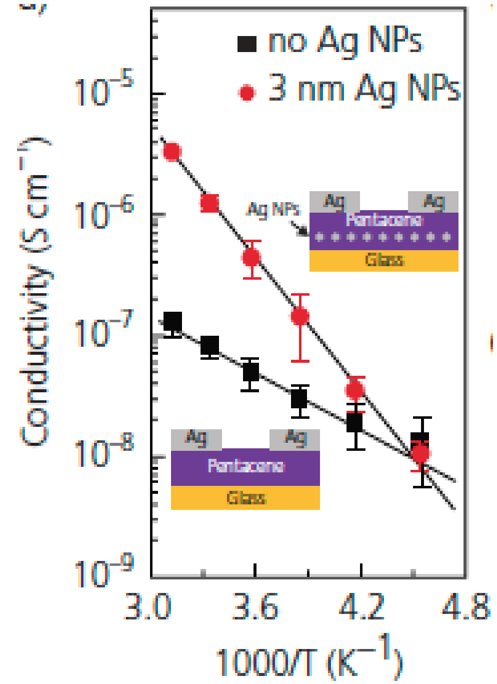




X. Tong, & S. R. Forrest, 2011. *Org. Electron.*, **12,** 1822-1825.

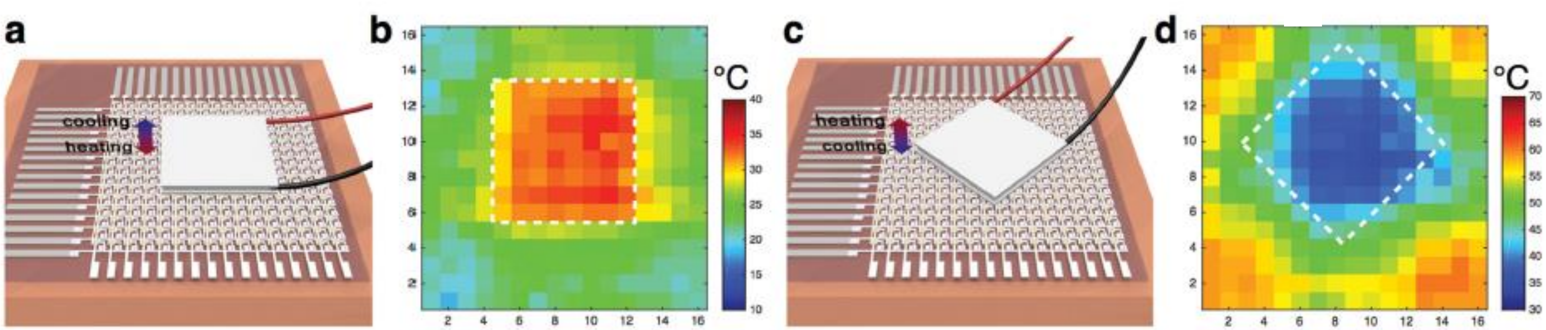
Thermal Position Sensing





Array used for detecting position of thermal source

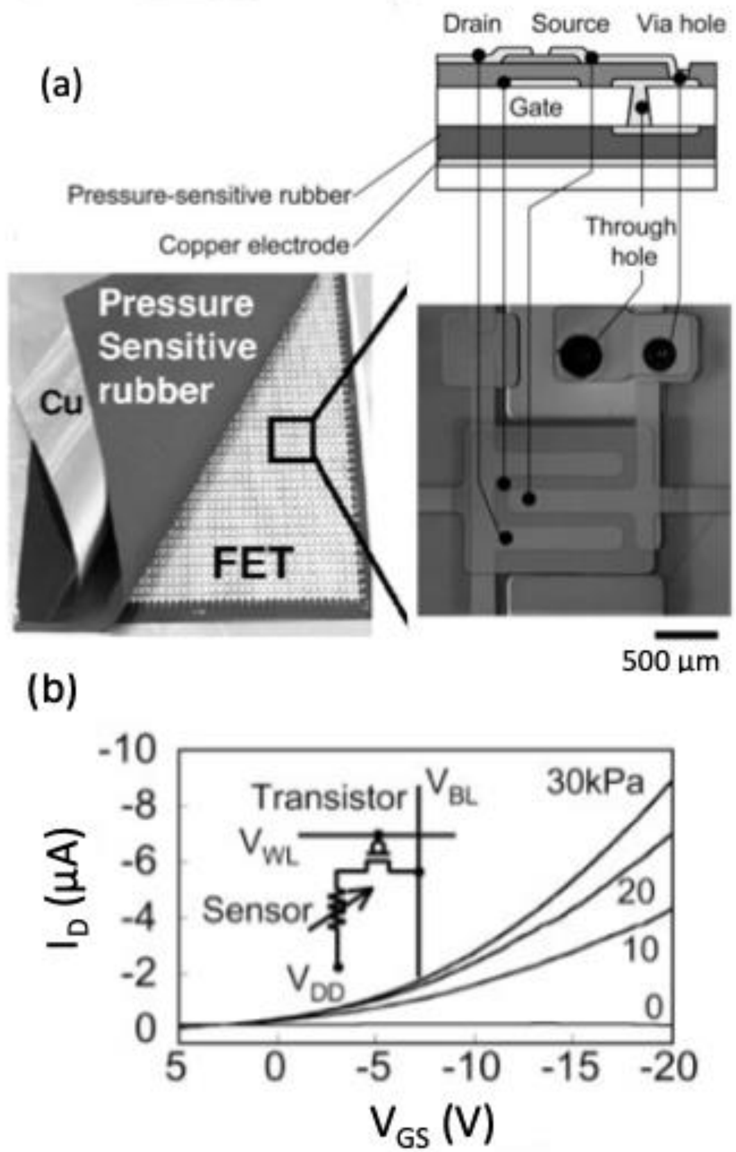
Sensing element: channel resistance with a Ag NP layer



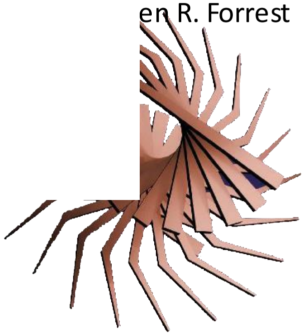
ganic Electronics
tephen R. Forrest

Ren, et al., Adv. Mater. **28**, 4832 (2016)

