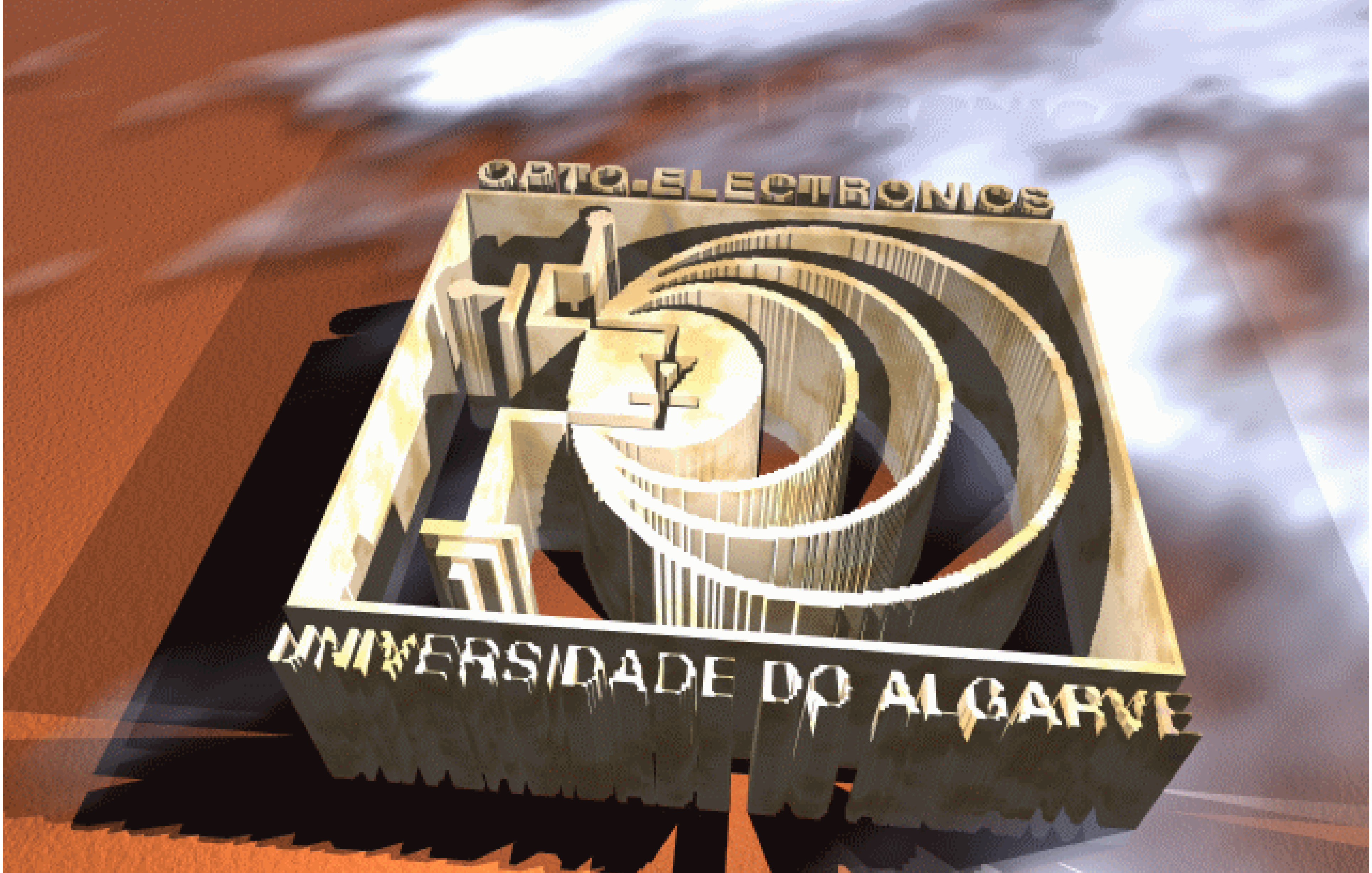

P. Stallinga (Universidade do Algarve)

MONA-LISA Wuerzburg, 3-VII-2003

NO SIGNAL

Introduction

MONA-LISA Würzburg 2003, P. Stallinga, UAlg

Introduction

- An FET needs VT to start working:

$$V_T = \ldots N_A^{1/2}$$

- From then on it is a capacitor:

$$Q = C_{ox}\,(V_G - V_T)$$

- In the linear region the current is proportional to the field and the charge density:

$$I_{ds} = V_{ds}\, Q\, \mu$$

Result:

$$I_{ds} = a\, V_{ds}\, C_{ox}\,(V_G - V_T)\, \mu$$

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Introduction

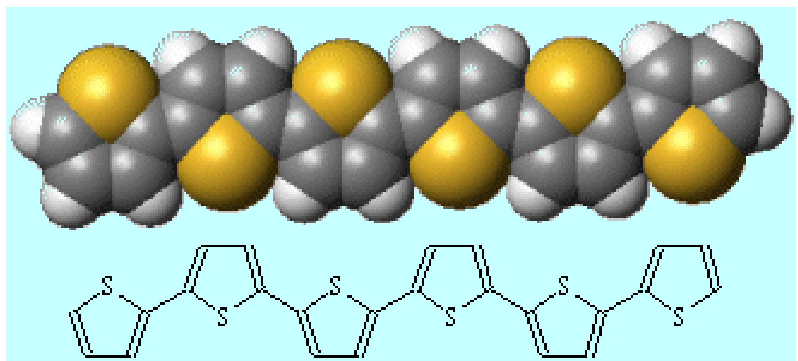
$$I_{ds} = a\, C_{ox}\, (V_G - V_T)\, \mu\, V_{ds}$$

a	device dimensions
$C_{ox}(V_G - V_T)$	charge density
μ	response of a carrier to the field
V_{ds}	field

Introduction

Special Effects

- Mobility depends on longitudinal field (V_{ds})
- Mobility *appears* to depend on transversal field (V_g)
- Mobility *appears* to depend on the frequency (ν)
- Threshold voltage not constant (V_g, t, T)



Transfer curves

Mobility *appears* to depend on Vg

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

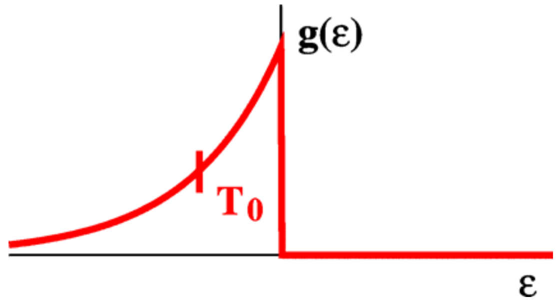
$$\text{SAT:} \quad I_{ds} = (^1/_2)(W/L)\, C_{ox}\, \mu\, (V_g - V_t)^{2+\gamma}$$

This implies that the **amount of free charge** in the channel grows faster-than-linear with the gate voltage, i.e. no longer a simple "parallel metal plates" device

Alternatively: define an as-measured (parametric) mobility that depends on V_g, example (LIN)

$$I_{ds} = (W/L)\, C_{ox}\, \mu(V_g)\, (V_g - V_t)\, V_{ds}$$

Vissenberg



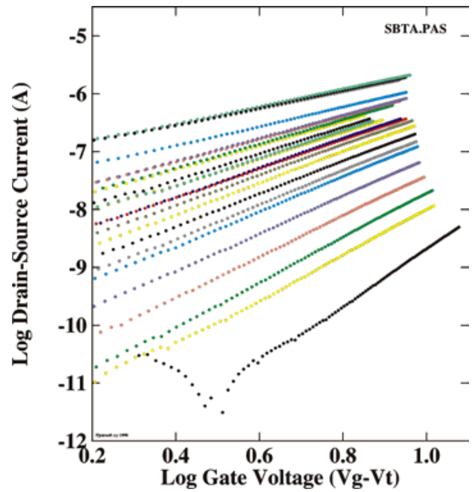
$$g(\varepsilon) = (N_T/kT_0)\ \exp\ (\varepsilon/kT_0)$$

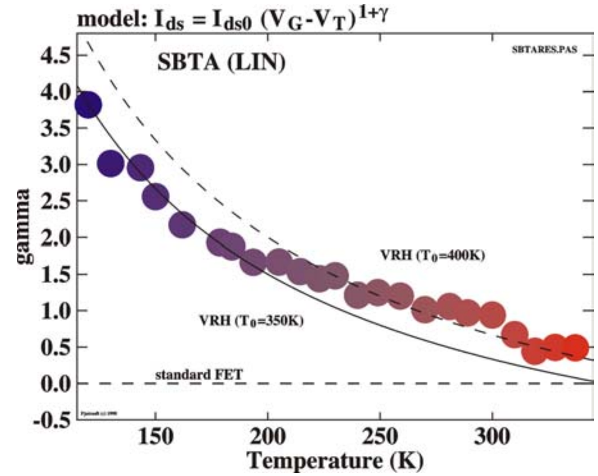
$$\gamma = 2(T_0/T-1)$$

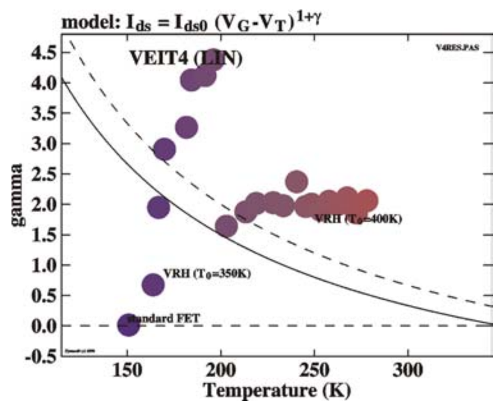
Vissenberg et al, PRB 57, 12964 (1998)

Mobility *appears* to depend on Vg

γ depends on T







Failure of the VRH/MTR theory, which cannot adequately describe the behavior of γ as a function of temperature.

