Electrical Characterization of Organic Electronics

“Radical new model for TFTs”

(thin-film field-effect transistors)

P. Stallinga,
Universidade do Algarve (FCT, OptoEl, CEOT)
Kazimierz Dolny, 2 de Outubro de 2005

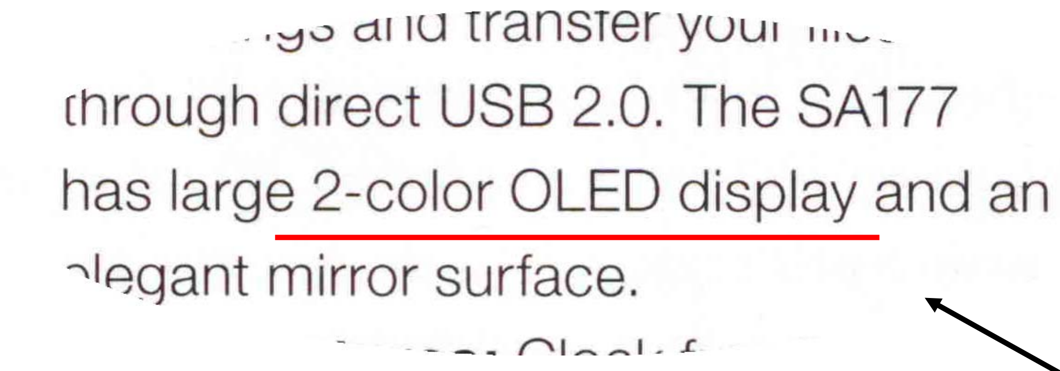
OPTO-ELECTRONICS
UNIVERSIDADE DO ALGARVE

Overview

Introduction of Faro, Opto-El and CEOT

History examples: DLTS, H_20, LE-FET

Modeling of Thin-Film Transistors



KLM in-flight brochure →

AMS-WAW, 24 sep 2005

The Algarve is famous for tourism:

300 days per year sunshine

Temperatures all year pleasant:15 - 30^{o}C

Great food, low prices, friendly people

300 km of clean sand beaches

Good airport and other infrastructures

"Ieder voordeel heb z'n nadeel"
(Every advantage has its disadvantage)

- Johan Cruyff

Universidade do Algarve (UAlg)

10,000 students, 5 Faculties, 4 Campi, 700 teachers, 60 courses.

Faculdade de Ciências e Tecnologia (FCT), 90 profs.

Departamento de Engenharia Electrónica e Informatica (DEEI), 20 profs.

3 Courses (ESI, EI and I)

Areas of ESI: Electronics, Control, Signal Processing, Telecommunications

The university is the heart of The Algarve

Faro, 6 Oct. 2004; 26 ºC

University

Although being a young university,
The university of the Algarve is the second most
science productive university of Portugal (2004)*.

… and still improving.

Our course (ESI) is becoming first choice for
Portuguese students of electronic engineering.

* counting number of papers per head

OptoEl - CEOT

Opto-Electrónica
Universidade do
Algarve

Founded: 1997

2 members (PhD)

Centro de Electrónica,
Opto-Electrónica e
Telecomunicações

Founded in 2001

9 members (PhD)

Electronics (design of RF electronic circuits)

Opto-Electronics (characterization of electronic materials, sensors)

Telecommunications. (Comm. protocols, network design, etc)

€ In 2003, CEOT was evaluated by an external committee of FCT (Portuguese foundation) as “very good” and received a 640 k€ equipment investment bonus in 2004 apart from the normal individual project grants.

Opto-El

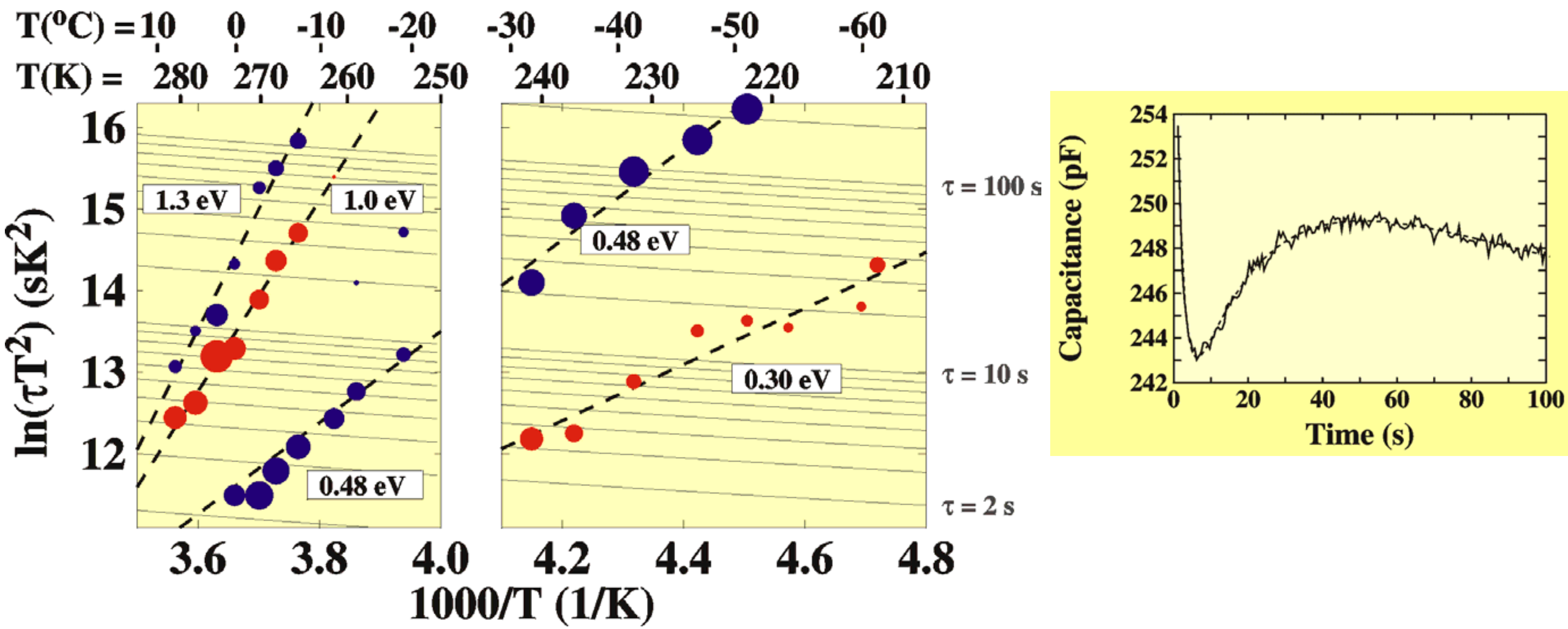
Specialized in characterization of organic electronic materials and devices

Apart from that, recently started
- sensors: TNT, DNA
- instrumentation: quartz-crystal oscillator, MEMs, etc.

Organic electronics

HIV detector

Opto-El. First successful implementation of a DLTS experiment in an organic material



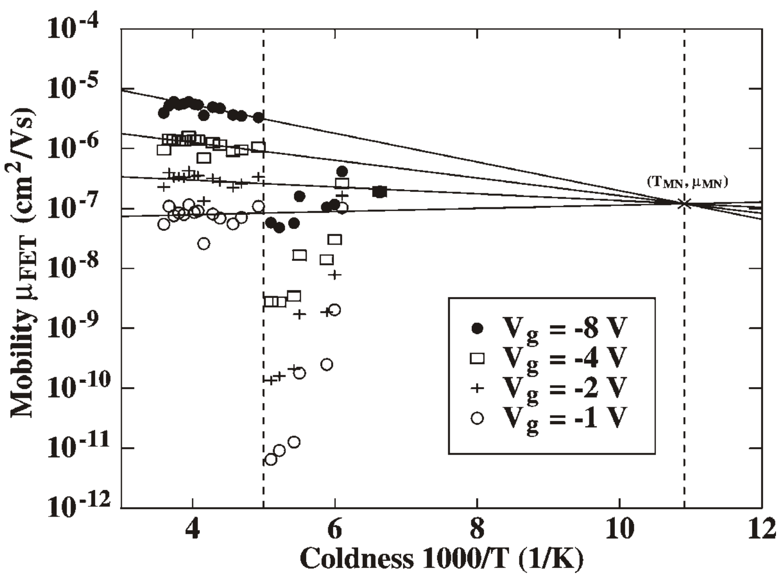
P. Stallinga *et al*., J. Appl. Phys. **89**, 1713(2001).pdf

example: $H_2 0$

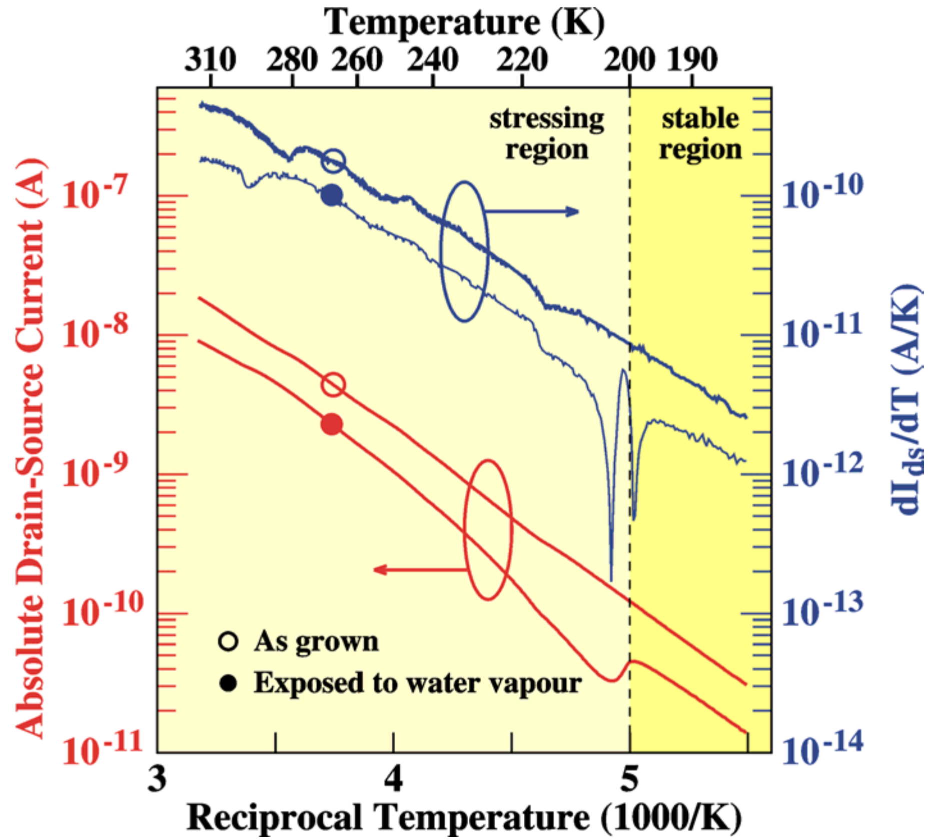
All organic materials suffer from the detrimental effects of water*.

