Explanation of the Meyer-Neldel Rule

OPTO-ELECTRONICS
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Rudolstadt, 30 September 2004

Trap states as an explanation of the Meyer-Neldel Rule

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Overview

What is the Meyer-Neldel Rule?

Background: Traps in organic FETs in Faro

Results and discussion

OptoEl-CEOT in Faro

Specialized in electronic characterization of organic and biological electronic devices.
Sensitive equipment with custom made control software.

DLTS (the only “organic” DLTS)

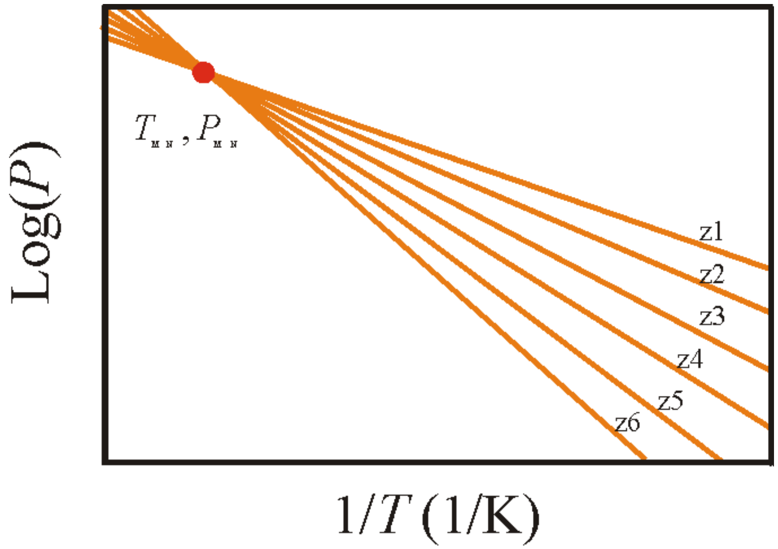
Organics-specific FET measurement system

What is the Meyer-Neldel Rule?

Observation without explanation*

The thermal activation energy of a process (P) depends on a certain parameter (z).

There exists a temperature (T_{MN}) where the dependence of P on z disappears.



$$P = P_0 \exp(-E_A/kT)$$

$$P_0 = P_{MN} \exp(E_A/kT_{MN})$$

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* Original article: W. Meyer and H. Neldel, Z. Techn. **18**, 588 (1937).

Examples of the Meyer-Neldel Rule

Processes	Parameters	Devices/materials
current	gas concentration	α-Si
diffusion*	pressure	organic ½cons
ionic currents	electrical bias	gas detectors
		High-Tc supercons
		glasses
		liquid ½cons
		polycryst. Si
		CCDs

* Here the MNR is called the Compensation Effect.

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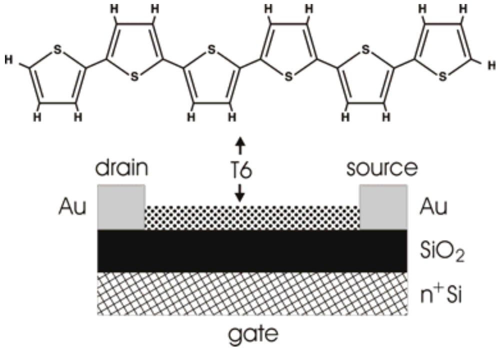
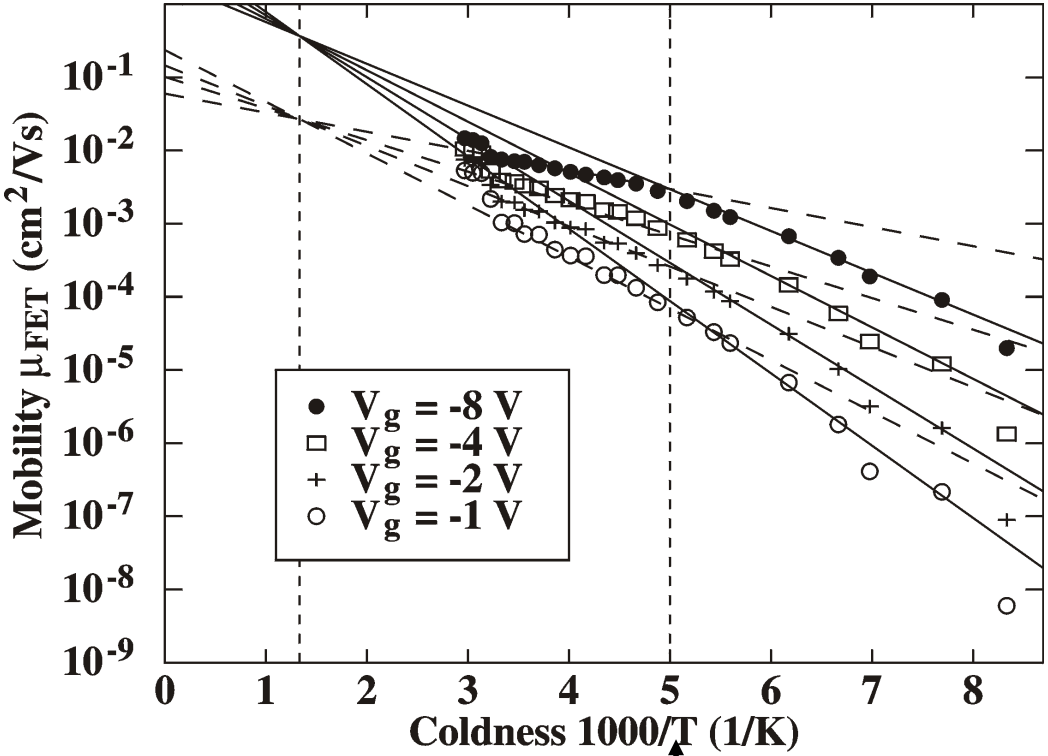
All less-than-perfect-crystalline materials

* Here the MNR is called the Compensation Effect.

