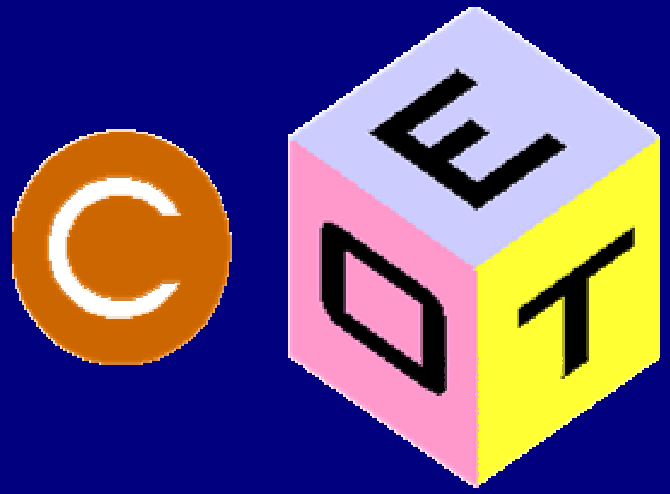
Electronic transport in Organic Semiconductors

Field Effect Transistors of sexithienyl



P. Stallinga, Universidade do Algarve (FCT, OptoEI, CEOT)

Overview

History of organic FETs in Faro

"Last time on OptoEl": Temperature scanned current

Stressing. Illumination experiments

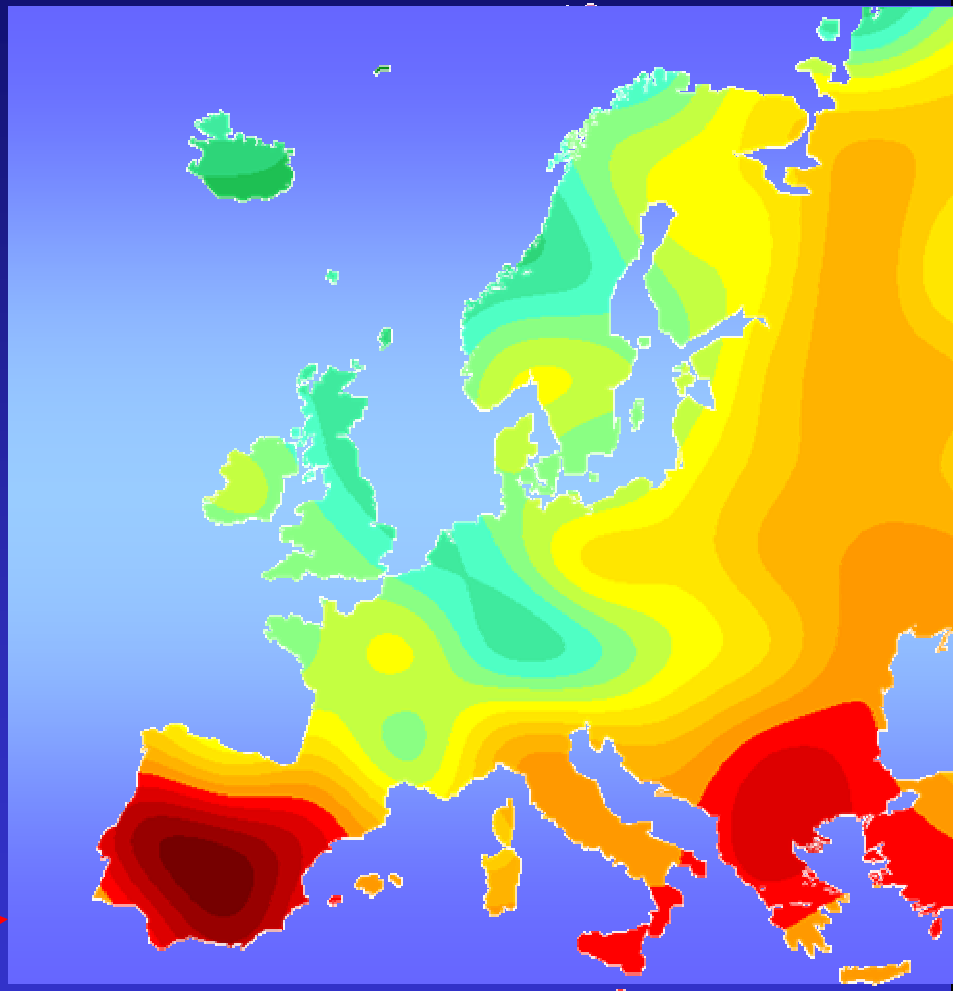
Poole-Frenkel results

Non-linear transfer curves explained

Geography

Universidade do Algarve

Faro, Portugal



Research visit Gdansk,December 2001

We don't have

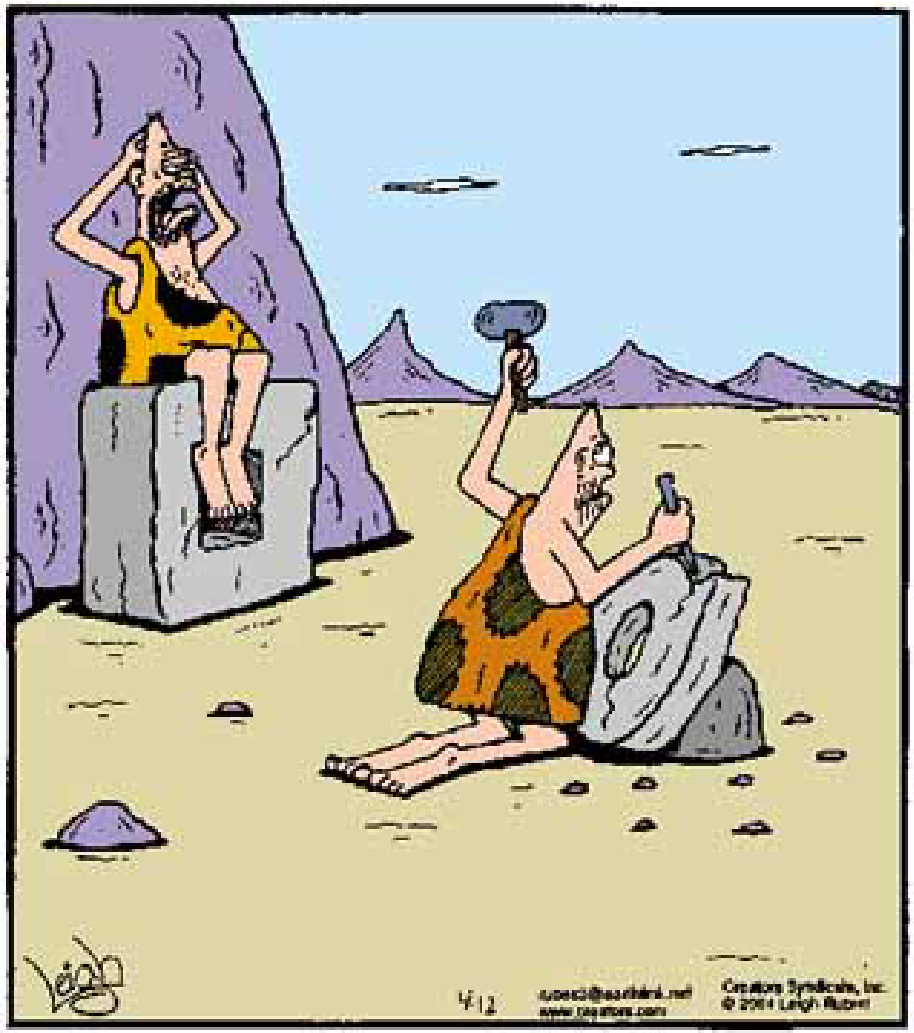
MBE, clean rooms, AFM, STM, EM, etc……

What do we have?

