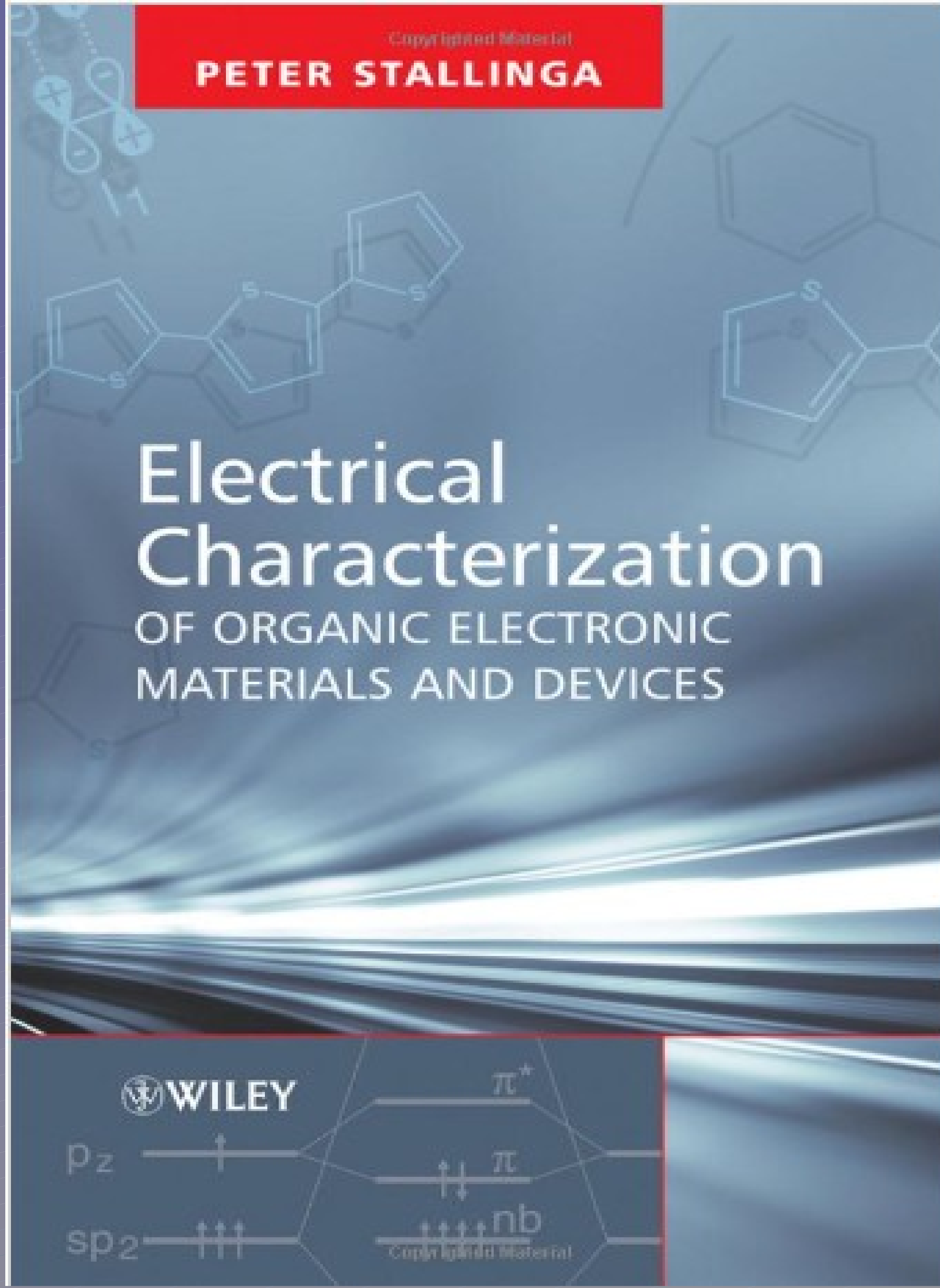
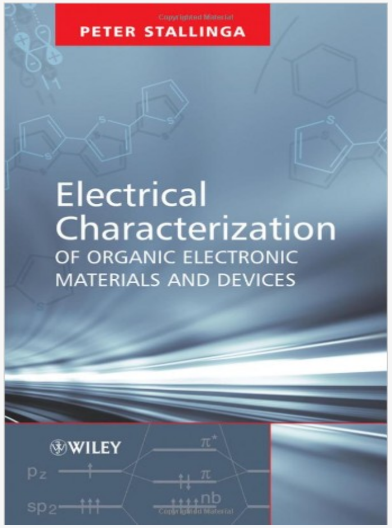

Copyrighted Material
PETER STALLINGA
Electrical Characterization
OF ORGANIC ELECTRONIC MATERIALS AND DEVICES
WILEY
π*
π
nb
pz
sp2
Copyrighted Material

Presentation of book

- Summary of 10 years of research in organic electronics in OptoEl/CEOT
- Not a summary of literature
- My 'real' thesis
- Editor: Wiley (top in physics)
- Full of original new ideas (some presented here today)



I: Conduction mechanism

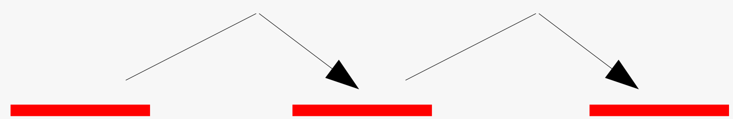
Conduction. charge moves from A to B under electrical field.
But, what IS that charge and HOW does it move?

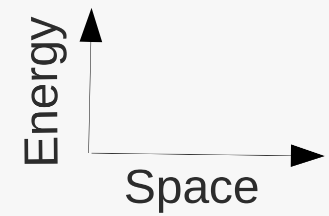
Scientific community of Organic Electronics is dominated by chemists. All effort is spent on finding new materials and production paths. (Electrical) characterization techniques are black boxes to test success of material or path.

Molecule is the basic unit. Moiety.
Conduction is a perturbation to the electronic level scheme.
Very good for low-conductive materials (traditional plastics).
New (conductive) materials were tested with old theories.

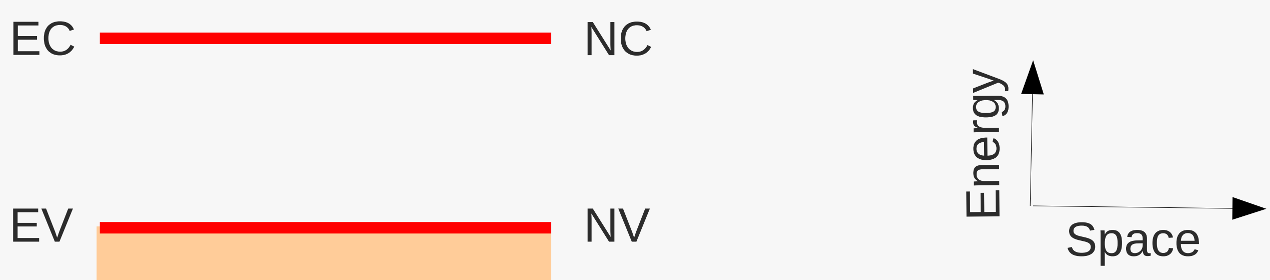
My background is semiconductor physics. “If you have a hammer as a tool you see every problem as a nail!”
Where does standard semiconductor theory fail? Nowhere!

Percolation Theory or Hopping Theory
Charge spends all its time on sites (moieties) and occasionally makes a jump to a near or far sites





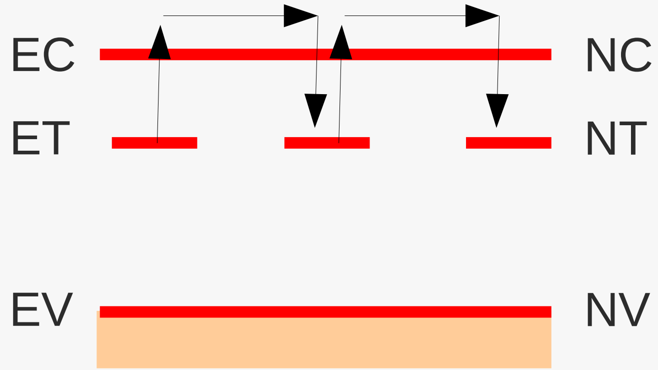
Band Theory.
Crystalline materials*
Individual (moiety) levels irrelevant
Electronic levels of entire crystal summarized as NV at EV and NC at EC.

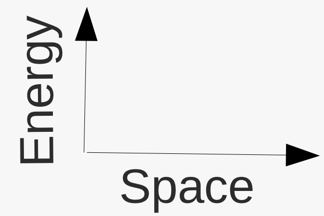


*: Ioffe, Regel and Gubanov, “A periodic electric field of the lattice is not essential for the occurrence of typical semiconducting properties and the band model may be applied also in the case in which there is a loss of periodicity of the lattice” (a citation of the work of Caserta, et al.). Amorphous materials? → Band Theory!

