Week 2-11

Thin Film Transistors 2

Ambipolar OTFTs

Circuits and Frequency Response

Noise

Alternative Transistor Structures

Phototransistors

Morphology & Patterning

Chapter 8.4-8.7

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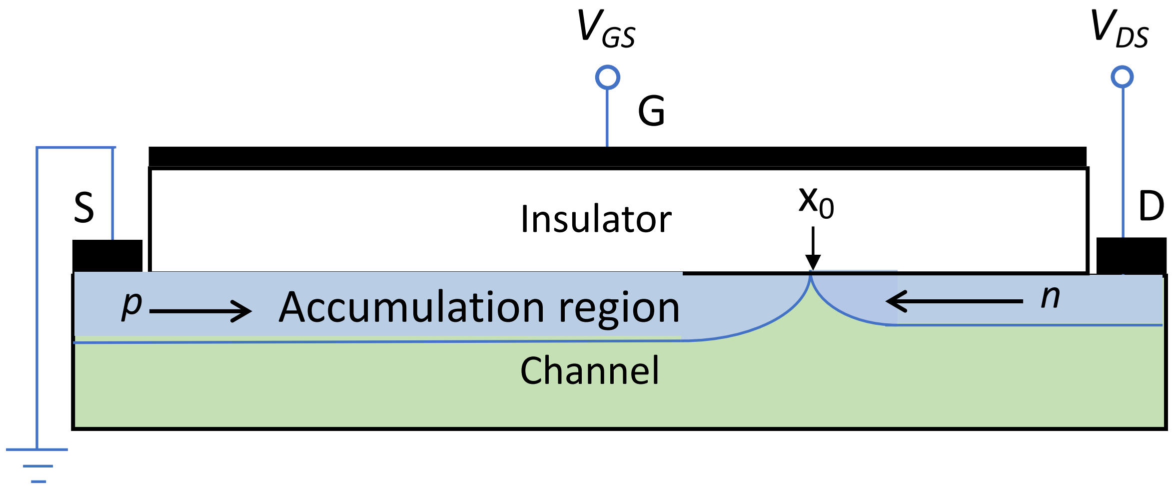
Ambipolar OTFTs

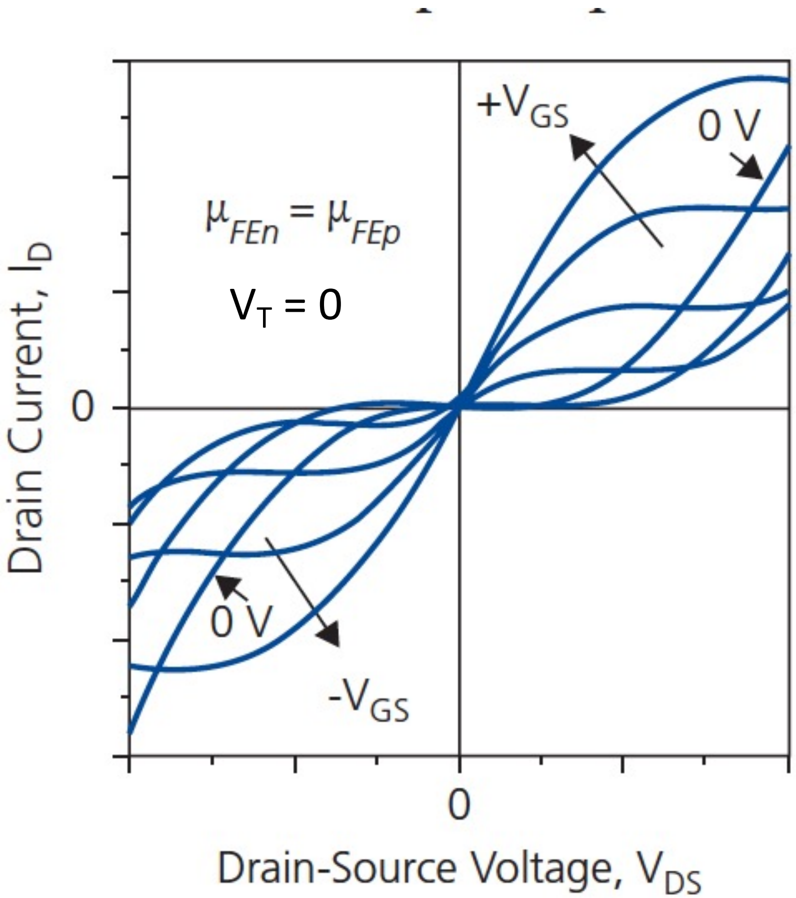
- Channel capable of supporting both electron and hole transport
- Advantage: Complementary logic possible with a single structure



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

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

$$\left(\begin{array}{c} 0 \le V_{DS} \le V_{DSsat} \\ V_{GS} > V_{Tn} \end{array}\right)$$

Saturation regime

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

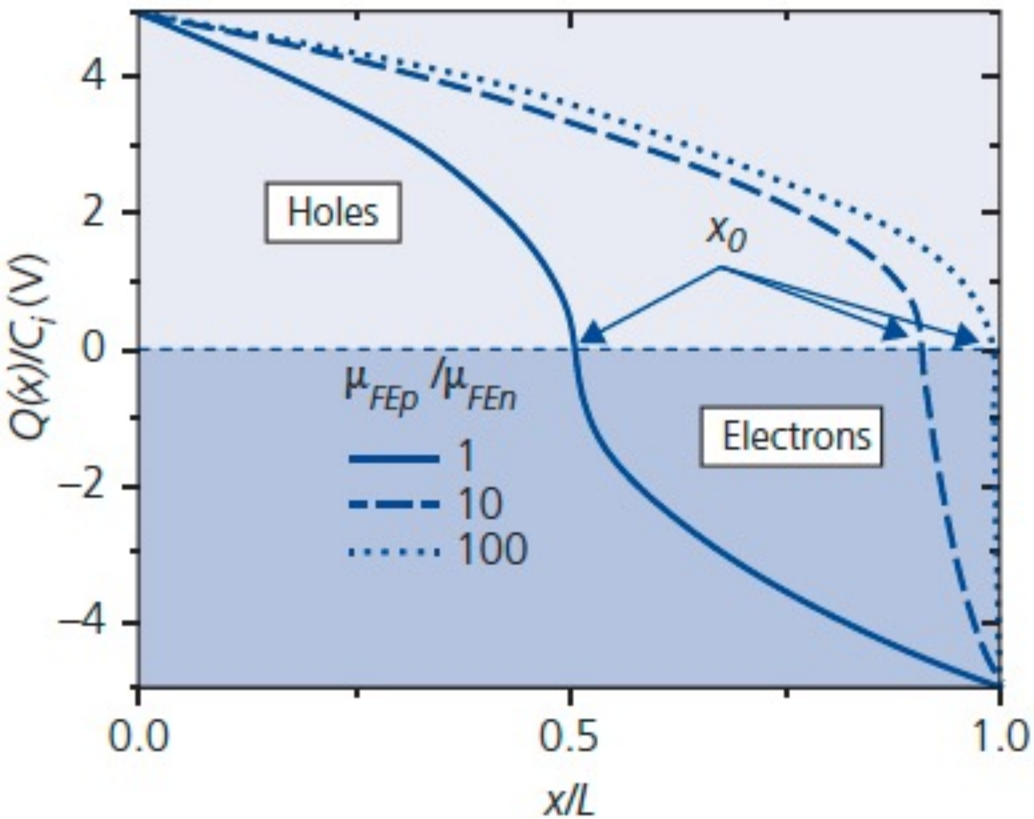
$$\left(\begin{array}{c} V_{DS} \ge V_{GS} - V_{Tn} \\ V_{DS} \le V_{GS} - V_{Tp} \end{array}\right)$$

Ambipolar (quadratic) regime

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

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

The recombination point depends on ratio of hole to electron μ_{FE}



V_{GS} = -15 V
V_{DS} = - 10 V
V_T = 0 V

(linear regime operation)

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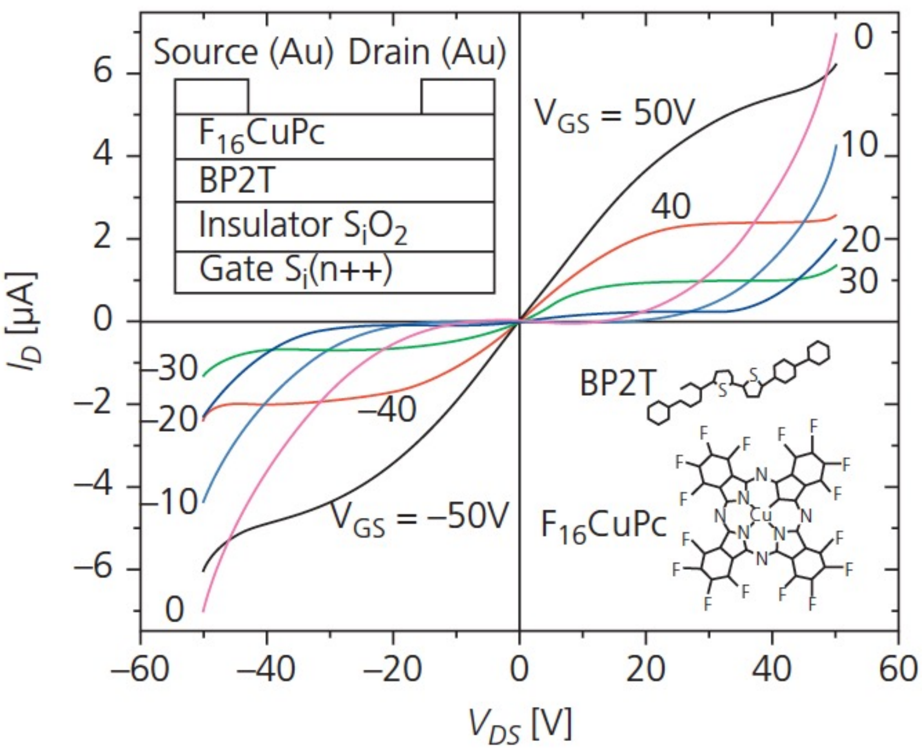
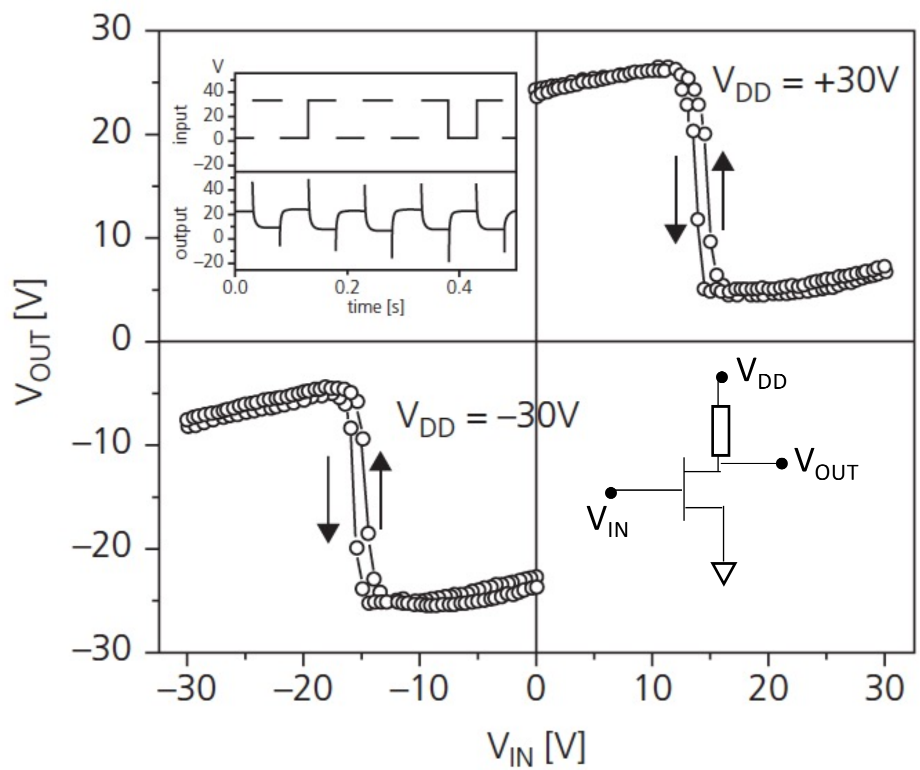
Schumechel et al. J. Appl. Phys. 98, 084511 (2005)