The most sophisticated system of electronic measurements:

DLTS (the only "organic" DLTS)

Organics-specific FET measurement system



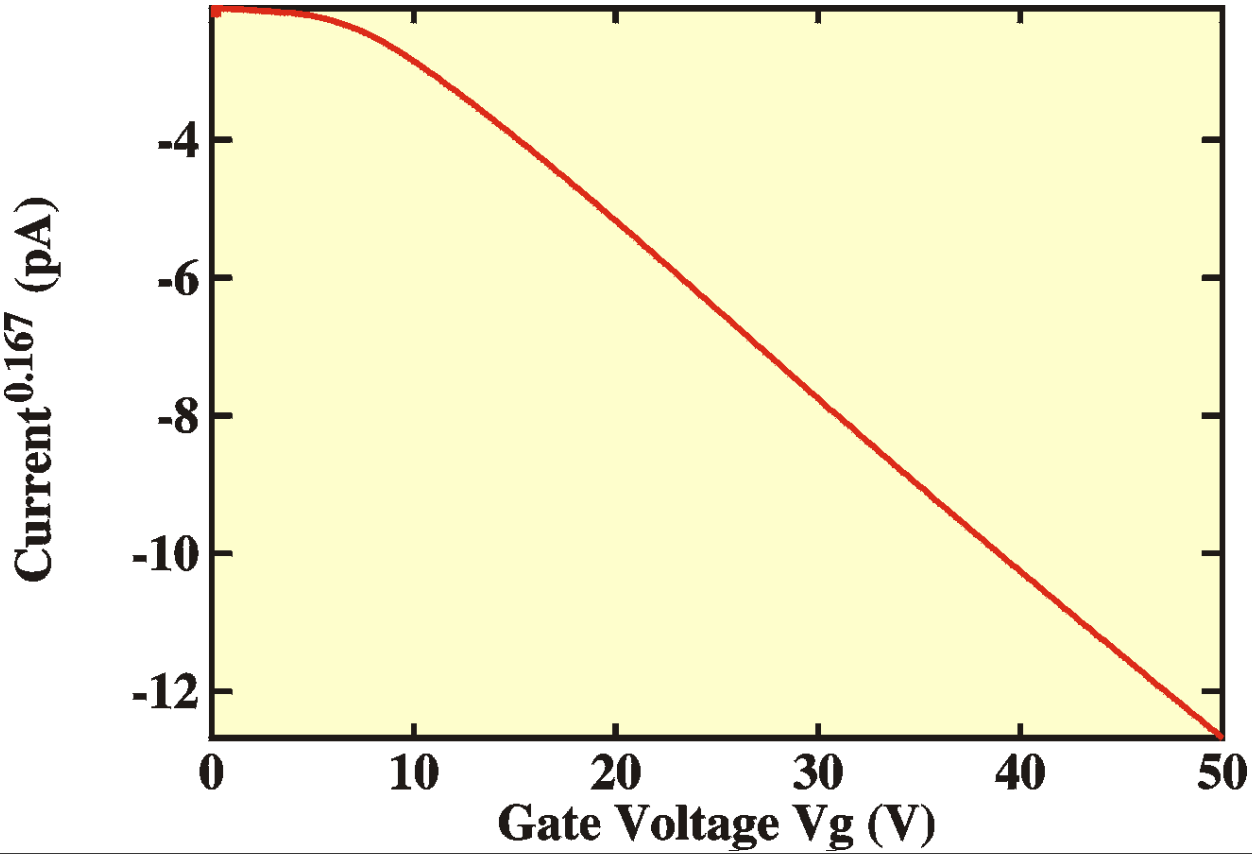
"I don't know why you're wasting your time. There's no point in reinventing the wheel."

Organic materials are like any other semiconductor

No point in reinventing the wheel

Organic FETs in Faro

Start with classic theory. However: Non-linear Transfer curves observed



Last meeting (Würzburg)

Failure of VRH model

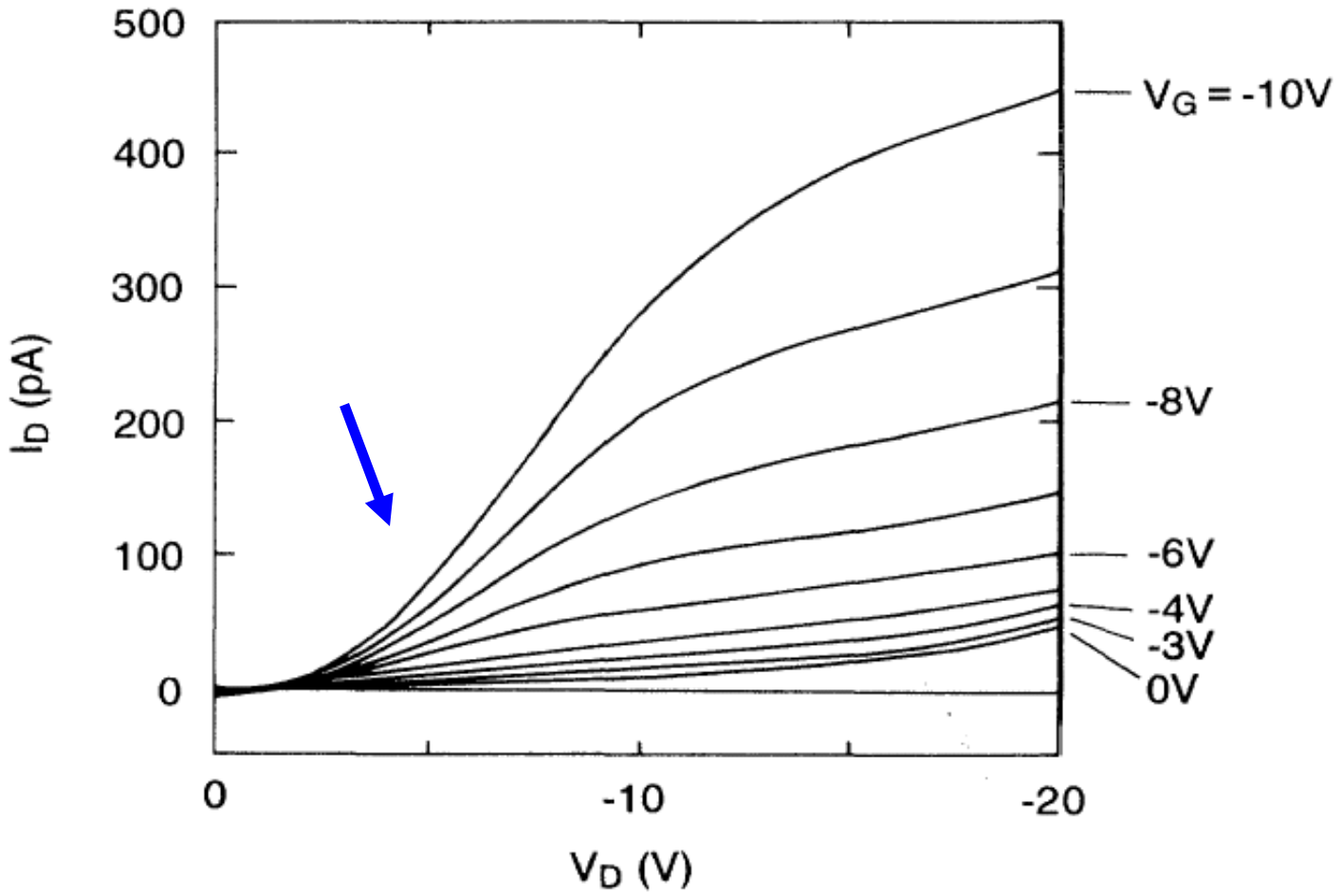
Poole-Frenkel / MTR conduction correct

Meyer-Neldel rule

Stressing (change of V_T induced by V_g)