*H.L. Gomes *et al*., submitted (2005).pdf

phase transition at 200 K

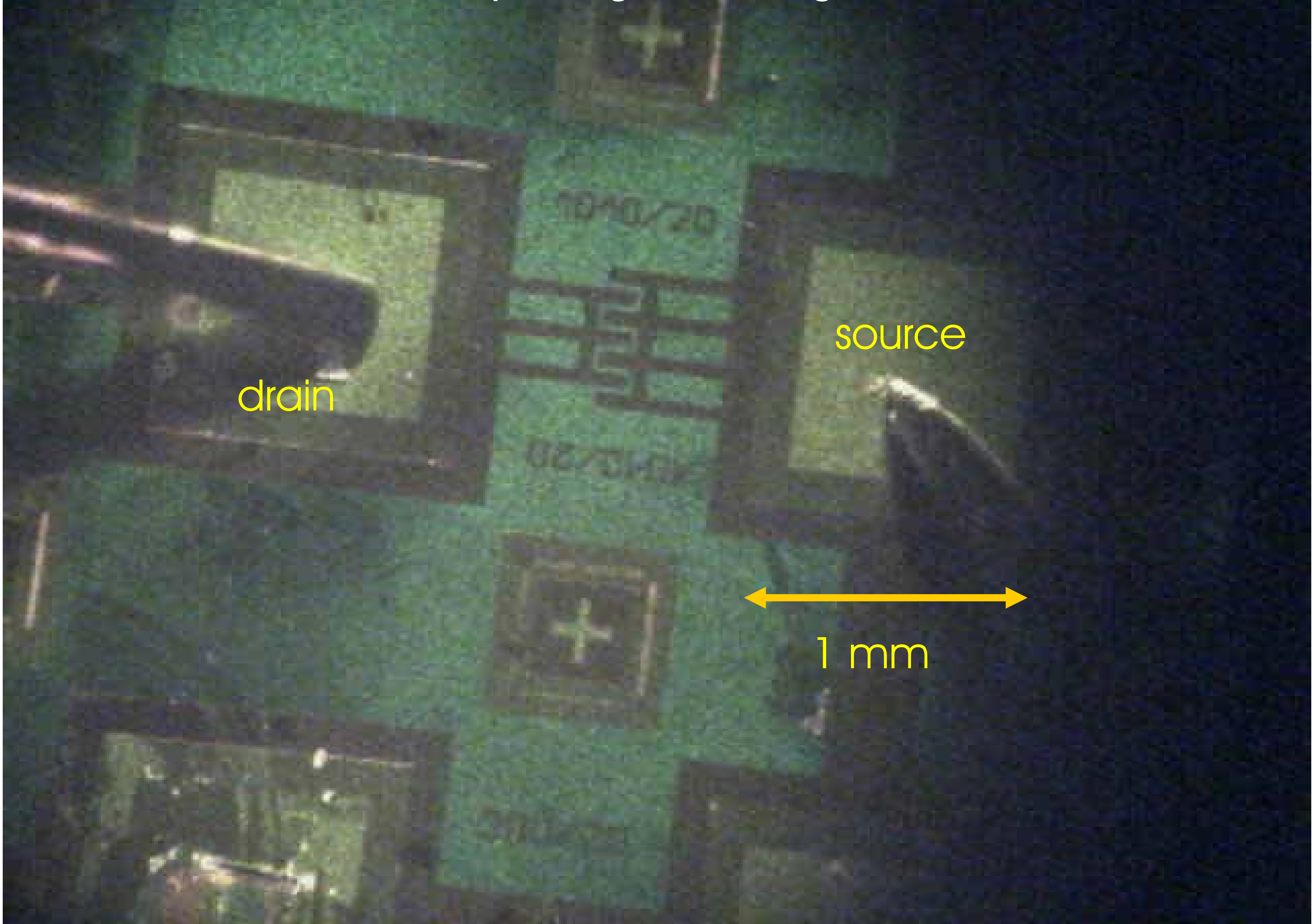


Attributed to water



Above 200 K all organic materials are electrically unstable

example: Light-emitting FET



example: Light-emitting FET

You are looking at the first picture ever taken showing light coming out of an FET … (Bologna, 2003)

C. Santato *et al.*, Synth. Metals **146**, 329 (2004)

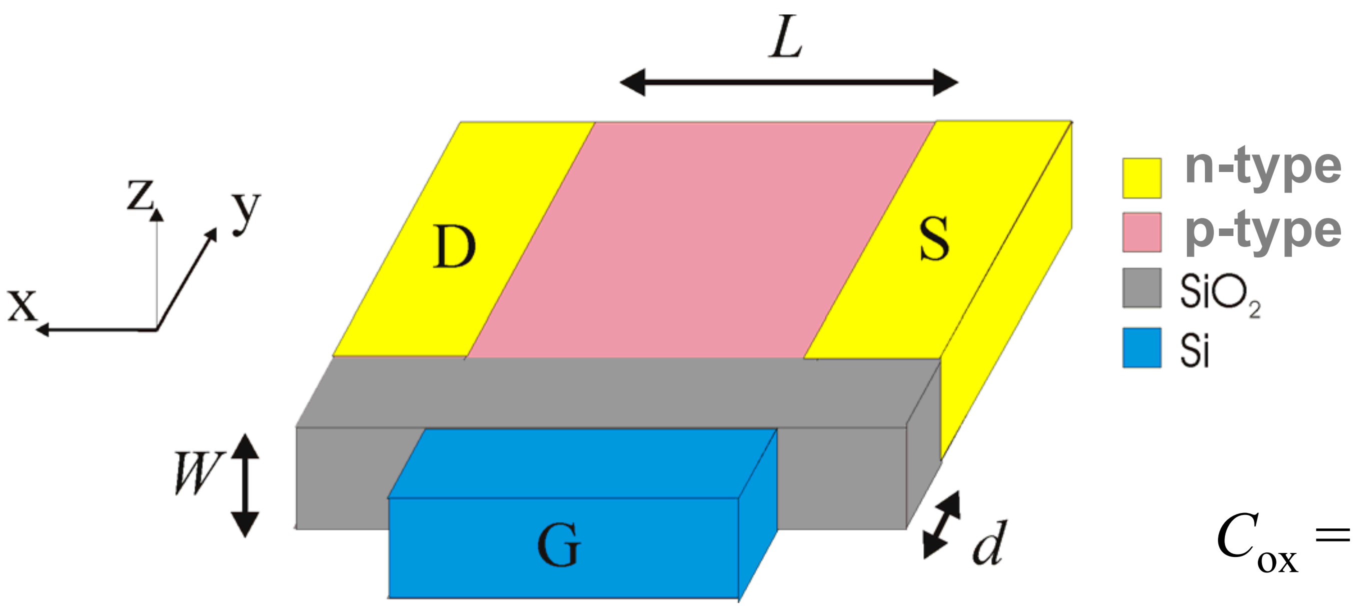
Organic TFTs

Main topic for today: (organic) thin-film transistors

Tradition is to use the inversion-channel metal-oxide field-effect-transistor (MOS-FET) model for TFTs

I will show you this is nonsense and then present an alternative
("If you don't give a solution, you are part of the problem!")