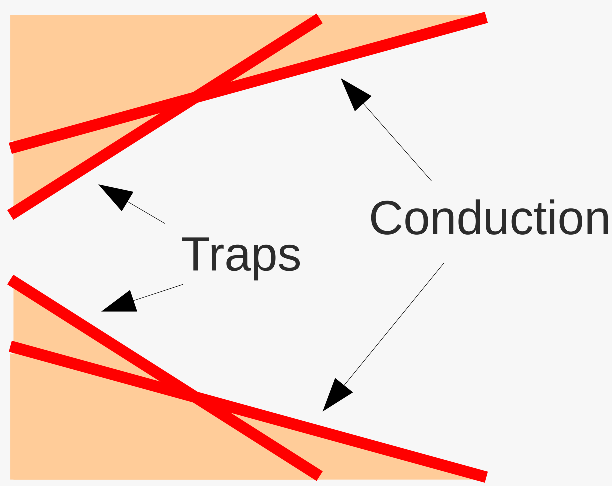
I: Conduction mechanism
Poole-Frenkel

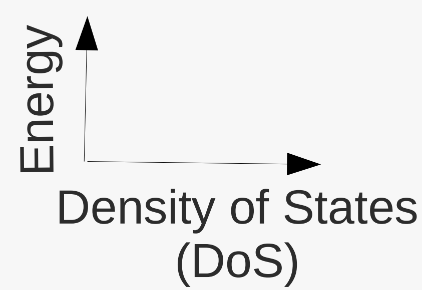
Modified Band Theory. Poole-Frenkel. Bands with localized trap levels





Amorphous Poole-Frenkel.





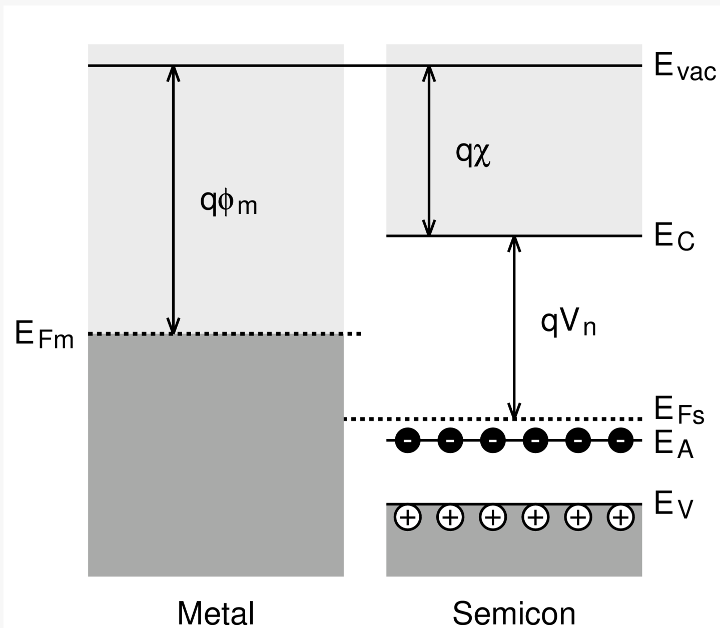
I: Conduction mechanism Poole-Frenkel

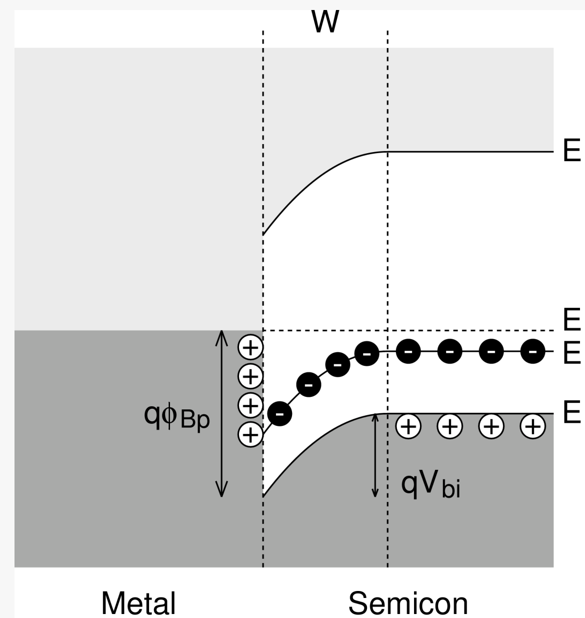
- Temperature activated mobility ($\mu \sim \mathrm{Exp}(E_\mathrm{A}/kT)$)
- Bias-dependent mobility ($\mu \sim V^a$)
- Transient effects ($I = f(t)$). Stressing, etc. Hysteresis
- Anomalous time-of-flight (ToF) behavior, $\mu_\mathrm{ToF} = f(d)$

One idea to explain everything. Not limited to a certain device or a certain measurement technique. Everything fits like a puzzle.

Conclusion. Band Theory vs. Percolation Theory:
"It walks like a duck, it talks like a duck. It is a duck!" (Band Theory!).

II: Device description: TFT precursor 1) Schottky barrier





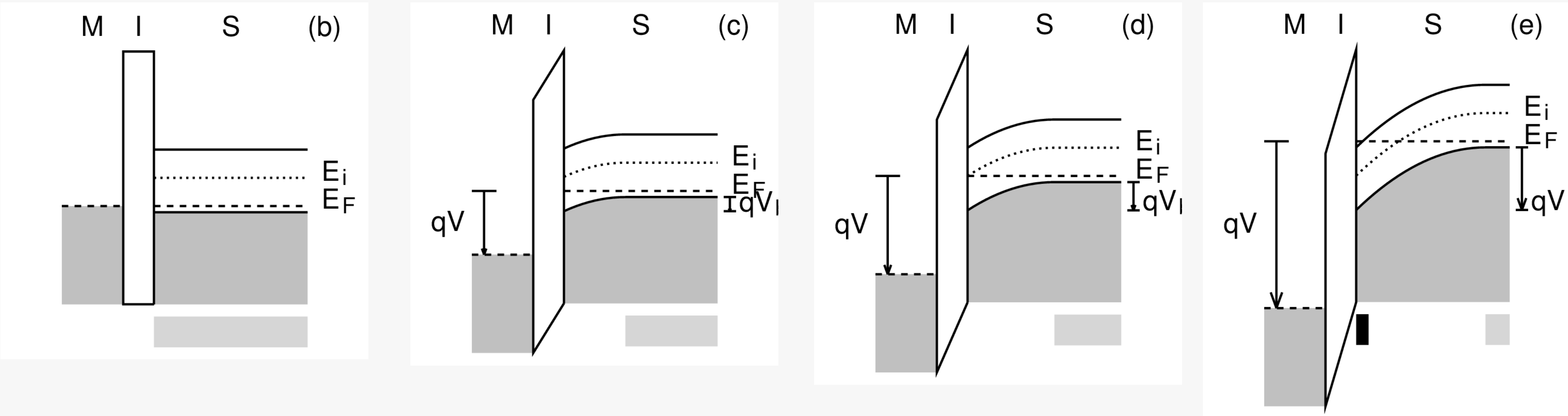
Charge jumps from one side to other, leaving behind uncompensated dopants

Poisson Equation: $\int\int \rho(x)\, d^2x = V(x)$

Rectangular space charge (uncompensated acceptors) ρ → quadratic V

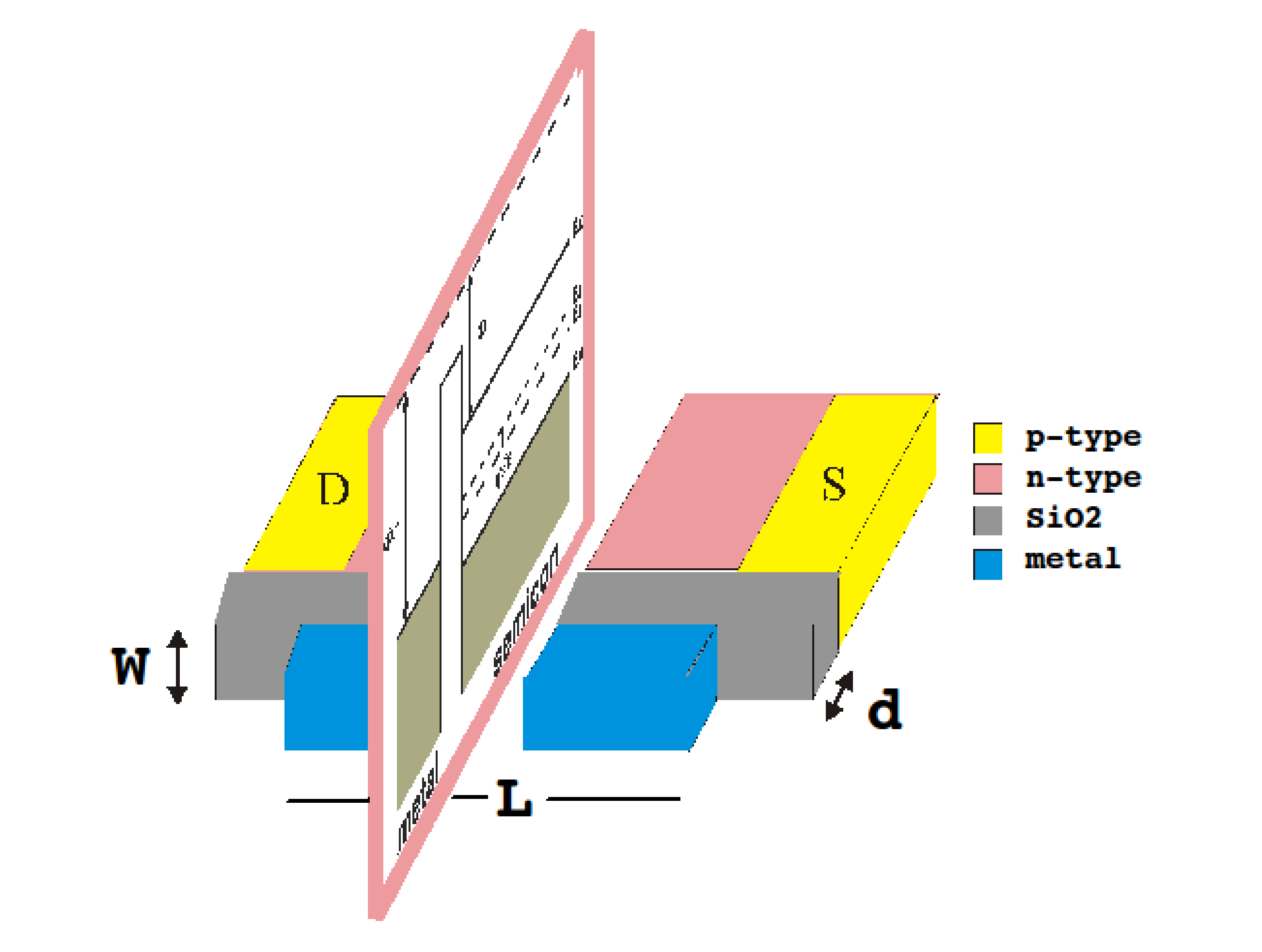
Thermionic emission theory → Exponential I-V curves (diode)