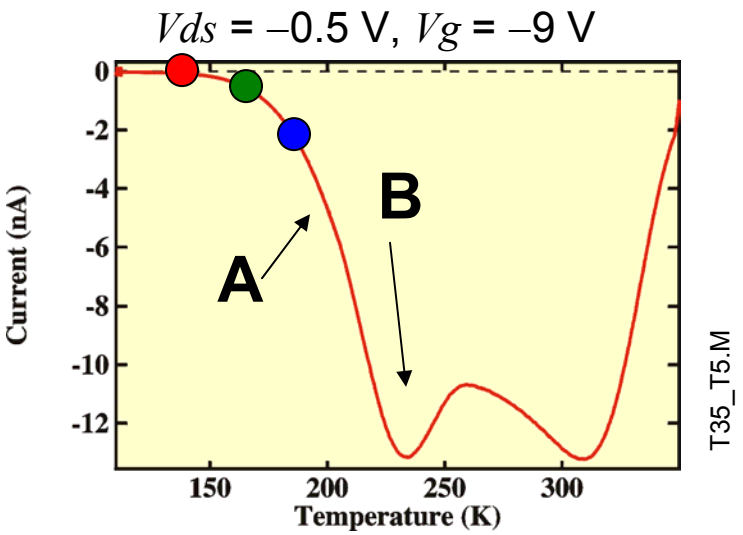
Frequency response of the FETs: $\mu(\nu)$ increases with ν

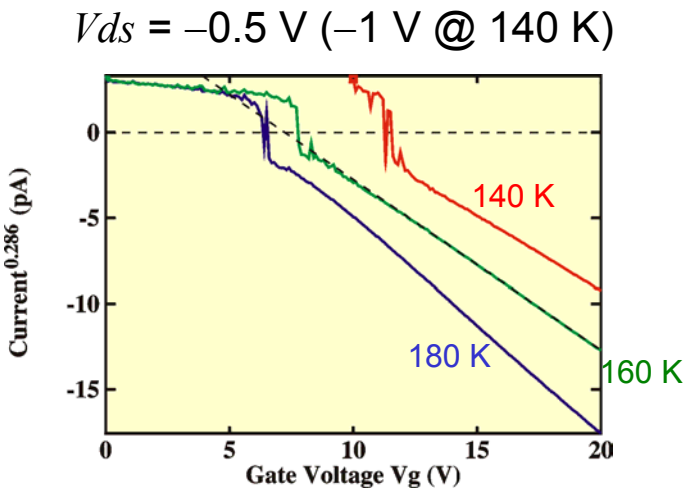
Poole-Frenkel conduction in literature



Waragai, “Charge transport in thin films of semiconducting oligothiophenes”, PRB **52**, 1786 (1995).

Temperature Scanned Current





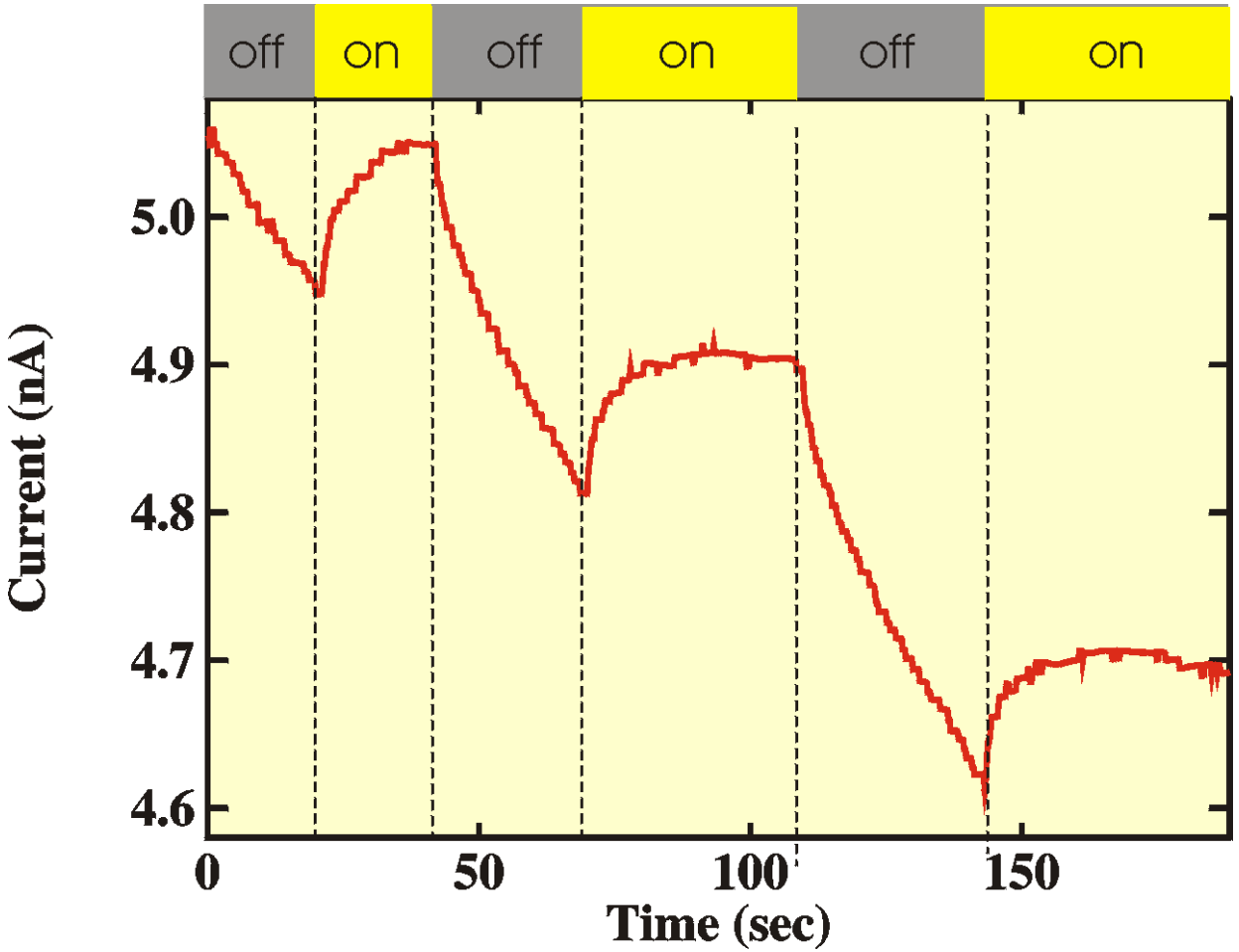
A: Poole-Frenkel / MTR: $\mu = \exp(-E_A/kT)$

B: V_T increases reversibly because N_T **new** defects appear. (Reversible upon annealing at 340 K without bias)