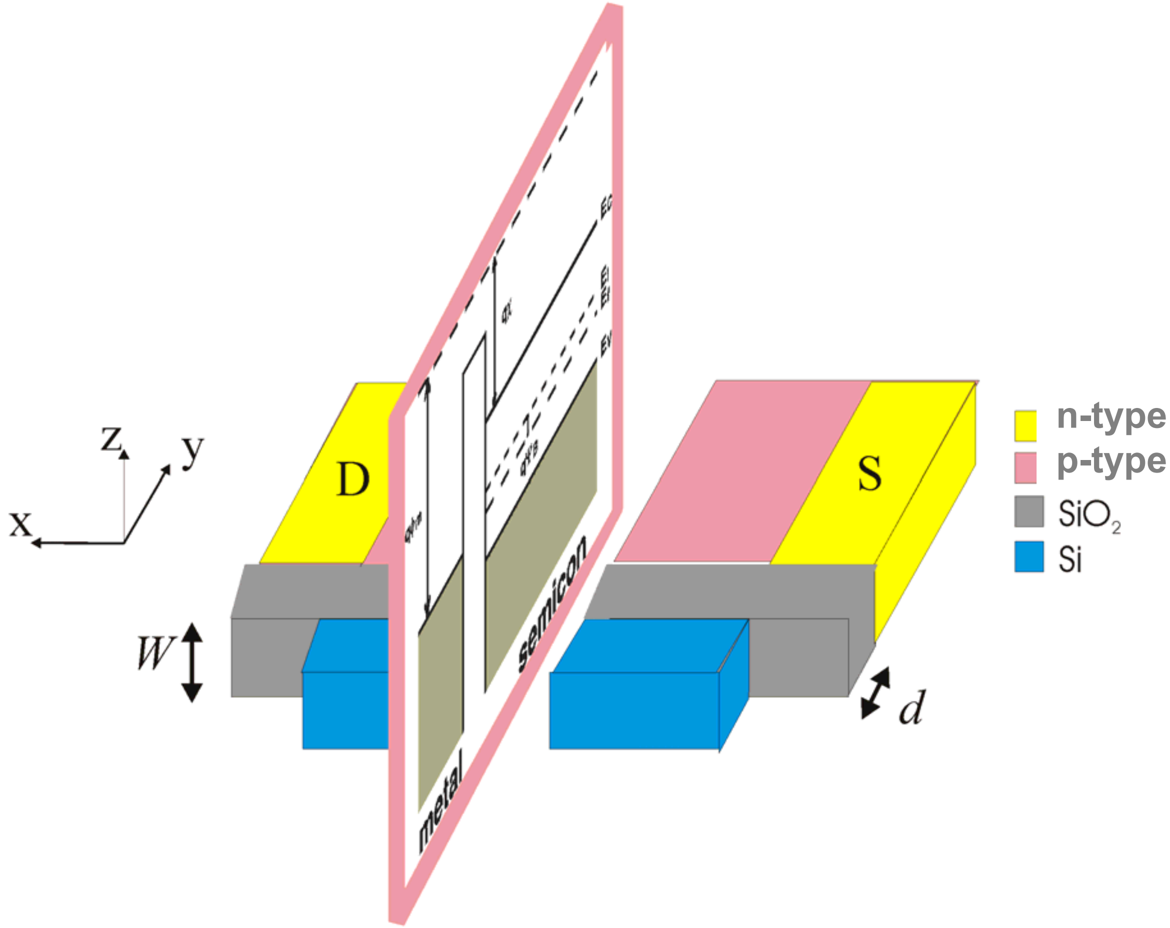
Inversion-channel MOS-FET



$$C_{ox} = \varepsilon_{ox}/d$$

taken from our OptoEl theory pages,
http://www.ualg.pt/fct/adeec/optoel/theory

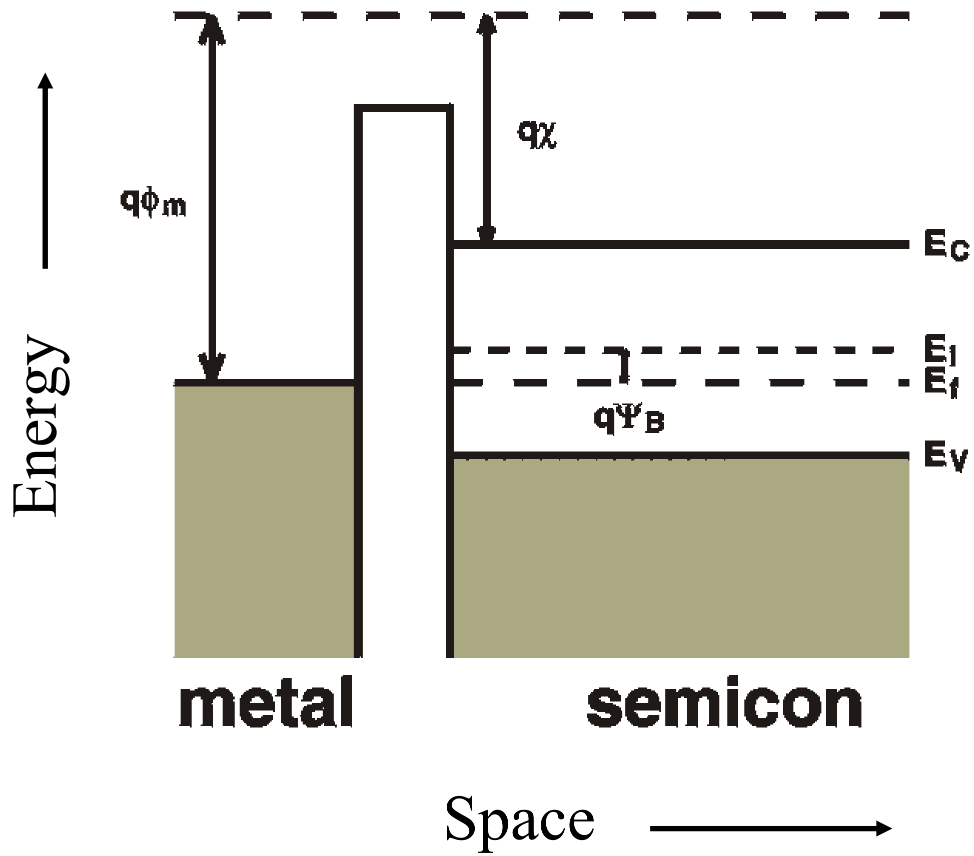
Inversion-channel MOS-FET



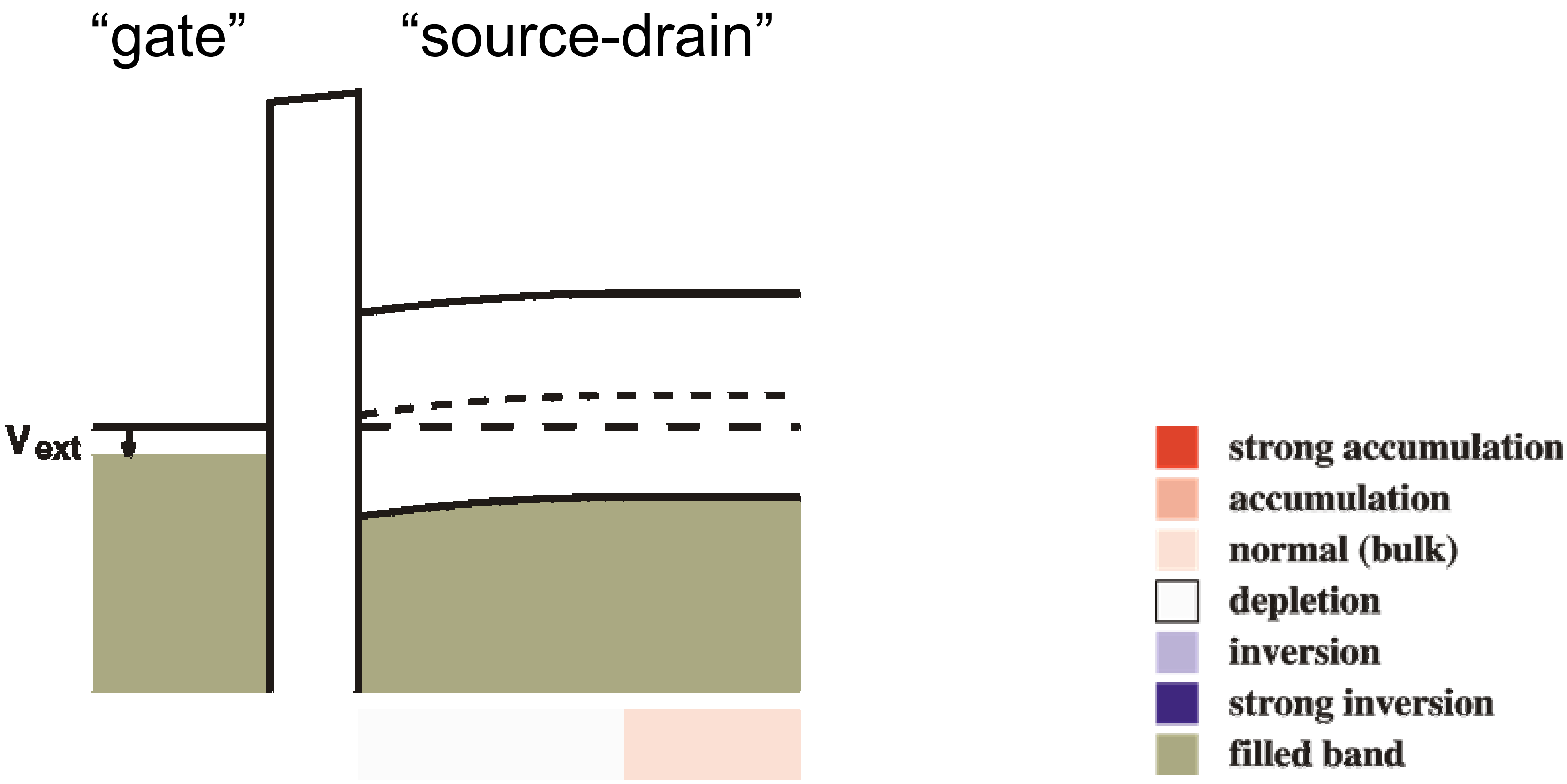
Next slide: look at cross-section of device

"Flat-band" situation
bulk is p-type

Starting structure: MIS diode
(= FET without electrodes)



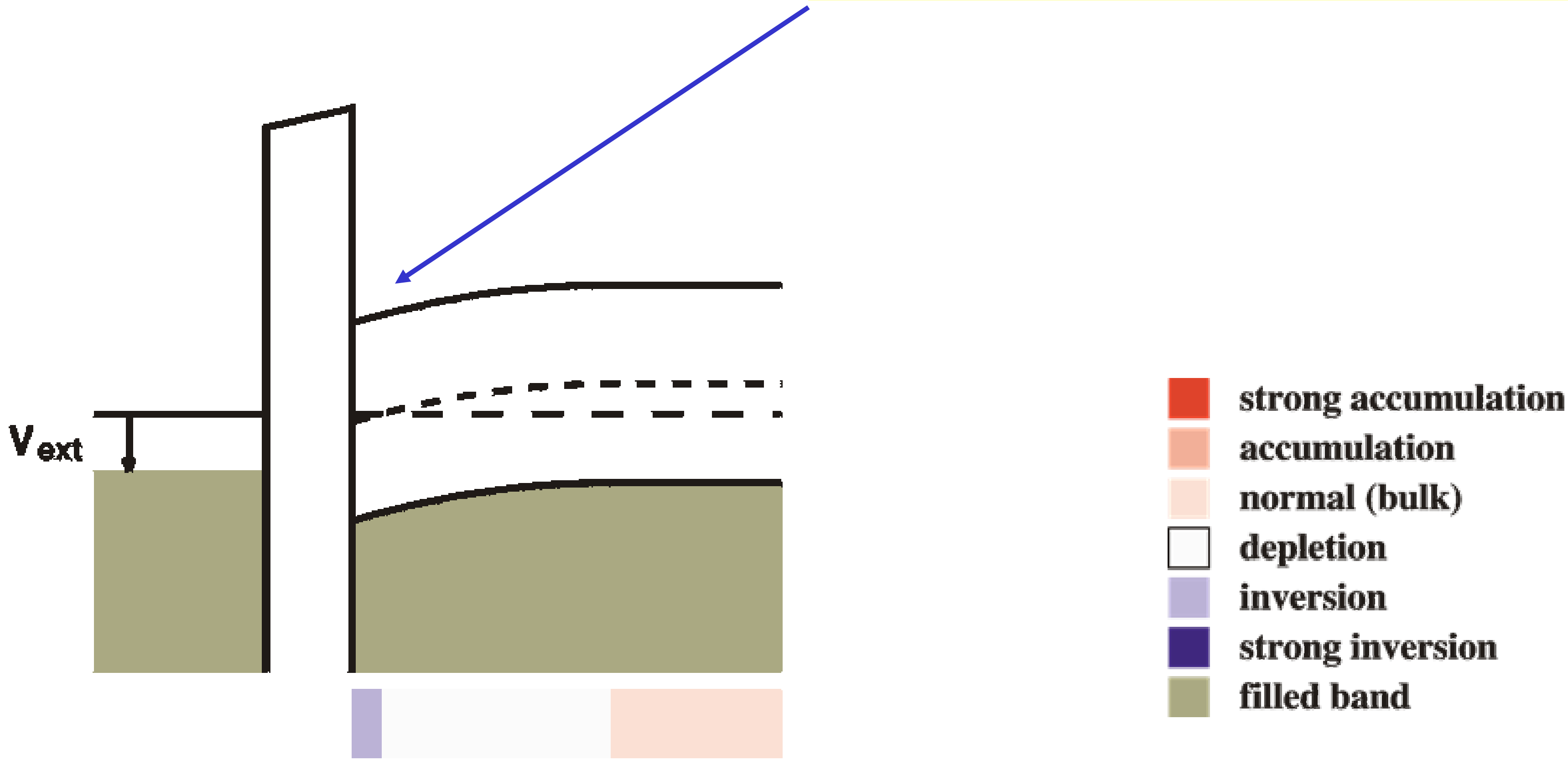
"Depletion" Applying bias



Inversion-channel MOS-FET

"Onset of inversion"

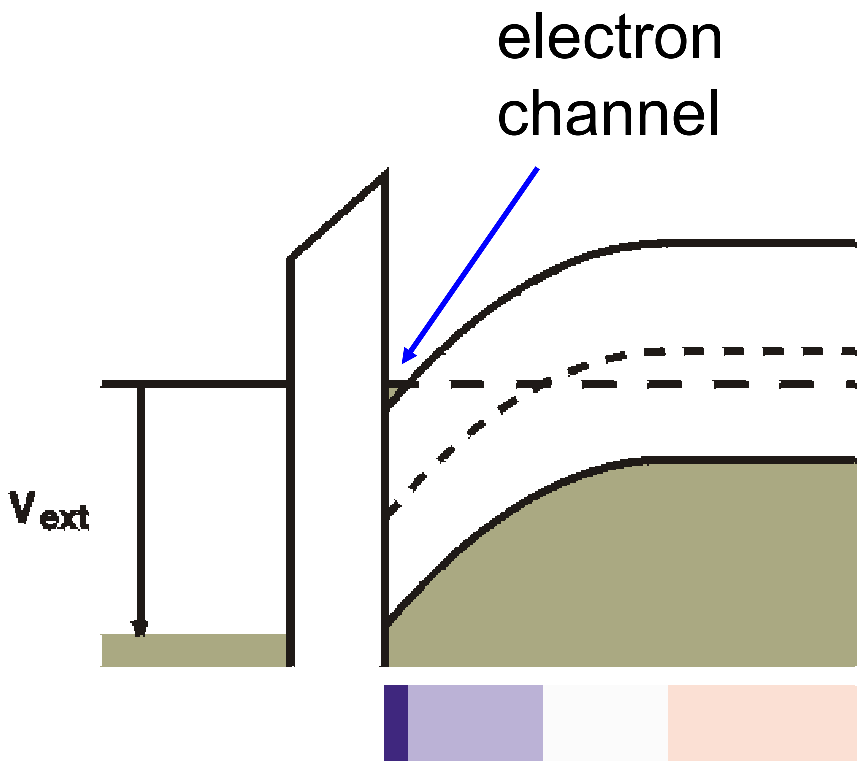
Free charge density, n, grows exponentially with bias



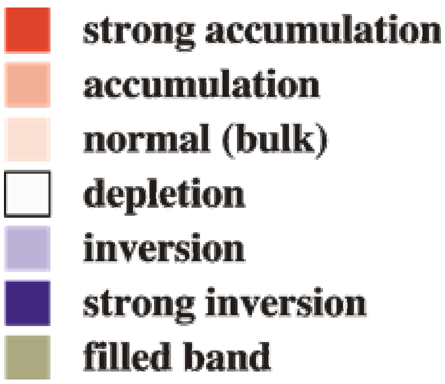
Inversion-channel MOS-FET

"Strong inversion"