II: Device description: TFT precursor 2) MIS Diode



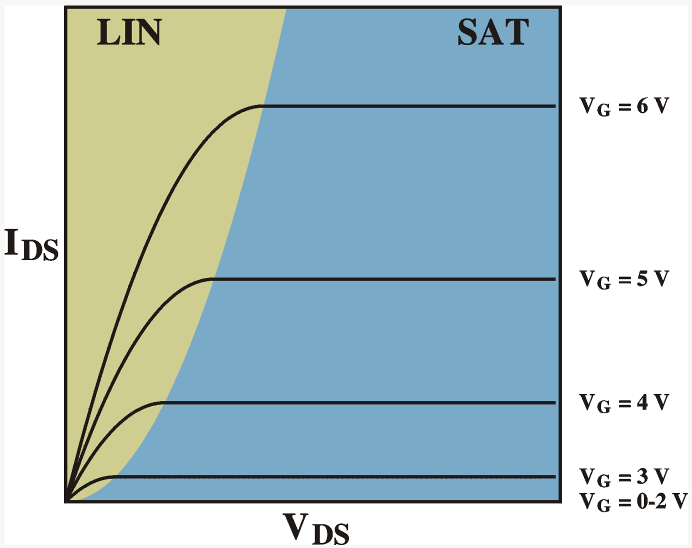
"flat band" "depletion" "inversion" "strong inversion"

Strong inversion: creation of sheet of free charge on semiconductor side

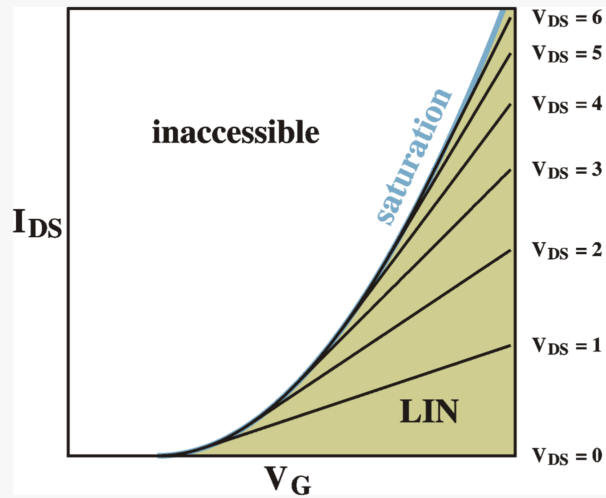


MOS-FET is MIS with lateral electrodes

IV curves



transfer curves



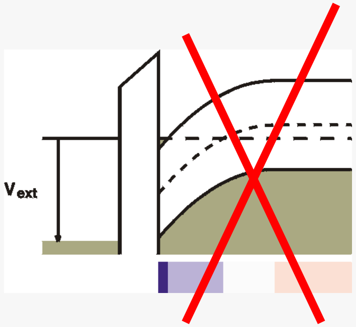
LIN: $I_{DS} = \mu\ (W/L)\ C_{ox}\ V_G \square V_{DS}$

SAT: $I_{DS} = \frac{1}{2}\ \mu\ (W/L)\ C_{ox}\ V_G^2$

Organic TFTs behave like MOS-FETs

A TFT is made of a **thin** film and cannot accommodate band bendings.

A TFT normally works in **accumulation** and thus cannot store the immobile charge needed for band bendings (there are no electronic states, N_D^+).



There **are** no band bendings!

Not even in thick film transistors! Not even at contacts!

All bias-induced charge is free charge, adjacent to the interface

II: Device description: TFT
The Algarve Model

One single simple axiom:

Any charge induced by the gate is at the interface

The device is purely **two-dimensional**

The device is a like a metal-plates capacitor

One single simple axiom:

Any charge induced by the gate is at the interface

The device is purely **two-dimensional**

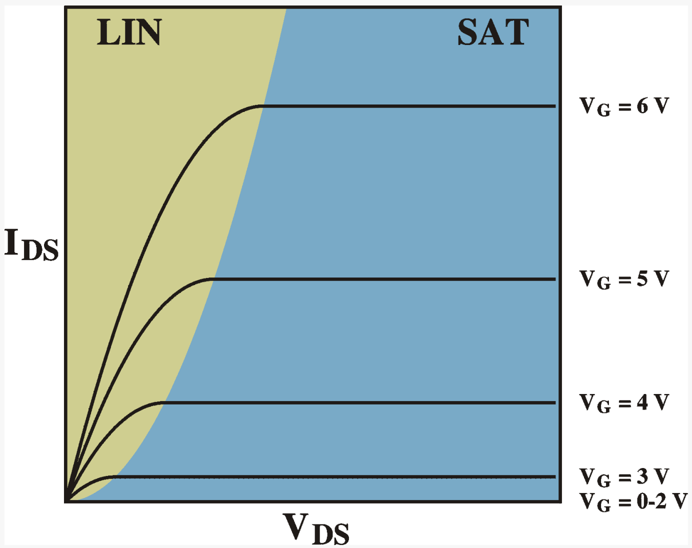
The device is a like a metal-plates capacitor

$$Q = C\,V$$

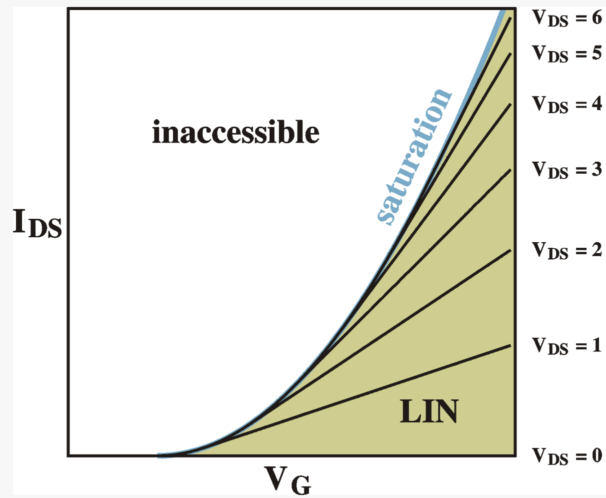
$$\boxed{\begin{aligned} Q(x) &= q\,p(x) = C_{\mathrm{ox}}[V(x)\text{-}V_{\mathrm{g}}] \\ I(x) &= W\,q\,p(x)\,\mu\,[-\mathrm{d}V(x)/\mathrm{d}x] \end{aligned}}$$