Meyer-Neldel Rule in our T6 TFT



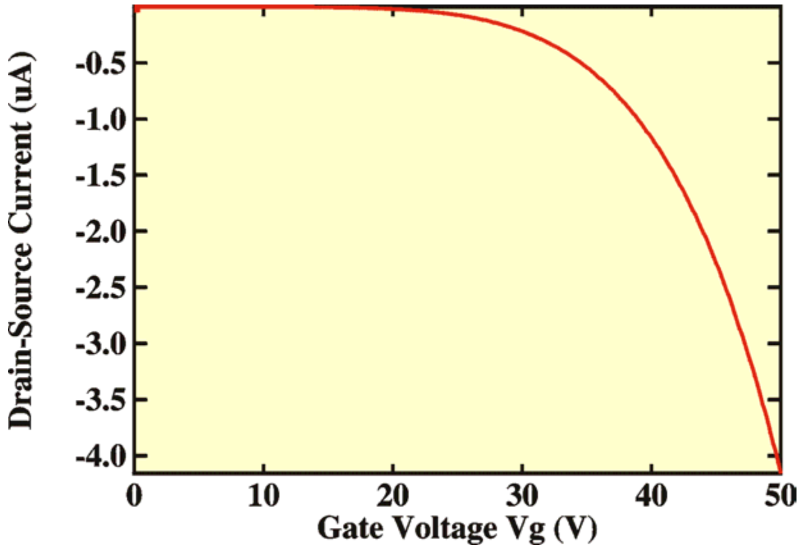


Phase transition (?) at 200 K

P. Stallinga *et al.*, J. Appl. Phys. October 2004

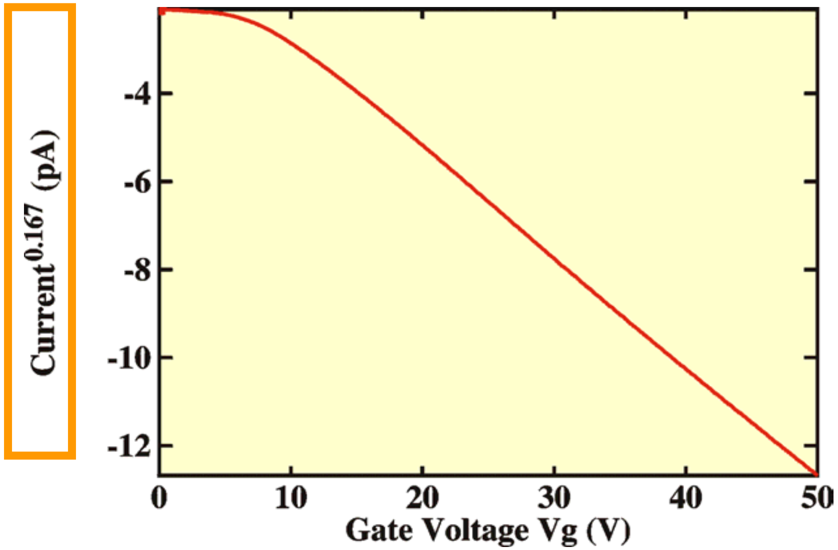
Non-linear transfer curves

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



Non-linear transfer curves

Currents are linearized by taking the nth root

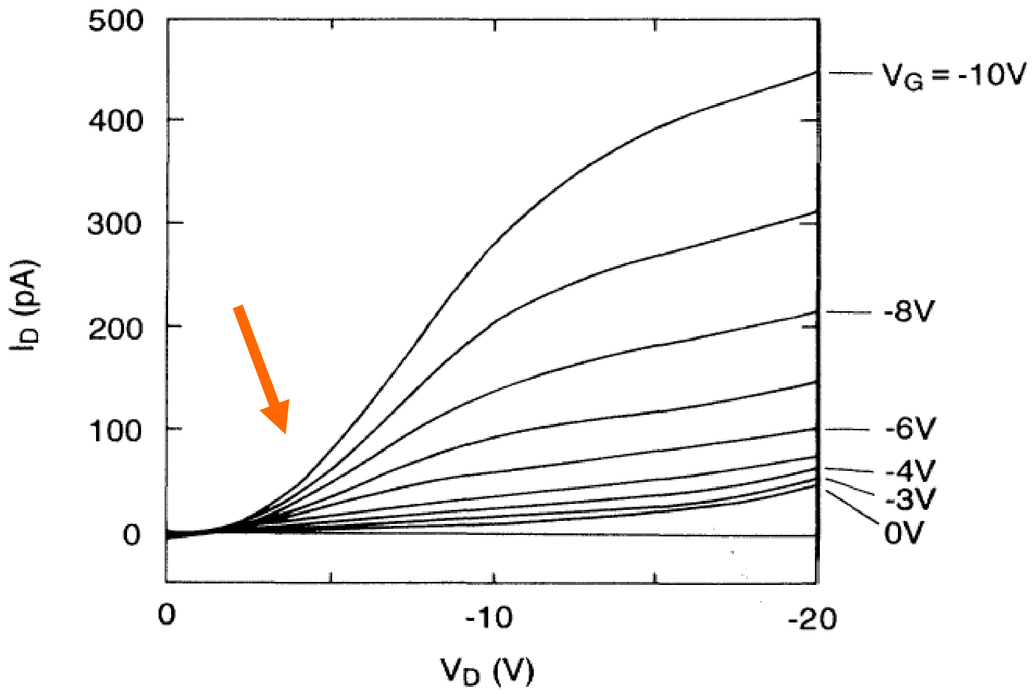