Bilayer ambipolar OTFT





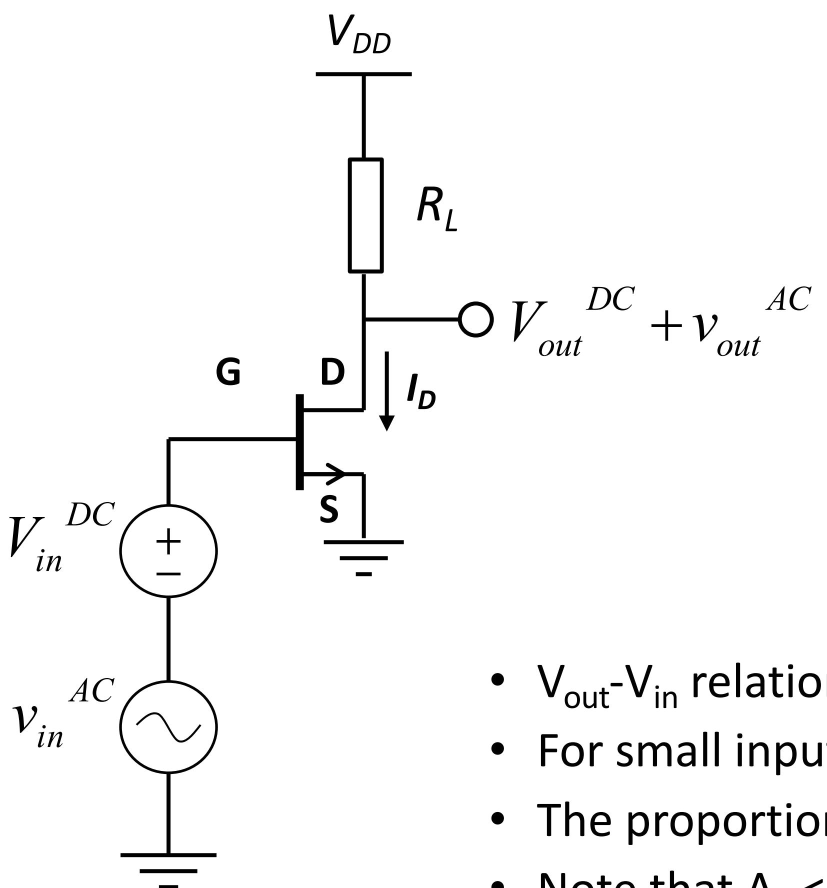
Disadvantage of the ambipolar OTFT: I_{on}/I_{off} is small since no condition where one carrier type is completely absent.

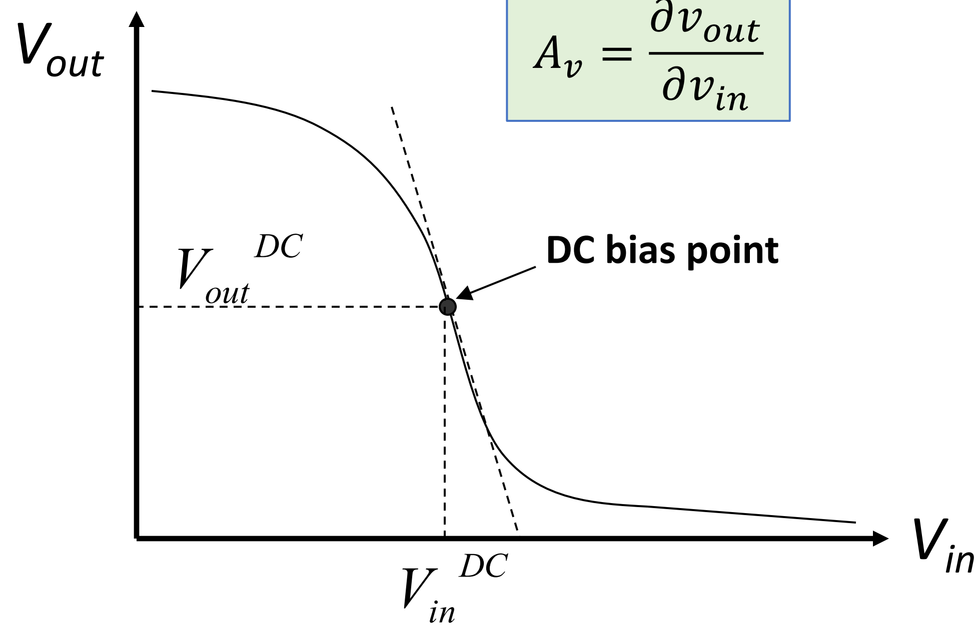
Wang et al., Appl. Phys. Lett. 88, 133508 (2006)

Common Source Amplifier Circuit

Input DC bias point, AC input signal

Output will be DC bias point, AC output signal





$$A_v = \frac{\partial v_{out}}{\partial v_{in}}$$

- V_{out}-V_{in} relation approximately linear near bias point
- For small input signal, linear relation $v_{out} = A_v v_{in}$
- The proportionality constant $|A_v| > 1$, voltage gain.
- Note that $A_v < 0$: **Inverting amplifier**

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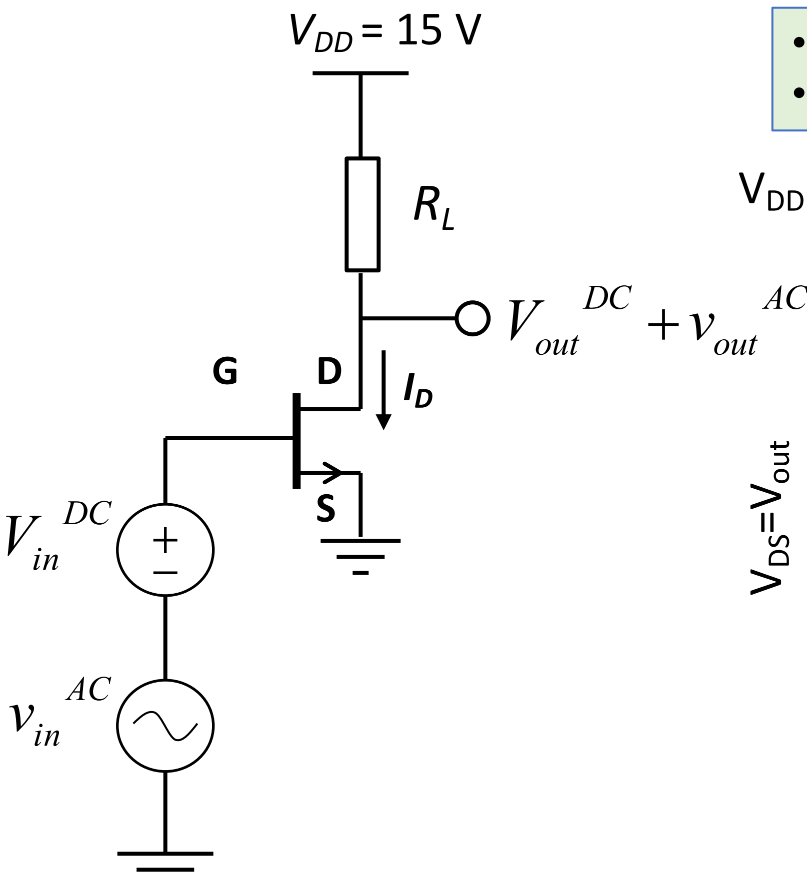
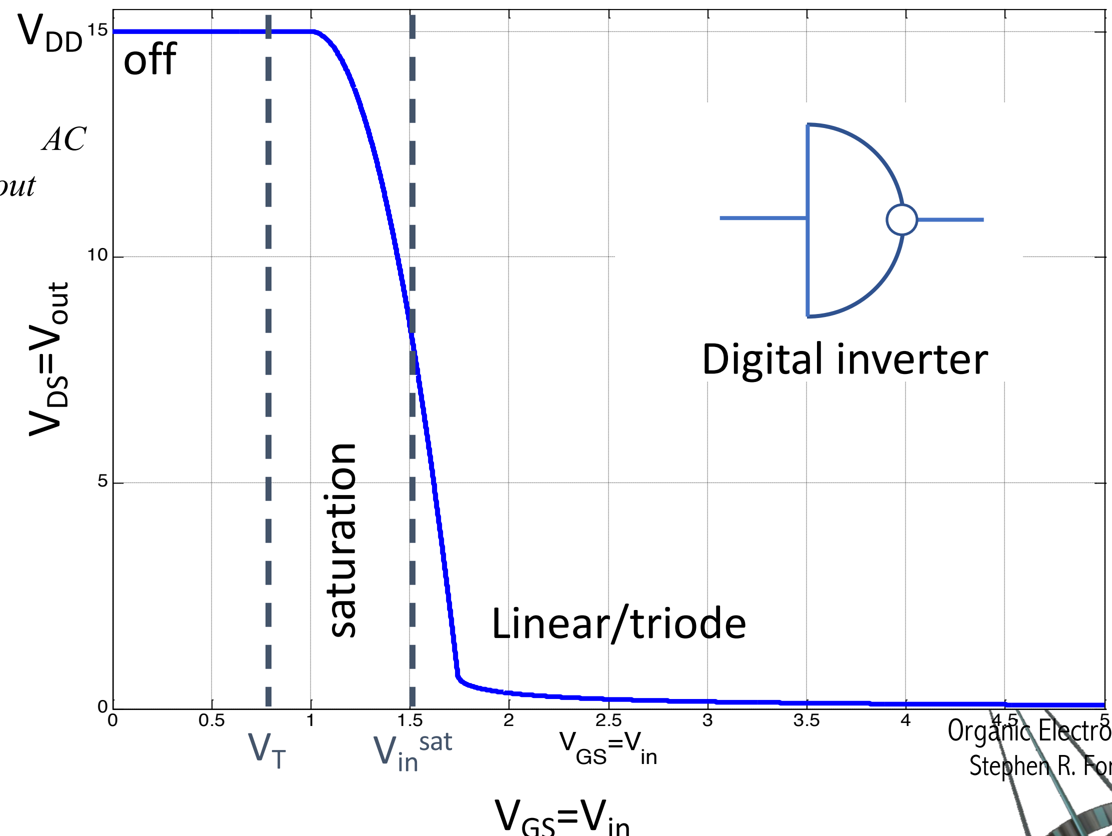
Input/Output Characteristics