The Algarve Model TFT curves

IV curves



transfer curves

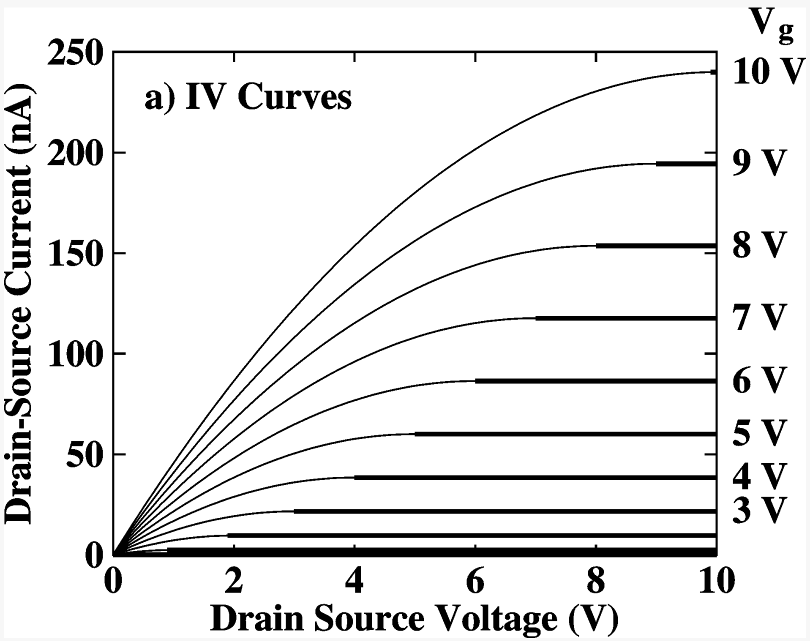


LIN: $I_{DS} = \mu\,(W/L)\, C_{ox}\, V_G V_{DS}$

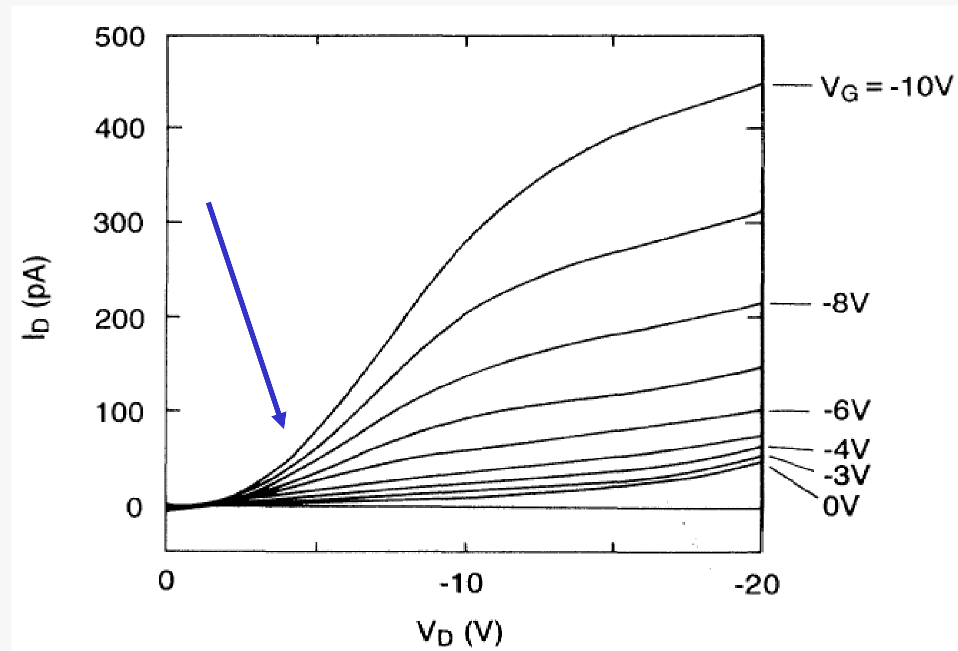
SAT: $I_{DS} = \frac{1}{2}\,\mu\,(W/L)\, C_{ox}\, V_G^2$

Organic TFTs behave like MOS-FETs

Theory:



Experiment:

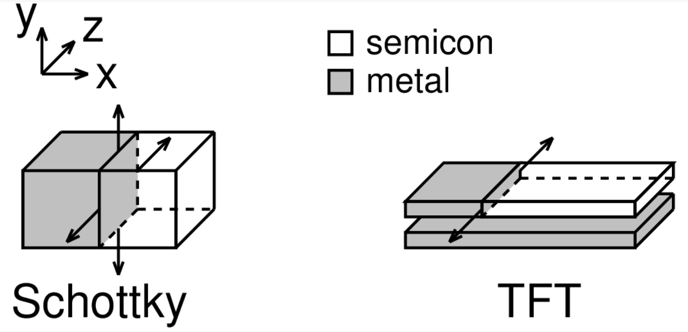


Waragai, PRB **52**, 1786 (1995).

Literature: contact effects

After all, a TFT contact is a ½con-metal junction. Like Schottky barrier. Diode. Exponential. Case closed!

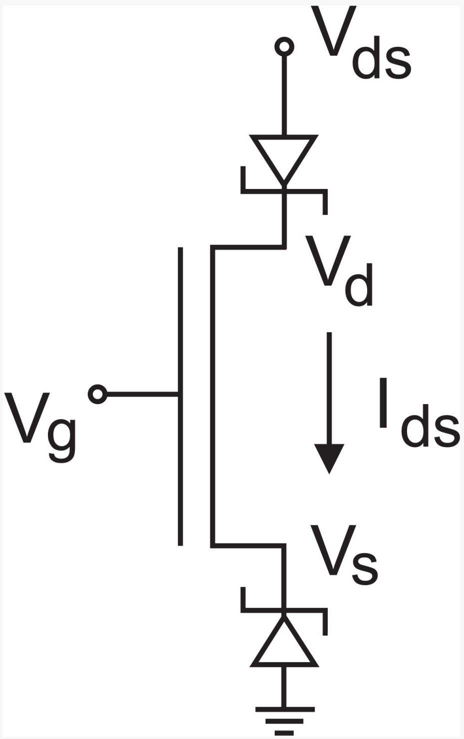
A TFT metal - ½ con contact is NOT a Schottky barrier

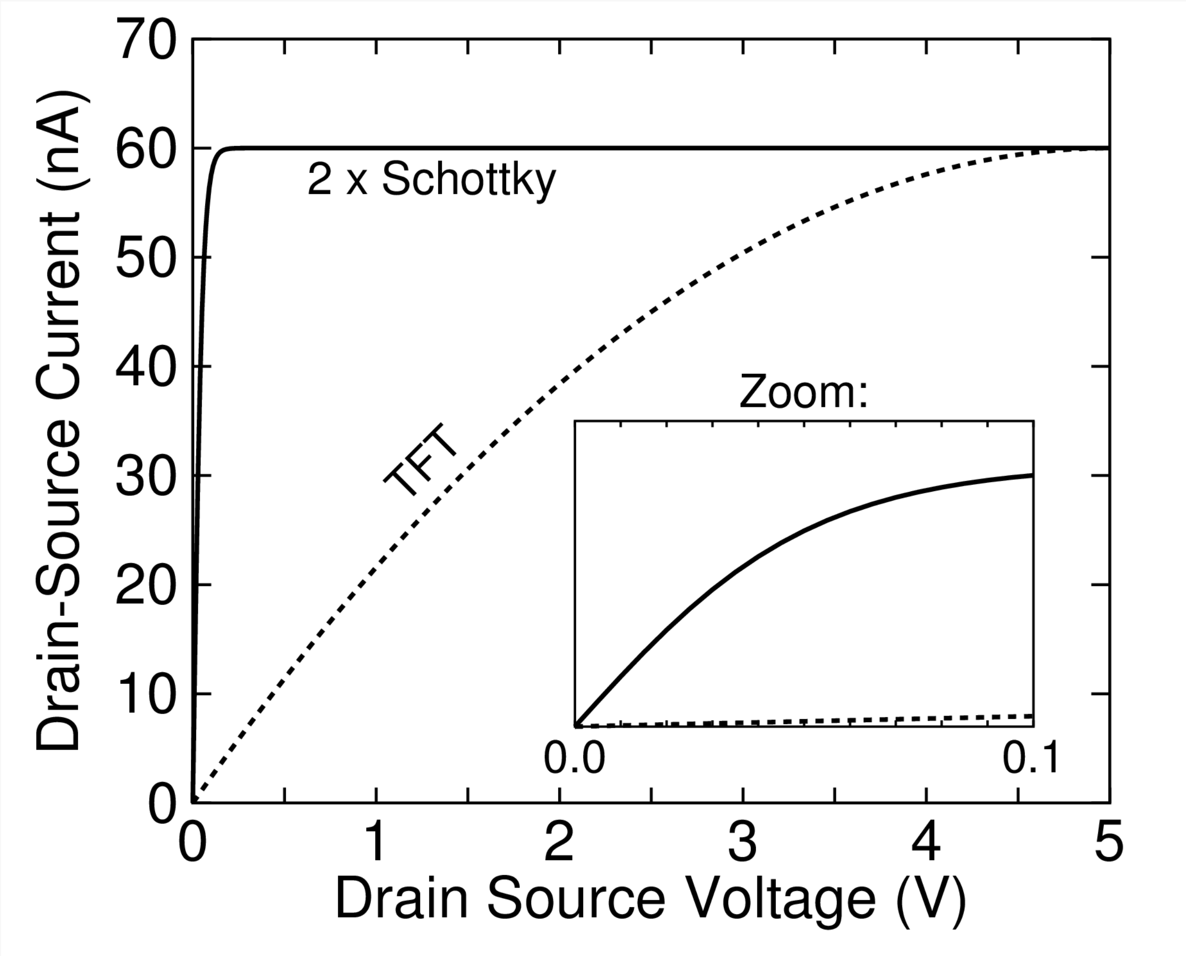


Symmetry is not correct (Poisson's Equation cannot be used)
note: Poisson's Equation is special case of Maxwell Equation