Recently explained on model for amorphous silicon, see P. Stallinga, J.Appl.Phys. October 2004.

→ Traps!

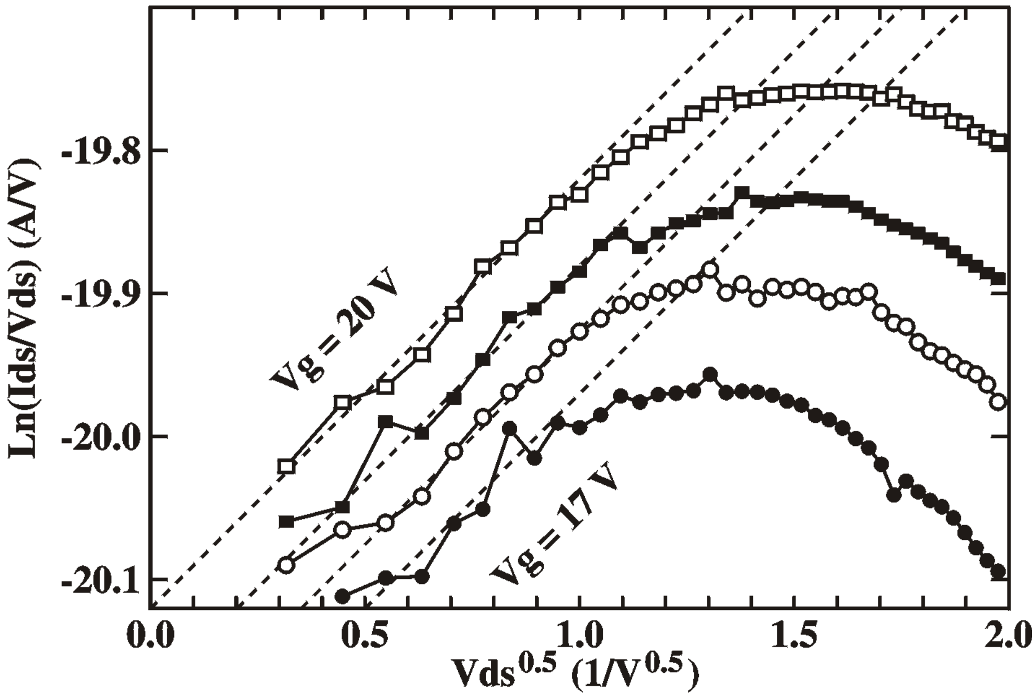
Poole-Frenkel

Non-linear IV curves observed



Poole-Frenkel

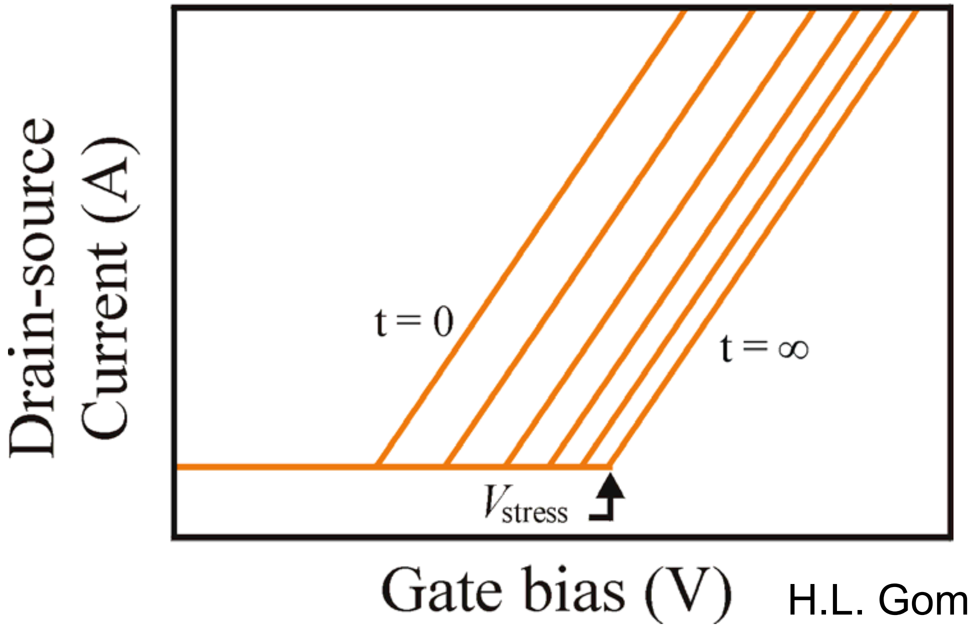
Non-linear IV curves explained



The fact that the plot is linear in this scale proofs the validity of the model of Poole-Frenkel. P. Stallinga, J.Appl.Phys. October 2004.