Free charge density n grows linearly with bias

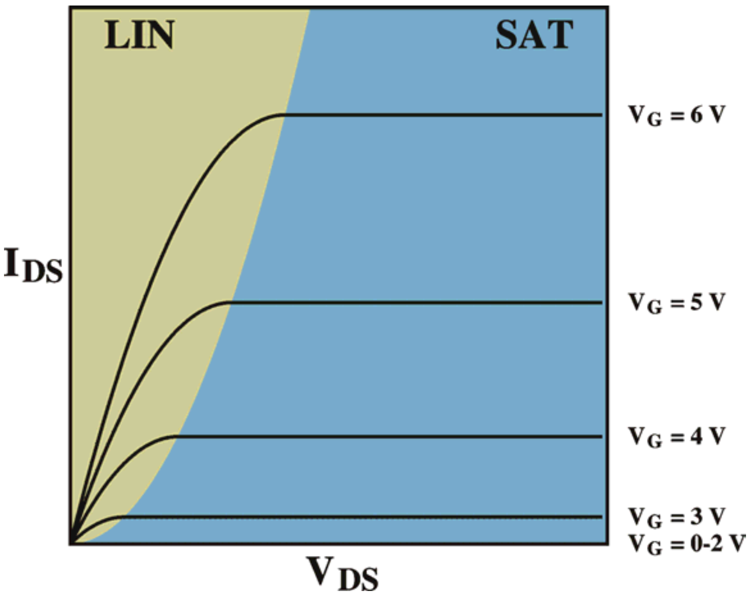


Defines "threshold voltage" Vt as voltage needed to start a channel

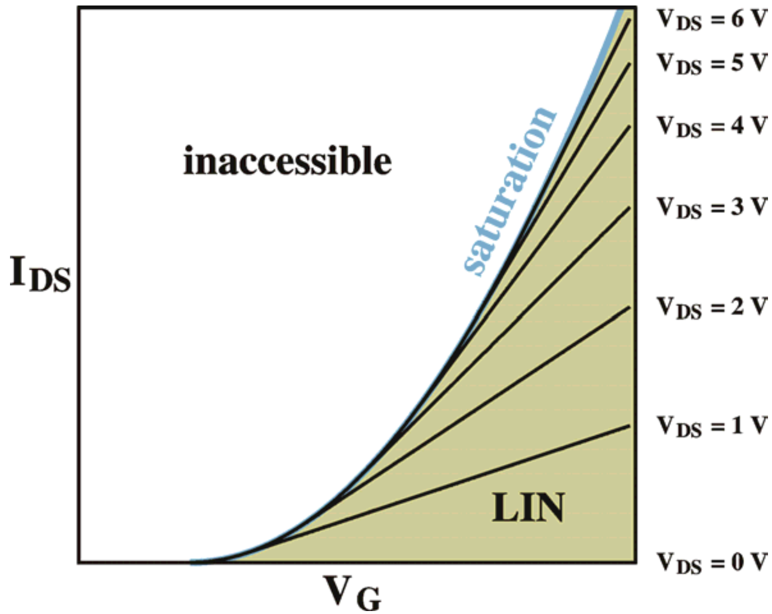


Inversion-channel MOS-FET: 1

IV curves



transfer curves



FET = MIS diode with lateral electrodes connected to measure the channel conductivity (charge density)

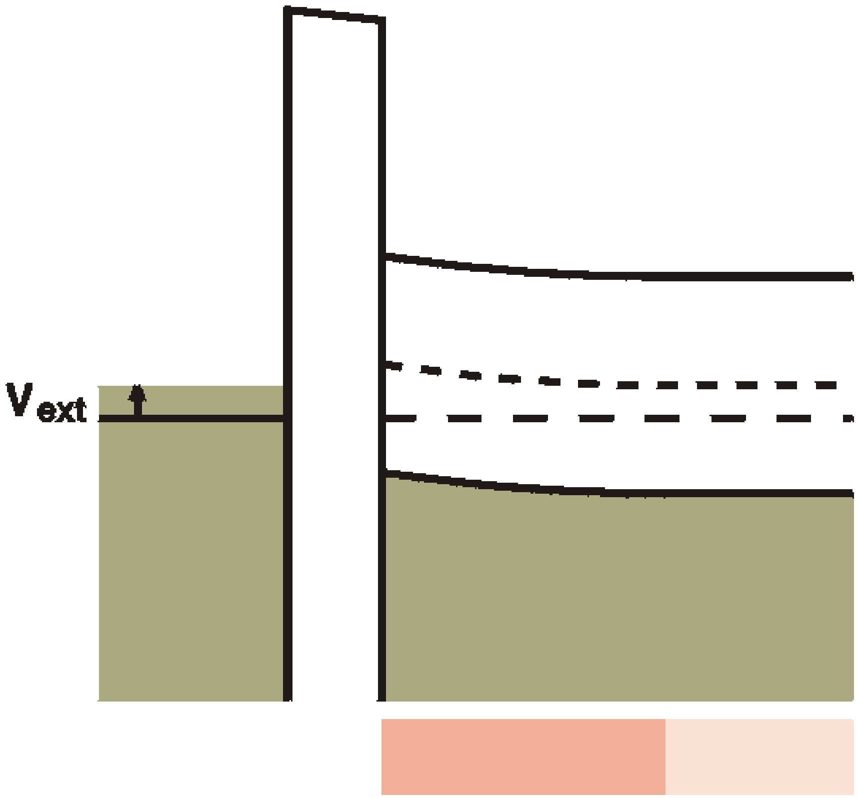
Inversion-channel MOS-FET

"Accumulation"

Convention in literature

p ?

Just reverse band bending!



- strong accumulation
- accumulation
- normal (bulk)
- depletion
- inversion
- strong inversion
- filled band

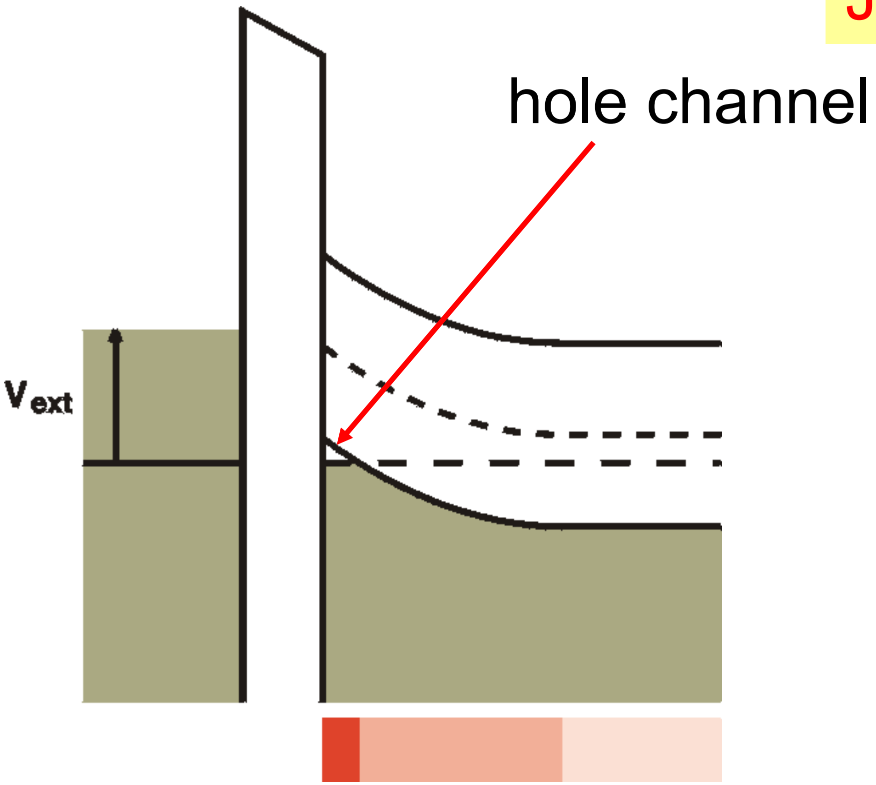
Inversion-channel MOS-FET

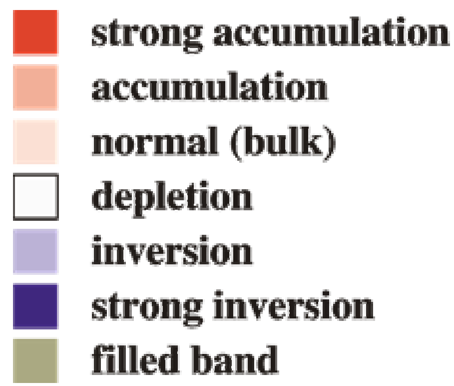
"Strong Accumulation"

Convention in literature

p ?

Just reverse band bending!





Two fundamental problems:

1: This doesn't work for TFTs!

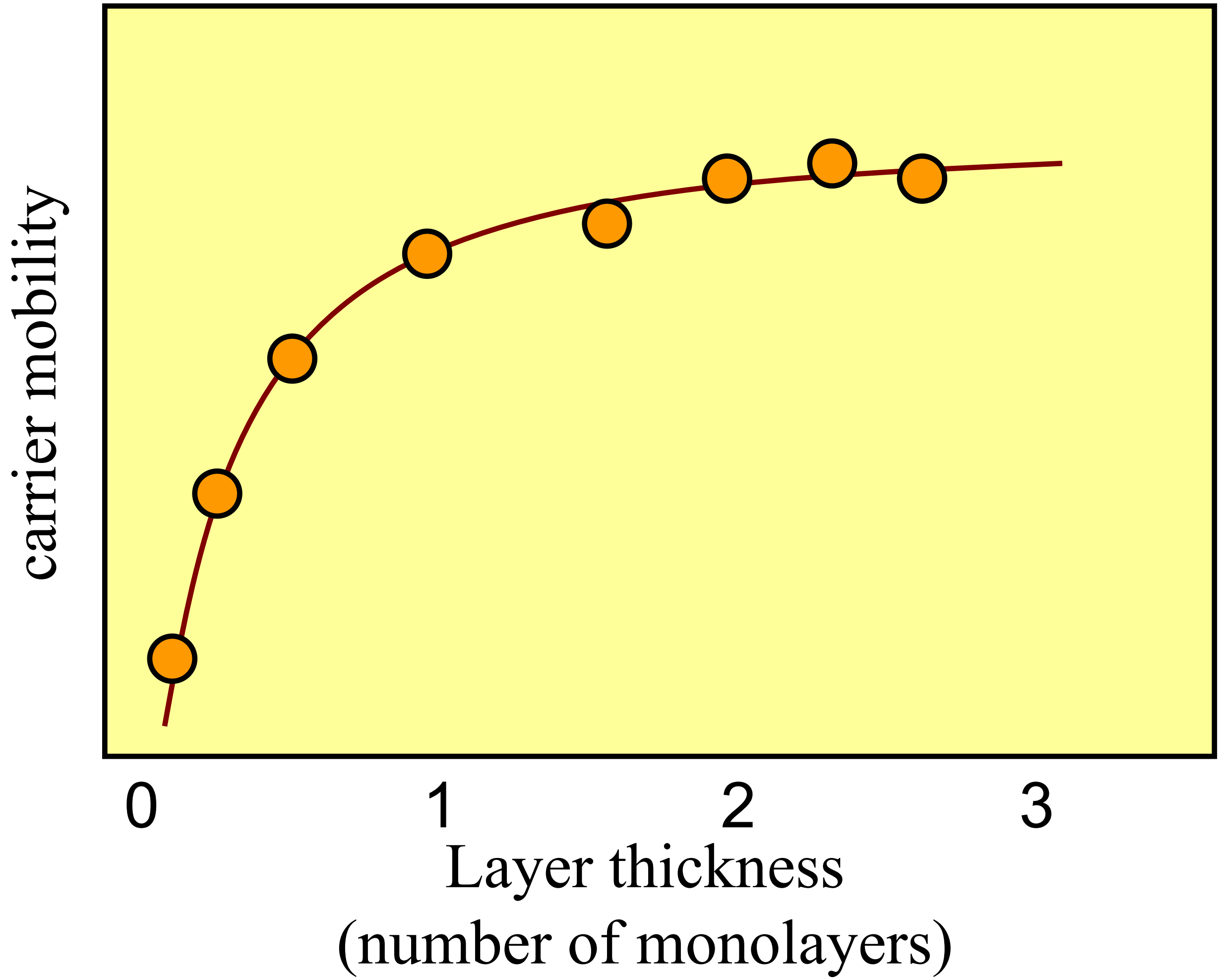
- thin films cannot accommodate band bendings!
  (there is simply no space for them)
  band-bendings are of order 300 nm ($N_A = 10^{16}$ cm^{-3}),
  films are 1 monolayer (5 nm), without loss of
  functionality.