Relationship between V_{out} and V_{in}

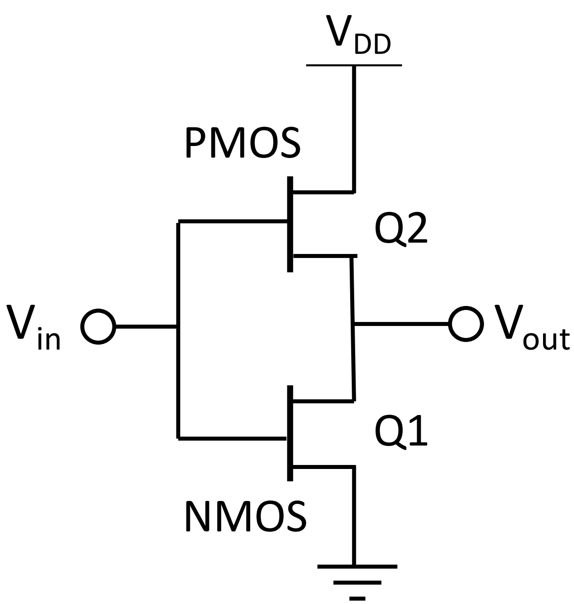
- In digital circuits, V_{in} swept from fully on to triode regime
- In linear circuits, work within saturation regime





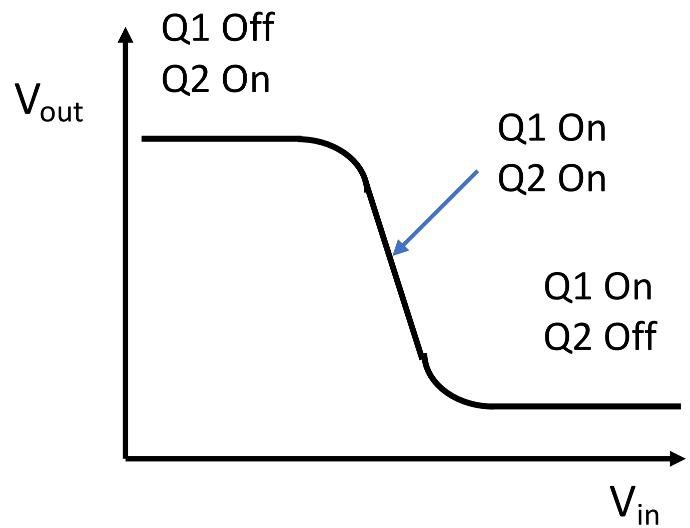
Digital Complimentary Logic Circuit

Either one or the other transistor is ON at one time (never both)
⇒Only power dissipation is in switching logic state from ON to OFF



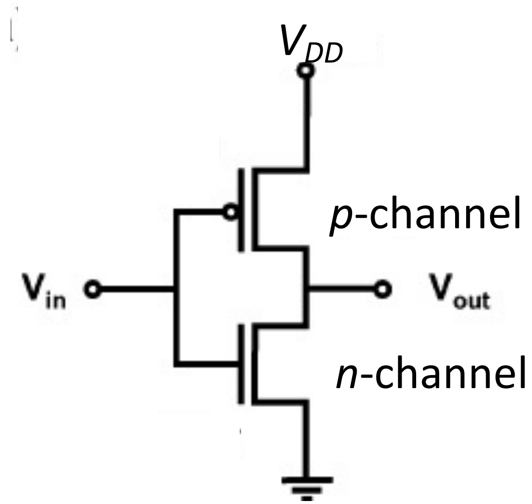
V_{in}=0 V
Q1 Off
Q2 On
$V_{out} = V_{OH}$

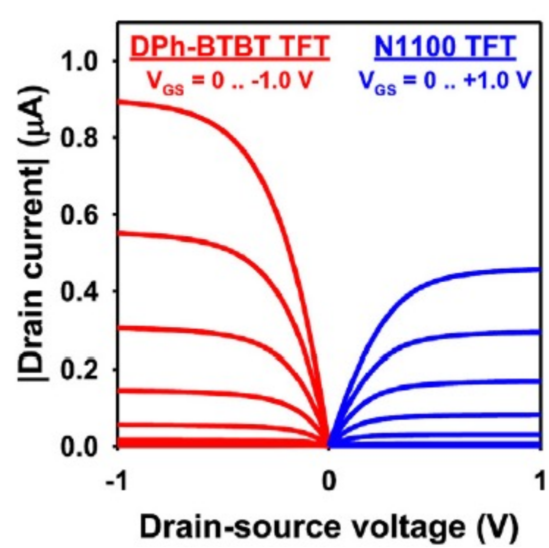
$V_{in} = V_{DD}$
Q1 On
Q2 Off
$V_{out} = V_{OL}$

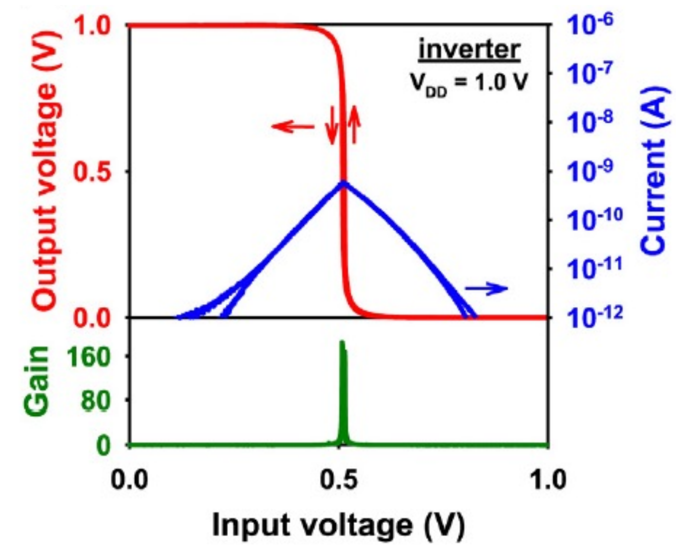


Digital Complimentary OTFT Circuit

Similar to CMOS technology in Si ICs
Uses n- and p-channel OTFTs or Ambipolar Channels





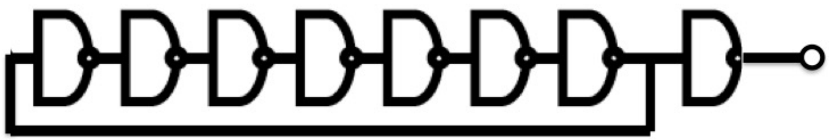


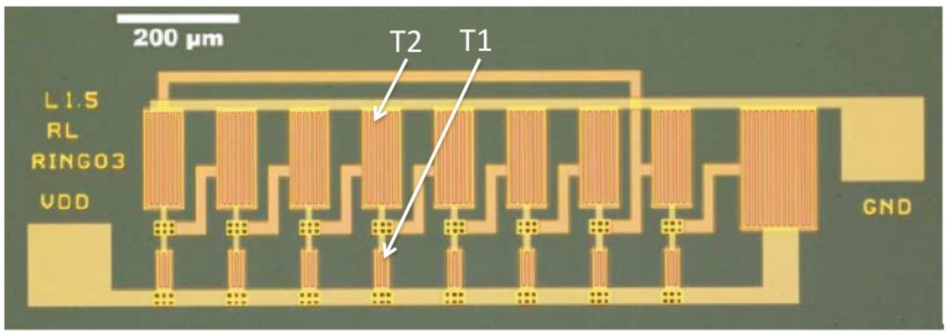
Zschieschang, et al., 2017. *Organic Electron.*, 49, 179.

Ring Oscillators can also Measure Frequency Response

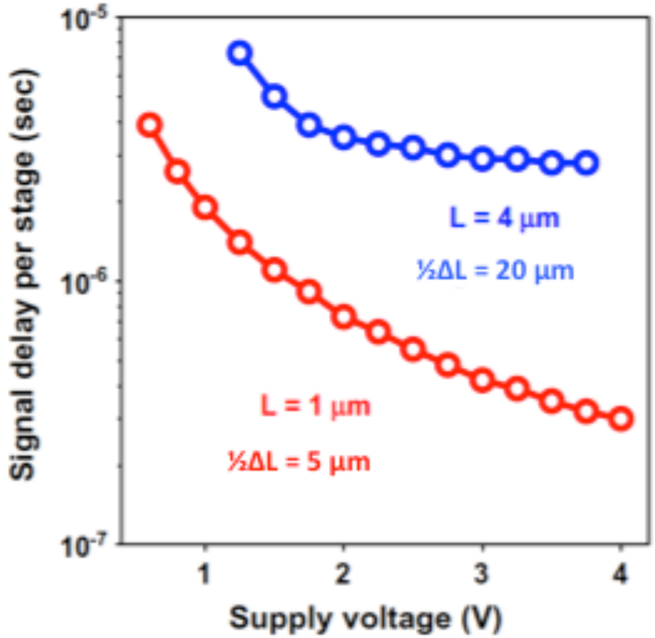
For an odd number (N) of inverter gates, feedback is positive driving the circuit to oscillate

7 stage ring oscillator





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



Oscillation frequency a function of the delay per gate

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

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

Zschieschang, et al., 2013. *Organic Electron.*, 14, 1516.