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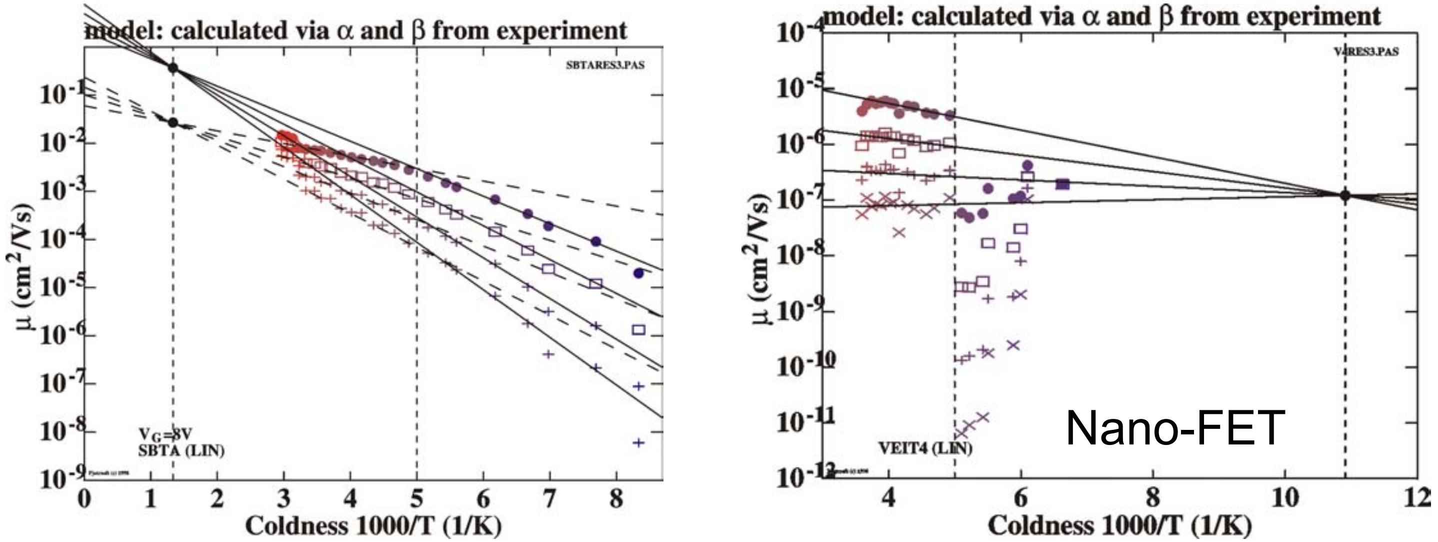
The Meyer-Neldel rule (MNR)

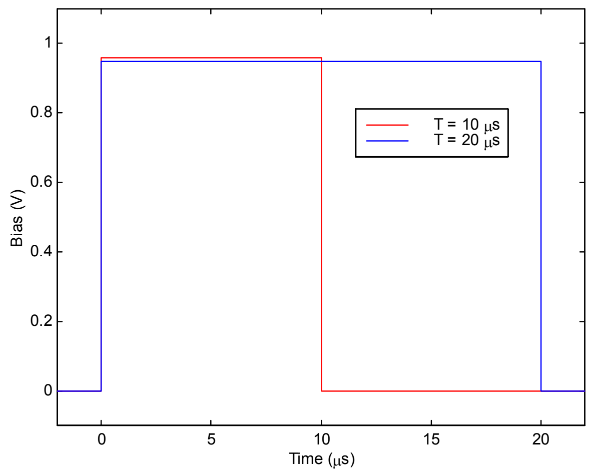
MNR: In Arrhenius plot all mobilities lie on line going through the same point (T_{MR}, μ_{MN})

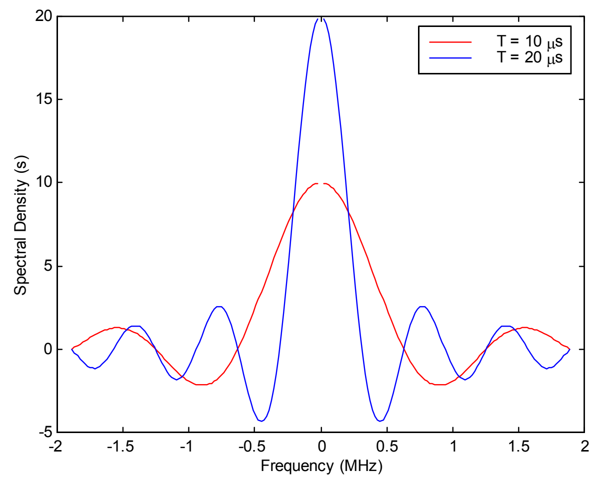


MNR holds, with a phase transition at 200 K

Current spectroscopy

Pulsed measurements





Fourrier transform of pulse:

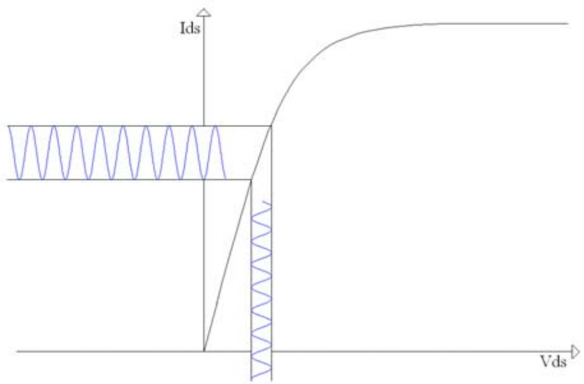
Shorter pulse: higher frequencies

Examples:
Pulse 20 μs = 0.25 MHz
Pulse 10 μs = 0.5 MHz

When doing pulsed measurement, you are doing FTCS (Fourrier-transform current-spectroscopy)

Important if μ depends on ν.