2: Concept of band-bending in accumulation is nonsense!

- There are no electronic levels to store immobile charge
  needed for band bending.

Thin-film transistors (TFTs)

Only first monolayer is important*



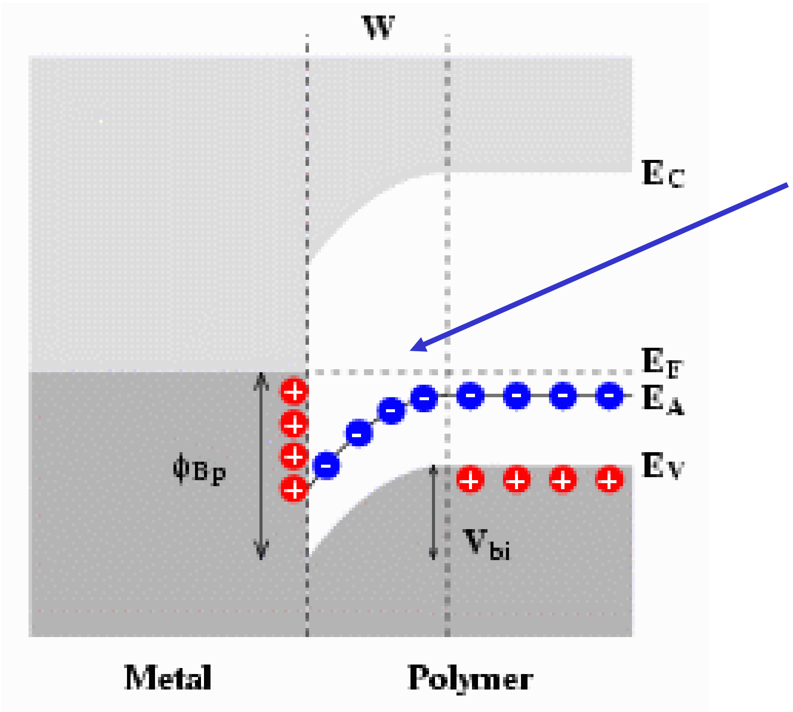
*F. Biscarini et al.

Band bending in accumulation? Nonsense!

2: Concept of band-bending in accumulation is nonsense!

Poisson's Equation:

$$V(x) = \iint \rho(x) dx^2$$



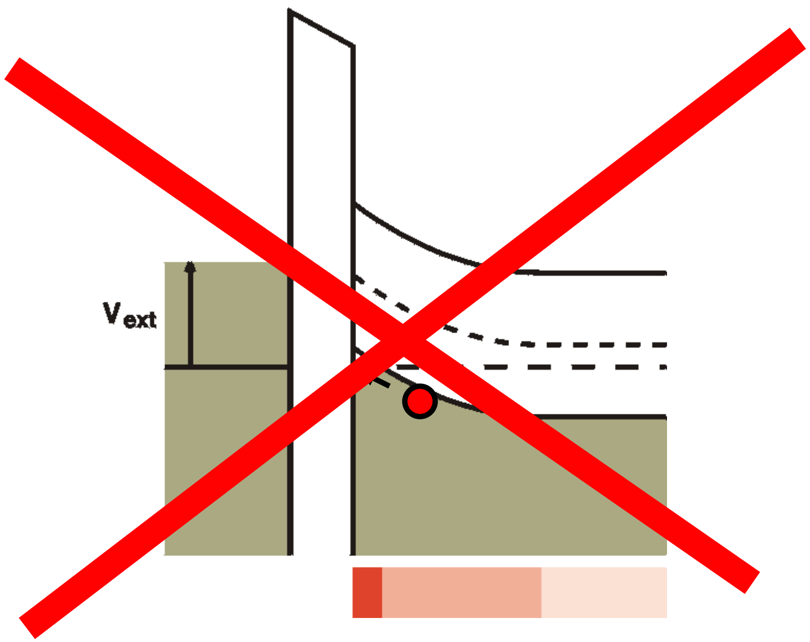
Inversion:
Negative charge needed
Band bending is caused by un-compensated ionized acceptors

Accumulation:
Positive charge needed. but:
Acceptors can only be neutral or negative

Band bending in accumulation? Nonsense!

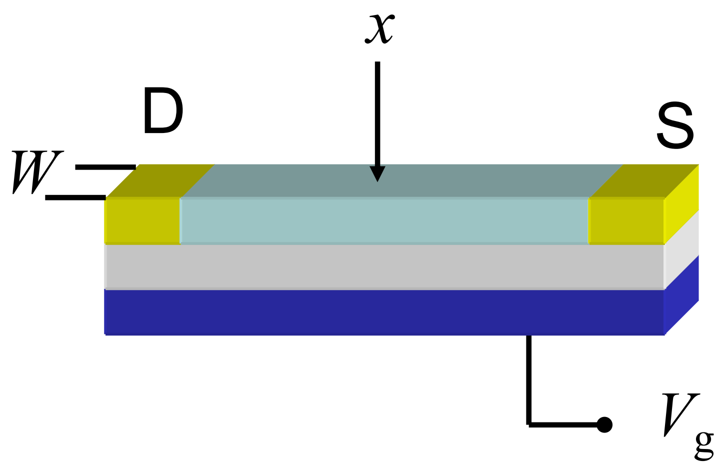
2: Concept of band-bending in accumulation is nonsense!

Accumulation:
Positive charge can only appear in the material as free holes. They will therefore always move towards the interface. No space charge (band bending)



Postulate for TFT: Purely two-dimensional treatment

All charge is at the interface.

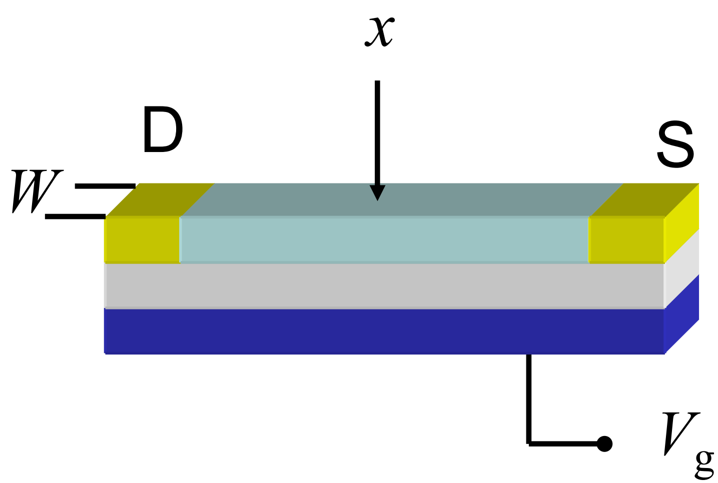


$$\rho(x) = C_{ox}[V(x) - V_g]$$

C/m^2 F/m^2 V

(note the two-dimensional units)

Is this allowed? How thick is an accumulation layer?



$$\rho(x) = C_{ox}[V(x) - V_g]$$

Example: Silicon TFT, typical values:

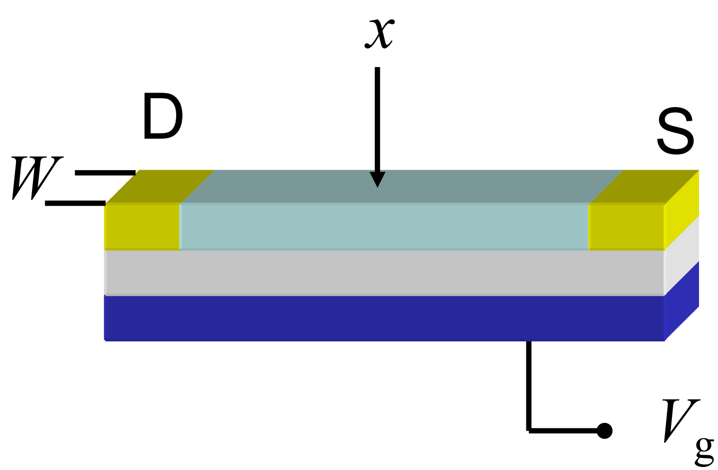
$V_g = -1$ V, $d_{ox} = 200$ nm ($C_{ox} = 170$ μF/m^2) :

$\rho = 0.17$ mC/m^2

with $N_V = 1.04 \times 10^{19}$ cm^{-3}:

$h < 1$ Å

Differential equations



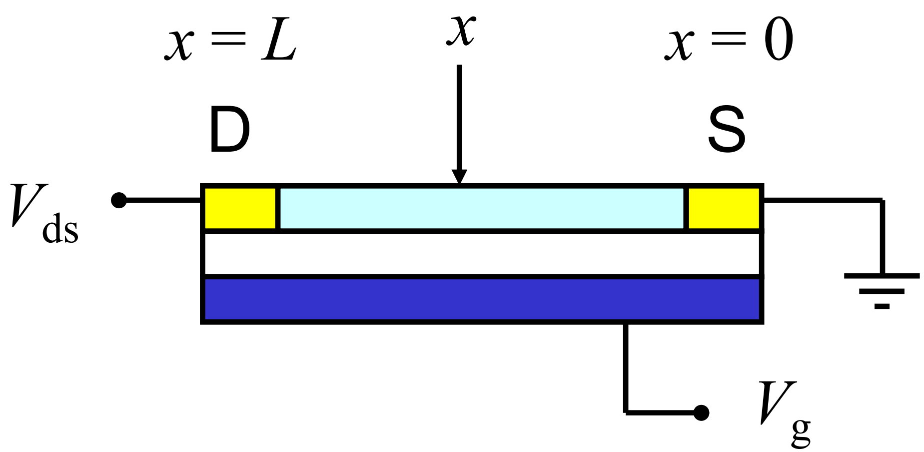
I: Assume ρ = p, free holes

II: Locally, current is proportional to charge density, mobility, electric field and channel width

$$p(x) = C_{ox}[V(x) - V_g] \quad \text{(I)}$$

$$I_x(x) = p(x) q \mu W \frac{dV(x)}{dx} \quad \text{(II)}$$

Solution



Boundary conditions:

$V(0) = 0$

$V(L) = V_{ds}$

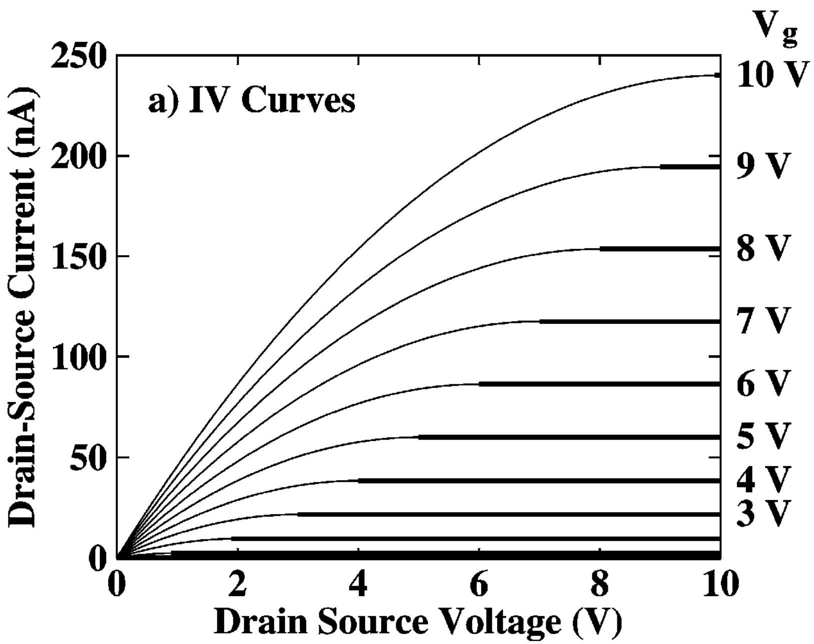
$I_x(x) = I_{ds}$

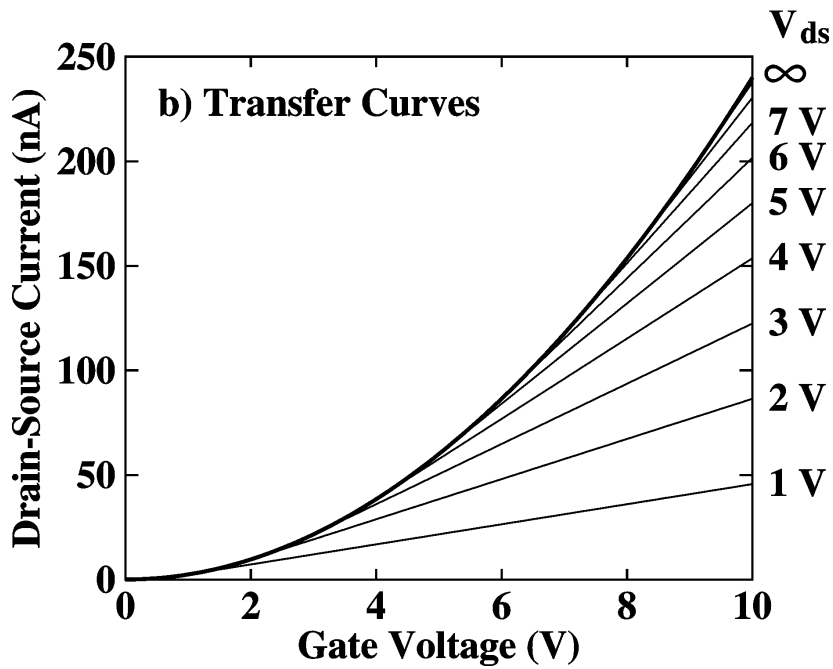
solution:

$$I_{ds} = \frac{W}{L} \mu C_{ox} (V_{ds} V_g - \tfrac{1}{2} V_{ds}{}^2)$$

Simulation

$$I_{ds} = \frac{W}{L} \mu C_{ox} (V_{ds} V_g - \tfrac{1}{2} V_{ds}{}^2)$$





Exactly equal to MOS-FET model!

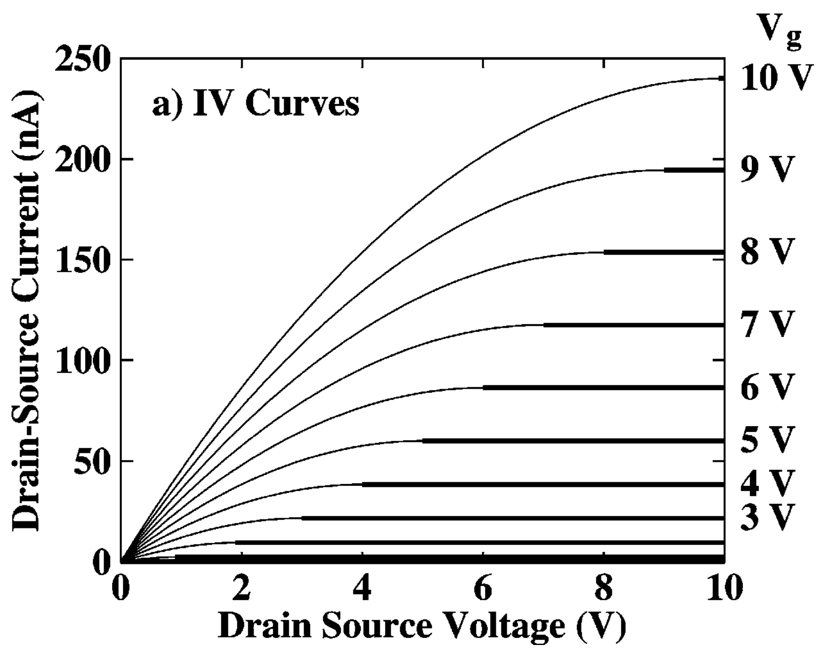
The basic model **doesn't** include

- Donors or acceptors
- Flat-band voltage
- Diffusion currents

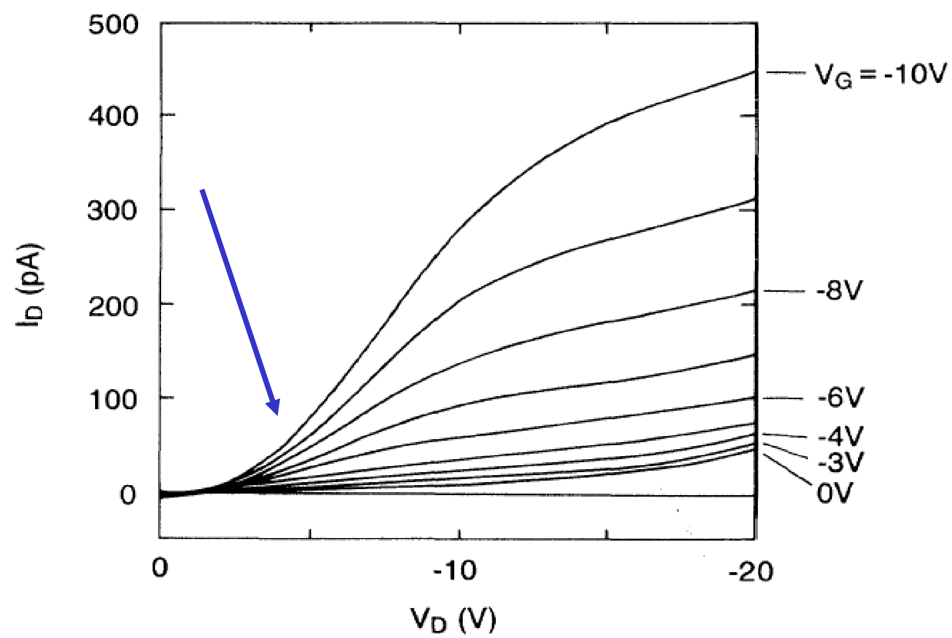
and still explain the data better

"Contact effects"

Theory:



Experiment:



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

Literature: contact effects

“Contact effects”

Literature: contact effects.

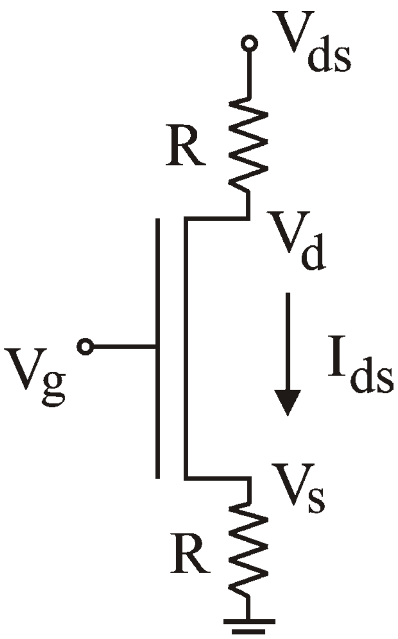
The idea is simple. Non-low-ohmic contacts hinder the injection of carriers and can cause non-linearities.

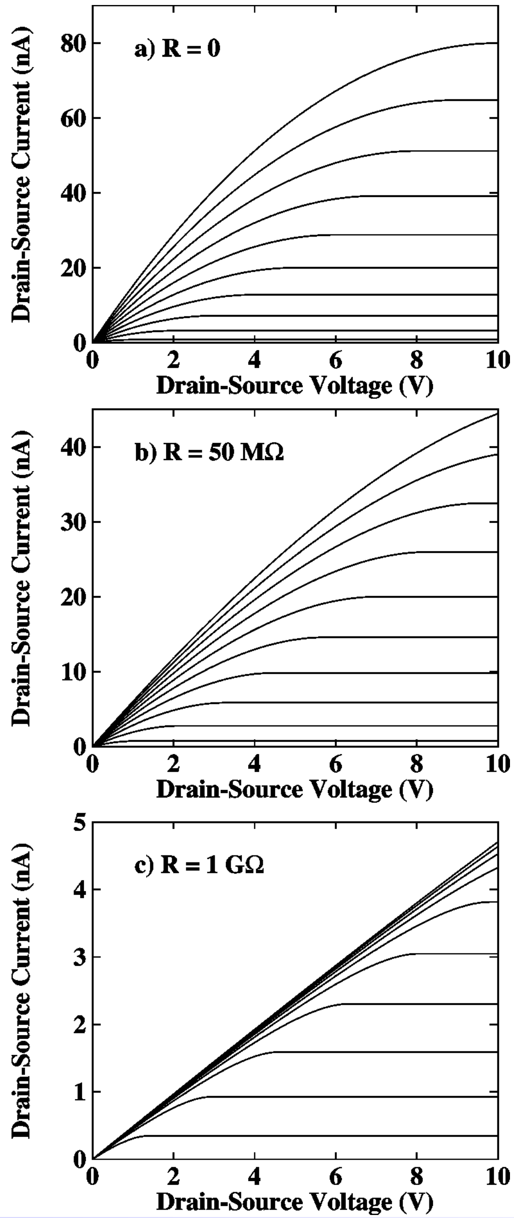
(Too) often used to explain the data.

“sweep-under-the-carpet” argumentation.

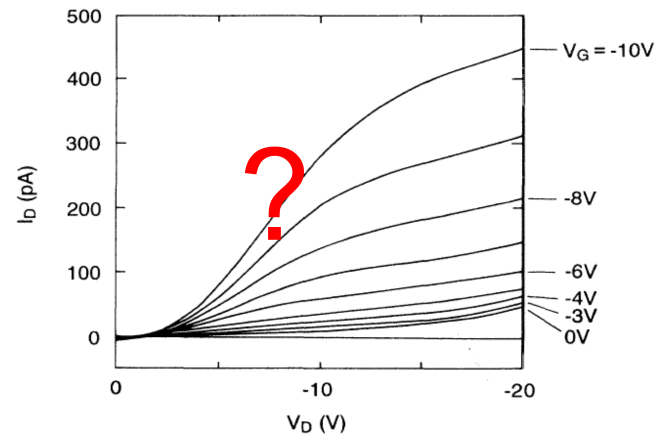
Next slides: simulations of high-resistive contacts and Schottky barriers.