Contributions to OTFT Noise

(See Ch. 7.1.1)

Noise quantified in terms of the mean square noise currents

$$S_{Itot} = \sum_n \left\langle i_n^2 \right\rangle$$

: S_{Itot} is the total noise spectral density

There are two white noise components due to channel Johnson (thermal) noise

$$S_{th} = \left\langle i_{th}^2 \right\rangle = 4k_B T g_0$$

Channel conductance noise

$$S_{th} = \left\langle i_{th}^2 \right\rangle = \frac{8}{3} k_B T g_m$$

Channel noise in saturation regime

An important noise in transistor is 1/f noise: this has a frequency dependence

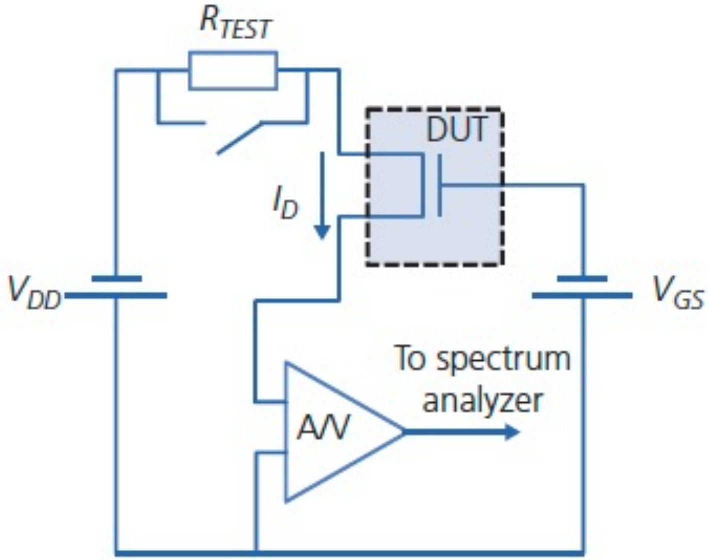
Hooge's empirical formula

$$\frac{S_f}{I_D^2} = \frac{\left\langle i_f^2 \right\rangle}{I_D^2} = \frac{\alpha}{N f^{\gamma}}$$

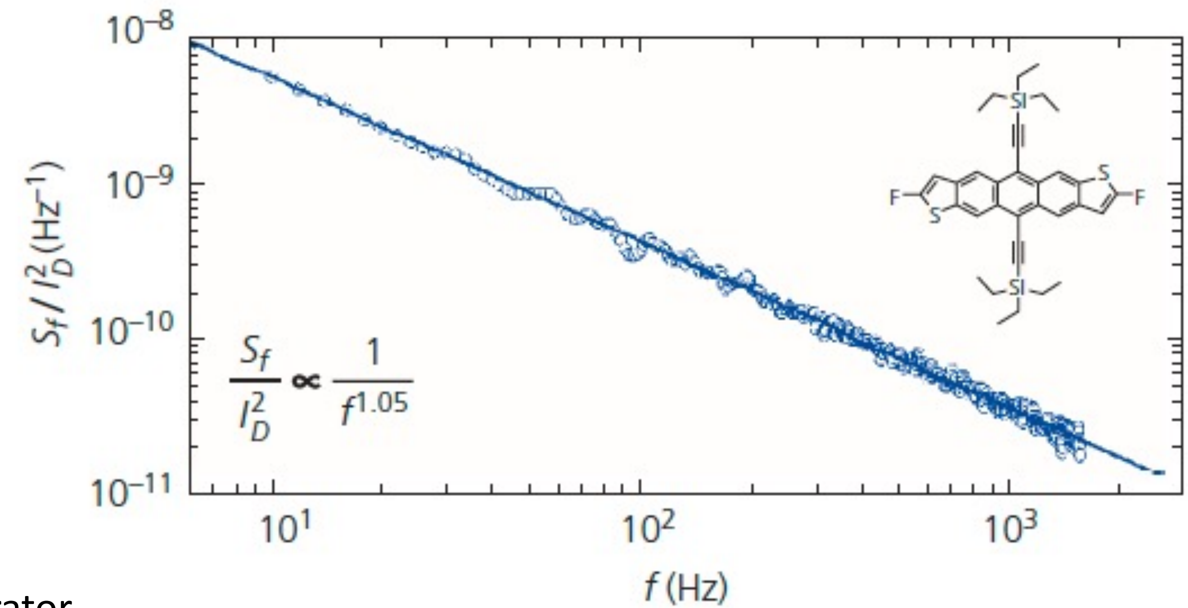
α = Hooge parameter (empirical)
N = # carriers in channel
γ ~ 1 (another empirical parameter)

Noise of a p-Channel OTFT in the Linear Regime

Noise measurement circuit



1/f dependence of noise diminishes as f→large



- R_{TEST} is "perfect" Johnson noise generator
- Change R_{TEST} until noise doubles, at which point noise from R_{TEST} = noise from DUT

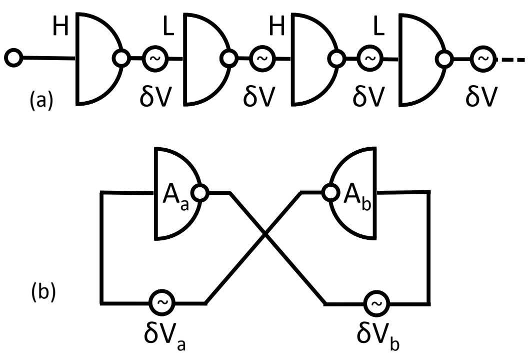
dif-TESADT channel OTFT

Jurchescu et al. Appl. Phys. Lett. 92, 132103(2008)

Noise Margin

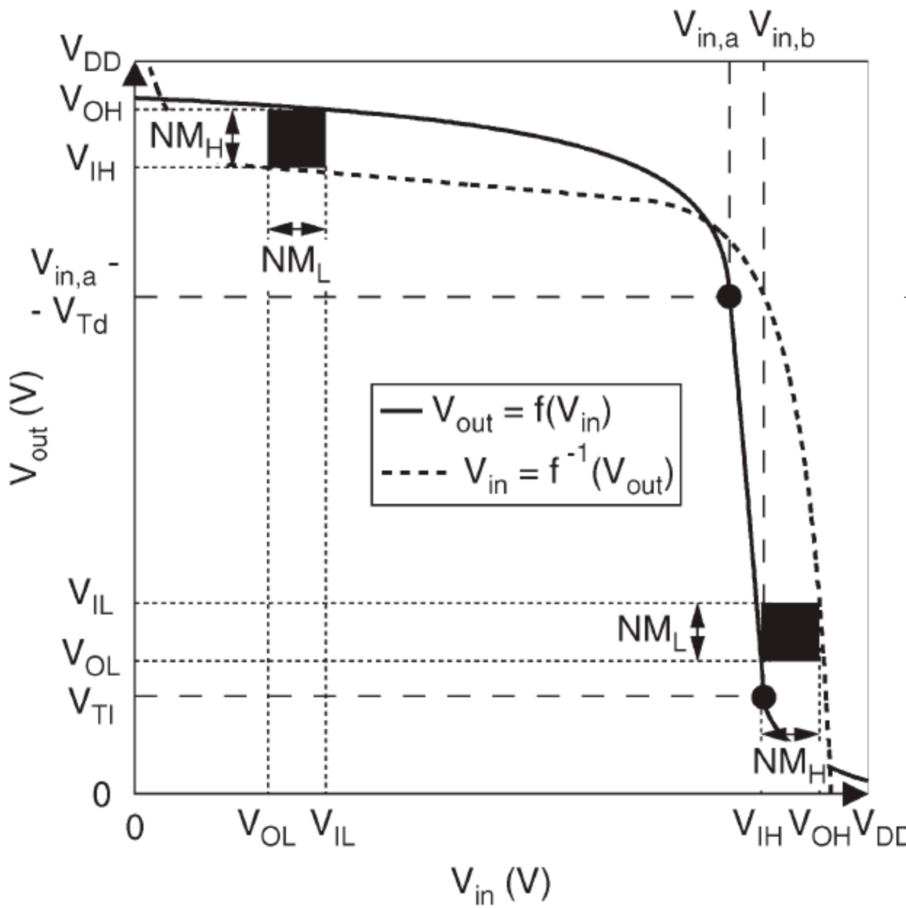
To guarantee reliable switching,
LOW and HIGH inputs must be clearly distinguished by the circuit.

Infinite chain of inverters



Equivalent circuit of the infinite chain

$V_{OL} = V_{out}$ (low)
$V_{IH} = V_{in}$ (high)

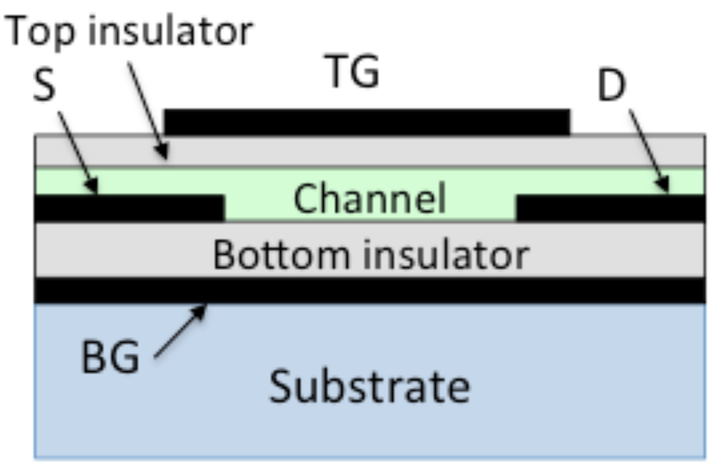


$$NM_H = V_{OH} - V_{IH}$$
$$NM_L = V_{IL} - V_{OL}$$

De Vusser, et al. IEEE Trans. Electron. Dev., 53, 601 (2006).