→ Traps!

Stressing

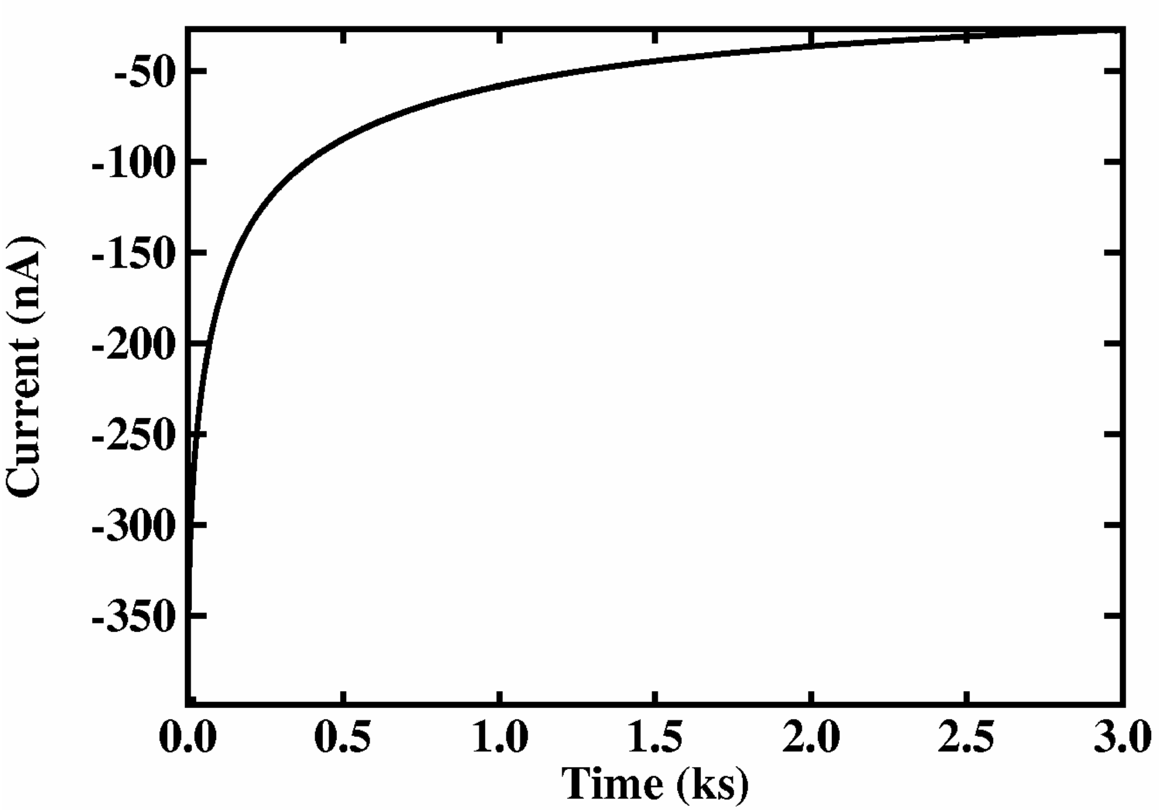


H.L. Gomes, Appl.Phys.Lett. 2004.

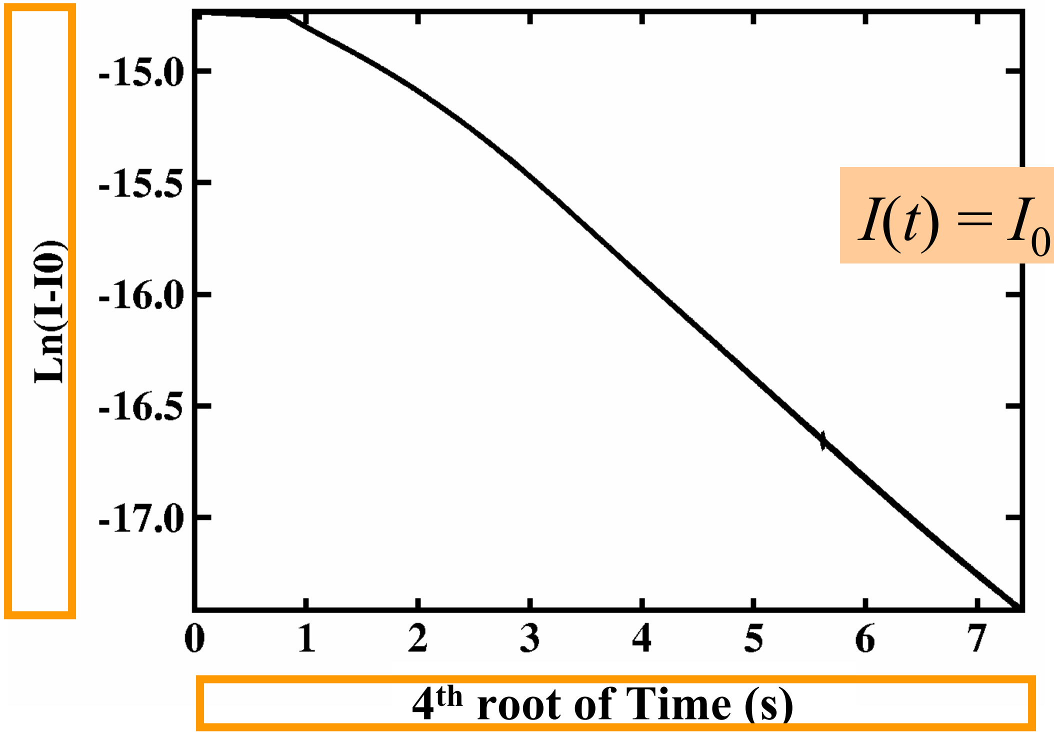
Note: Already the fact that a threshold voltage exists in an accumulation-type FET proofs the existence of traps! Theoretically, the threshold voltage is zero (or >0, “Normally-on FET”).