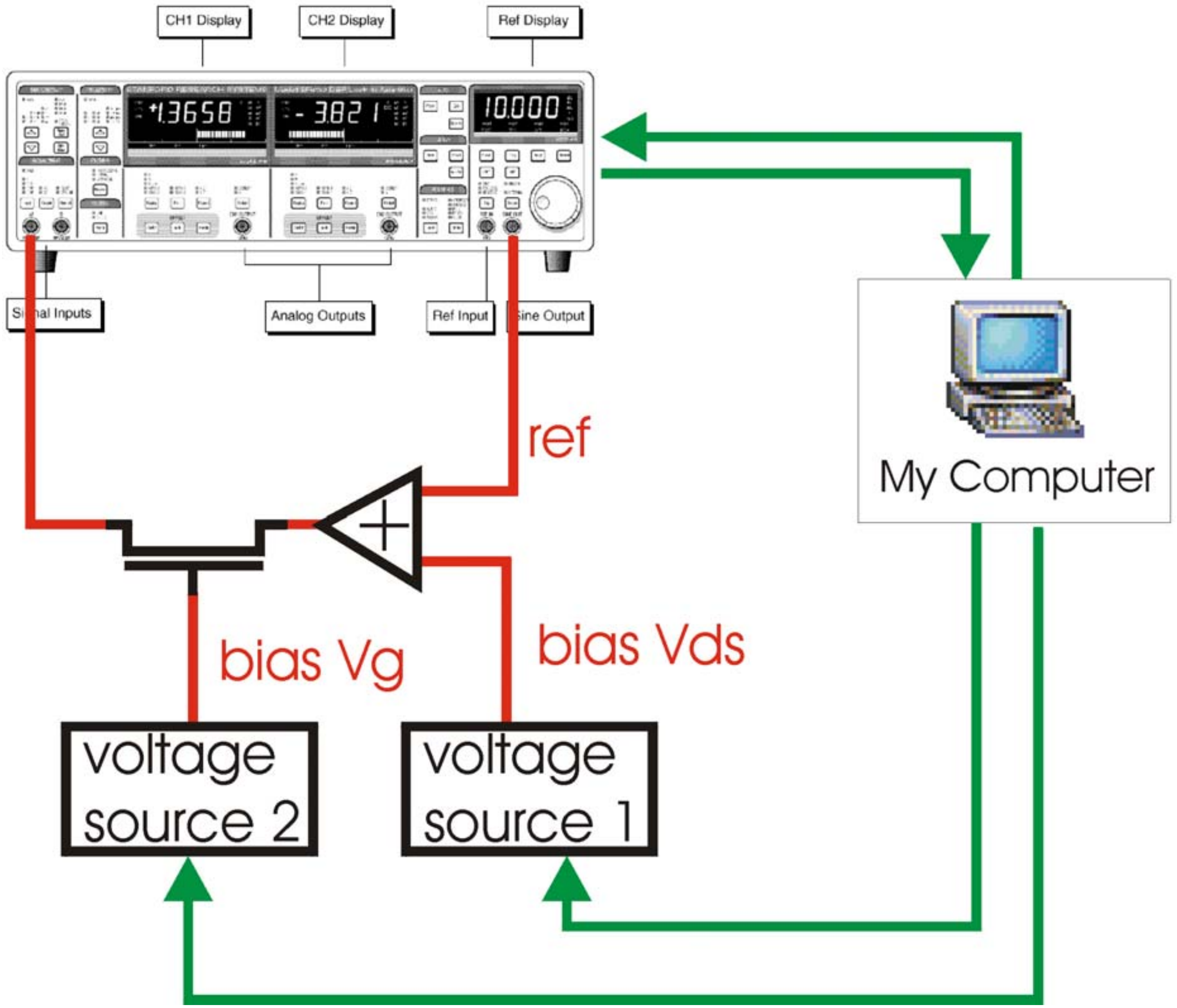
Current Spectroscopy



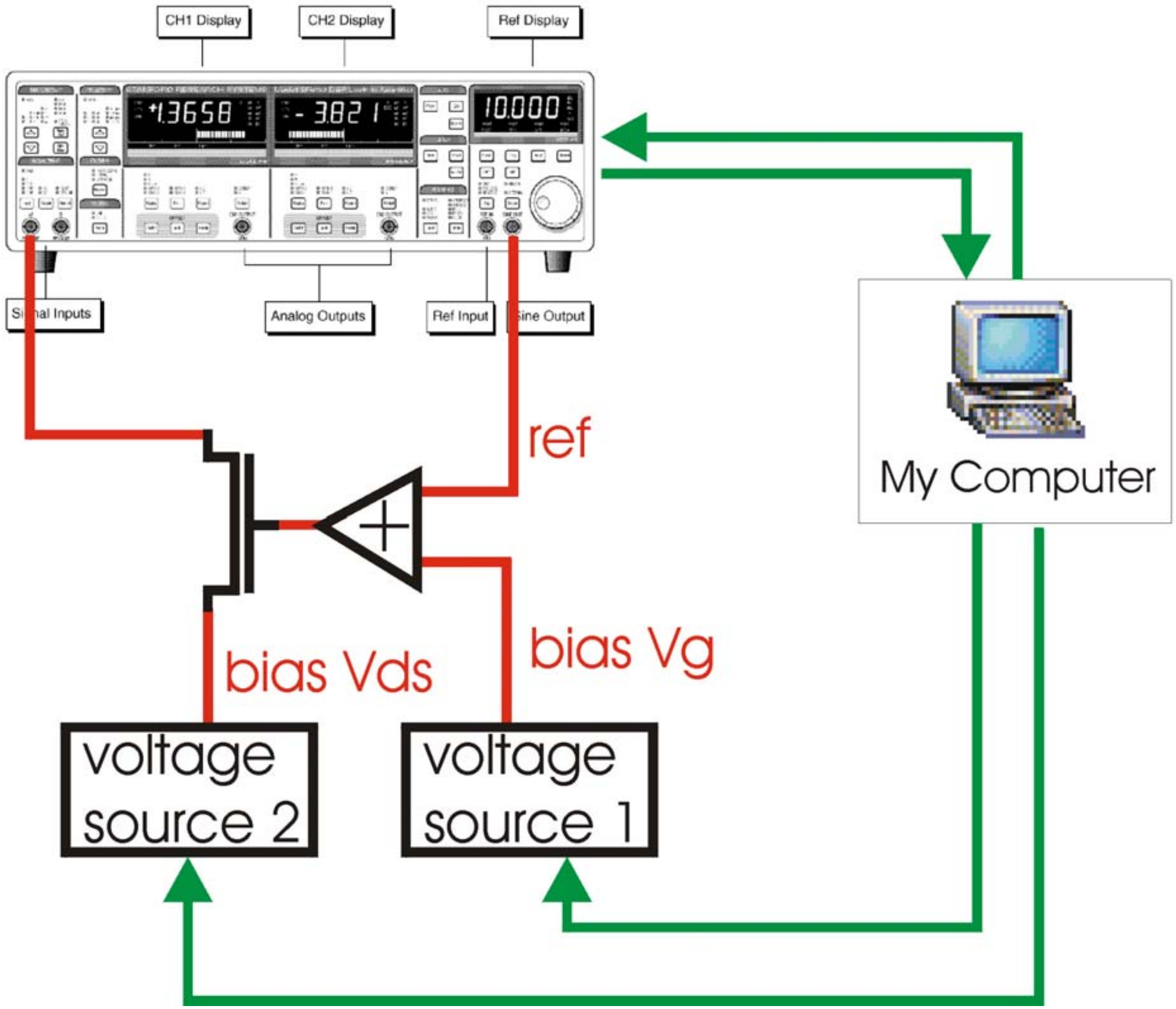
Amplitude of response proportional to μ

Using lock-in detection

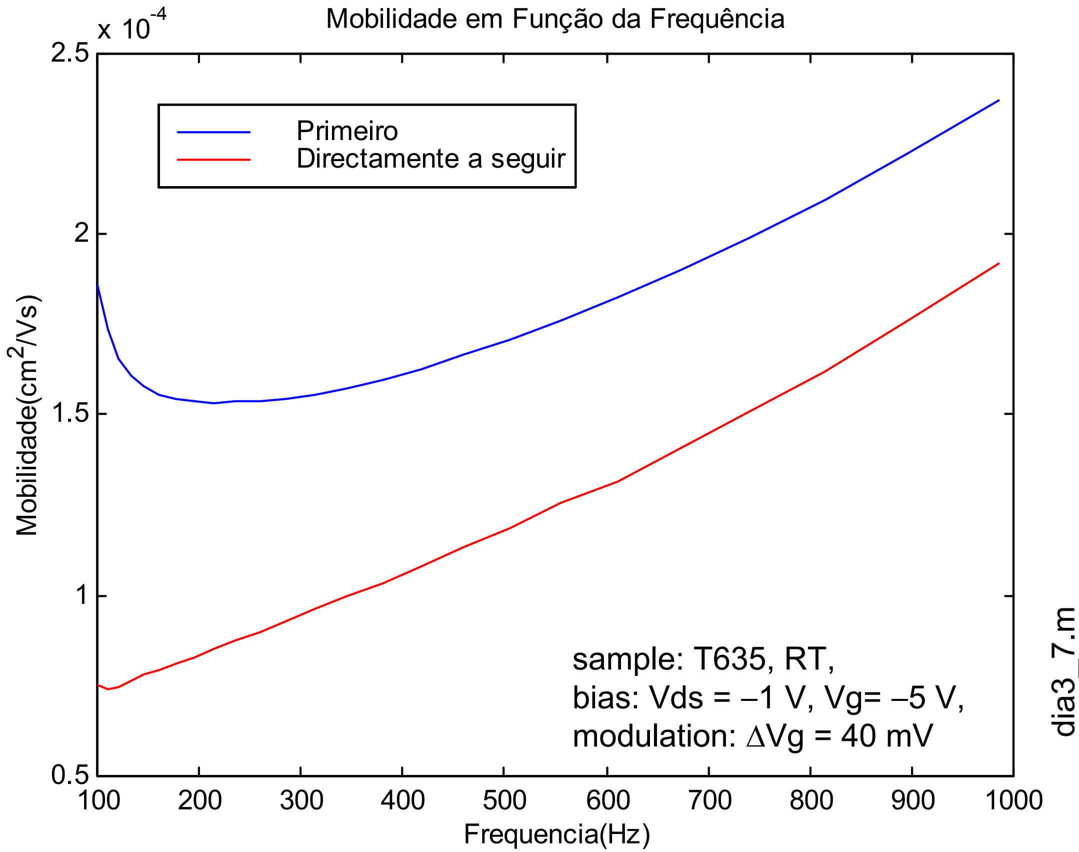
Experimetal Setup



Experimetal Setup



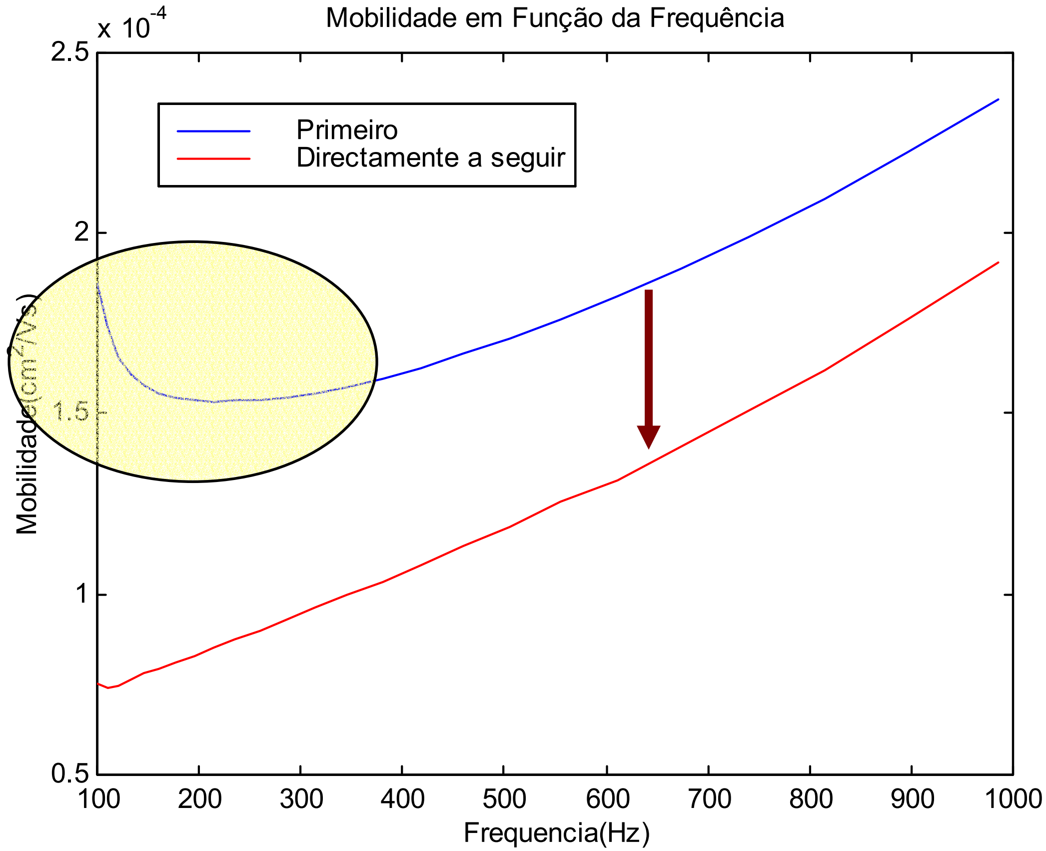
Current Spectroscopy



The as-measured mobility depends on the frequency!