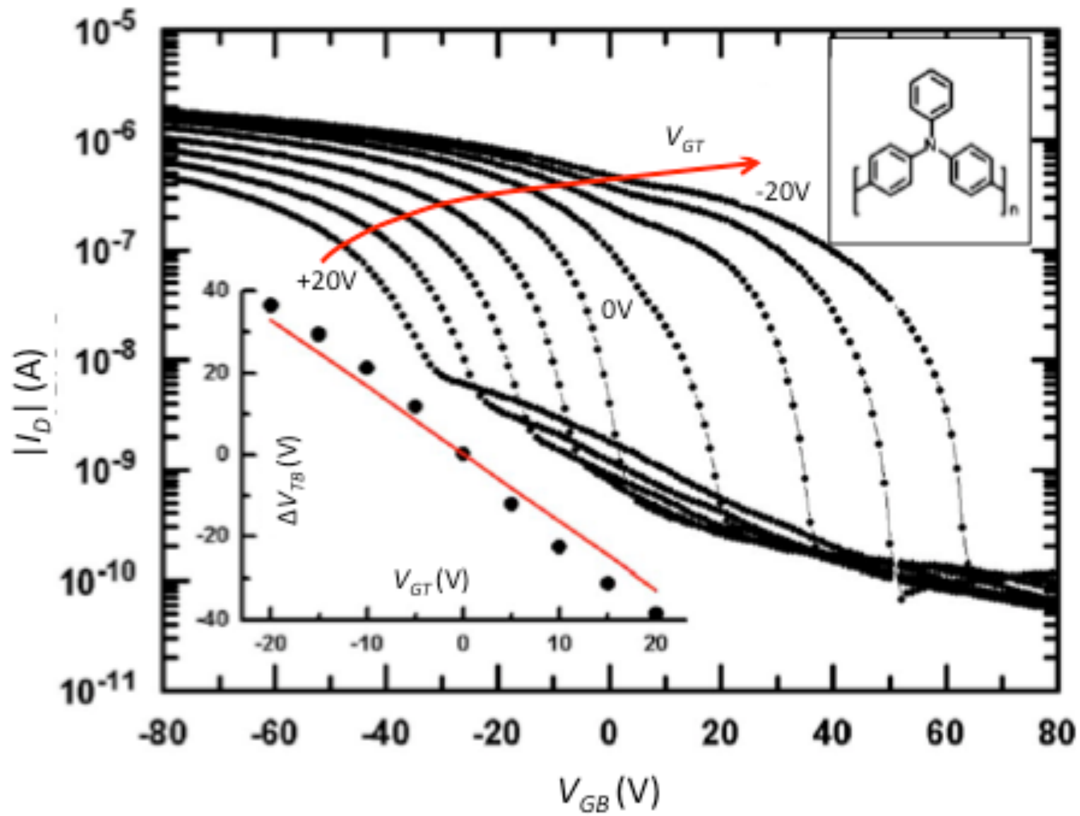
Dual gate transistors

- 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



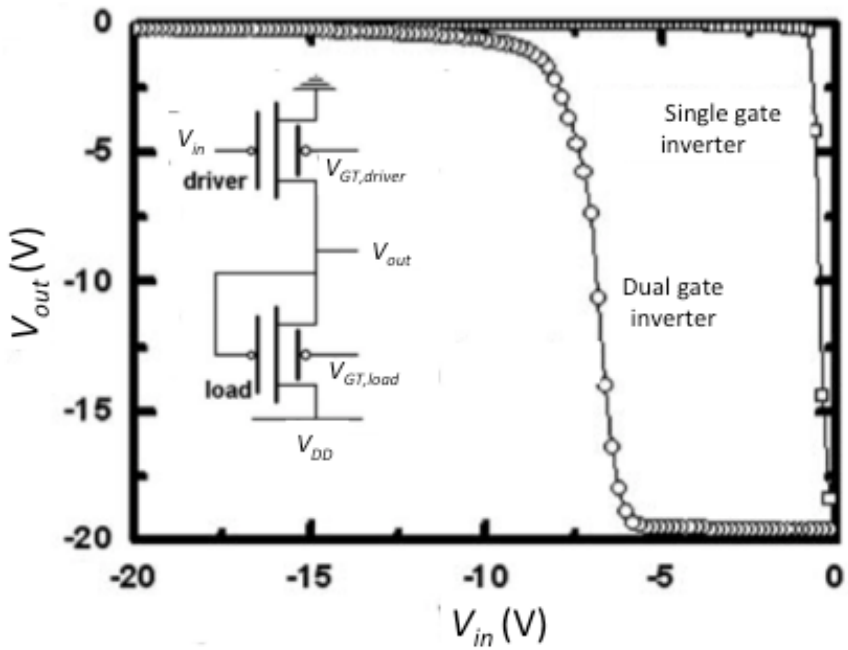
Shift in top gate threshold related to bottom gate voltage:

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



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

Dual gate control

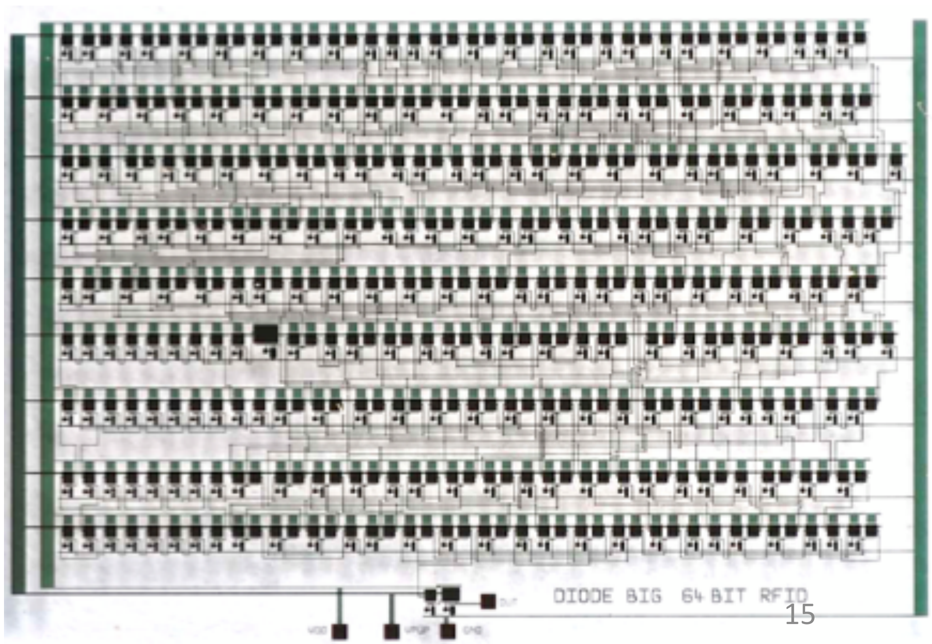


Improved noise margin
Control of circuit gain

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

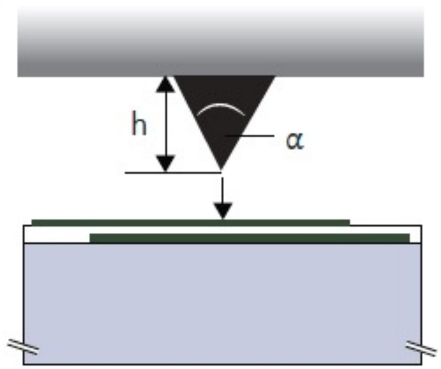
Photograph of a 64-bit RFID transponder operating at 4.3 kb/s using dual gate inverter logic.

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

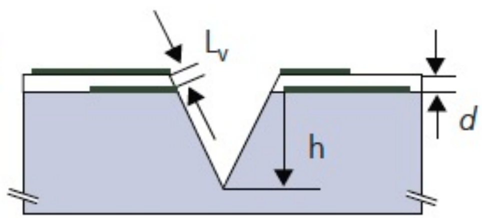


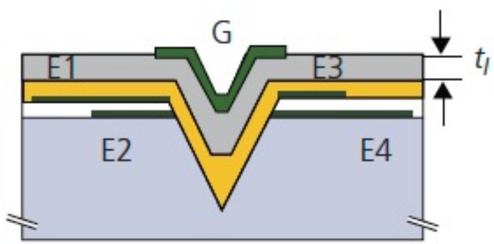
Other Device Types

V-gate transistor



Knife edge cuts through contact layers



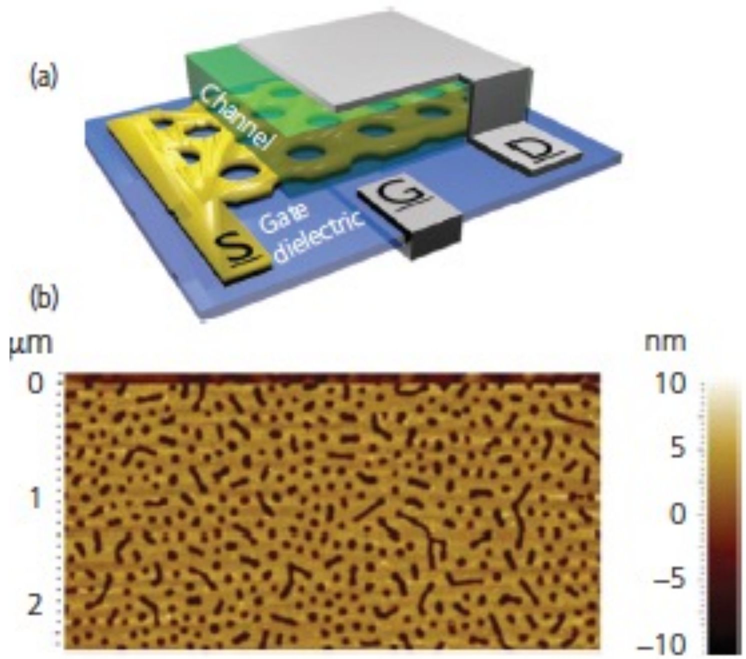


Channel and gate insulator deposited

Vertical geometries reduce channel transit times ⇒ higher bandwidth
Can be more compact than lateral OTFTs
Can run in vertical mode ($S=E_1$, $D=E_2$) or horizontal mode ($S=E_1$, $D=E_3$)

Stutzman, et al., Science, 299, 1881 (2003)

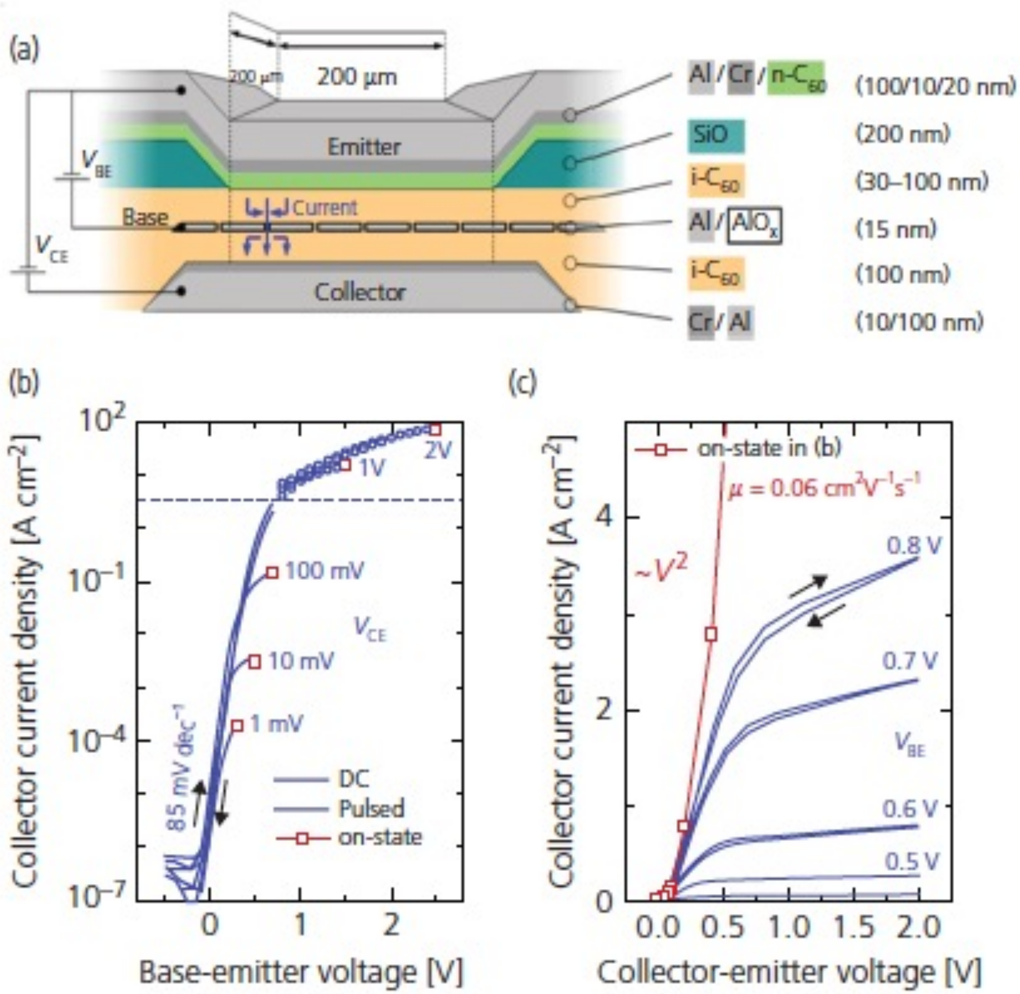
Permeable source transistor

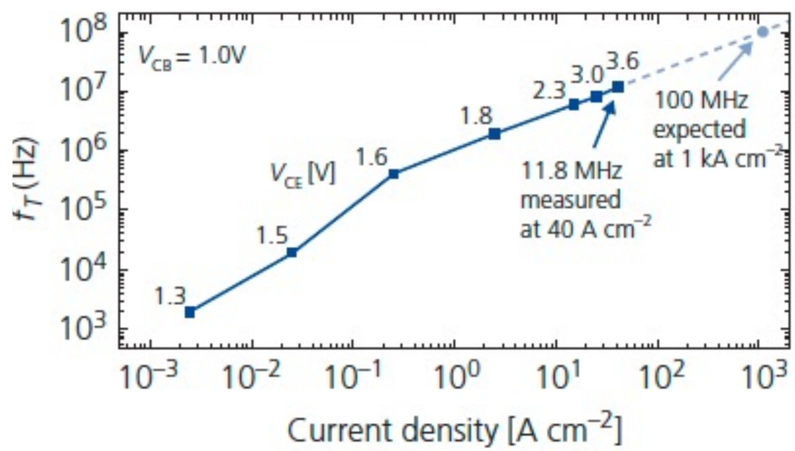


Gate (separated from S by gate dielectric) controls S-D current by attraction or repulsion of charge emitted from S
Operates similar to transistor in the triode mode (can have low g_O)

Ben-Sasson et al., (2009). Appl. Phys. Lett., 95, 302.