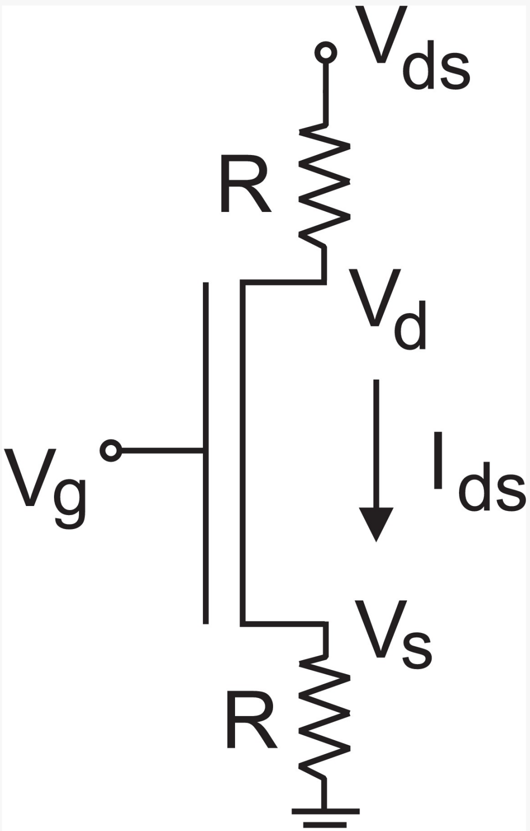
$$\nabla \cdot D = \rho(x, y, z)$$

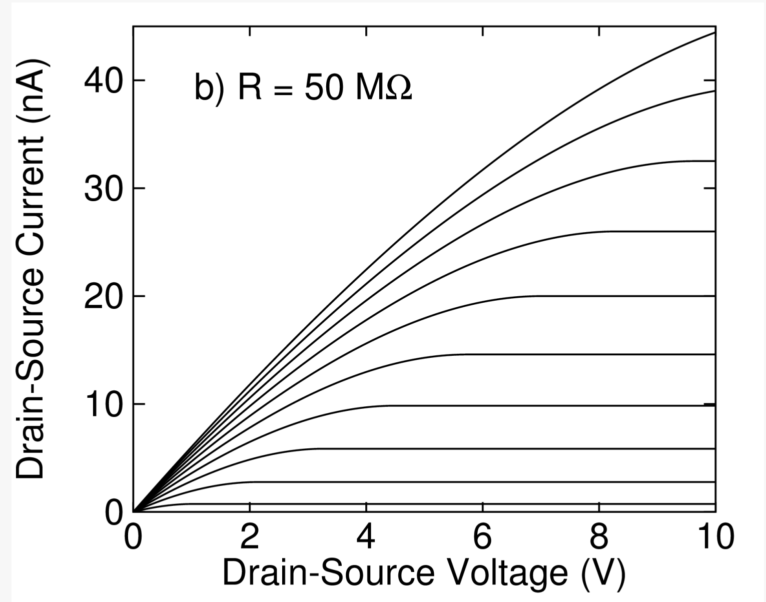
Presence of gate is not a perturbation

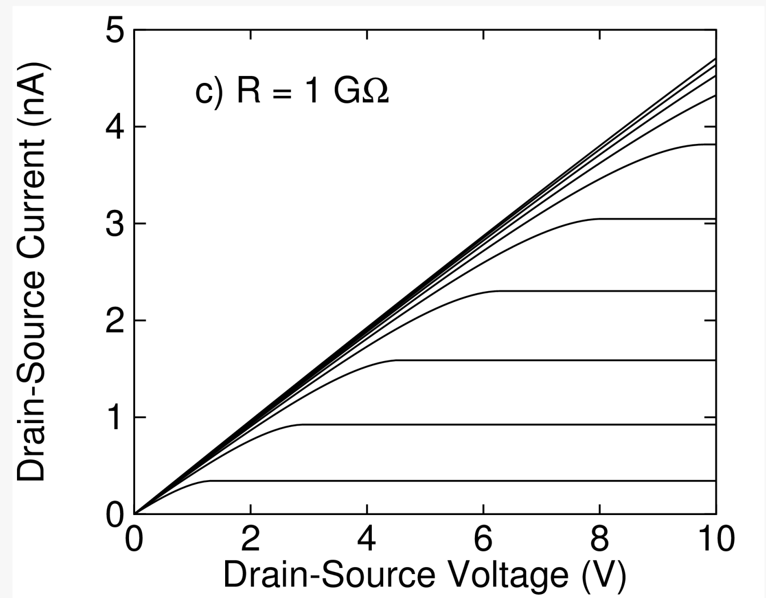




Contrary to what expected, no non-linearities are observed for Schottky barrier contacts

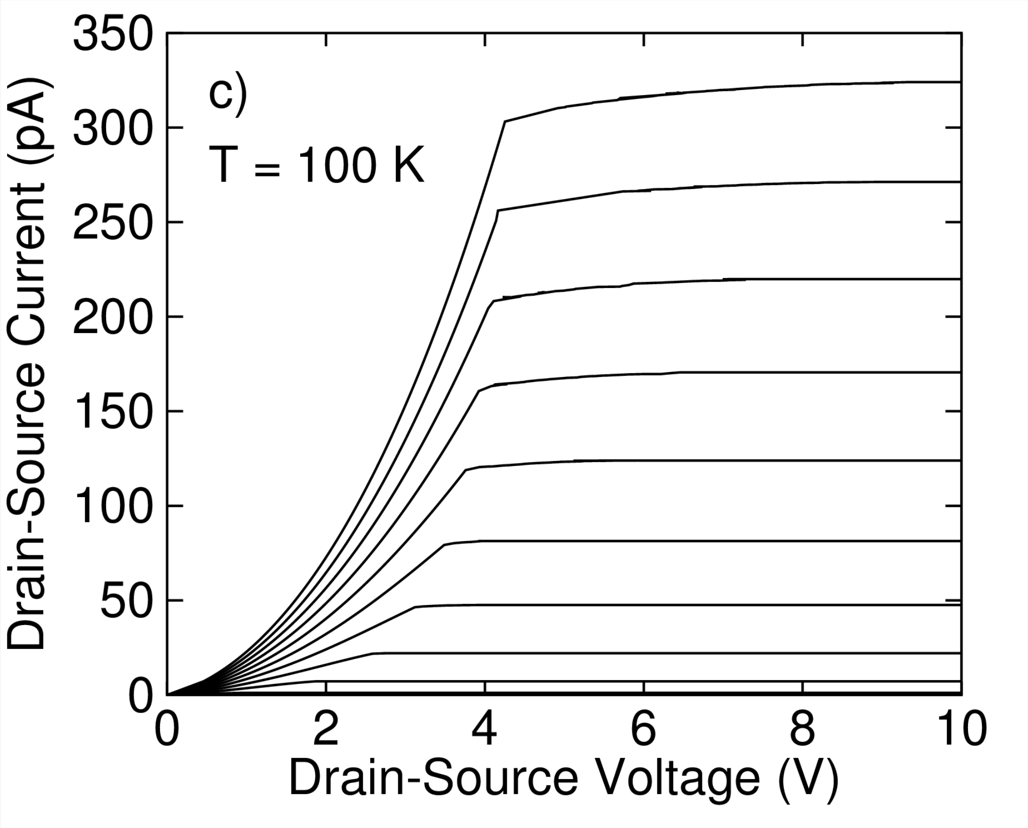






"Current crowding" is observed for contact resistance

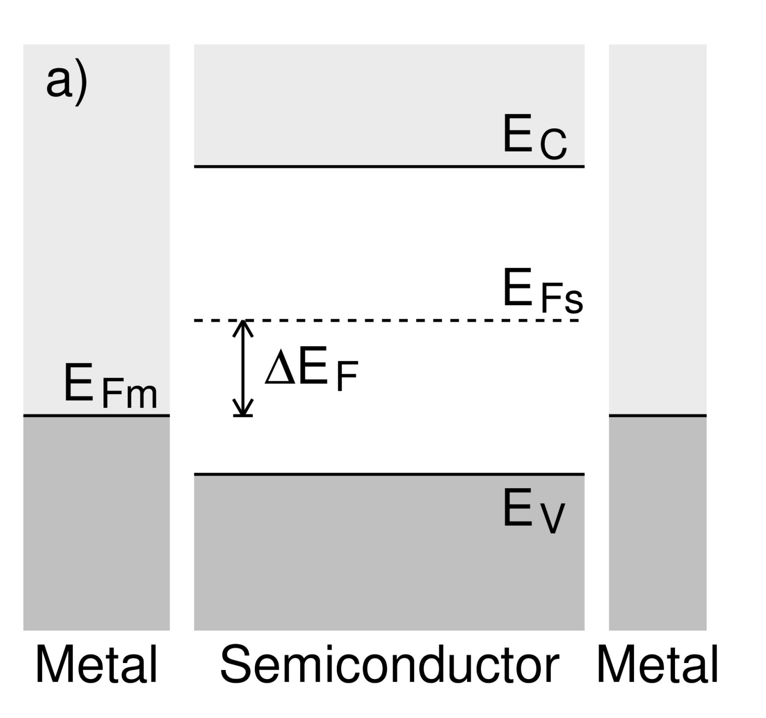
II: Device description: TFT
Non linearities? Poole-Frenkel!