Tactile sensor arrays



Y. Noguchi, et al.. 2006. *Applied Physics Letters,* 89**,** 253507



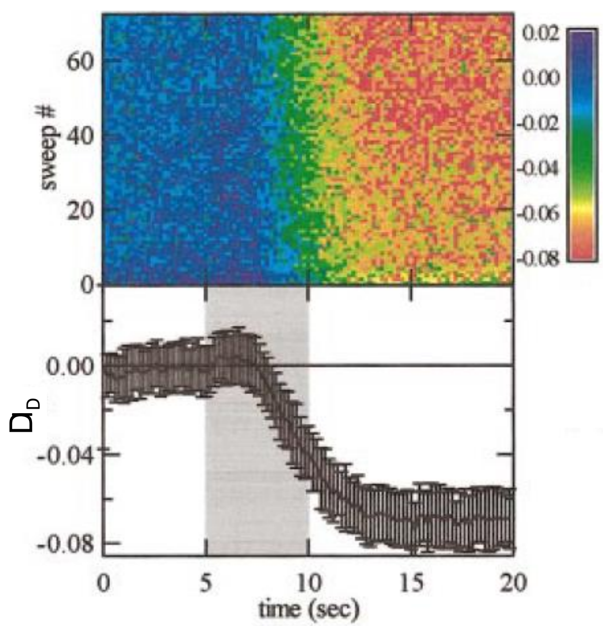
Chemical sensing

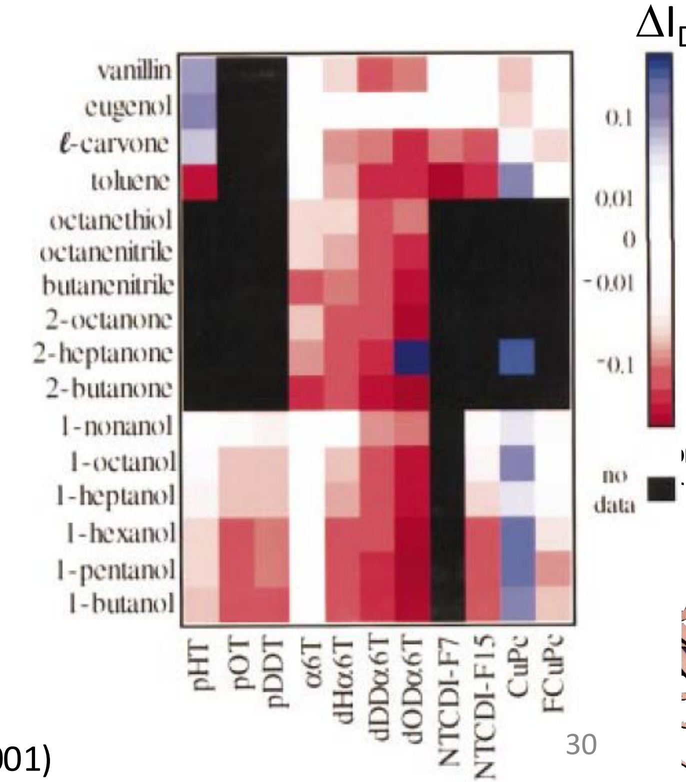
- OTFTs have demonstrated voltage drifts due to water.
- Are there other analytes that can be sensed?
- Sensor attributes
  - Fast
  - Sensitive to small doses
  - Reversible
  - <u>Specific</u>

16 analytes
11 transistor channel mater.