Vertical Permeable Gate OTFT



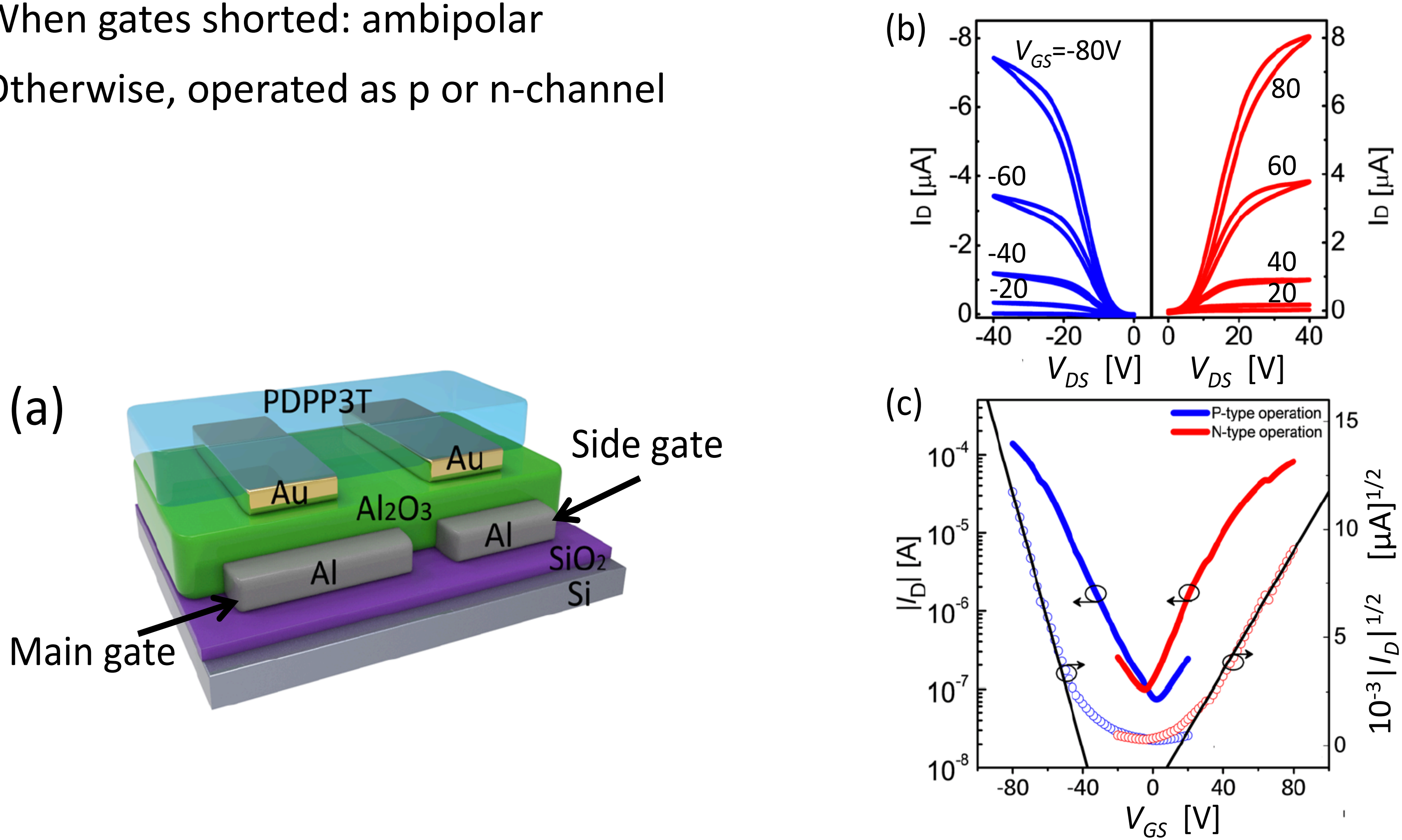


- Vertical geometry
  - ⇒short distance between emitter & collector
  - ⇒potentially high frequency
- Not shown in this particular device compared to conventional OTFTs

Klinger et al. (2017). Scientific Reports, 7, 44713.

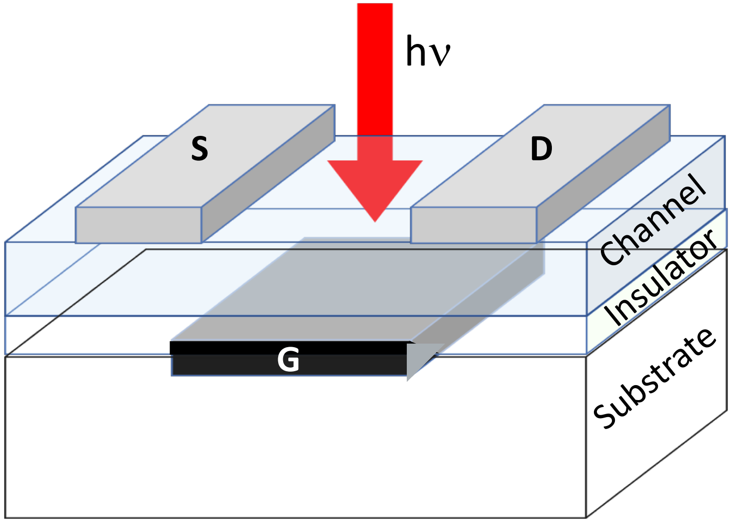
Other Device Types
Split gate transistor

- When gates shorted: ambipolar
- Otherwise, operated as p or n-channel



Phototransistors

- Changing the number of charges in the channel results in changing the drain current ⇒ gain
- Optical generation in a phototransistor is one such means
- While current gain can potentially be large, gain-bandwidth product limits frequency response
- An exciton dissociating junction needed to create the charge
- Possible charge generating mechanisms include exciton dissociation at:
    - contacts
    - traps at the insulator surface
    - field ionization



Phototransistor operating principles

Incident light generates charge, which changes the gate capacitance:

$$\Delta C_{GS} = \frac{\partial Q}{\partial V_{GS}} = q^2 \frac{\partial n_s}{\partial E_F}$$

This produces a gate photovoltage:

$$qV_{ph} = \Delta E_F$$

The photovoltage induces charge at the interface:

$$n_T = n_0 \exp\left(q\Delta E_F / k_B T\right)$$

Which produces a photocurrent that adds to the dark current in the channel:

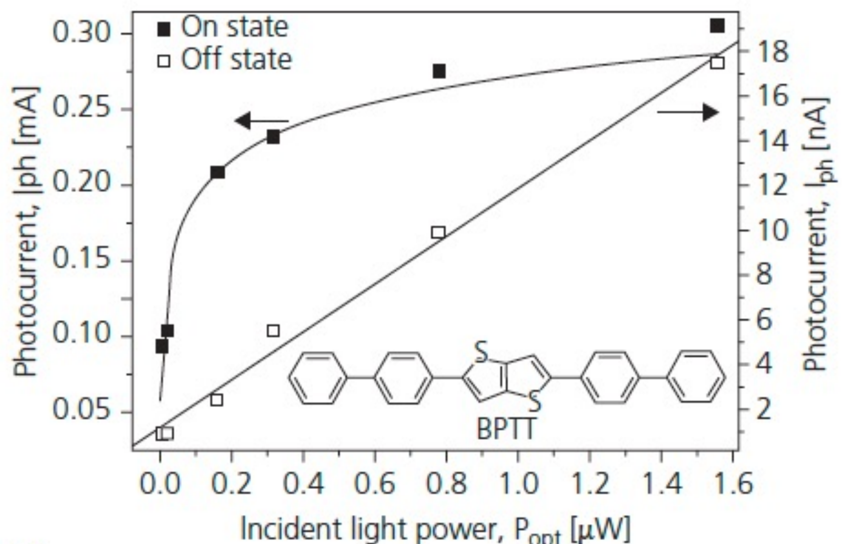
$$n_T = n_{ph} + n_0 = \frac{\left(j_{ph} + j_D\right)}{q\mu F}$$

Then: $V_{ph} = \frac{nk_BT}{q}\ln\left(\frac{j_{DT}}{j_D}\right) = \frac{nk_BT}{q}\ln\left(1 + \frac{j_{ph}}{j_D}\right)$ or: $V_{ph} = \frac{nk_BT}{q}\ln\left(1 + \frac{q\eta_{ext}\lambda P_{inc}}{j_D hc}\right)$

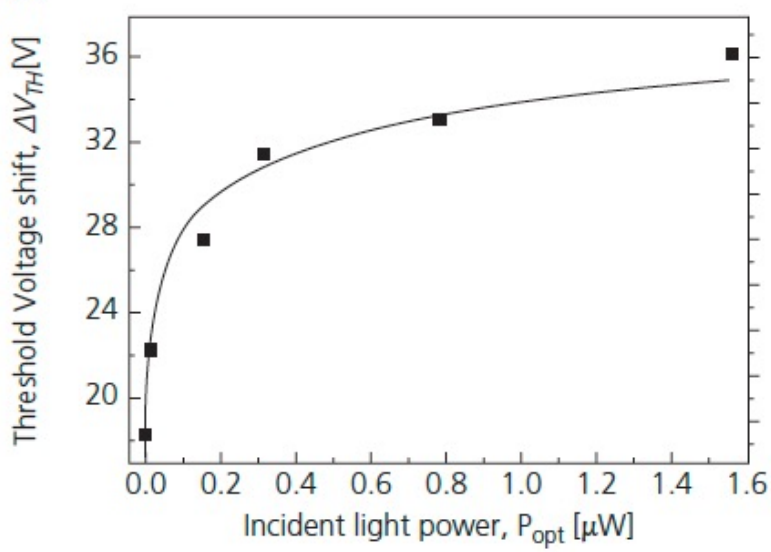
Finally yielding the channel photocurrent:

$$I_{ph} = g_m V_{ph} = \frac{g_m nk_BT}{q}\ln\left(1 + \frac{q\eta_{ext}\lambda P_{inc}}{j_D hc}\right)$$