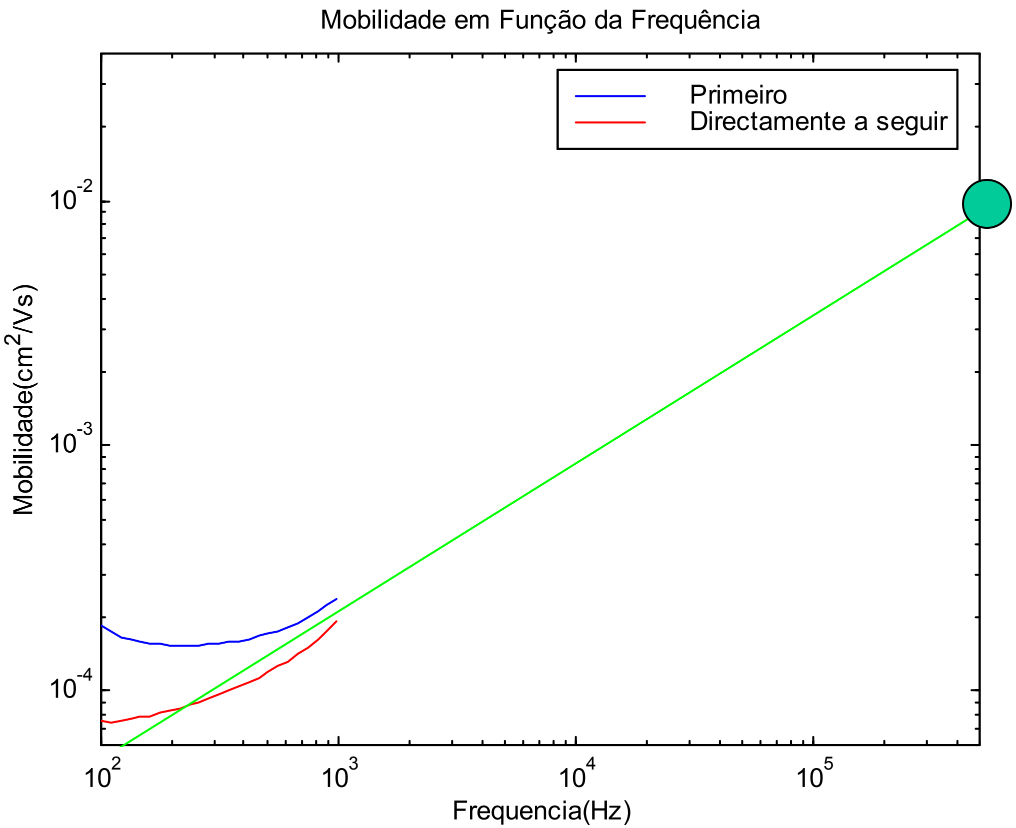
Intro
Transfer curves
Spectroscopy
Poole-Frenkel
TSC
Conclusions

Spectroscopy results



Stressing effects (V_T changes)

Spectroscopy results



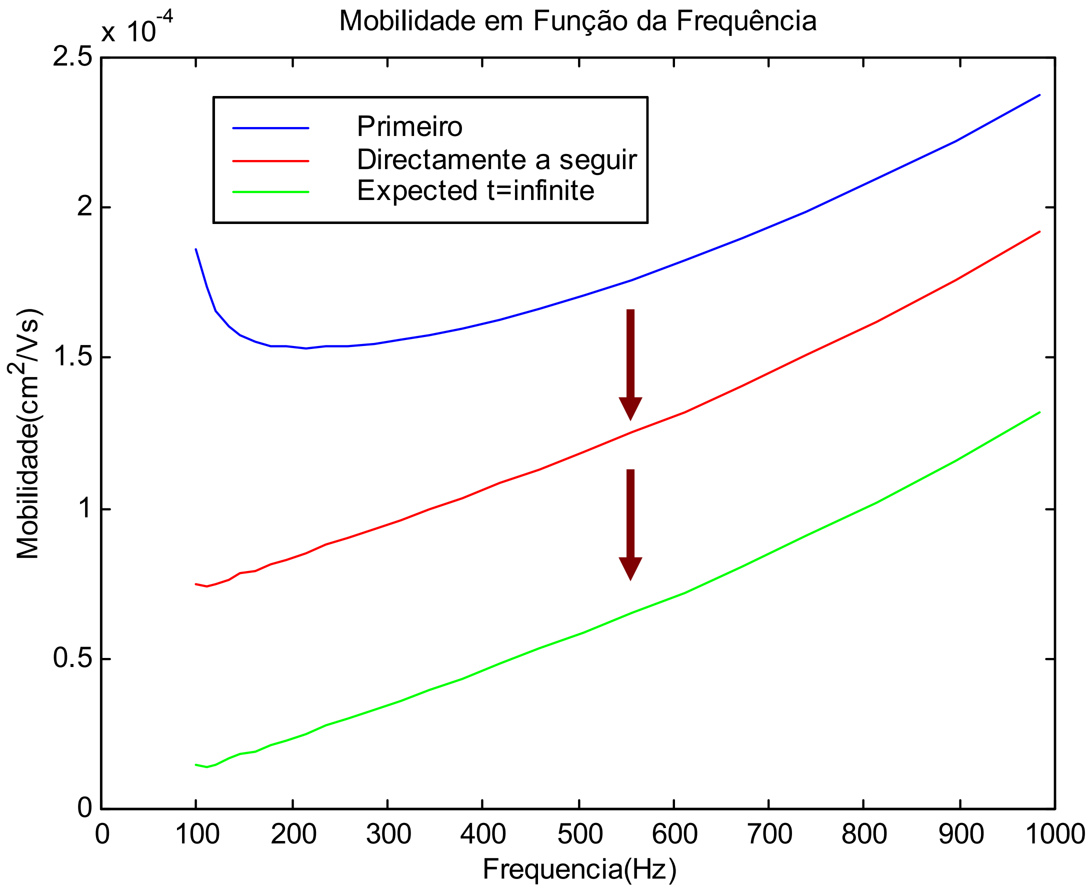
Δt = 10 μs

μ = 10^{-2} cm^2/Vs

Extrapolation to pulsed measurements

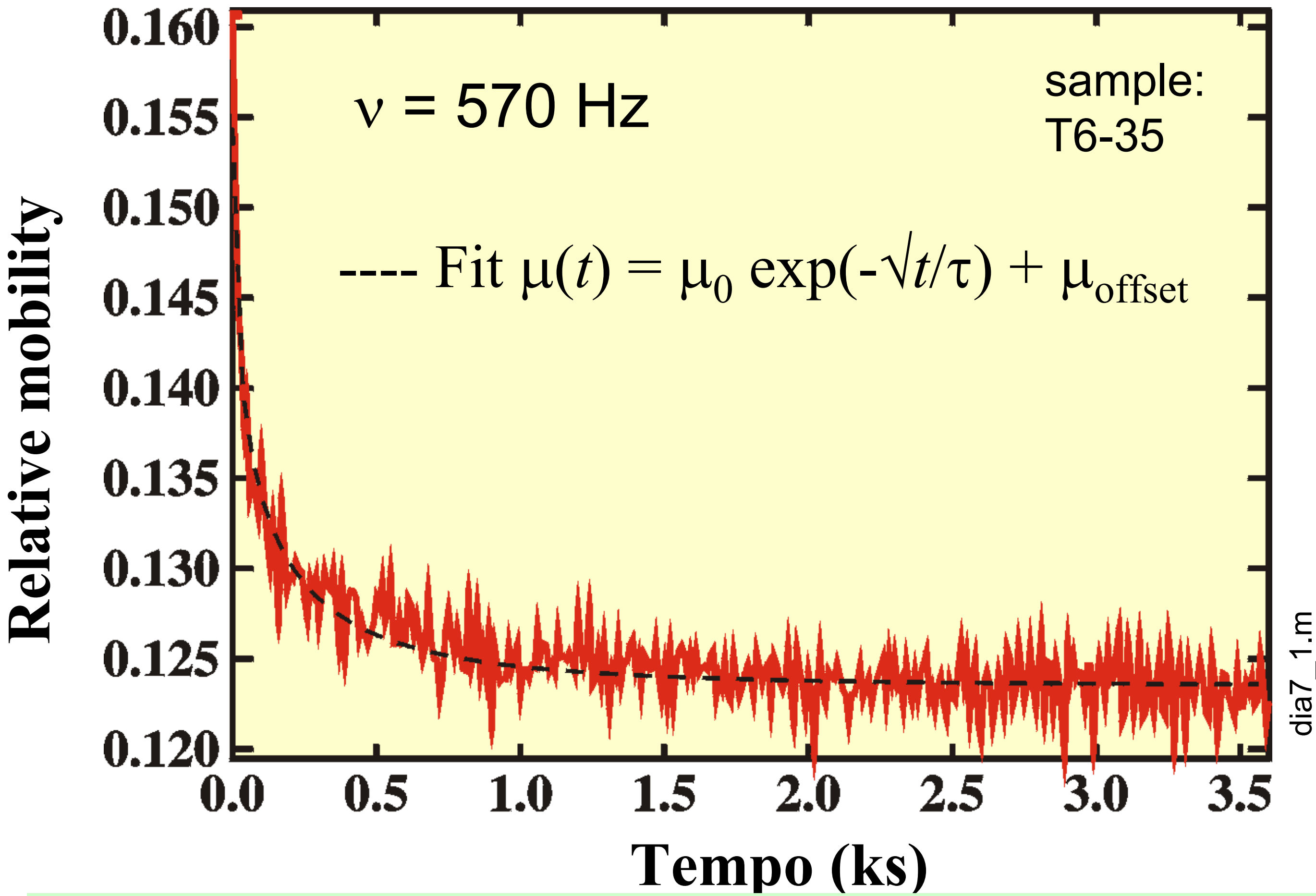
Pulsed experiments give 500x mobility

Spectroscopy results



Expected for $t = \infty$: DC mobility = 0 because $V_T = V_G$. AC mobility is not 0 (?)

Transient of mobility vs. time.

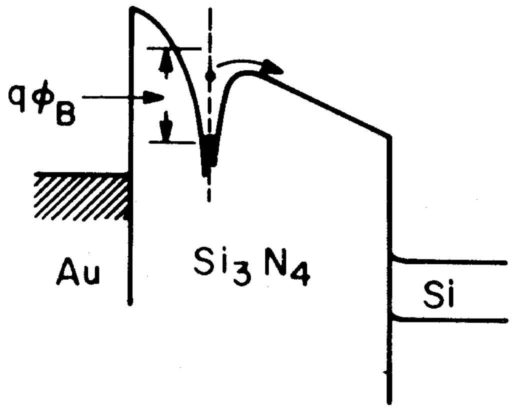


Note that in this experiment Vg is always on

Poole-Frenkel

Poole-Frenkel Conduction model

For low-conductivity materials, the conducting model might be “field-assisted hopping”.