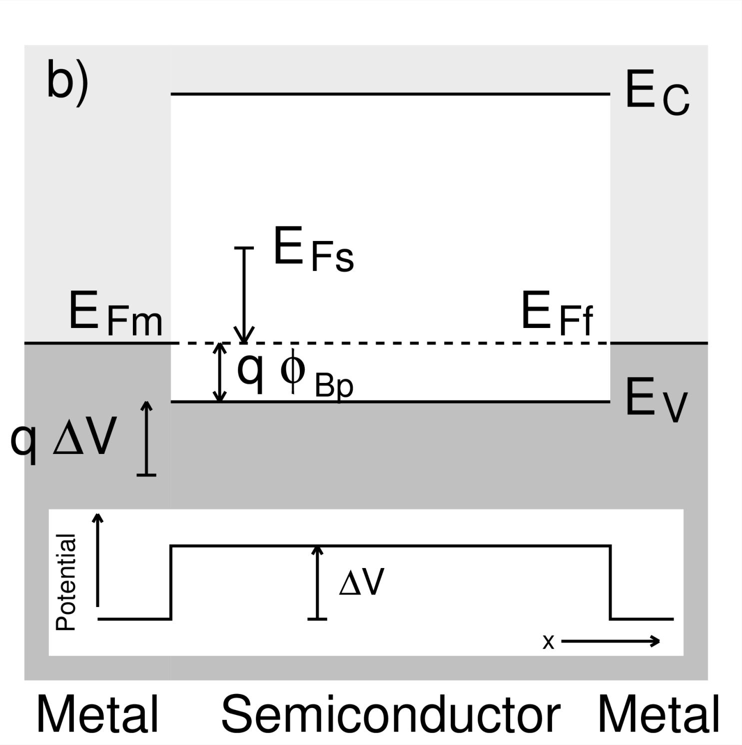


$$Q(x) = q\,p(x) = C_{ox}[V(x)\text{-}V_g]$$

$$I(x) = W\,q\,p(x)\,\mu(E(x))\,[-\mathrm{d}V(x)/\mathrm{d}x]$$

Algarve Model contacts

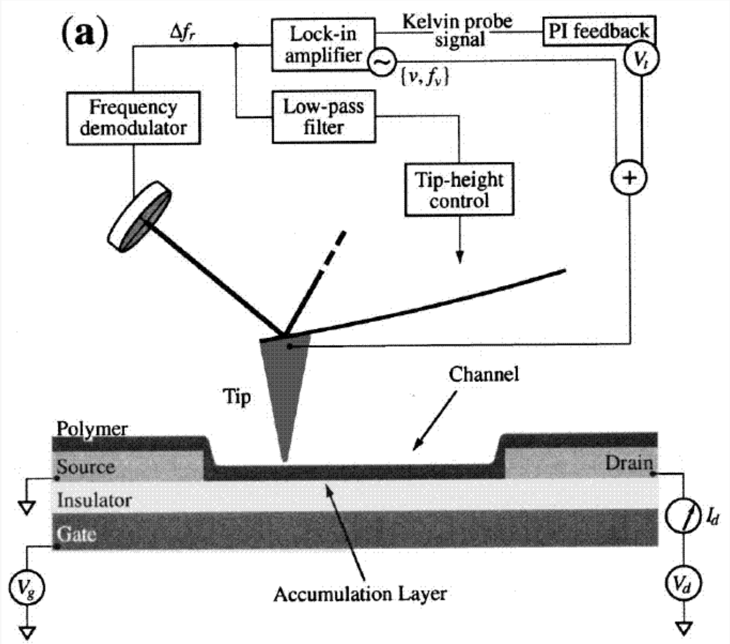


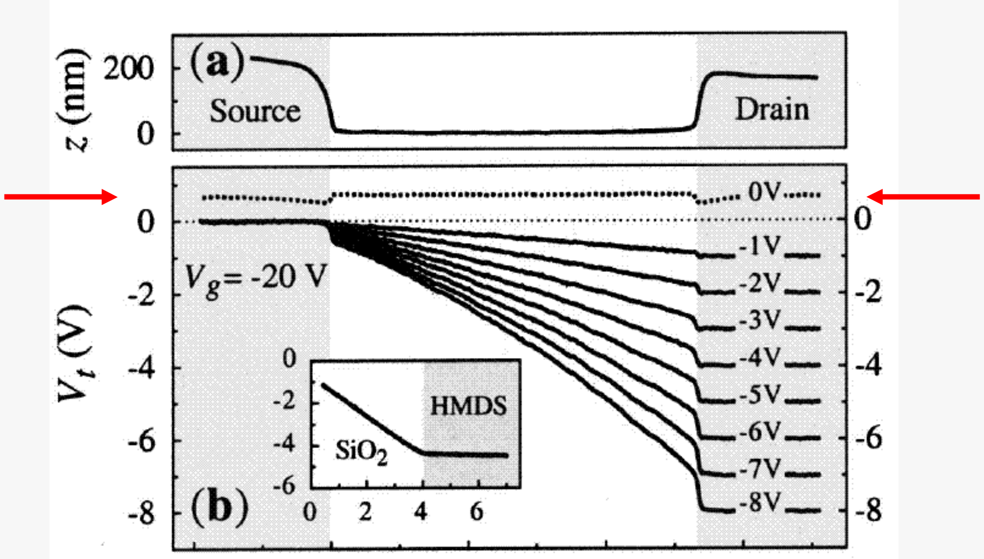


Upon contact, charge flows into the ½con
raising the potential V (and associated levels such as EF)

Result:
1) In-channel zero-bias potential (up to volts) ($Q = C\ V$)
2) Tiny bias-dependent contact barrier 60-80 meV

Algarve Model contacts





Bürgi Appl. Phys. Lett. **80**, 2913 (2002)

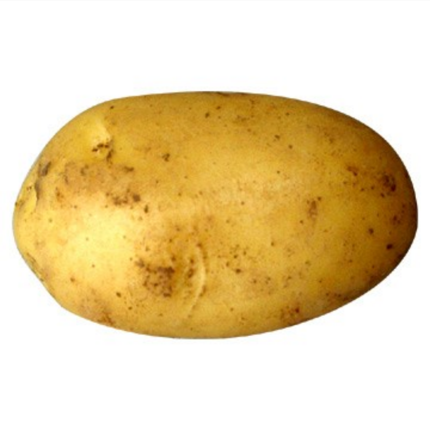
“If what you are saying is correct, we can use other materials as well for TFTs”

Yes! Since doping is not essential.

As long as the mobility of the charges is high enough

As long as the charges have a barrier going (leaking) to the gate

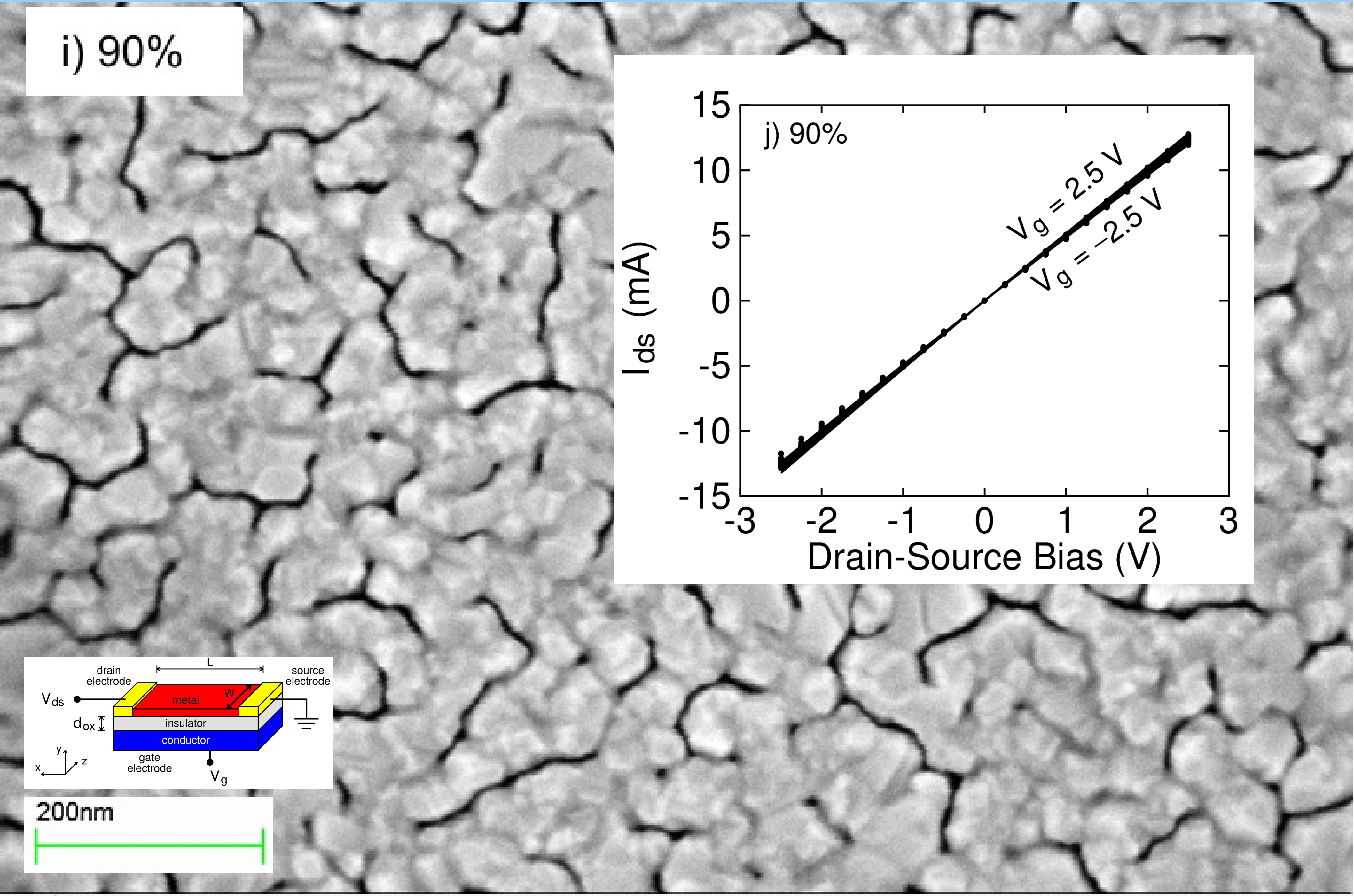
Any semiconductor will do. Wait, any material will do. Even a potato!