Operating Characteristics of an OTFT



(b)



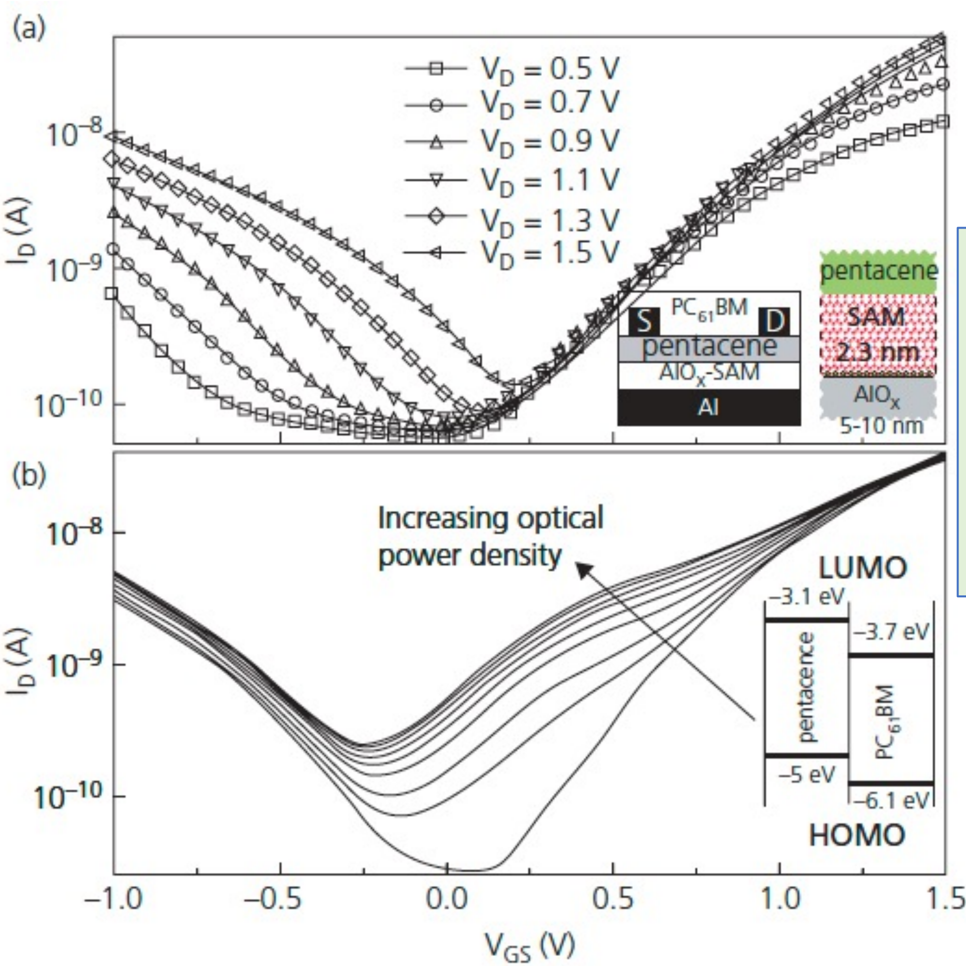
W/L=5mm/20 µm

μ_{FEp} = 0.82 cm^2/V s

$\mathcal{R}$=82 A/W at I_{inc} = 1.55 mW/cm^2

Noh, et al. Appl. Phys. Lett. 86, 043501 (2005)

OTFT With Exciton Dissociating HJ

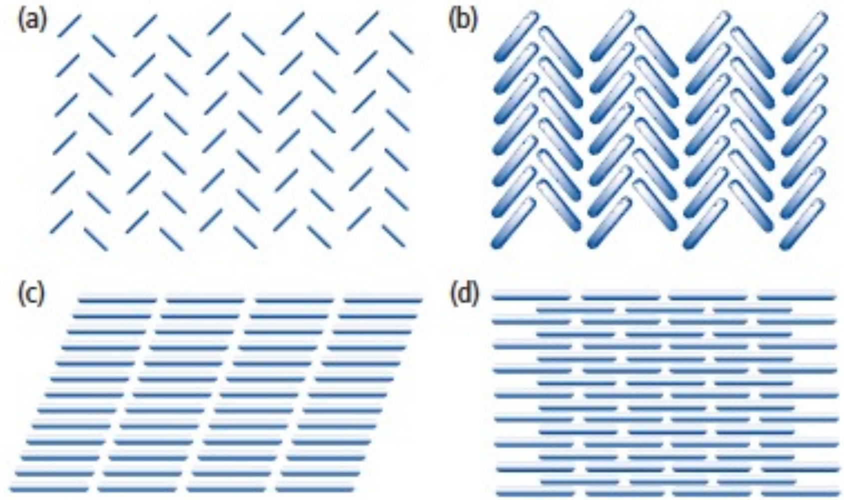


- Channel contains a D-A pentacene/C_{60} HJ for exciton dissociation
- Ambipolar response due to combination of D & A layers
- λ = 469 nm
- Maximum η_{ext} = 0.8 %.

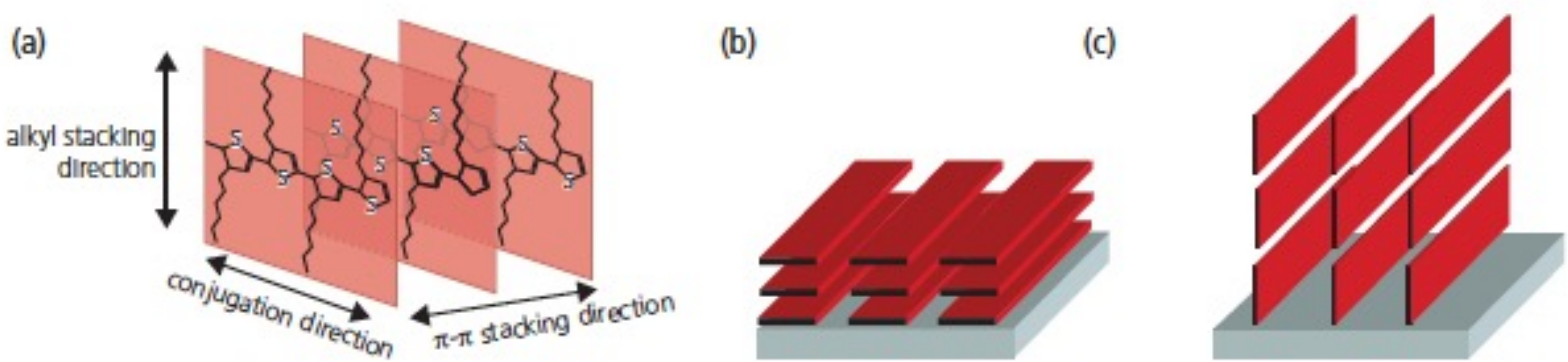
Labram et al. Org. Electron. 11, 1250 (2010)

Morphology Determines OTFT Mobility

Highest mobilities when π-stacking is in the transistor plane



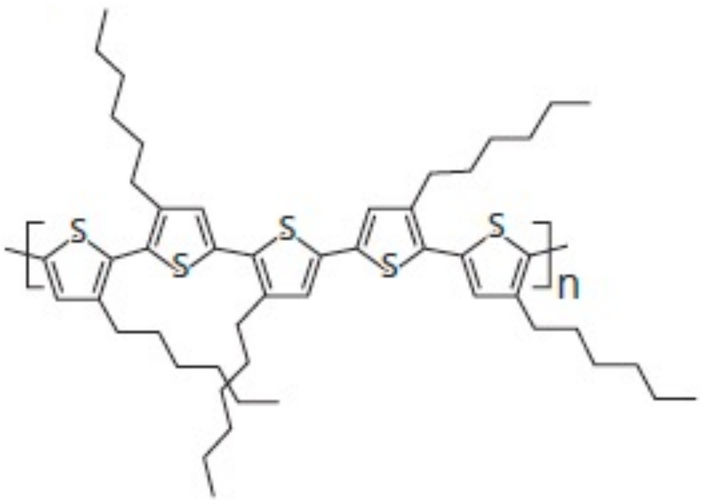
Different, common organic stacking motifs
(see Chapter 2)



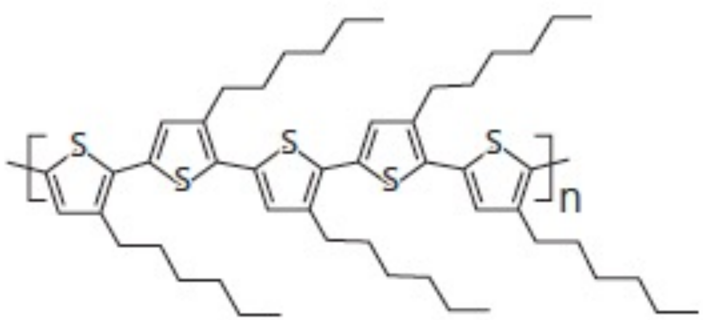
best vertical conduction

best in-plane conduction

Structural Conformity Can Improve π-Stacking



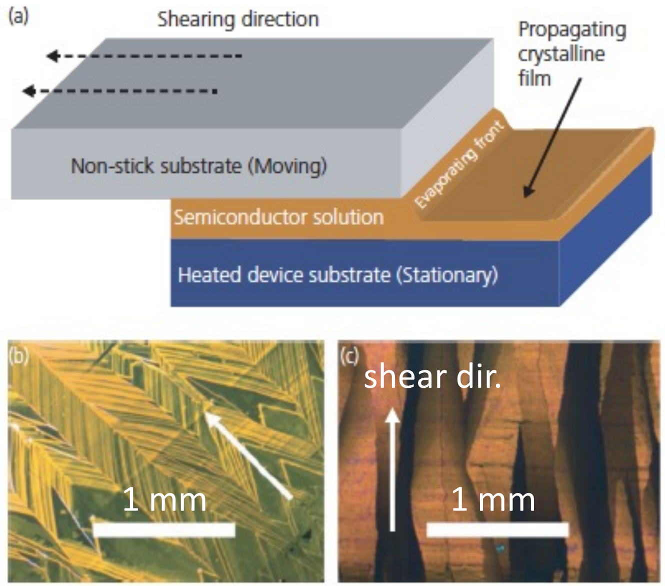
Regiorandom alkane groups in this irregular arrangement leads to poor π-stacking
⇒Low mobility between thiophene cores in adjacent molecules



Regioregularity leads to improved π-stacking
⇒Improved mobility between thiophene cores