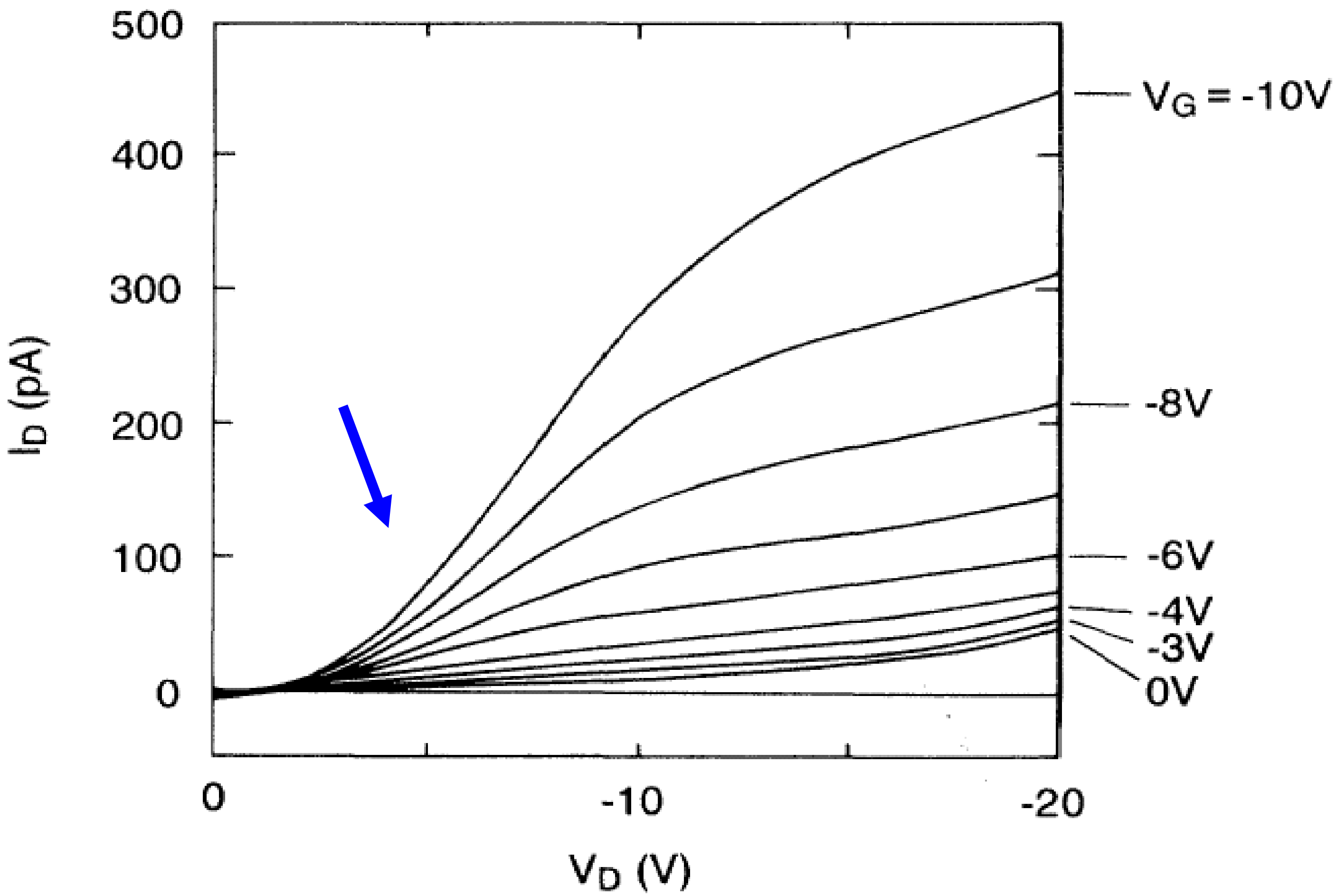
Frenkel–Poole emission

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

The as-measured mobility then depends on the longitudinal field (Vds)

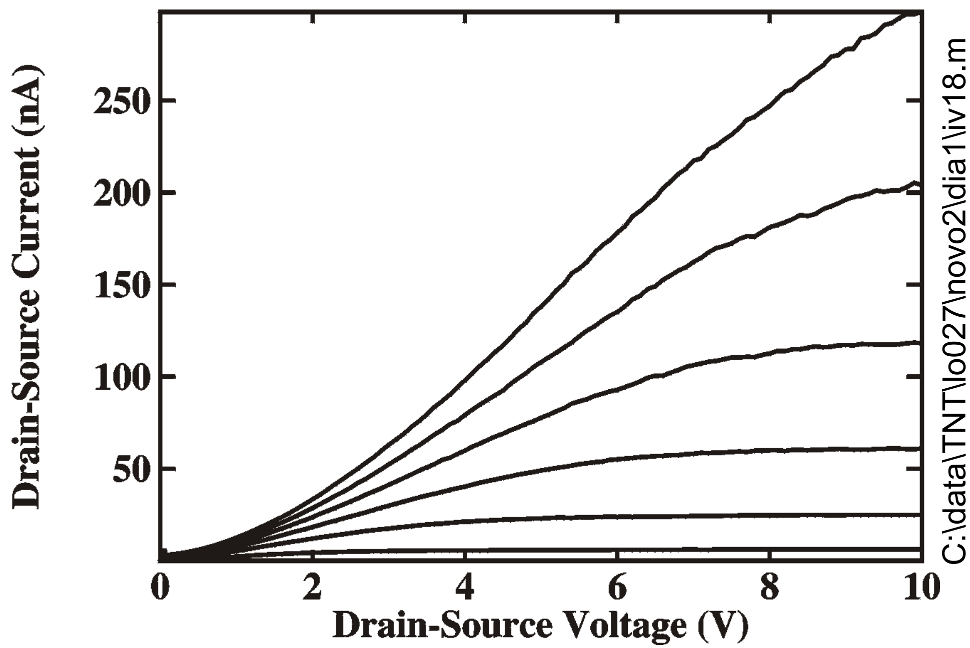
Images and equations: Sze, “Physics of Semiconductor Devices”, 2^{nd} ed., p403.

Poole-Frenkel conduction in literature



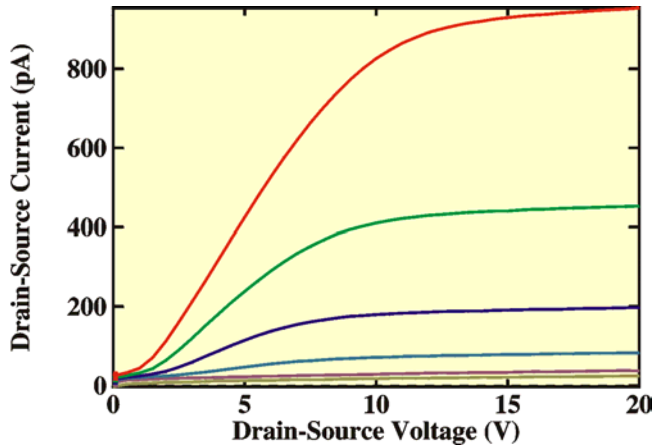
Waragai, “Charge transport in thin films of semiconducting oligothiophenes”, PRB **52**, 1786 (1995).

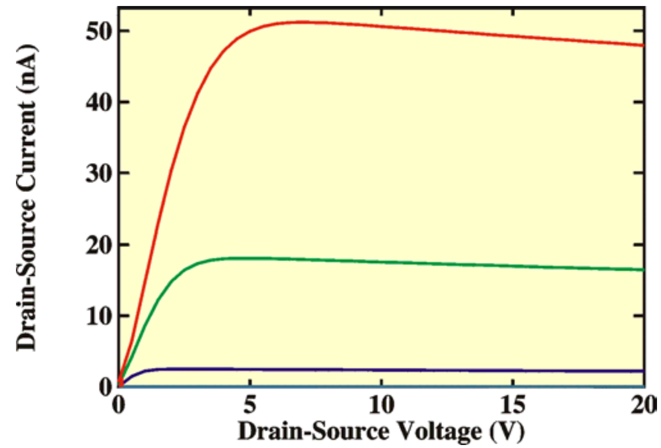
Experimental observation of Poole-Frenkel conduction



Sample: LO27 (Tobias), RT, LV

Poole-Frenkel: Effect of temperature





C:\data\tobias\lo023_8m\day4\iv_2m6.m

C:\data\tobias\lo023_8m\day4\iv_2n6.m

T = 210 K

T = 340 K

Frenkel–Poole emission

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

$$\sim V \exp(+2a\sqrt{V}/T - q\phi_B/kT)$$

Sample: LO23 (Tobias)

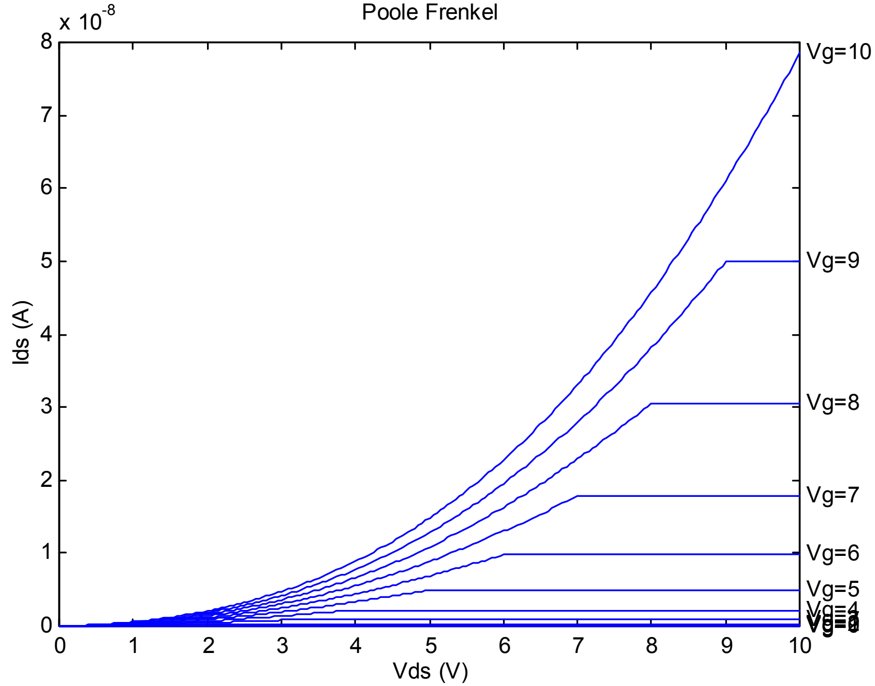
Simulation of Poole-Frenkel conduction

1: Simple model: field (and μ) constant in space

$$E = V_{ds}/L$$

$$\mu = \mu_0 \exp(\gamma E^{1/2})$$

$$I_{ds} = a\, C_{ox}\, (V_G - V_T)\, \mu\, V_{ds}$$



waragai3.m

Simulation of Poole-Frenkel conduction

2: Full simulation. System of differential equations

Differential equations:

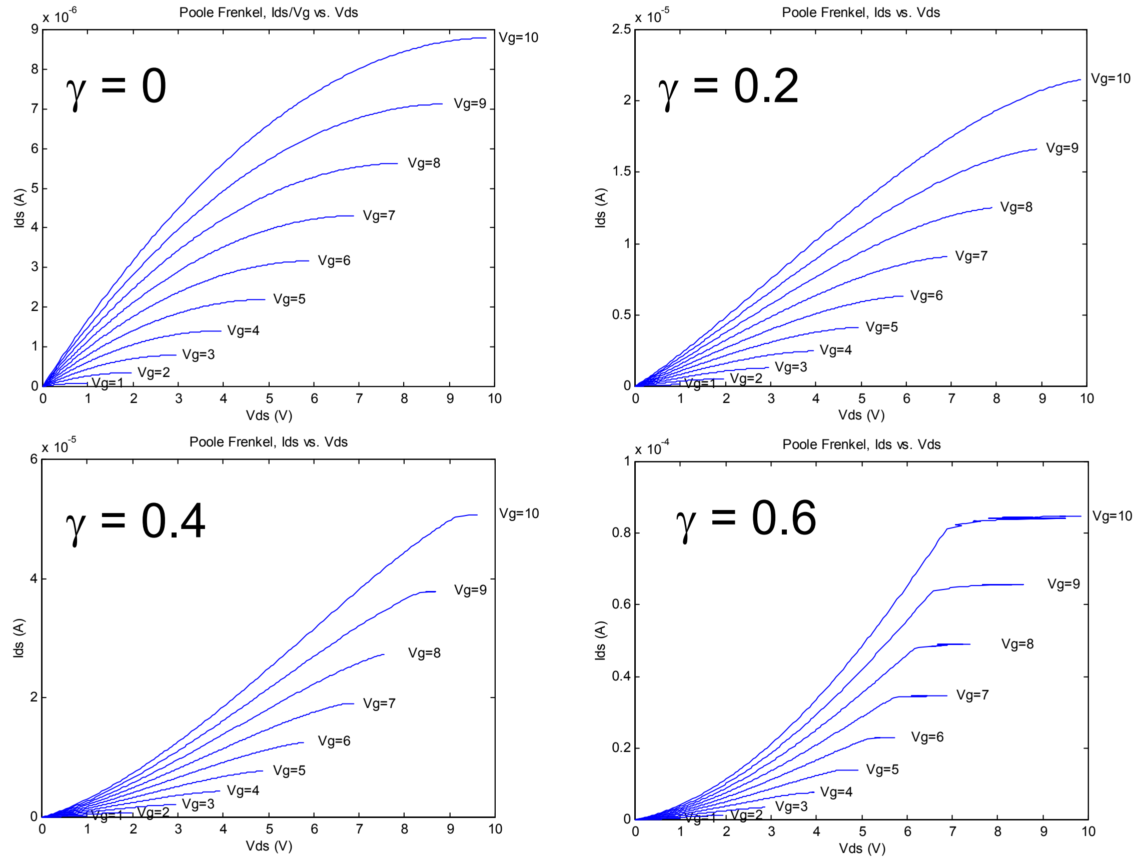
1. $E(x) = \mathrm{d}V(x)/\mathrm{d}x$
2. $\mu(x) = \mu_0 \exp[\gamma E(x)^{1/2}]$
3. $Q(x) = C_{ox} [Vg - Vt - V(x)]$
4. $I(x) = W\, Q(x)\, \mu(x)\, E(x)$

Boundary conditions:

- I constant in space, $I(x) = I_{ds}$
- $V(0) = 0$
- $V(L) = V_{ds}$ (or $I = I_{ds}$)

Simulation of Poole-Frenkel conduction

2: Full simulation. System of differential equations



Note: $\gamma \sim 1/T$

Alternative: Schottky Barrier Contacts

Schottky emission

$$J = A^{*}T^{2}\exp\left[\frac{-q(\phi_B - \sqrt{q\mathscr{E}/4\pi\epsilon_i})}{kT}\right] \sim T^{2}\exp(+a\sqrt{V}/T - q\phi_B/kT)$$

Frenkel–Poole emission

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

- Very similar to Poole-Frenkel emission
- Can be modeled by diodes in series with the FET

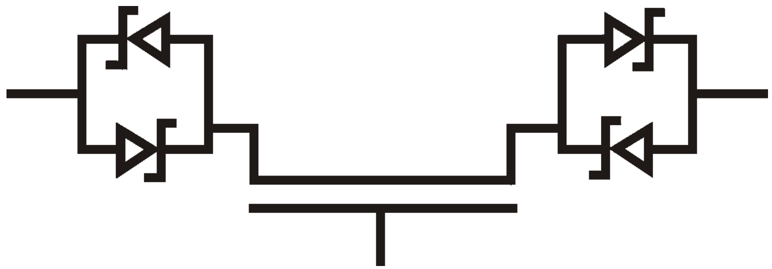
- But: maximum current through device would be reverse-bias saturation current of a Schottky diode.

Schottky Barrier Contacts

Schottky emission $J = A^* T^2 \exp\left[\frac{-q(\phi_B - \sqrt{q\mathcal{E}/4\pi\epsilon_i})}{kT}\right] \sim T^2 \exp(+a\sqrt{V}/T - q\phi_B/kT)$

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

- Very similar to Poole-Frenkel emission
- Can be electrically simulated by 4 diodes in series with the FET

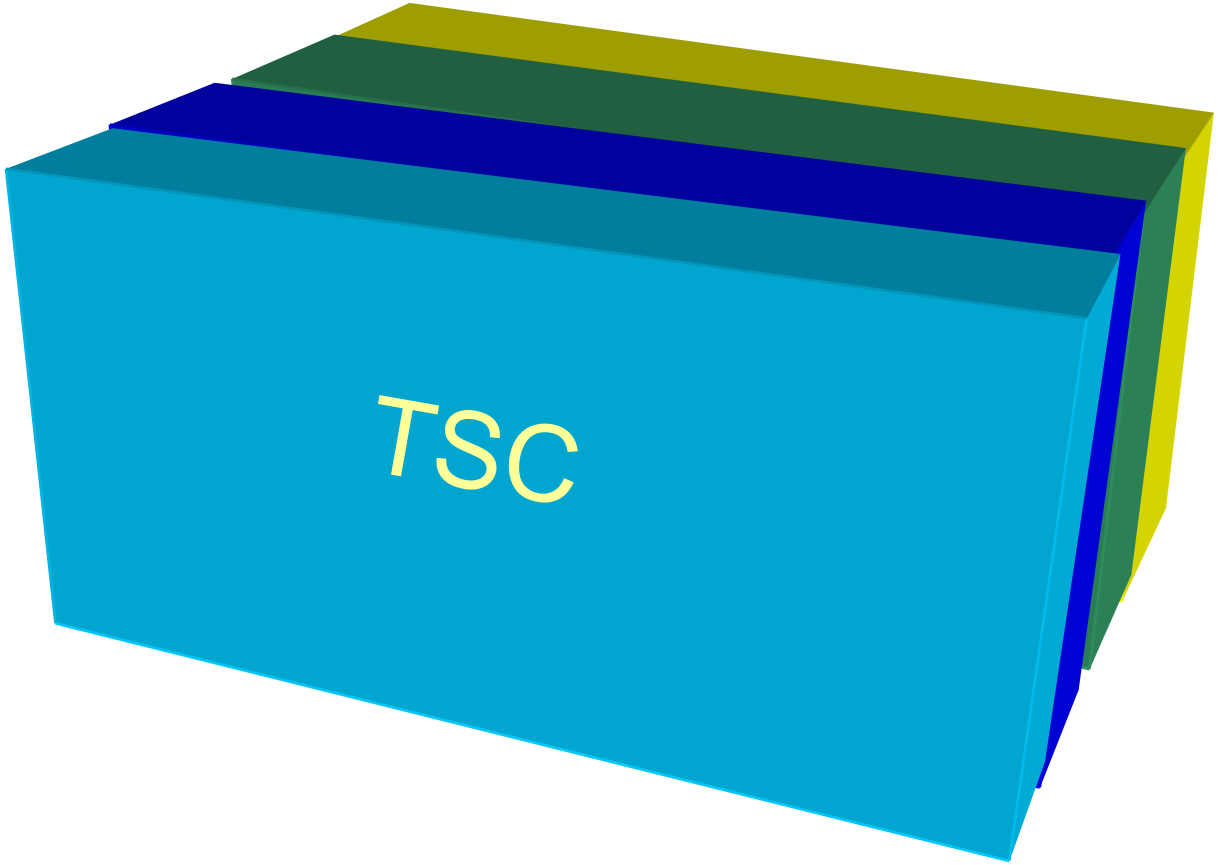


- But: connection to a physical model is lost.