α–6T transistor

Analyte: 1-hexanol
Exposure: 5 s
Recovery: 1 min

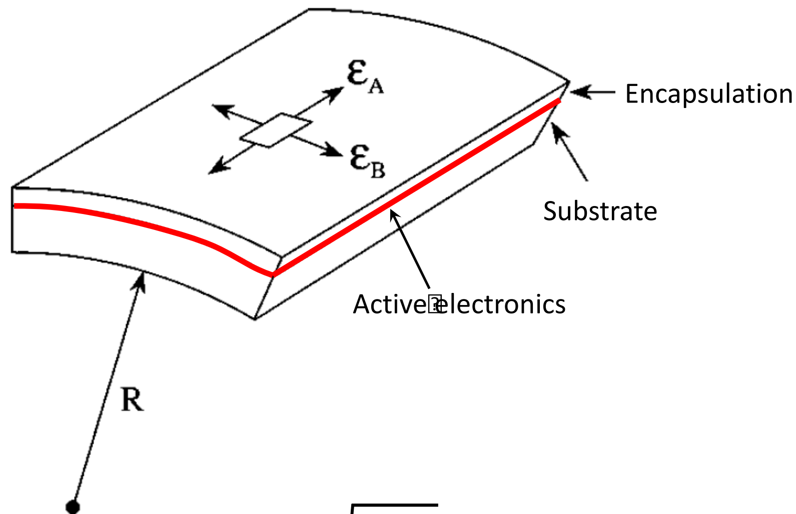




B. Crone *et al.*, **78**, 2229, (2001)

Bendable Electronics

Placing active electronics at the neutral strain point
⇒ minimal stress to circuits on bending even over sharp angles

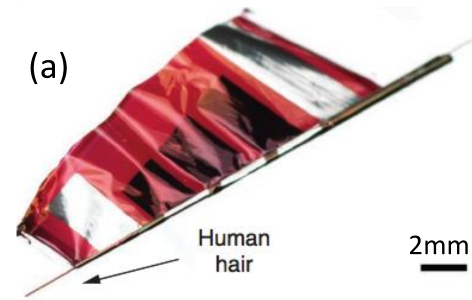


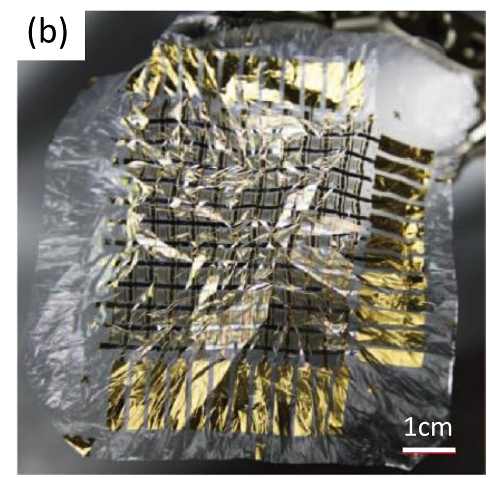
Neutral strain: $$\frac{d_{sub}}{d_e} = \sqrt{\frac{Y_e}{Y_{sub}}}$$