→ Traps!

Decaying currents



Decaying currents



$$I(t) = I_0 \exp(-(t/\tau)^{\alpha})$$

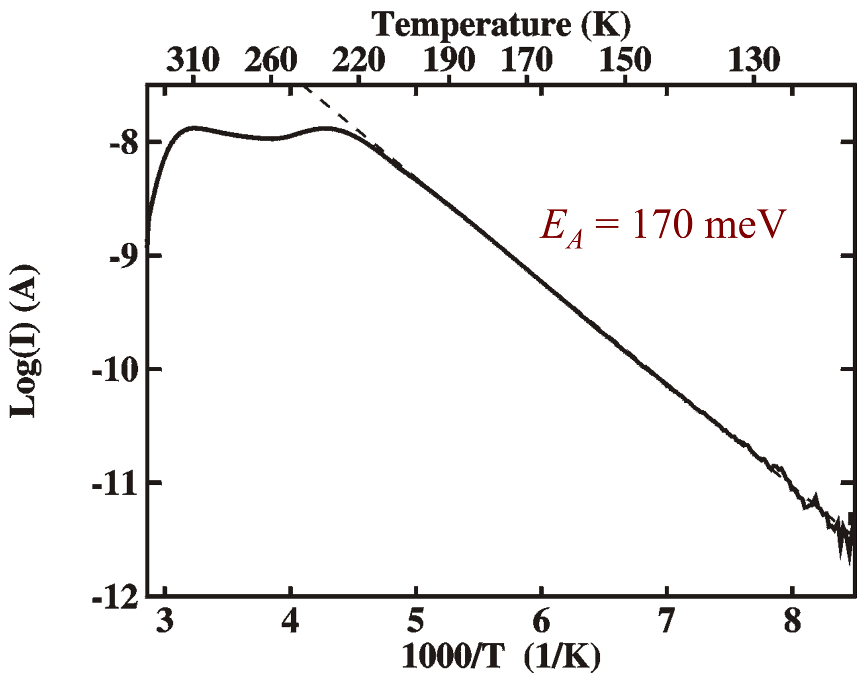
“Glassy relaxation”* or “stretched exponential”.
Transient caused by trapping.

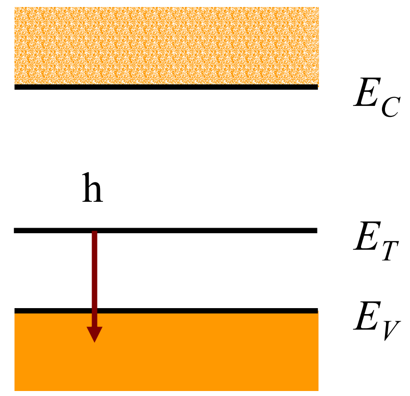
→ Traps!

P. Stallinga, J.Appl.Phys. October 2004.

*original article: R. Kohlrausch in Rinteln, Ann. Phys. und Chemie **72**, 353 (1847).

Thermally scanned current





$Tr \rightarrow Tr^- + h$ or

$Tr^+ \rightarrow Tr + h$

An *I*-*T* curve shows that charges are liberated from trap states.