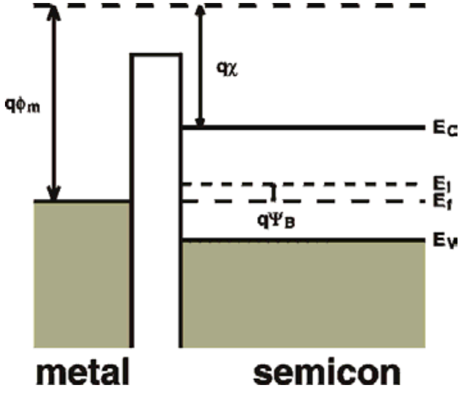
Poole-Frenkel Conduction model

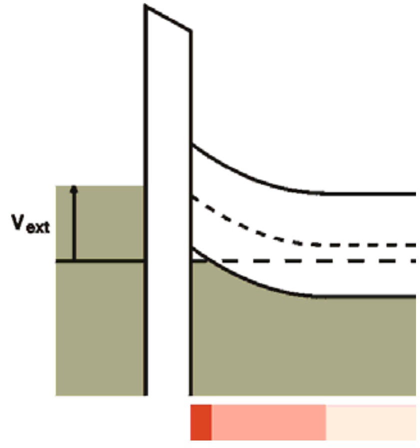
Conclusions:

- Region at contact is highly resistive or entire sample is controlled by hopping conduction (MTR: multi-trap and release?).
- correlation seen with other effects? (non-linear transfer curves)


TSC

Temperature Scanned Current





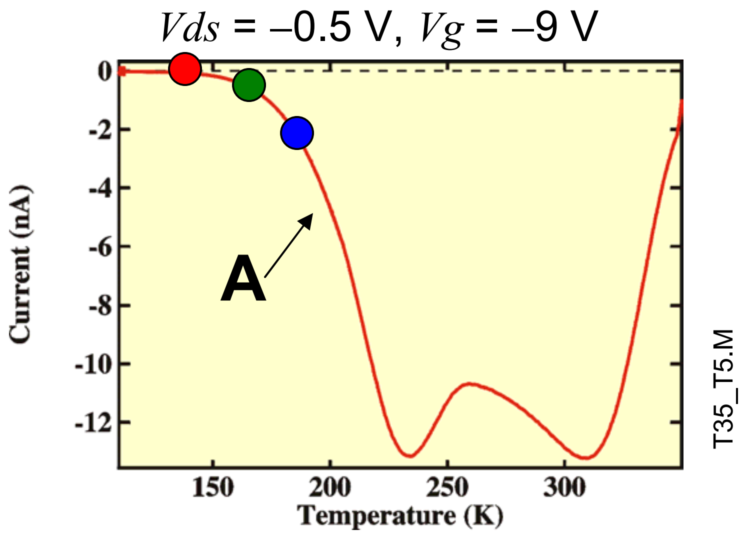
$$V_T = (4q\varepsilon_s\psi_B N_A^-)^{1/2} / C_{ox} + 2\psi_B$$

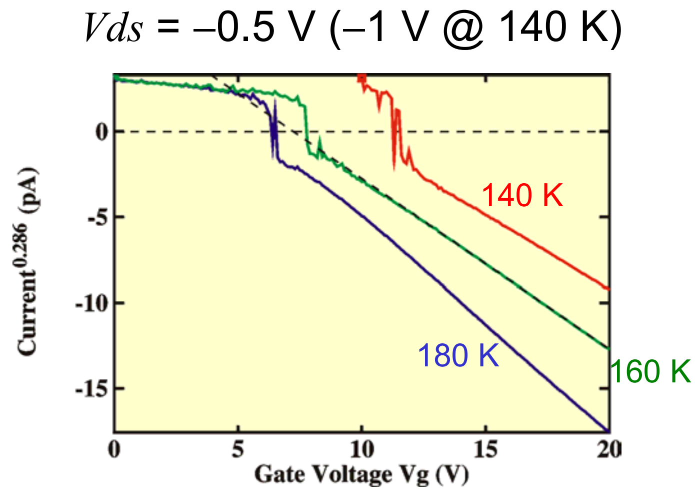
Dependence on temperature

	Classic ½-con	Organic ½-con
N_A^-	No	Yes
ψ_B	Yes	Yes

p452 of Sze

Temperature Scanned Current



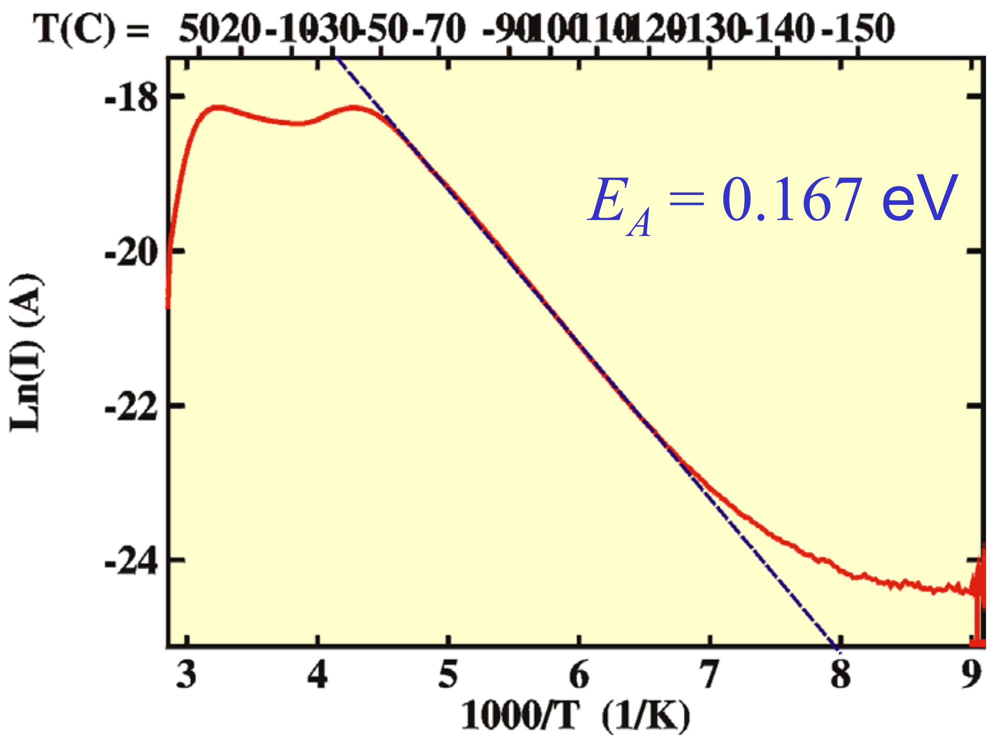


A:

- V_T decreases reversibly because ψ_B changes (linear)
- Poole-Frenkel: $\mu = \exp(-E_A/kT)$

PF "wins", current is exponentially growing

Temperature Scanned Current

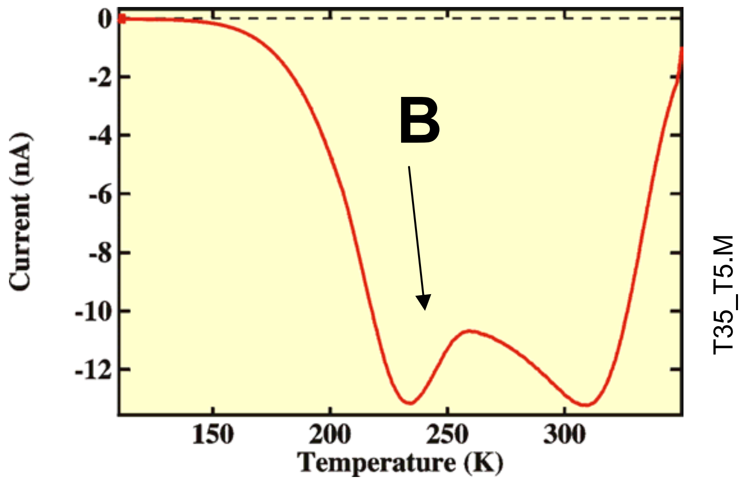


PF: $E_A = q\,\phi_B - 2\,a\,k\,\sqrt{V_{ds}}$

Frenkel–Poole emission

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

Temperature Scanned Current



Vds = –0.5 V, *Vg* = –9 V

B:

$$V_T = (4q\varepsilon_s\psi_B N_A^-)^{1/2} / C_{ox} + 2\psi_B$$

- V_T increases irreversibly because N_A appear/ionize.

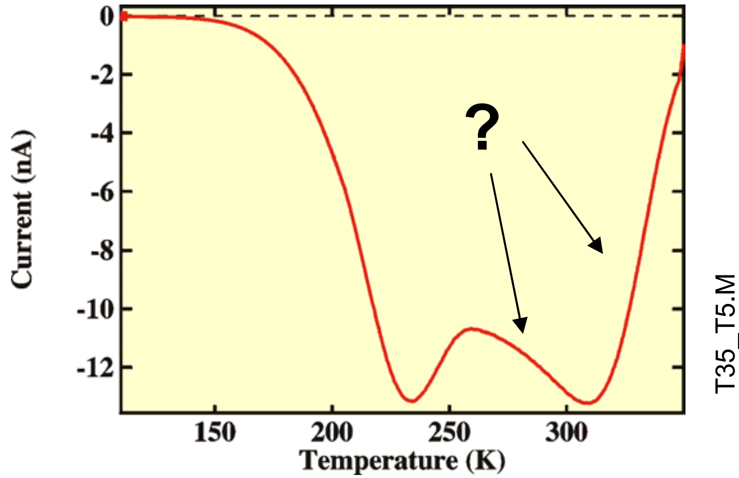
Stressing!

- $\tau = \tau_0 \exp(-E_A/kT)$, $N_A^-(t) = N_A^-(\infty)[1-\mathrm{Exp}(t/\tau)]$

Stressing wins because of slow scanning.