Y = Young's modulus (measure of material stiffness)

$$Y = \frac{FL_0}{A\Delta L}$$

- F = force to extend solid
- L_0 = original length
- ΔL = length change
- A = cross sectional area perpendicular to F



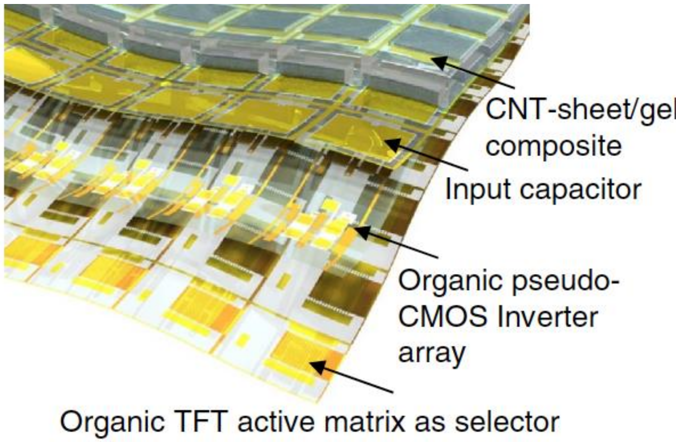


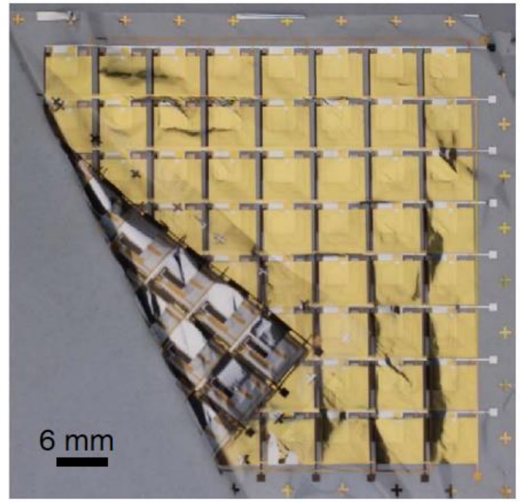
12x12 array of tactile pixels

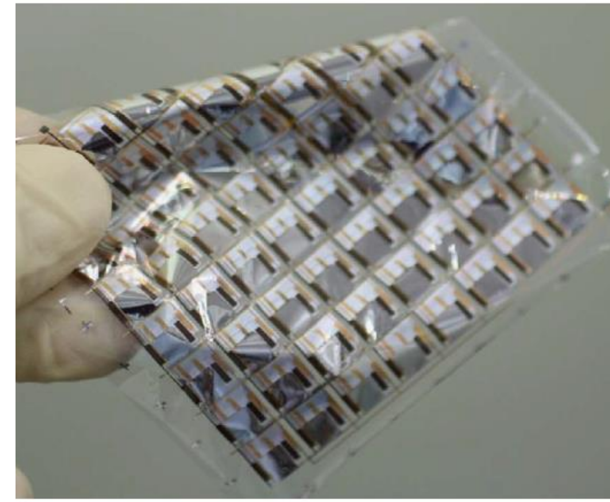
lectronics
R. Forrest

Kaltenbrunner et al. Nat. Commun. **3**, 770 (2012); Nature **499**, 458 (2013)