$I(T) \propto \mu \times p(T)$

not: $I(T) \propto \mu(T) \times p$

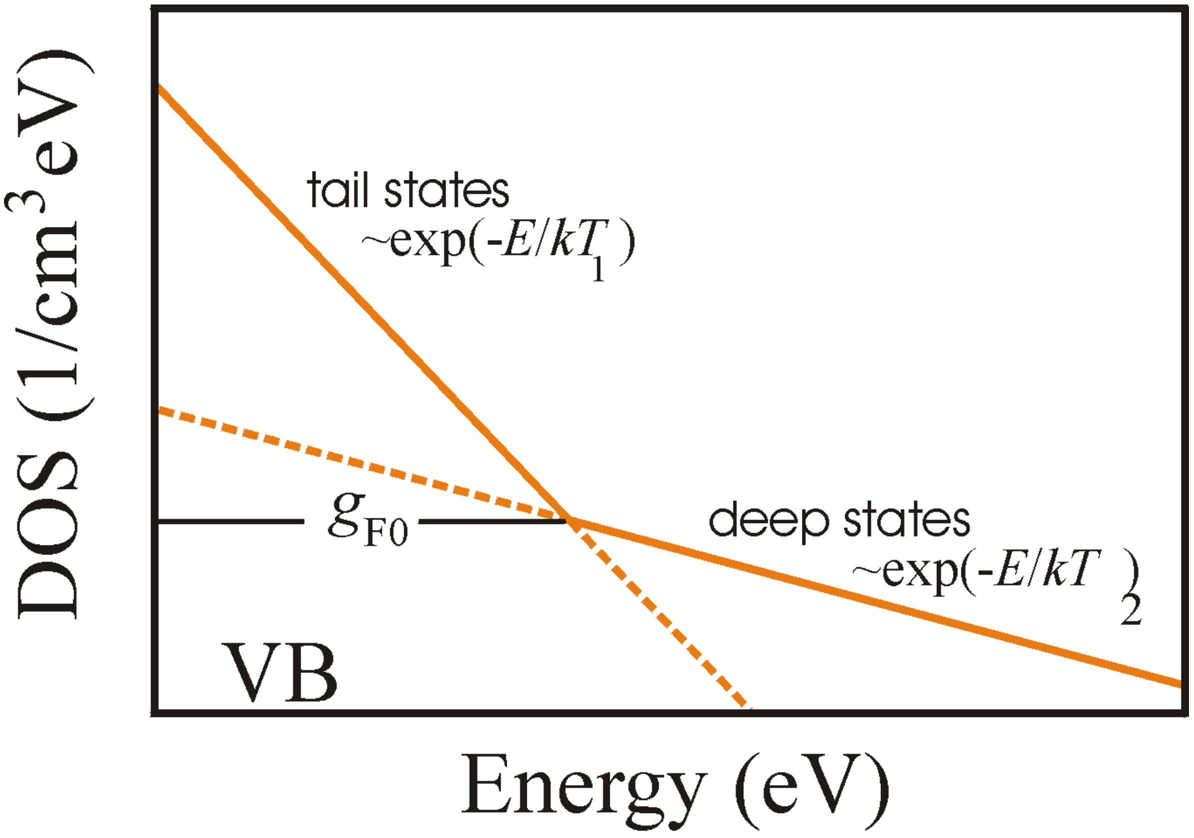
→ Traps!

Charges are liberated from trap states.

not $I(T, V_g) \propto \mu(T, V_g) \times p$

but $I(T, V_g) \propto \mu \times p(T, V_g)$

Amorphous silicon: Shur & Hack



* Original article: M. Shur and M. Hack, J. Appl. Phys. **55**, 3831 (1984).

Shur & Hack

$$I_{\mathrm{ds}} = \frac{q\mu_0 W}{L} f\left(T, T_2\right) \left[C_{\mathrm{ox}}\left(|V_{\mathrm{g}} - V_t|\right)\right]^{\left(\frac{2T_2}{T}-1\right)} V_{\mathrm{ds}} \tag{53}$$

$$f(T, T_2) = N_{\mathrm{V}} \exp\left(\frac{-E_{F0}}{kT}\right) \frac{kT\epsilon}{q} \left(\frac{\sin(\pi T/T_2)}{2\pi\epsilon T_2 kT g_{F0}}\right)^{T_2/T} \tag{51}$$

Notes:

A factor q was deleted from original Equation 51.

The model is similar to Vissenberg's, with difference that conduction is through band states instead of hopping conduction.

Linking Shur-Hack to our organic FETs

I_{ds} depends on V_{g}, but not in a classical way (not $\propto V_{\mathrm{g}}$). Non-linear transfer curves

$$I_{\mathrm{ds}} = \frac{q\mu_0 W}{L} f\left(T,T_2\right)\left[C_{\mathrm{ox}} \boxed{\left(\left|V_{\mathrm{g}} - V_t\right|\right)\right]^{\left(\frac{2T_2}{T}-1\right)}} V_{\mathrm{ds}} \qquad (53)$$

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Linking Shur-Hack to Meyer-Neldel

First halve of Meyer-Neldel Rule:

Dependence on V_g disappears at a temperature $T = 2T_2$.

$$I_{\mathrm{ds}} = \frac{q\mu_0 W}{L} f\left(T, T_2\right) \left[C_{\mathrm{ox}} \left(|V_{\mathrm{g}} - V_t|\right)\right]^{\boxed{\left(\frac{2T_2}{T} - 1\right)}} V_{\mathrm{ds}} \tag{53}$$

$$f(T, T_2) = N_{\mathrm{V}} \exp\left(\frac{-E_{F0}}{kT}\right) \frac{kT\epsilon}{q} \left(\frac{\sin(\pi T/T_2)}{2\pi\epsilon T_2 kT g_{F0}}\right)^{T_2/T} \tag{51}$$

Linking Shur-Hack to Meyer-Neldel

Second halve of Meyer-Neldel Rule:

Activation energy depends on V_g :
For $T << T_2$ the Arrhenius plots are linear and