Even a metal will do!

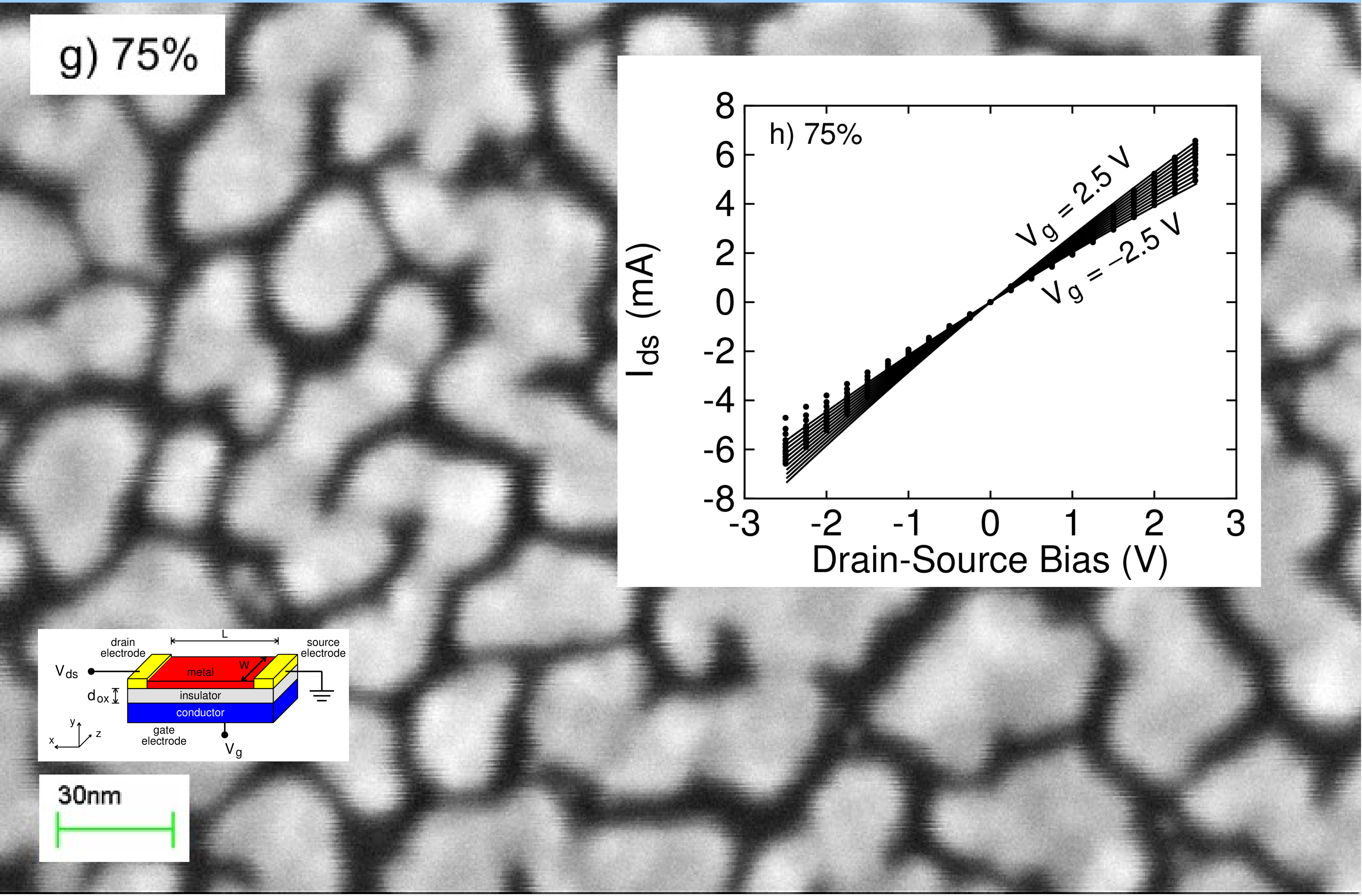
I'll show you!

IV: Metal TFT

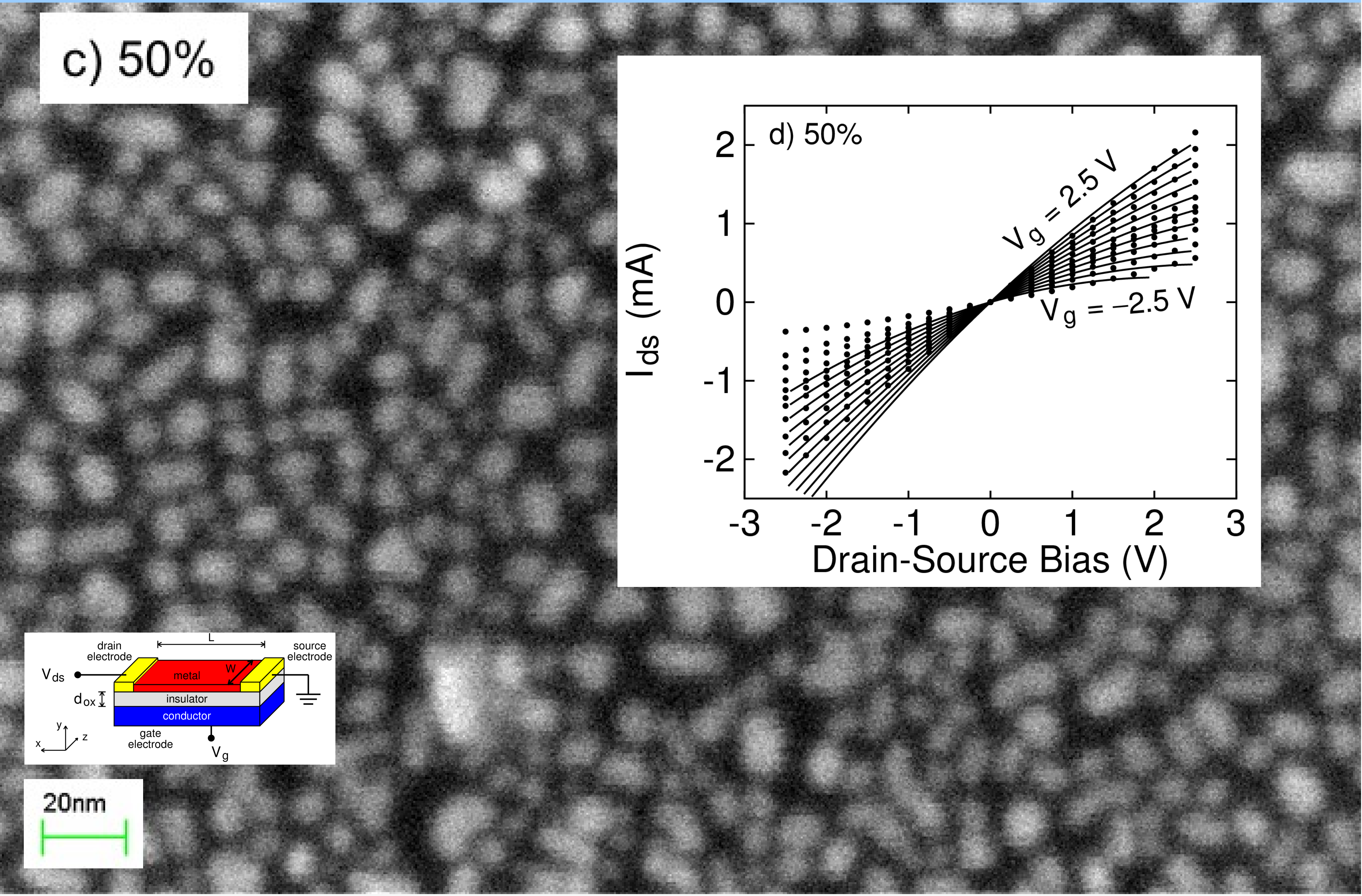


i) 90%
200nm
j) 90%
$V_g = 2.5$ V
$V_g = -2.5$ V
I_{ds} (mA)
15
10
5
0
-5
-10
-15
-3
-2
-1
0
1
2
3
Drain-Source Bias (V)
drain electrode
L
source electrode
V_{ds}
metal
W
d_{ox}
insulator
conductor
y
z
x
gate electrode
V_g