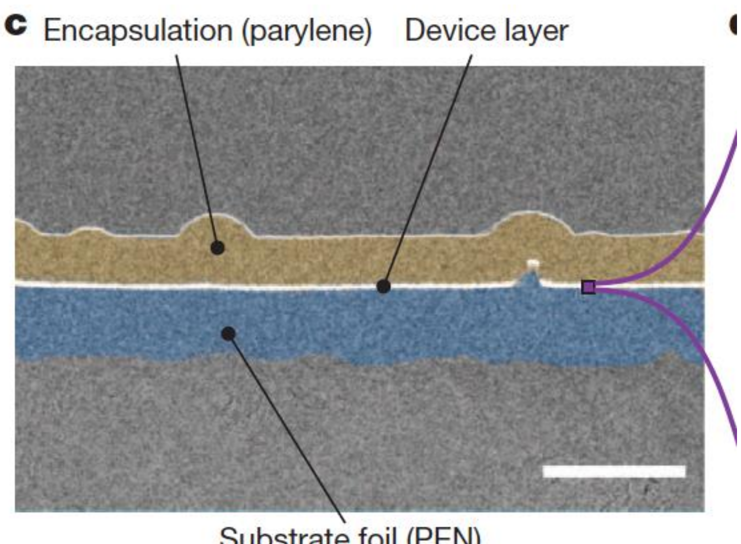
"Imperceptible" Electronics

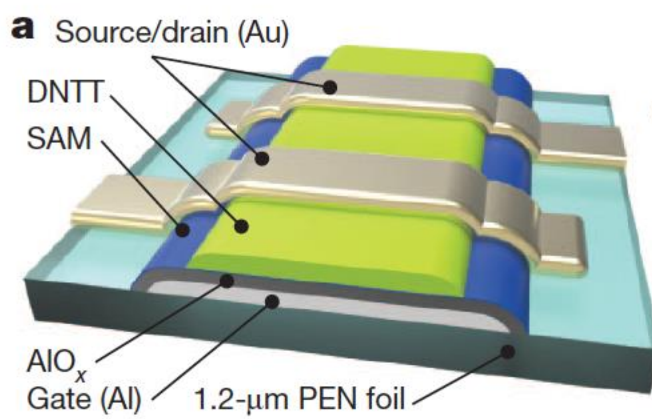






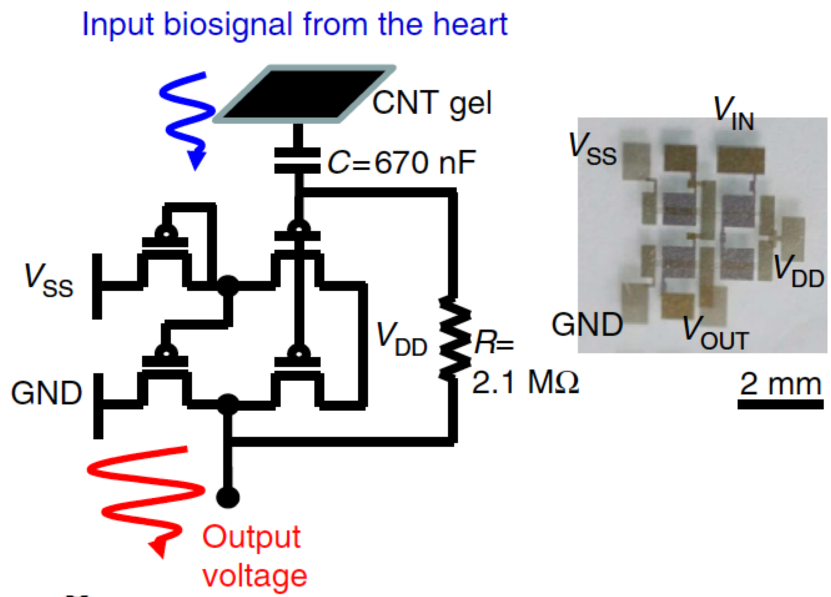
Substrates are 1 μm thick!