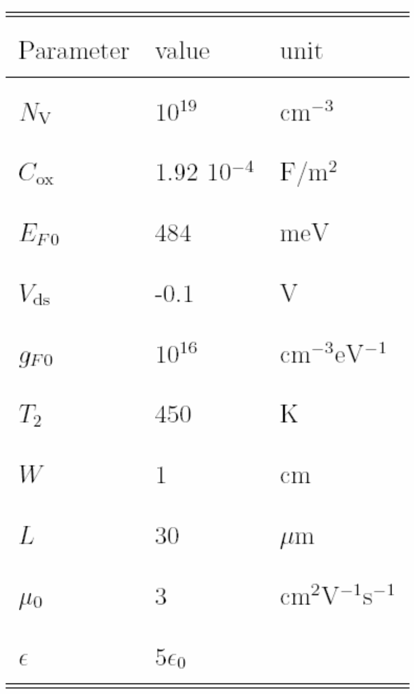
$$\boxed{E_A = E_{F0} - kT_2 \left[\ln \left(\frac{1}{2\epsilon (kT_2)^2 g_{F0}} \right) - 2 \ln \left(C_{\text{ox}} \left(|V_{\text{g}} - V_t| \right) \right) \right]}$$

$$I_{\text{ds}} = \frac{q\mu_0 W}{L} f\left(T, T_2\right) \left[C_{\text{ox}} \left(|V_{\text{g}} - V_t| \right) \right]^{\left(\frac{2T_2}{T} - 1 \right)} V_{\text{ds}} \tag{53}$$

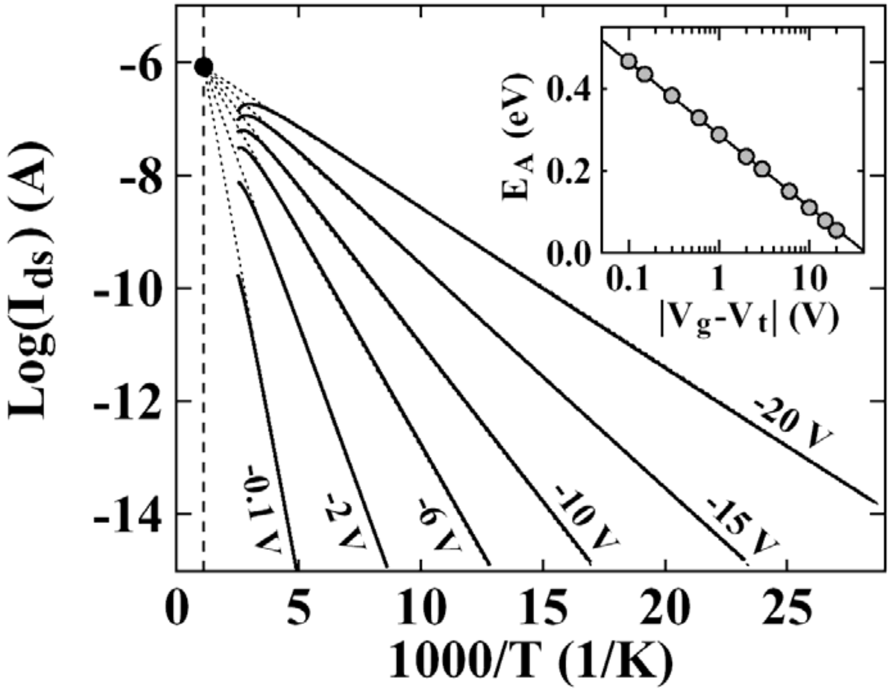
$$f(T, T_2) = N_{\text{V}} \exp \left(\frac{-E_{F0}}{kT} \right) \frac{kT\epsilon}{q} \left(\frac{\sin(\pi T / T_2)}{2\pi \epsilon T_2 k T g_{F0}} \right)^{T_2/T} \tag{51}$$