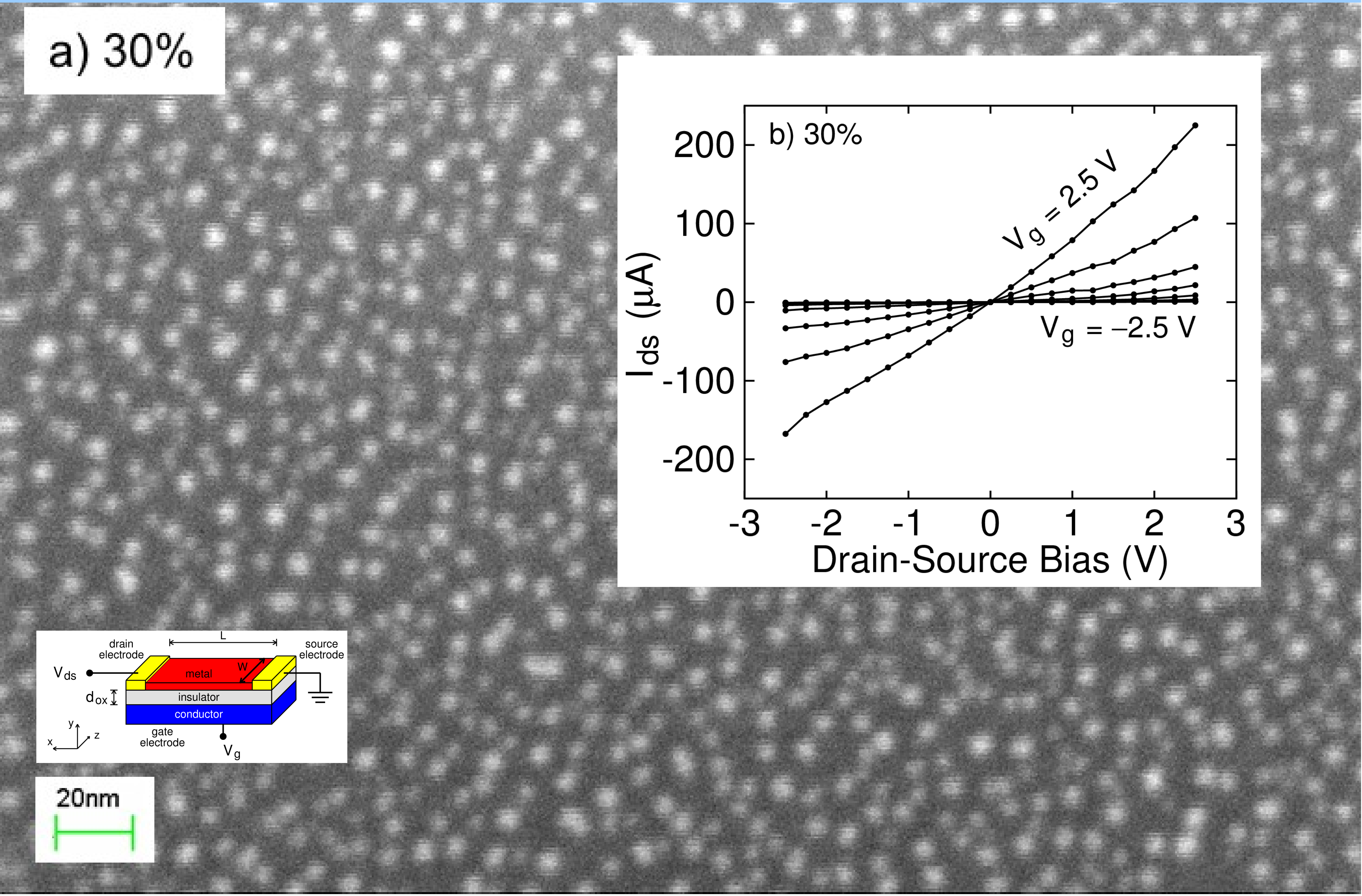
IV: Metal TFT



g) 75%
h) 75%
8
6
4
2
0
-2
-4
-6
-8
-3
-2
-1
0
1
2
3
I_{ds} (mA)
Drain-Source Bias (V)
$V_g = 2.5$ V
$V_g = -2.5$ V
drain electrode
source electrode
L
W
metal
insulator
conductor
gate electrode
V_{ds}
d_{ox}
V_g
y
x
z
30nm

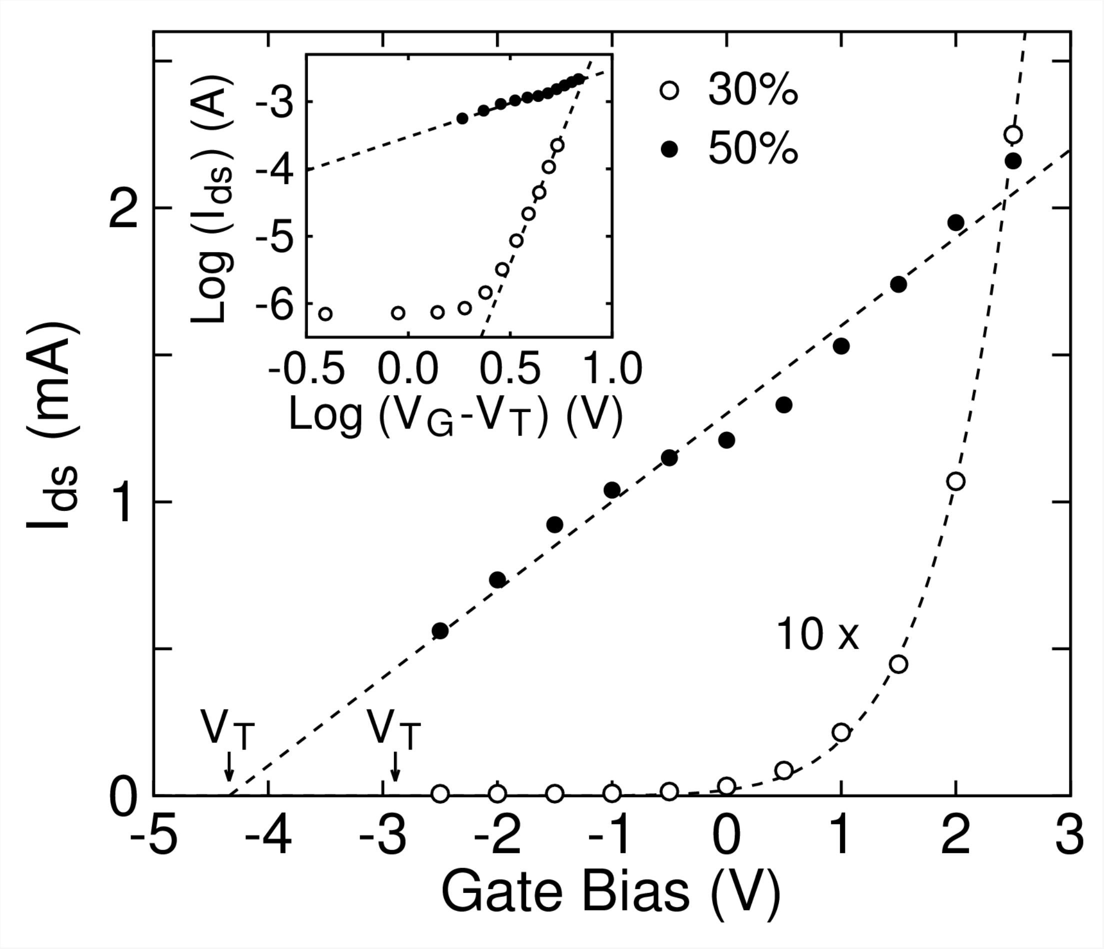

c) 50%
20nm
d) 50%
$V_g = 2.5$ V
$V_g = -2.5$ V
I_{ds} (mA)
Drain-Source Bias (V)
2
1
0
-1
-2
-3
-2
-1
0
1
2
3
drain electrode
L
source electrode
V_{ds}
metal
W
d_{ox}
insulator
conductor
y
x
z
gate electrode
V_g

IV: Metal TFT



a) 30%
b) 30%
200
100
0
-100
-200
I_{ds} (μA)
-3
-2
-1
0
1
2
3
Drain-Source Bias (V)
V_g = 2.5 V
V_g = –2.5 V
drain electrode
L
source electrode
V_{ds}
metal
W
d_{ox}
insulator
conductor
gate electrode
V_g
y
x
z
20nm

Fast electronics



$$f_T = \frac{g_m}{2\pi C_{gs}} = \frac{\partial I_{ds} / \partial V_{gs}}{2\pi W L C_{ox}}$$

should be orders of magnitude faster than state-of-the-art silicon technology MOS-FET transistor

$(V_{gs}-V_T)$ [V]	f_T/f_{TMOS}
1	0.01
2	5
2.5	30
3	100

Bastos, submitted Electr. Lett. 2010

Summary

Conduction mechanism: substitution of difficult Hopping Theory by simple Band Theory

Two-dimensional approach for TFT

Correct description of contact effects

Any material can be used for a TFT. End of semiconductor era!