“Contact effects”, simulation of contact resistance





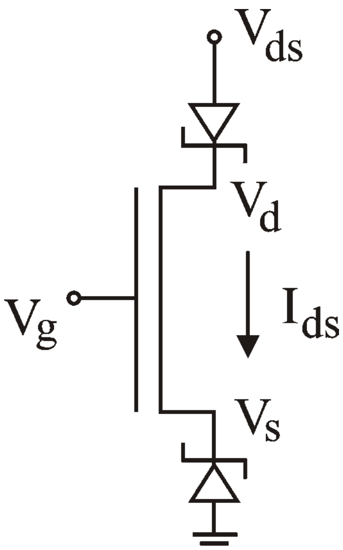
experiment:

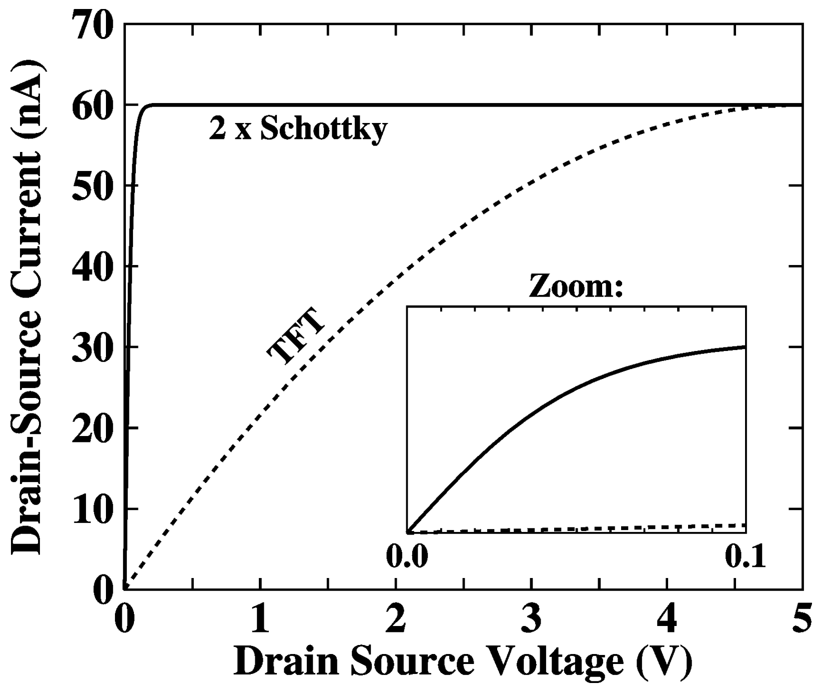


current crowding observed for high R (curves indep. of V_g)

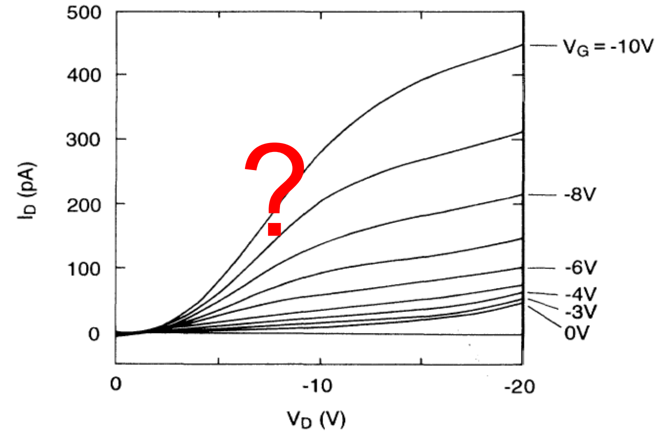
No non-linearities

“Contact effects”, simulation with Schottky barriers





experiment:



Double Schottky barrier:

$$I_{ds} = \tanh(V_{ds})$$

No non-linearities!

Simulation with Poole-Frenkel

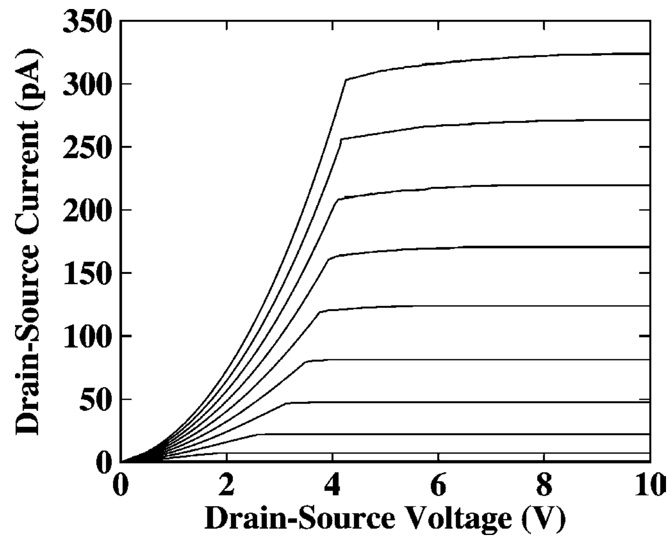
$$p(x) = C_{ox}[V(x) - V_g] \qquad \text{(I)}$$

$$I_x(x) = p(x)q\mu(x)W\frac{dV(x)}{dx} \qquad \text{(II)}$$

$$\mu(x) = \mu_0 \exp(dV(x)/dx) \qquad \text{(III)}$$

Poole-Frenkel:
"Field-assisted thermal activation from traps"

Simulation:



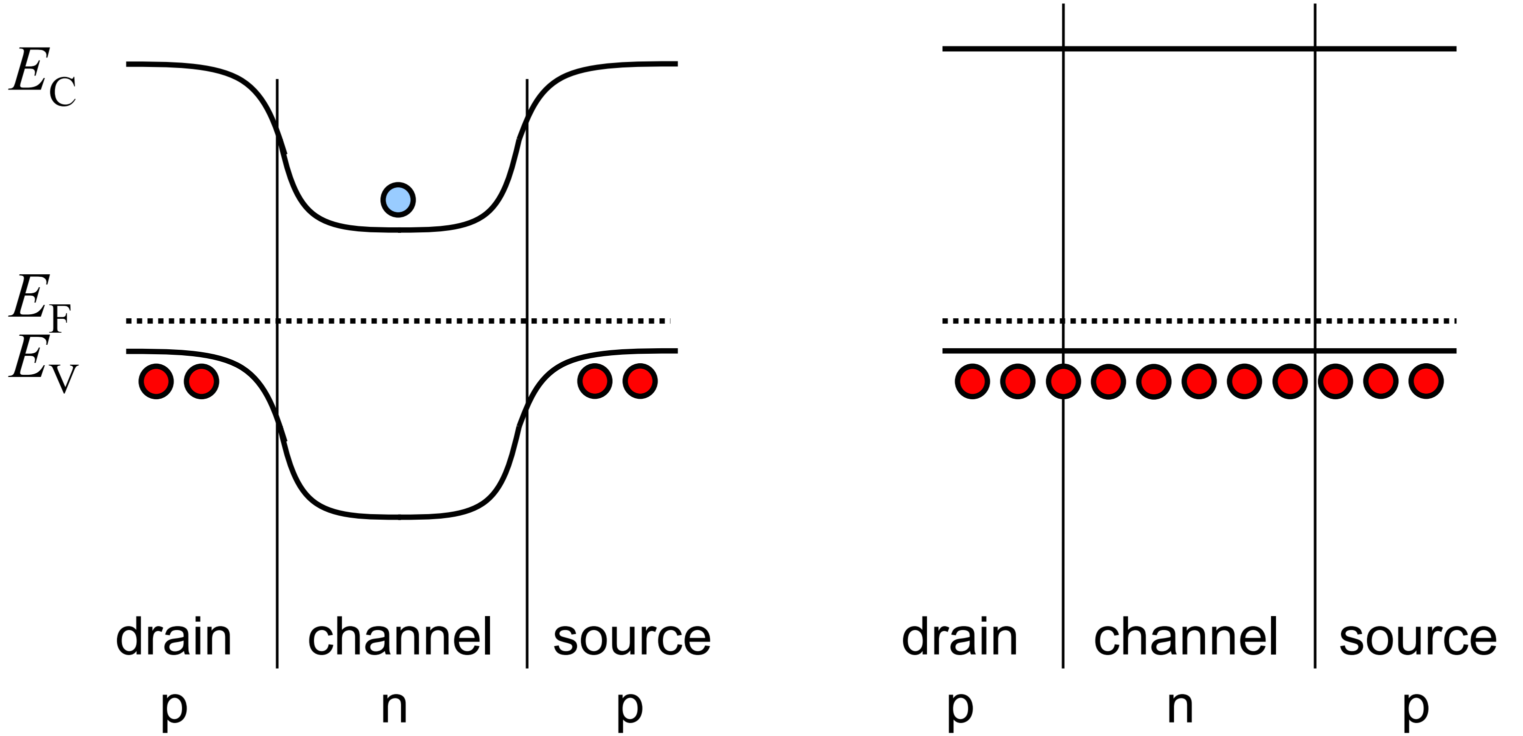
Modeling the contacts

This is, of course, only half the story.

If contacts are not resistance nor Schottky barrier, what are they?

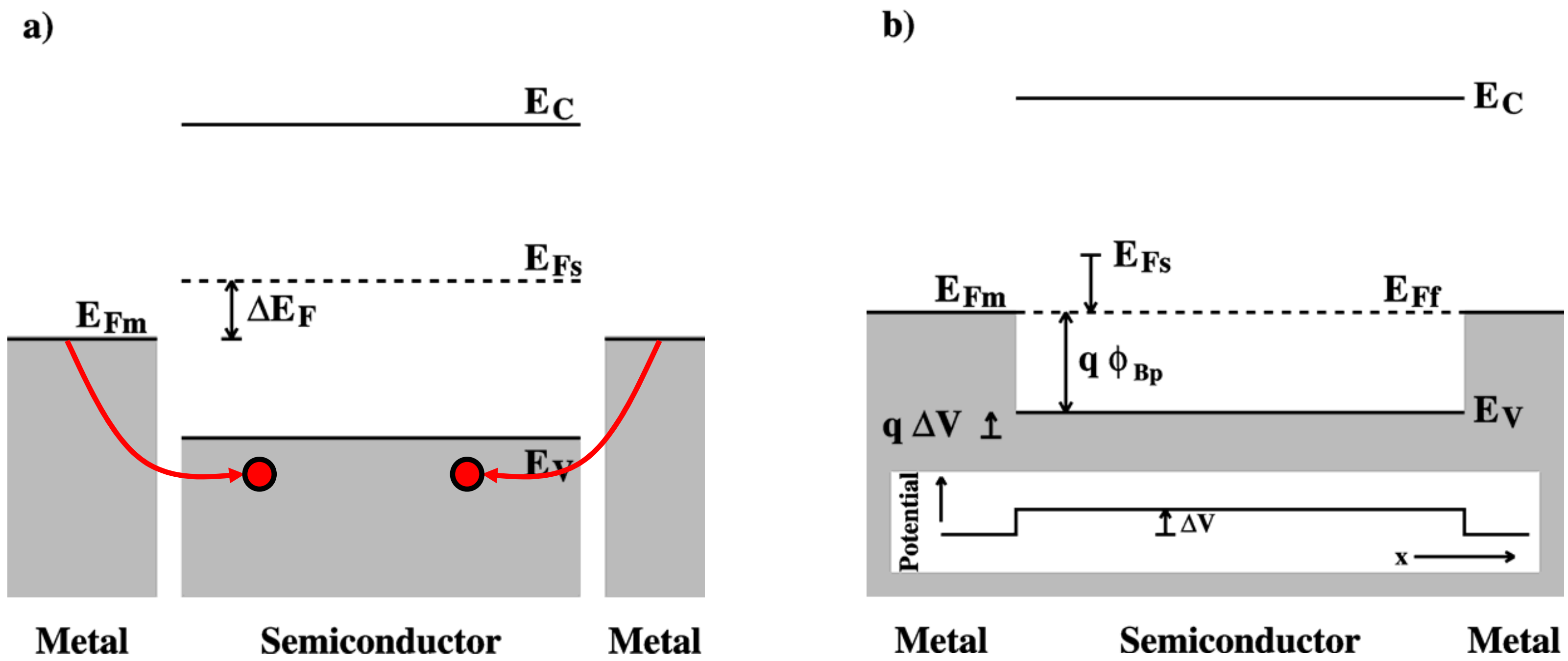
First observation. Analysis of an MOS-FET n-p-n Si-Si-Si device

zero bias: $V_g = V_t$:



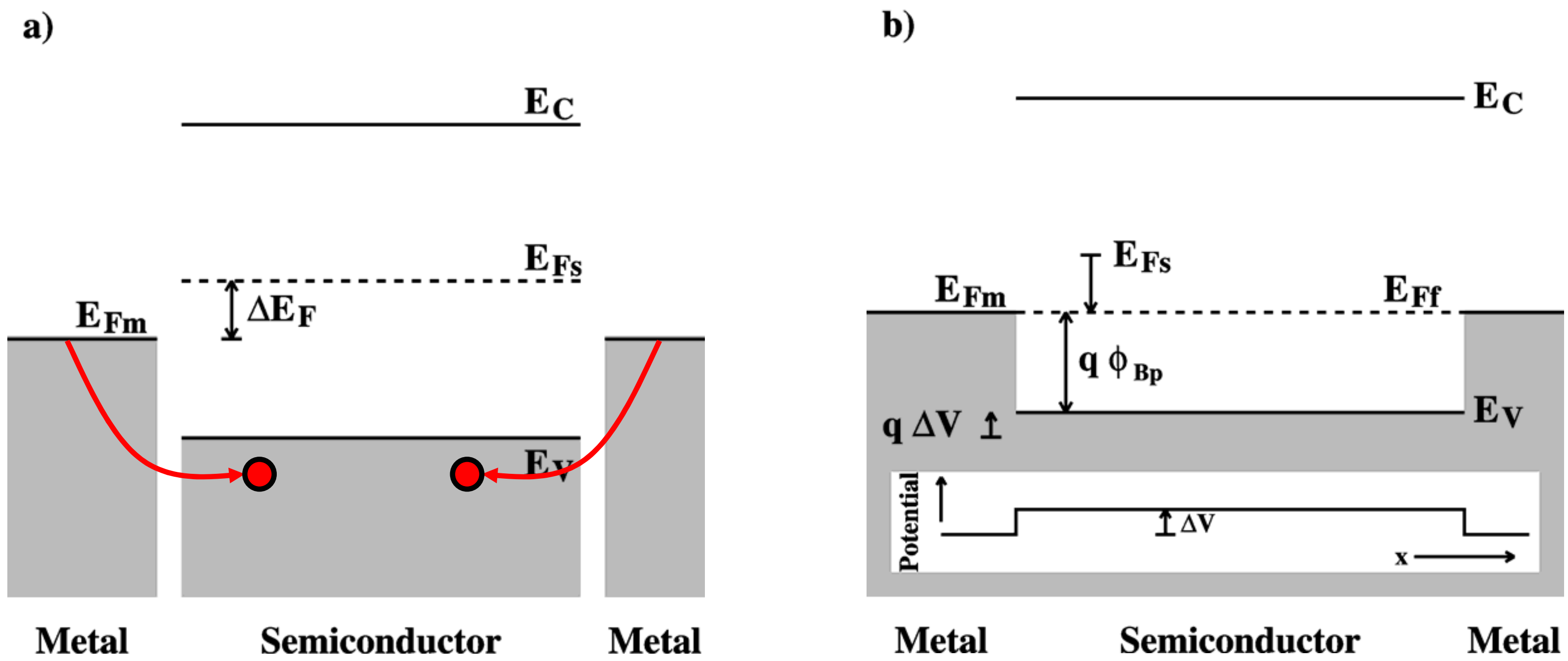
Barrier disappears exactly at start of strong inversion

Metal-1/2con-metal contact



1: charge will raise potential of channel ($p = C_{ox} V$)

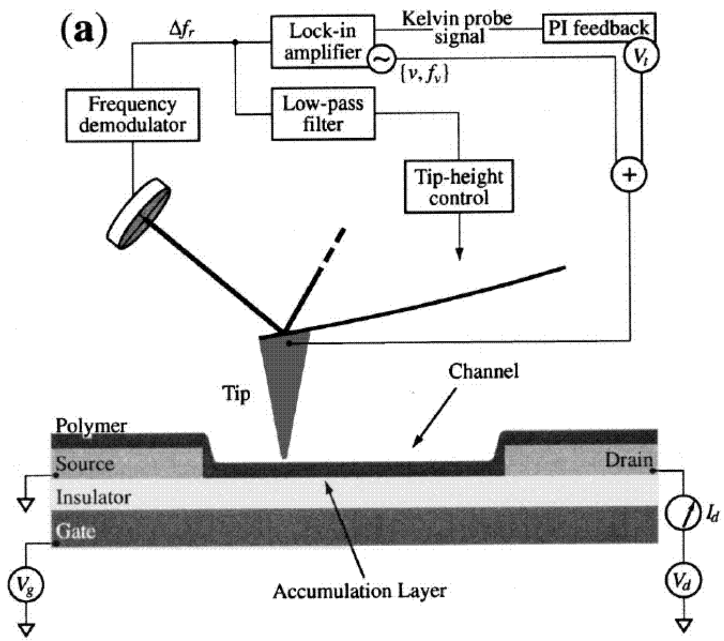
2: charge will move Fermi level ($p = \mathrm{Exp}(-E_F/kT)$)

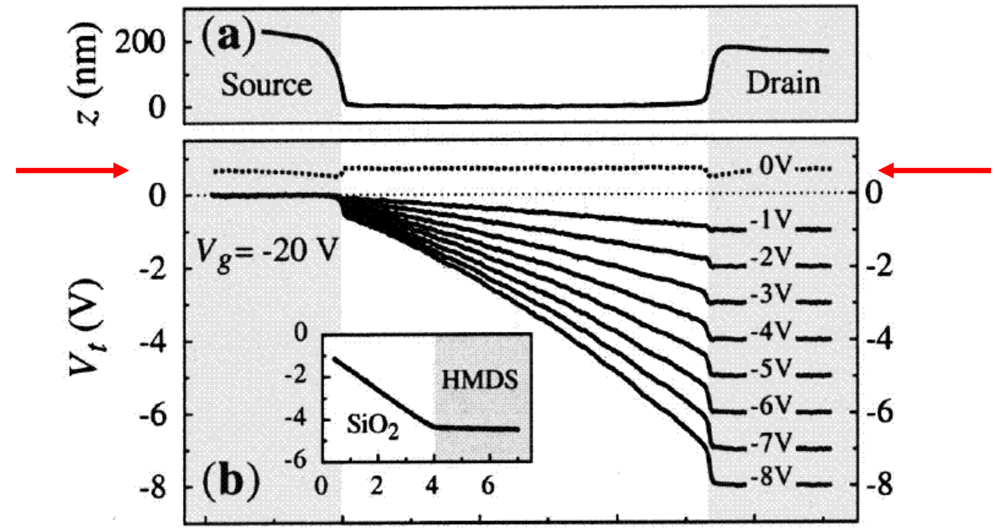


The channel has a potential ΔV, up to ~1 V even without bias

There exists a residual barrier $q\phi_{\mathrm{B}}$ of order 50-100 meV (depends on bias)

In-channel voltage profiling of Bürgi *et al.*





The channel has a potential ΔV, up to ~1 V even without bias

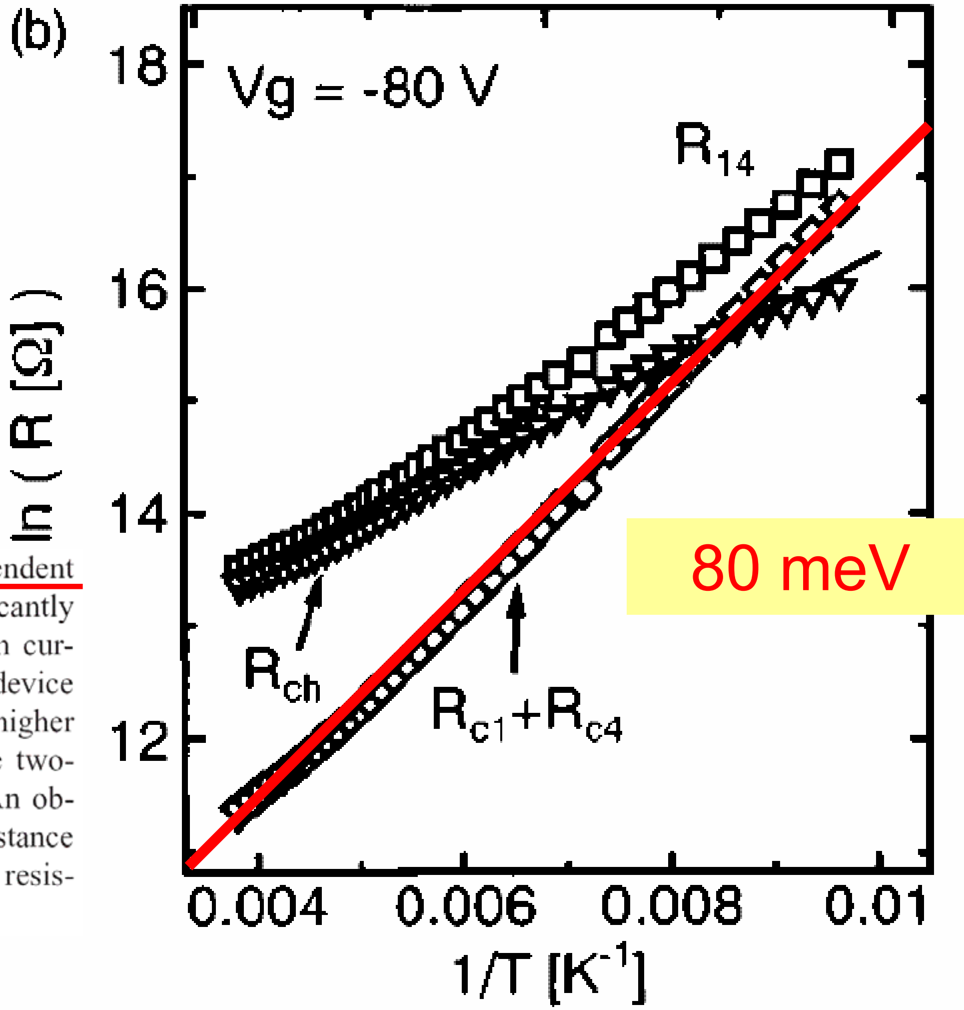
Bürgi Appl. Phys. Lett. 80, 2913 (2002)

Contact barrier height, Yagi *et al.*

There exists a residual barrier $q\phi_B$ of order 50-100 meV (depends on bias)

Pentacene TFT with gold electrodes

We obtained direct evidence of a gate-voltage-dependent contact resistance change: the induced charge significantly reduced contact resistance and increased source–drain current. Furthermore, the temperature dependence of the device clearly indicated that the contact resistance was much higher than the channel resistance and was dominated in the two-terminal total resistance of the device below 120 K. An observed activation energy of 80 meV for contact resistance was higher than that of 42 meV for pentacene channel resistance.



Yagi, Appl. Phys. Lett. **84**, 813(2004)

Summary

New model can explain

- Basic electrical characteristics
- Contact effects
- Ambipolar devices

where conventional model fails.

Adding a **HUGE** density of traps can explain

- Bias-dependent mobility $\mu = V_g^{\alpha}$, $I_{ds} = V_g^{\alpha+1}$
- Temperature dependence, $\mu = \mathrm{Exp}(-E_a/kT)$
- Transients, exponential and non-exponential,

$$I_{ds} = \mathrm{Exp}(-(t/\tau)^{\beta})$$

where conventional models fail.

The basic model **doesn’t** include

- Donors or acceptors
- Flat-band voltage
- Diffusion currents

and still explain the data better

Occam’s Razor:

“One should not increase, beyond what is necessary the number of entities required to explain anything”

- William of Occam

Final remark: Occam's Razor

The basic model **doesn't** include

- Donors or acceptors
- Flat-band voltage
- Diffusion currents

and still explain the data better

Occam's Razor:

"Of all the models explaining the data, that one with the least features is the best"

- William of Occam