Illumination experiments

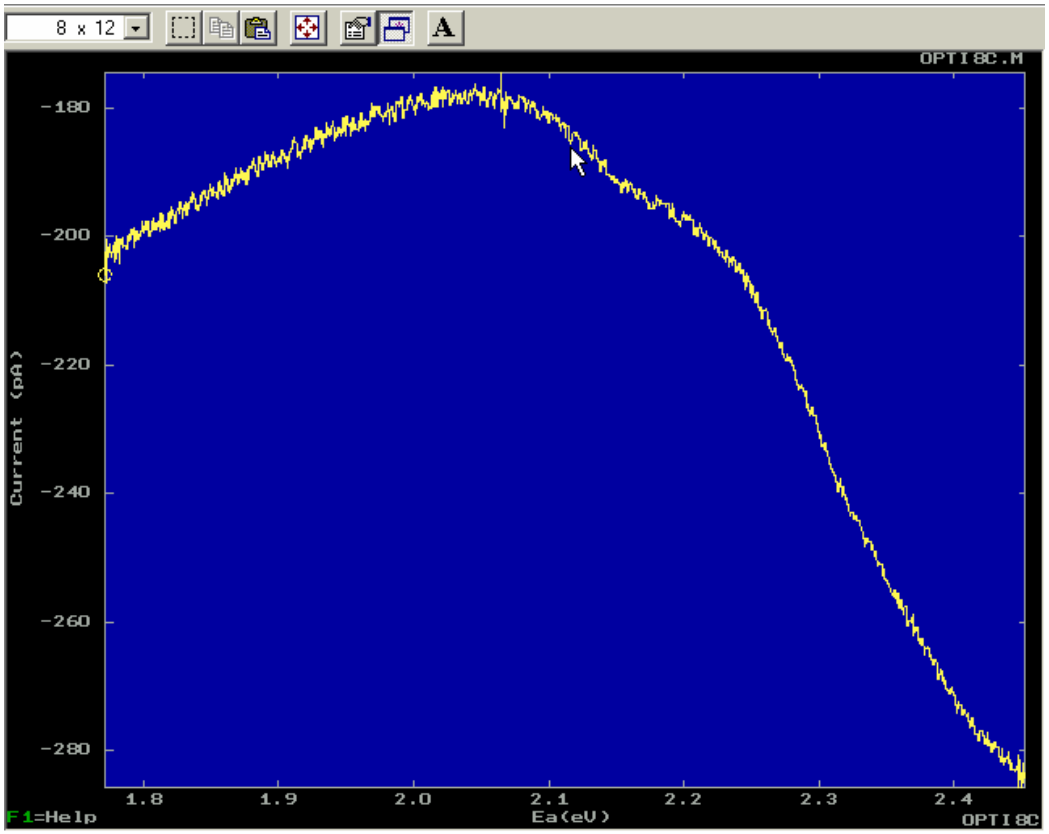
Response to white light

Fixed bias $V_{ds} = -0.5$ V, $V_g = -10$ V, $\lambda = 500$ nm



Spectrum

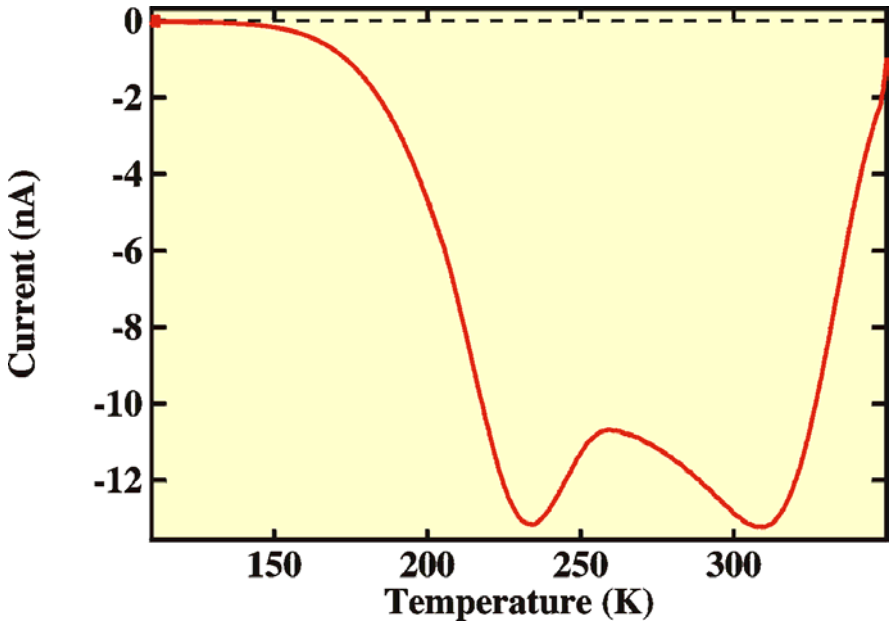
Fully stressed device (1 weekend Vg on); channel closed

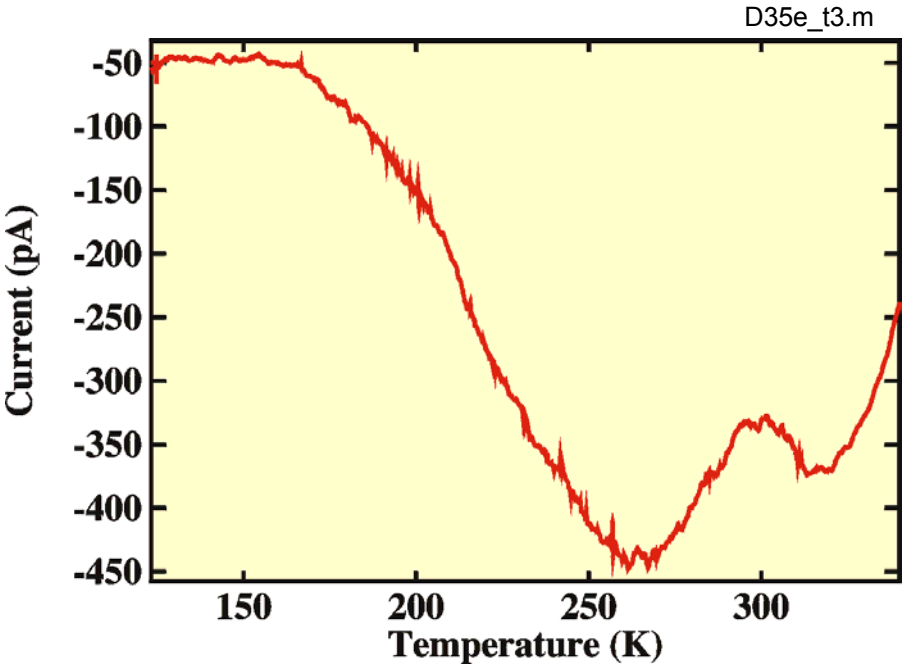


Current (pA)

Energy (eV)

After illumination to white light





Before:

Max at 230 K, 13 nA

After:

Max at 265 K, 0.45 nA

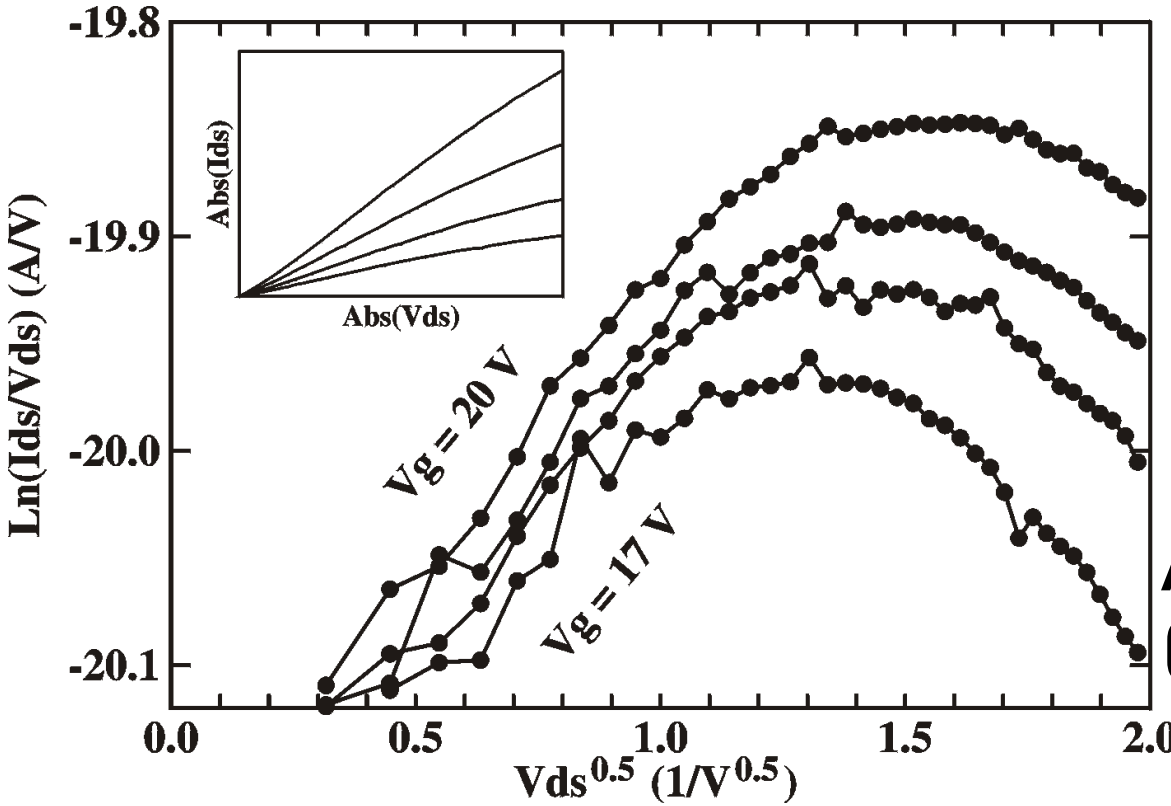
Irreversible!

Poole-Frenkel

Poole-Frenkel

Frenkel–Poole emission

$$J \sim \mathscr{E} \exp\left[\frac{-q(\phi_B - \sqrt{q\mathscr{E}/\pi\epsilon_i})}{kT}\right] \sim V \exp(+2a\sqrt{V}/T - q\phi_B/kT)$$



A: region (140 K)

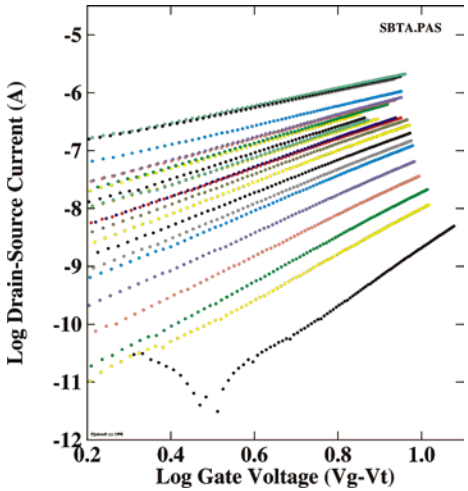
Theoretical slope ($\varepsilon_i = 5.0\ \varepsilon_0$): 0.89 $V^{-0.5}$

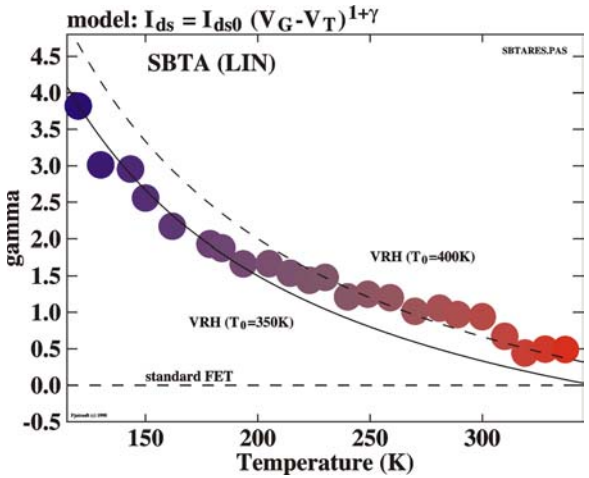
Experimental slope: 0.29 $V^{-0.5}$

Transfer curves

Non-linear transfer curves

$$\text{LIN:} \quad I_{ds} = (W/L)\, C_{ox}\, \mu\, (V_g - V_t)^{1+\gamma}\, V_{ds}$$



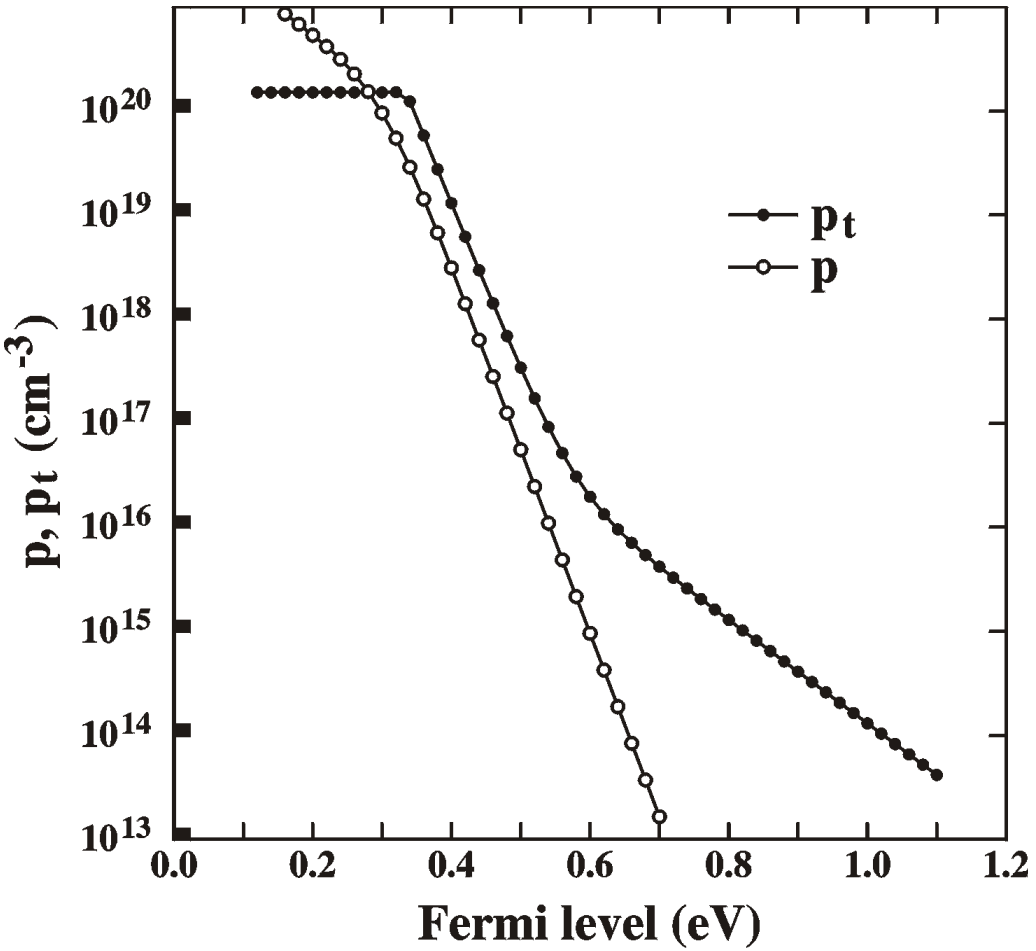


Experimental γ ranging from 0 to 5, sometimes depending on T, sometimes abrupt changes, etc. etc.