Used: $\sin(x) \approx x$ for $x << 1$ and $a^x = \exp(x \ln(a))$

Simulation

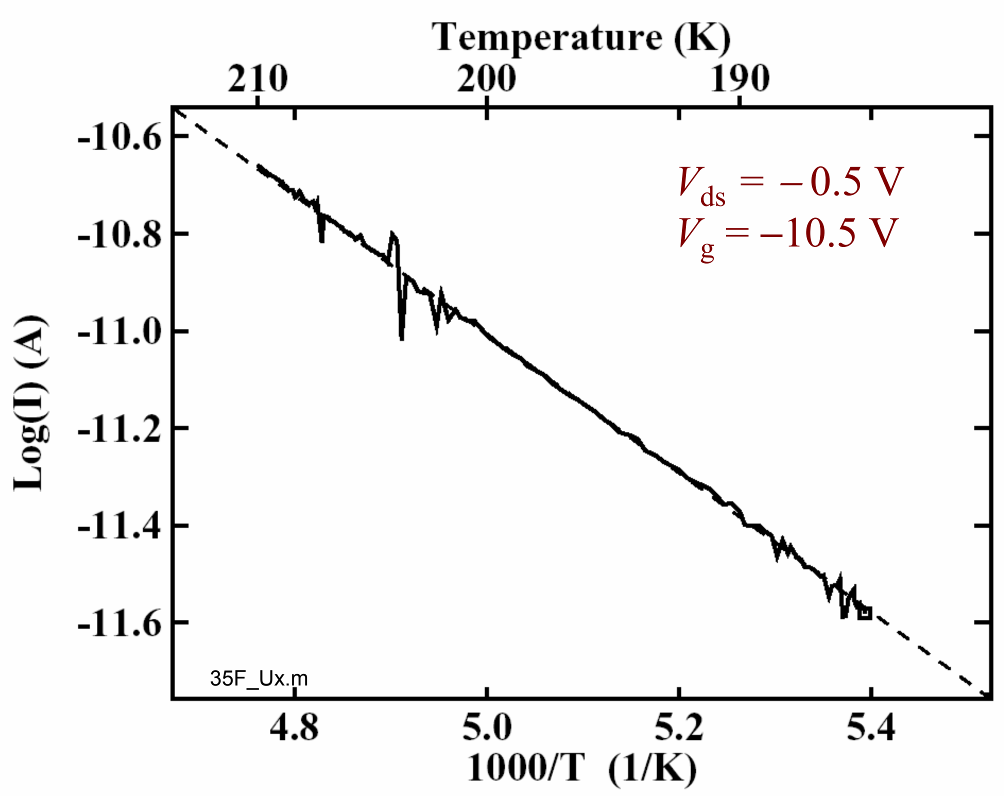


Parameter	value	unit
N_V	10^{19}	cm^{-3}
C_ox	$1.92\ 10^{-4}$	$\mathrm{F/m}^2$
E_{F0}	484	meV
V_ds	-0.1	V
g_{F0}	10^{16}	$\mathrm{cm}^{-3}\mathrm{eV}^{-1}$
T_2	450	K
W	1	cm
L	30	μm
μ_0	3	$\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$
ϵ	$5\epsilon_0$	



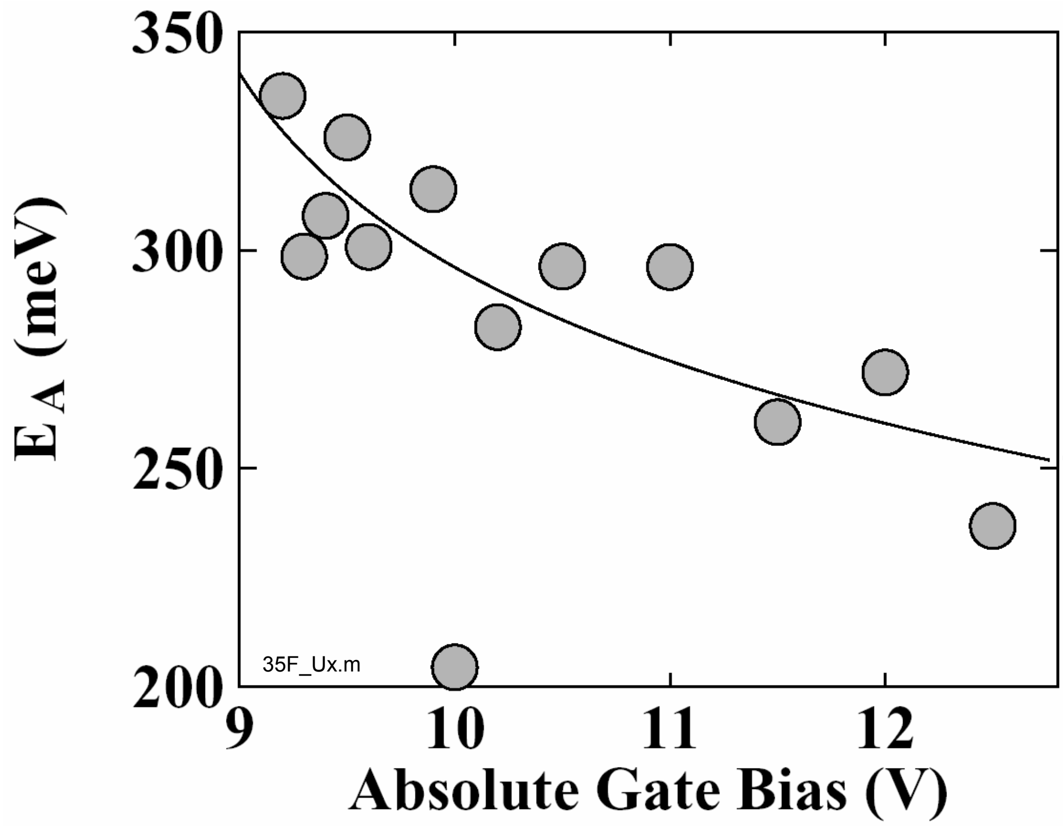
Note: No measurements possible at/close to T_2 (currents drop and diverge).

Experiment. Sexithiophene TFT



Note: To avoid stressing, measurements limited to below 220 K (see talk of Henrique)

Experiment. Sexithiophene TFT



fitting

Conclusions

3 things important for organic FETs (T6):

Traps traps & traps

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

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

A: Responsible for temperature activation of current

A: (P. Stallinga *et al*., J. Appl. Phys., Oct. 2004)

B: Responsible for stressing

B: (H.L.Gomes *et al*., Appl. Phys. Lett. 2004)

C: Responsible for the Meyer Neldel Observation

C: (P. Stallinga *et al*., to be published)

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