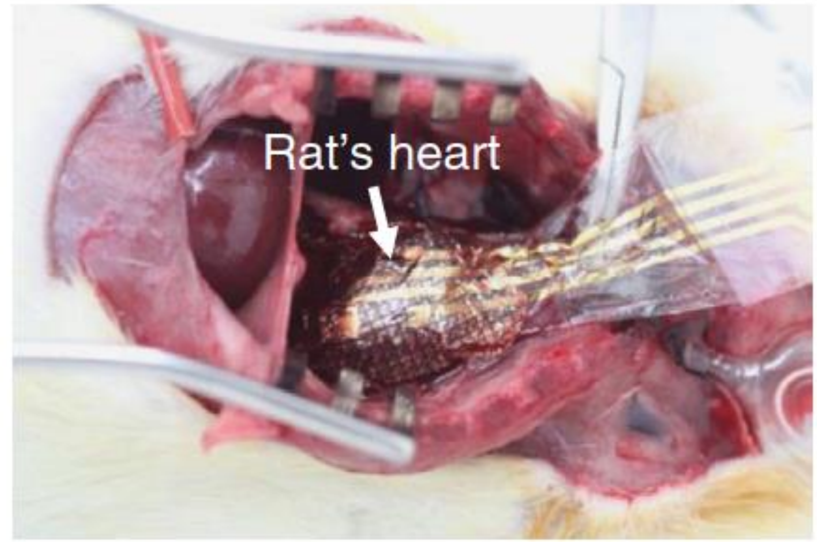


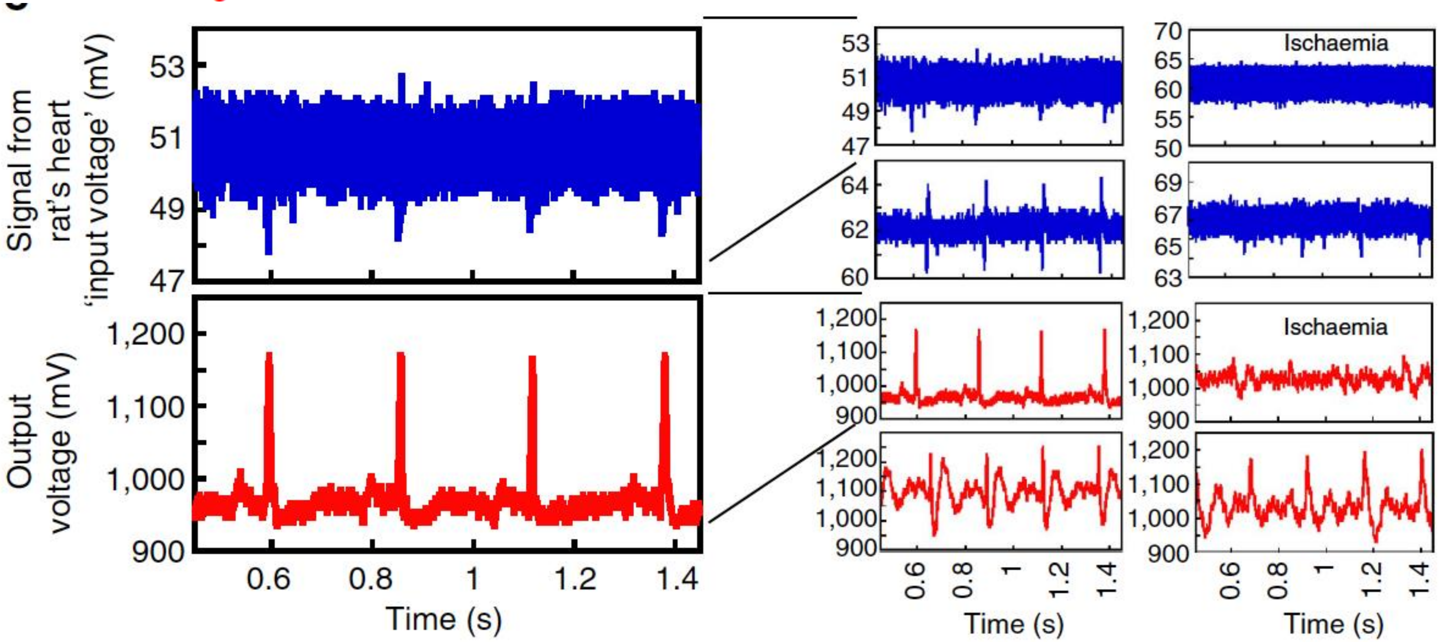


Kaltenbrunner, et al., *Nature*, **499**, 458 (2013).

In Vivo Cardiac Monitoring







Sekitani, et al. *Nat. Comm*. DOI: 10.1038/ncomms11425 (2016)

What we learned

- OTFTs have made extraordinary progress since their first demonstration in 1986
- Their properties can be modified through chemical design
- Morphology is key to high performance
- Very small gate transistors are common in BG/TC configurations
- Very large circuits demonstrated (100’s of transistors)
- Reliability depends on exposure to contaminants
- Most promising applications in sensing and medicine
- But….there is no “killer app” yet identified that can drive this technology to a commercial success