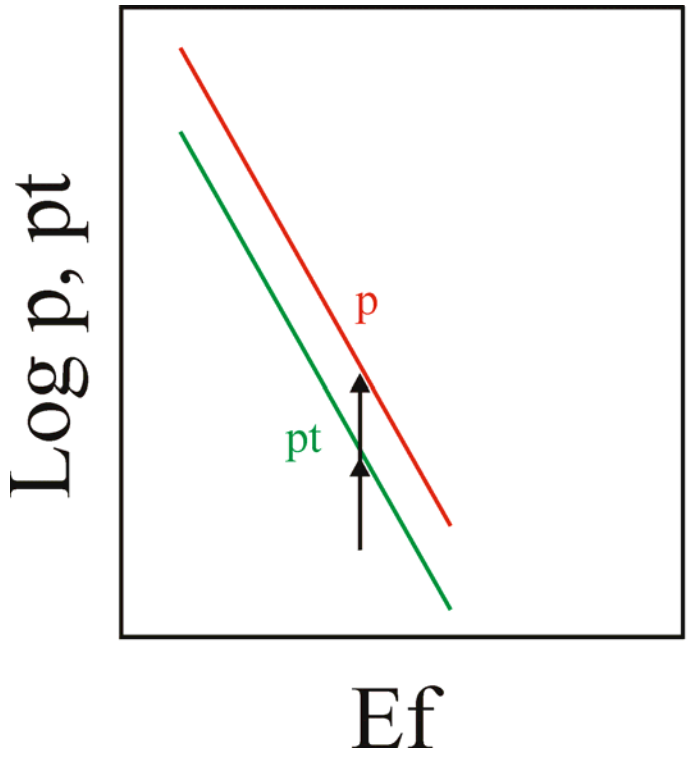
Rejection of VRH theory

Explanation Shur

Section 4-12 of "Physics of Semiconductor Devices", M. Shur
Amorphous silicon Thin Film Transistors

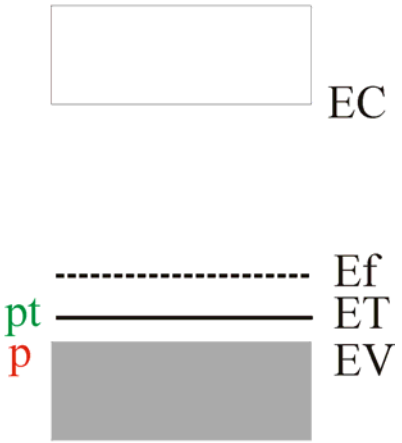


Classical trap in classical semiconductor



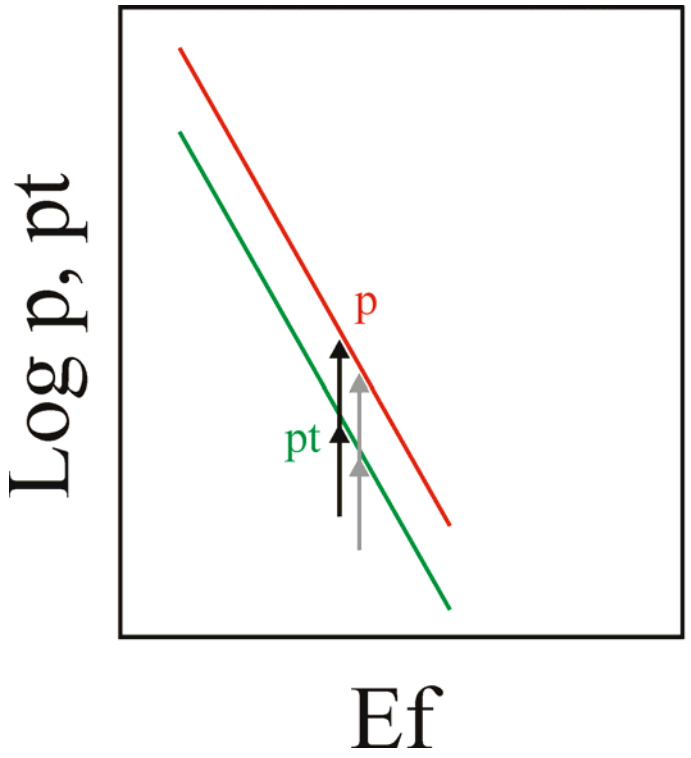
$$p = N_V \exp[(E_V - E_f)/kT]$$

$$p_t = N_t \exp[(E_t - E_f)/kT]$$



For certain E_f: ratio $p_t/(p+p_t)$ is small

Classical trap in classical semiconductor



$$p = N_V \exp[(E_V - E_f)/kT]$$

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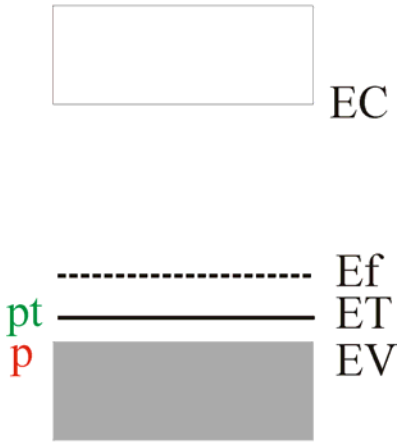
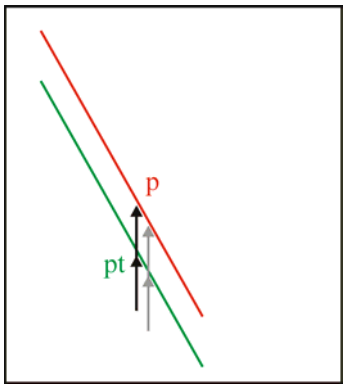


For certain E_f: ratio $p_t/(p+p_t)$ is small … and constant!