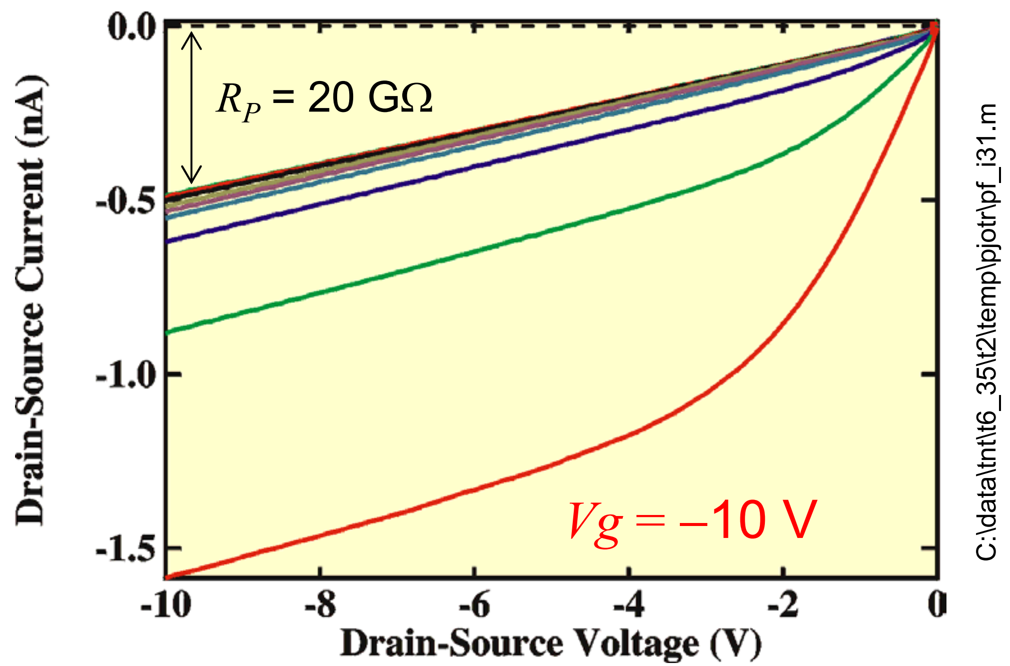
Temperature Scanned Current

Vds = –0.5 V, Vg = –9 V



Temperature, Poole-Frenkel

Sample 35 T = 180 K

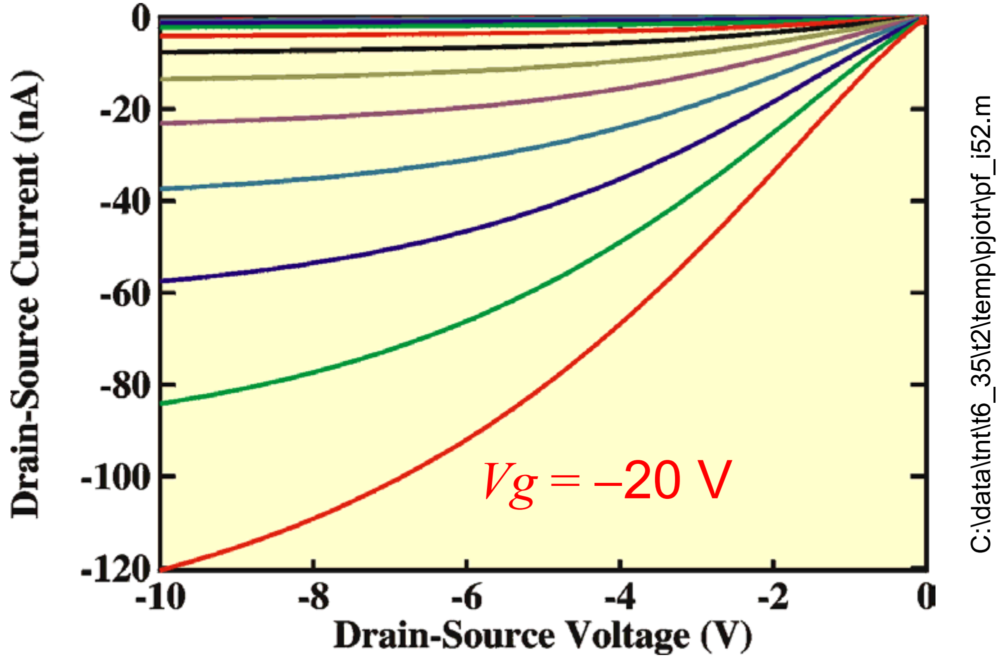


Frenkel–Poole emission

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

Temperature, Poole-Frenkel

Sample 35 T = 160 K

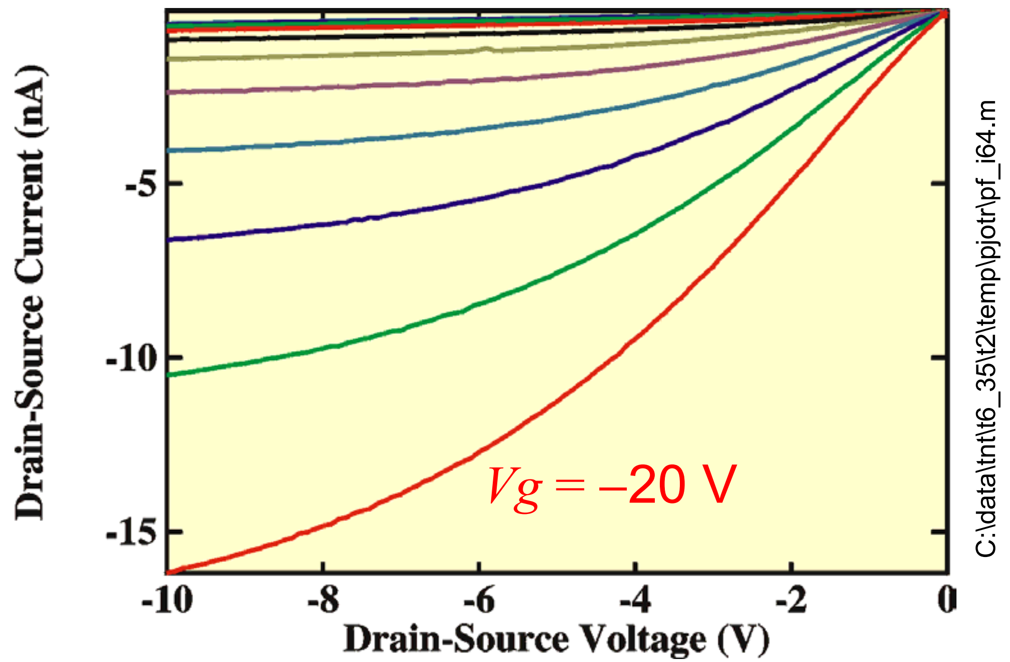


Frenkel–Poole emission

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

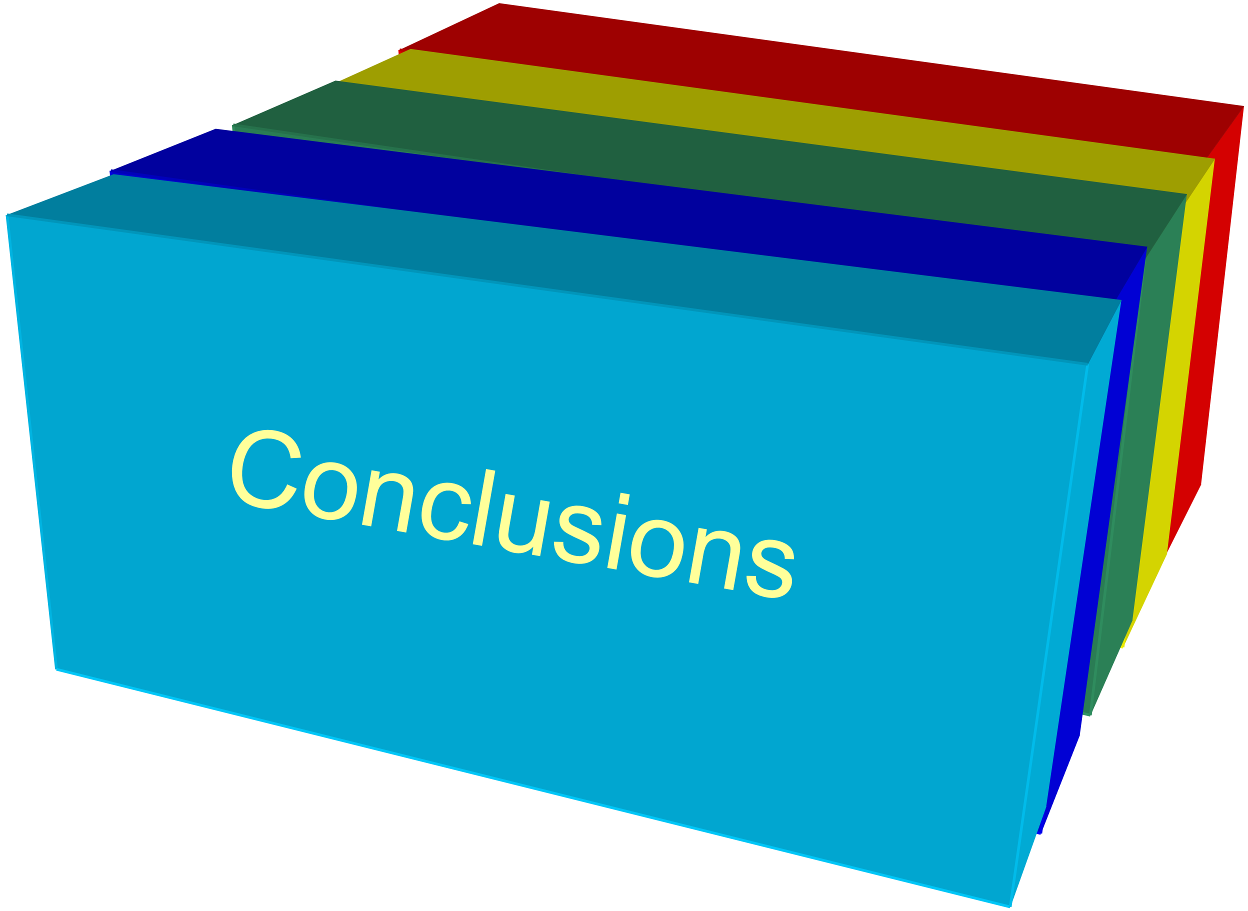
Temperature, Poole-Frenkel

Sample 35 T = 140 K



Frenkel–Poole emission

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


Conclusions

Conclusions

Magical temperature (phase transition?) at 200 K

Behavior up to 250 K well understood

VRH doesn't work

MNR applies

Poole-Frenkel can explain a lot
Is it the same as MTR (multi-trap-and-release)?
Gilles Horowitz ….

Mobility spectra. Careful with pulsed measurements, μ depends on ν

Thanks

Current Spectroscopy:
José Almada, Nelson Pimenta
Final-year project students

Henrique Gomes

All the partners in the MONA-LISA project

The Callas (re)insurance group for giving this computer