Explanation of the Meyer-Neldel Rule

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Rudolstadt, 30 September 2004
Trap states as an explanation of the Meyer-Neldel Rule

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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.

\[
P = P_0 \exp\left(-\frac{E_A}{kT}\right)
\]

\[
P_0 = P_{MN} \exp\left(\frac{E_A}{kT_{MN}}\right)
\]

* Original article: W. Meyer and H. Neldel, Z. Techn. 18, 588 (1937).
# Examples of the Meyer-Neldel Rule

*Here the MNR is called the Compensation Effect.*

<table>
<thead>
<tr>
<th>Processes</th>
<th>Parameters</th>
<th>Devices/materials</th>
</tr>
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<tbody>
<tr>
<td>current diffusion*</td>
<td>gas concentration</td>
<td>α-Si</td>
</tr>
<tr>
<td>ionic currents</td>
<td>pressure</td>
<td>organic ½cons</td>
</tr>
<tr>
<td></td>
<td>electrical bias</td>
<td>gas detectors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High-Tc supercons</td>
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<td></td>
<td></td>
<td>glasses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>liquid ½cons</td>
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<tr>
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<td></td>
<td>polycryst. Si</td>
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<td></td>
<td>CCDs</td>
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### Examples of the Meyer-Neldel Rule

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<td>gas concentration</td>
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...polycryst. Si
...CCDs

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* All less-than-perfect-crystalline materials

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* 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
Start with classic theory. However: Non-linear Transfer curves observed
Currents are linearized by taking the $n^{th}$ root

Non-linear IV curves observed

![Graph showing non-linear IV curves](image-url)
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.
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”).

Decaying currents

![Graph showing decaying currents over time](image)
Decaying currents

I(t) = I_0 \exp\left(-\left(\frac{t}{\tau}\right)^\alpha\right)

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


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

An \(I-T\) curve shows that charges are liberated from trap states.

\[ I(T) \propto \mu \times p(T) \quad \text{not: } I(T) \propto \mu(T) \times p \]

\(E_A = 170\) meV

\(Tr \rightarrow Tr^- + h\) or \(Tr^+ \rightarrow Tr + h\)
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

Shur & Hack

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

\[ f(T, T_2) = N_V \exp \left( \frac{-E_{F0}}{kT} \right) \frac{kT \epsilon}{q} \left( \frac{\sin(\pi T/T_2)}{2\pi \epsilon T_2 kT g_{F0}} \right)^{T_2/T} \quad (51) \]

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

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

$$f(T, T_2) = N_V \exp \left( \frac{-E_{F0}}{kT} \right) \frac{kT^2}{q} \left( \frac{\sin(\pi T/T_2)}{2\pi T_2 kT g_{F0}} \right)^{T_2/T} \quad (51)$$
First halve of Meyer-Neldel Rule:

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

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

\[ f(T, T_2) = N_V \exp \left( \frac{-E_{F0}}{kT} \right) \frac{kT\epsilon}{q} \left( \frac{\sin(\pi T/T_2)}{2\pi \epsilon T_2 kT g_{F0}} \right)^{T_2/T} \quad (51) \]
Second halve of Meyer-Neldel Rule:

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

$$E_A = E_{F0} - kT_2 \left[ \ln \left( \frac{1}{2e(kT_2)^2 g_{F0}} \right) - 2 \ln (C_{ox} (|V_g - V_t|)) \right]$$

$$I_{ds} = \frac{q\mu_0 W}{L} f(T, T_2) [C_{ox} (|V_g - V_t|)]^{(2T_2/T_2 - 1)} V_{ds}$$

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

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_V$</td>
<td>$10^{19}$</td>
<td>cm$^{-3}$</td>
</tr>
<tr>
<td>$C_{ox}$</td>
<td>$1.92 \times 10^{-4}$</td>
<td>F/m$^2$</td>
</tr>
<tr>
<td>$E_{F0}$</td>
<td>484</td>
<td>meV</td>
</tr>
<tr>
<td>$V_{th}$</td>
<td>-0.1</td>
<td>V</td>
</tr>
<tr>
<td>$g_{p0}$</td>
<td>$10^{16}$</td>
<td>cm$^{-3}$eV$^{-1}$</td>
</tr>
<tr>
<td>$T_2$</td>
<td>450</td>
<td>K</td>
</tr>
<tr>
<td>$W$</td>
<td>1</td>
<td>cm</td>
</tr>
<tr>
<td>$L$</td>
<td>30</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>3</td>
<td>cm$^2$V$^{-1}$s$^{-1}$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>$5\epsilon_0$</td>
<td></td>
</tr>
</tbody>
</table>

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

![Graph showing the relationship between $E_A$ (meV) and Absolute Gate Bias (V).](35F_Ux.m)
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
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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