$$p/p_t = (N_V/N_t)\exp[(E_V - E_t)/kT]$$

Classical trap in classical semiconductor



As a result:

$$\Delta Q = \Delta(p+p_t) = C_{ox}\,\Delta V_g$$

becomes (only p contributes to current):

$$\Delta I_{ds} = V_{ds}\,\mu\,\Delta p$$

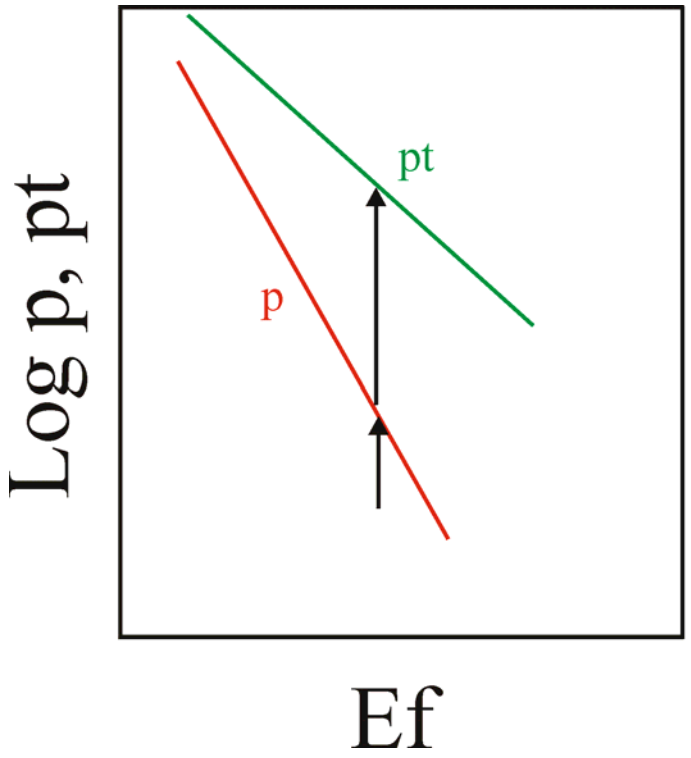
$$= V_{ds}\,\mu\,(\Delta p/\Delta(p+p_t))\,C_{ox}\,\Delta V_g$$

$$= V_{ds}\,\mu\,\alpha\,C_{ox}\,\Delta V_g$$

i.e. classical FET equation with tiny correction $\alpha \approx 1$ independent of V_g

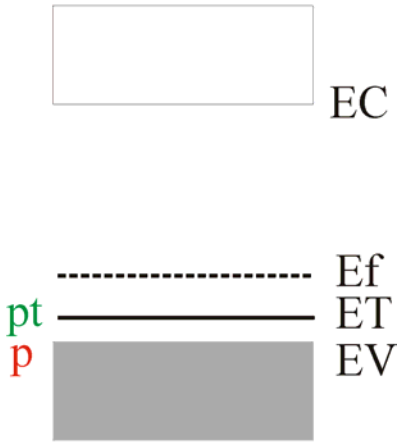
Because slopes in Ef plot are equal

Abundant trap in amorphous semiconductor



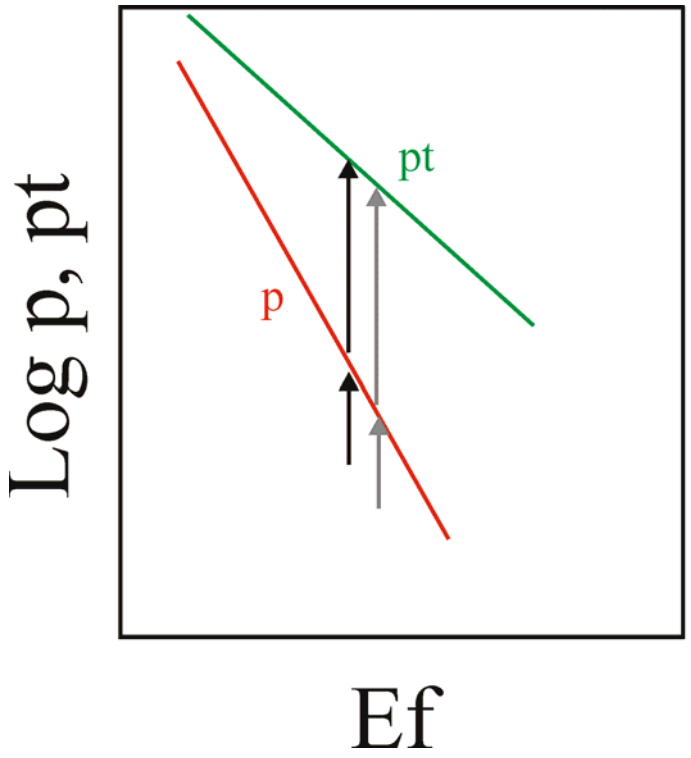
$$p = N_V \exp[a(E_V - E_f)/kT]$$

$$p_t = N_t \exp[b(E_t - E_f)/kT]$$



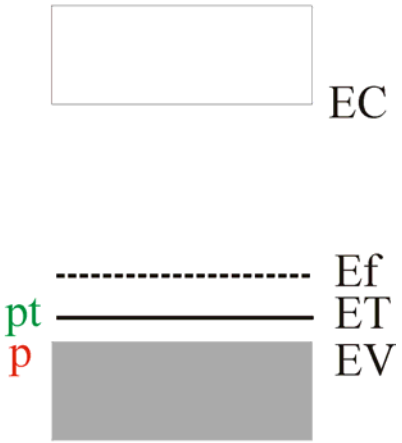
For certain E_f, ratio $p_t/(p+p_t)$ is large

Abundant trap in amorphous semiconductor



$$p = N_V \exp[a(E_V - E_f)/kT]$$

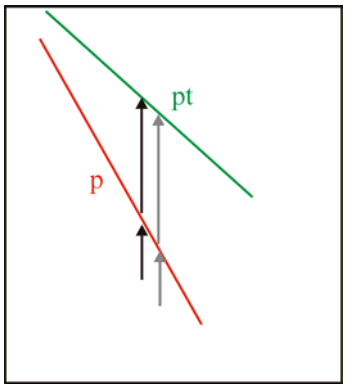
$$p_t = N_t \exp[b(E_t - E_f)/kT]$$



For certain E_f, ratio $p_t/(p+p_t)$ is large … and depends on E_f

$p/p_t = (N_V/N_t)\exp[(aE_V - bE_t + \{a-b\}E_f)/kT]$ and thus on V_g

Abundant trap in amorphous semiconductor



As a result:

$$\Delta Q = \Delta(p+p_t) = C_{ox}\,\Delta V_g$$

becomes (only p contributes to current):