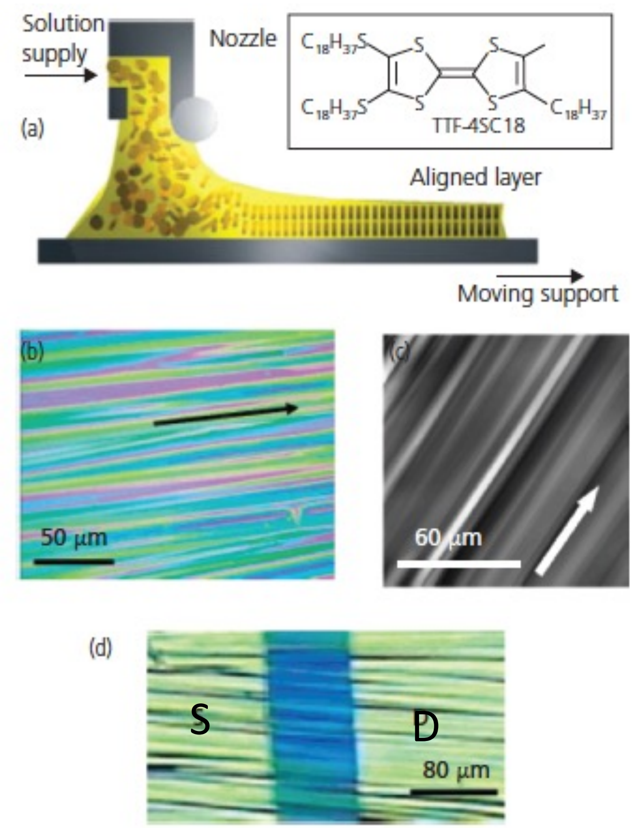
Methods for Orienting the Channel Semiconductor

solution shearing



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

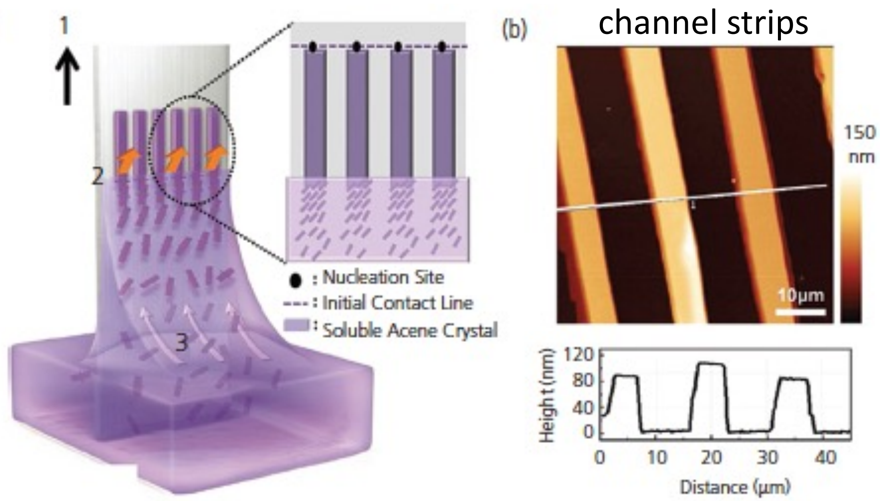
zone casting



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

dip coating

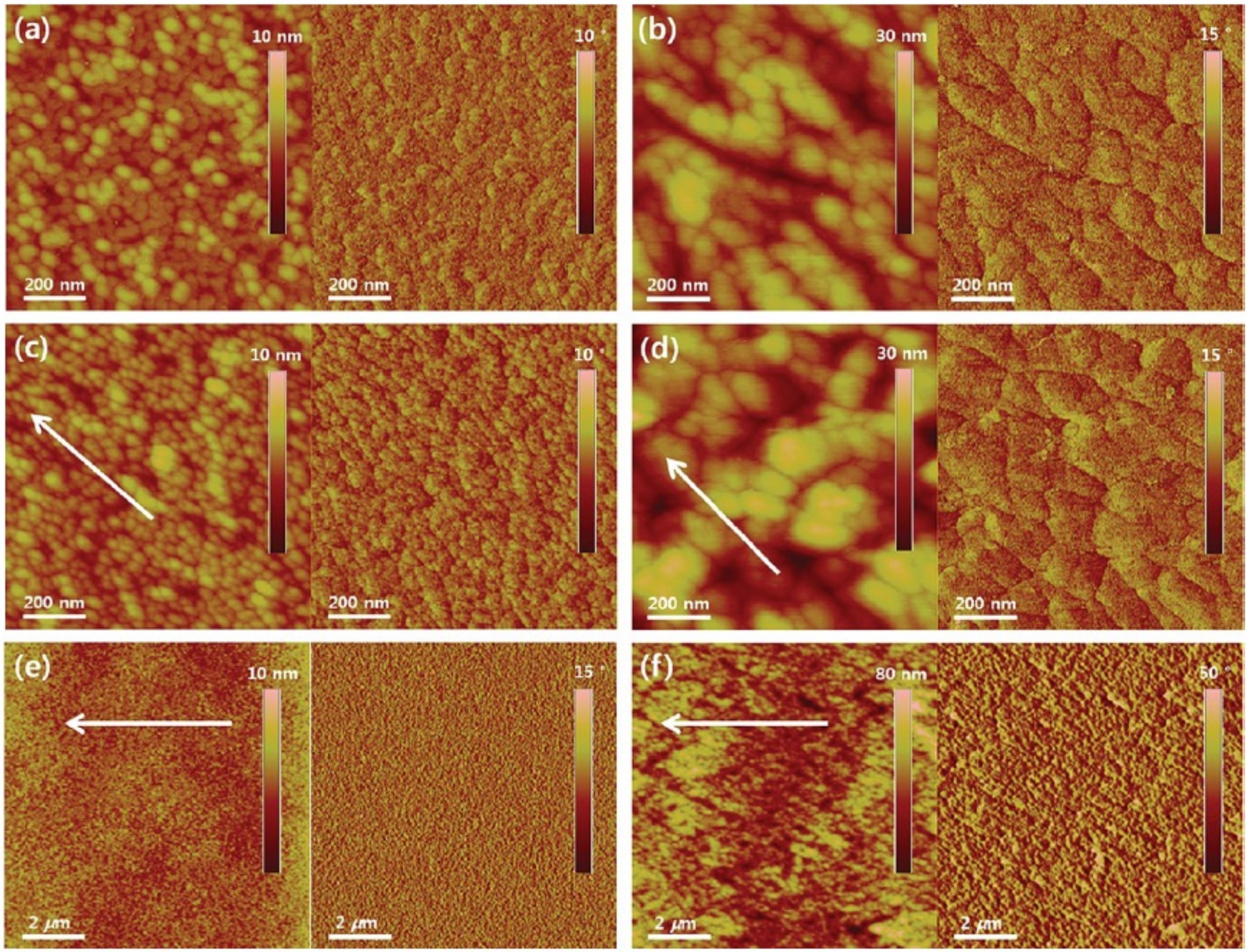
TIPS-pentacene channel strips



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

Morphologies Achieved by Drop Casting vs. Solution Shearing

PTDPPSe PTDPPSe-Si



Drop casting

Solution shearing
(arrows = shear dir.)

- Drop cast films show some directionality
- Mobilities ~2X drop cast films

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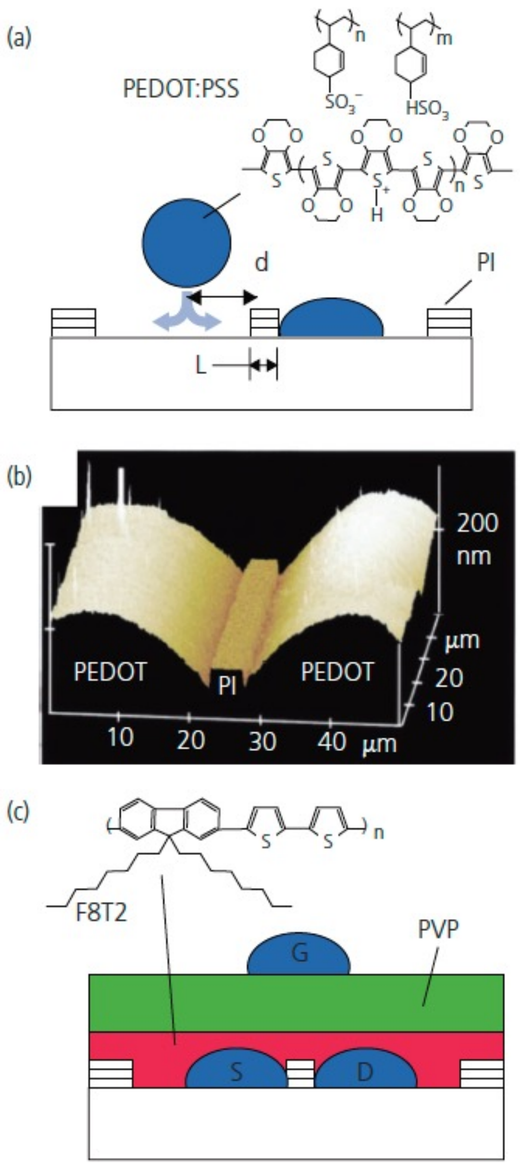
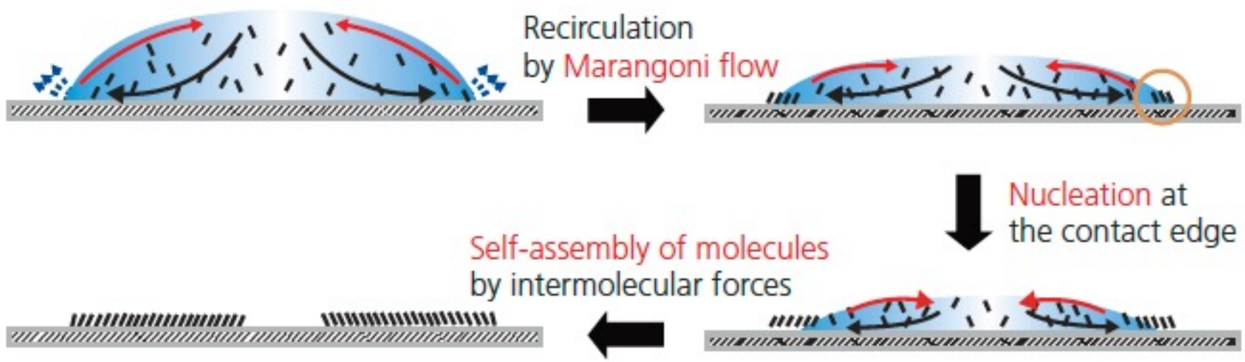
Lee et al., J. Am. Chem. Soc. 134, 20713 (2012)

Ink-Jet Printed Channels: Morphology Depends on Drying Dynamics





- Marangoni flow creates convection in two component solution
- Volatile component evaporates quickly at edges
- Can result in aligned molecular stacks forming a “coffee ring” pattern

Ink confined by choice of hydrophilic or hydrophobic surfaces on which it is deposited

Sirringhaus et al. Science 290, 2123 (2000)

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