$$\Delta I_{ds} = V_{ds}\,\mu\,\Delta p$$

$$= V_{ds}\,\mu\,\Delta V_g^{a/b}$$

i.e. **our observed T6 FET transfer curves!**

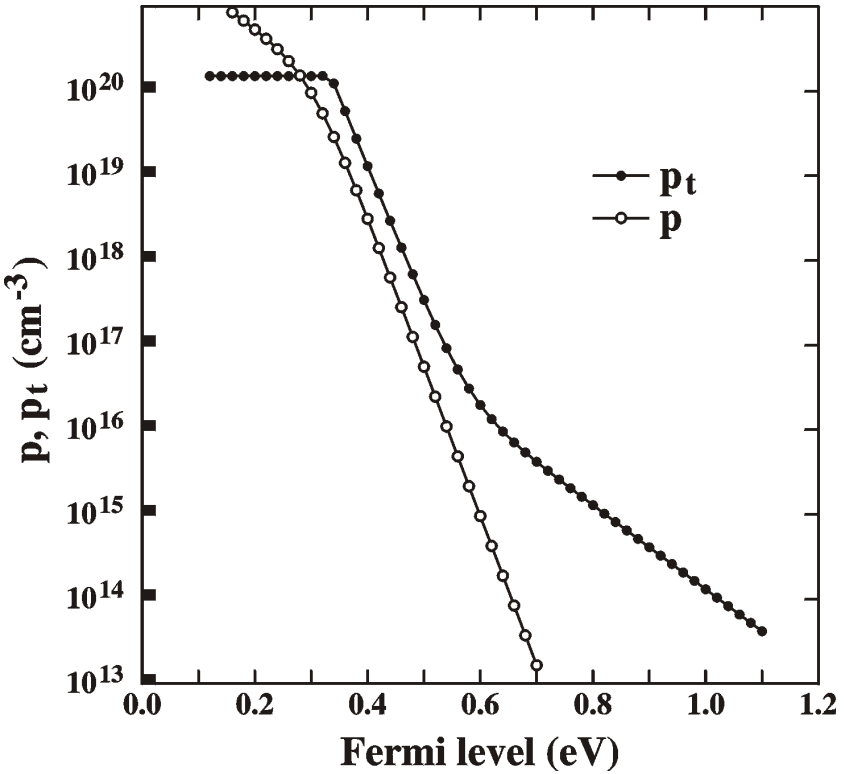
Because slopes in Ef plot are different

p (and I_{ds}) grow faster-than-linear with V_g

Remarks

- Any γ can be explained by this idea.
- γ can change from device to device and even from day to day, depending on the density and energetic distribution of traps
- This γ can depend on T, but doesn't have to be
- Once a channel is formed, E_f doesn't move much anymore and γ is constant.
- When the gate bias is changed, newly induced carriers are necessarily of the conductive type. (otherwise they would never reach the interface from the drain/source.): Initilially $\Delta Q = \Delta p = C_{ox}\Delta V_g$
- From there they get trapped: measuring fast results in a large carrier mobility. Measuring slow results in a low and gate-dependent mobility.

All amorphous materials show this behavior



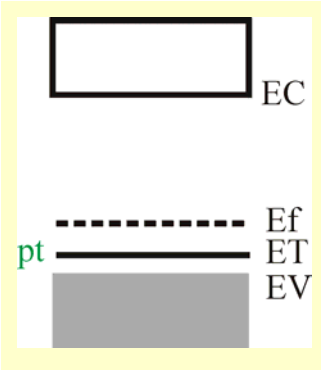
Amorphous Si.

Shur

How to explain $p_t = N_t \exp[\boldsymbol{b}(E_t\text{-}E_F)/kT]$

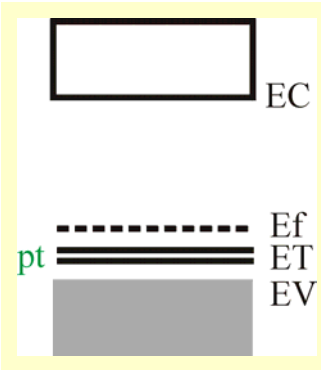
What type of traps?

single



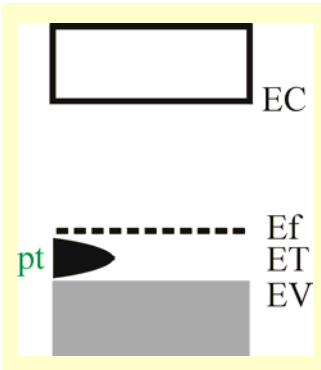
$$p_t = N_t \exp[(E_t - E_f)/kT]$$

double



$$p_t = N_{t1} \exp[(E_{t1} - E_f)/kT] + N_{t2} \exp[(E_{t2} - E_f)/kT] = p_{t0} \exp[-E_f/kT]$$

Distrib.

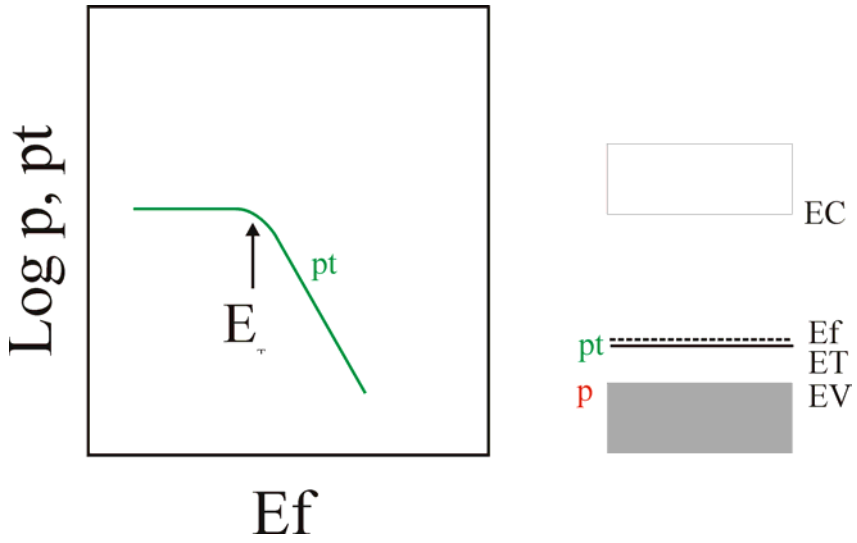


$$p_t = p_{t0} \exp[-E_f/kT]$$

Still the same slope in plots! $(-1/kT)$

When E_f close to trap:

$$p_t = N_t \exp[(E_t - E_f)/kT]$$

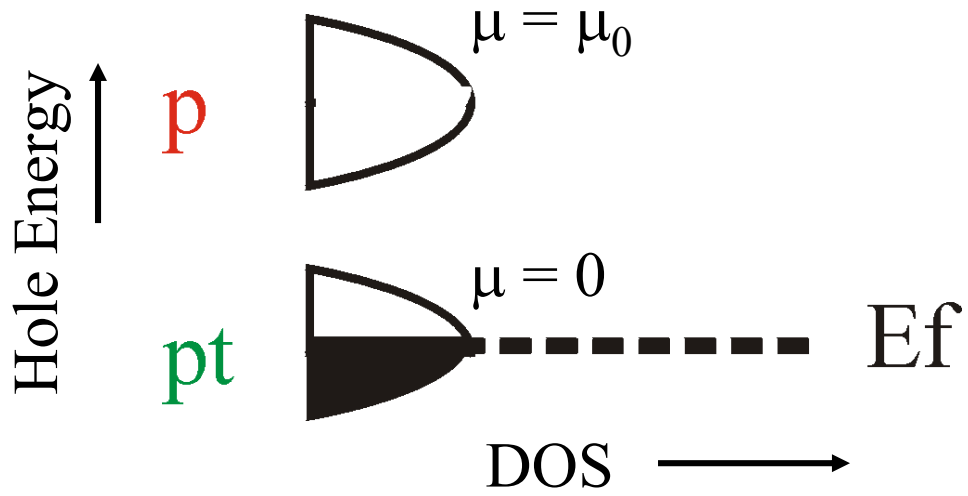


is

$$p_t = N_t \frac{1}{1+\exp[(E_f - E_t)/kT]}$$

Conclusions about non-linear transfer curves

- Abundant trap. Every molecule a trap!
- Distributed in energy
- E_f resonant with trap
- Conductive states above trap states
- Conductive states mostly empty (at steady state)
- New charges always injected in conductive states



Conclusions

3 things important for organic FETs: Traps traps & traps

Responsible for non-linear transfer curves ($I_{ds} \propto V_g^{\gamma}$)

Responsible for non-linear IV curves ($I_{ds} \propto V_{ds} \exp(-\sqrt{V_{ds}})$)

Responsible for temperature activation of current (0.17 eV)

Responsible for stressing

- Reversible creation of new traps in dark (>200 K)
- Irreversible creation of new traps under illumination

10Q4yor@+ion