NO SIGNAL
Introduction
Introduction

• An FET needs VT to start working:
  \[ V_T = \ldots N_A^{\frac{1}{2}} \]

• 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:

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

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

Special Effects

- Mobility depends on longitudinal field \( (V_{ds}) \)
- Mobility \textit{appears} to depend on transversal field \( (V_g) \)
- Mobility \textit{appears} to depend on the frequency \( (\nu) \)
- Threshold voltage not constant \( (V_g, t, T) \)
Intro
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Spectroscopy
Poole-Frenkel
TSC
Conclusions
Mobility \textit{appears} to depend on $V_g$

\begin{align*}
\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}
\end{align*}

This implies that the \textbf{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)

$$I_{ds} = (W/L) \, C_{ox} \, \mu(V_g) \, (V_g - V_t) \, V_{ds}$$
\[ g(\varepsilon) = \left(\frac{N_T}{kT_0}\right) \exp\left(\frac{\varepsilon}{kT_0}\right) \]

\[ \gamma = 2\left(\frac{T_0}{T} - 1\right) \]

Vissenberg et al, PRB 57, 12964 (1998)
Mobility appears to depend on $V_g$

$\gamma$ depends on $T$

Failure of the VRH/MTR theory, which cannot adequately describe the behavior of $\gamma$ as a function of temperature.
The Meyer-Neldel rule (MNR)

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

MNR holds, with a phase transition at 200 K
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 $\mu$

Using lock-in detection
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Experimetal Setup

![Experimental Setup Diagram]
The as-measured mobility depends on the frequency!
Spectroscopy results

Stressing effects ($V_T$ changes)
**Spectroscopy results**

Extrapolation to pulsed measurements

Pulsed experiments give 500x mobility

\[ \Delta t = 10 \ \mu s \]

\[ \mu = 10^{-2} \ \text{cm}^2/\text{Vs} \]
Expected for $t = \infty$: DC mobility = 0 because $V_T = V_G$. AC mobility is not 0 (?)
Transient of mobility vs. time.

\[ \nu = 570 \text{ Hz} \]

Sample: T6-35

\[ \mu(t) = \mu_0 \exp(-\sqrt{t/\tau}) + \mu_{\text{offset}} \]

Note that in this experiment Vg is always on
Poole-Frenkel Conduction model

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

Frenkel–Poole emission

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

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

Poole-Frenkel conduction in literature

Experimental observation of Poole-Frenkel conduction

Sample: LO27 (Tobias), RT, LV
Poole-Frenkel: Effect of temperature

\[ T = 210 \text{ K} \quad \text{and} \quad T = 340 \text{ K} \]

Frenkel-Poole emission

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

Sample: LO23 (Tobias)
Simulation of Poole-Frenkel conduction

1: Simple model: field (and $\mu$) constant in space

$$E = \frac{V_{ds}}{L}$$

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

$$I_{ds} = a C_{ox} (V_G - V_T) \mu V_{ds}$$
Simulation of Poole-Frenkel conduction

2: Full simulation. System of differential equations

Differential equations:
1. \( E(x) = \frac{dV(x)}{dx} \)
2. \( \mu(x) = \mu_0 \exp[\gamma E(x)^{1/2}] \)
3. \( Q(x) = C_{ox} \left[ V_g - V_t - V(x) \right] \)
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

\[ I = V_s L_s \exp \left[ \frac{K L}{-q(\phi_B - V_A/\sqrt{q/\varepsilon})} \right] \sim L_s \varepsilon \exp(+A \sqrt{V}/L - d\phi_B/K L) \]

Frenkel-Poole emission

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

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

\[ \begin{array}{c}
\text{\includegraphics[width=0.5\textwidth]{diagram}}
\end{array} \]

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

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

\[ I = \mathcal{V} \times \mathcal{I}_0 \exp \left( \frac{K_0}{d(\phi_R - \sqrt{q\mathcal{E}/\pi\epsilon_i})} \right) \sim \mathcal{I}_0 \exp \left( +a \sqrt{\mathcal{V}/T} - \phi_R/kT \right) \]

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

- But: connection to a physical model is lost.
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)
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Temperature Scanned Current

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

Dependence on temperature

<table>
<thead>
<tr>
<th></th>
<th>Classic ½-con</th>
<th>Organic ½-con</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_A^{-} )</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>( \psi_B )</td>
<td>Yes</td>
<td>Yes</td>
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http://www.ualg.pt/fct/adeec/optoel/fet/

p452 of Sze
A:

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

PF “wins”, current is exponentially growing
Temperature Scanned Current

$T(C) = 5020-1030-50-70-90100110120130-140-150$

$E_A = 0.167 \text{ eV}$

**PF:**

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

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

Frenkel–Poole emission

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B: \[ V_T = \left(4q\varepsilon_s\psi_B N_A^-\right)^{1/2} / C_{ox} + 2\psi_B \]

- \( V_T \) increases irreversibly because \( N_A \) appear/ionize. Stressing!

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

Stressing wins because of slow scanning.
Temperature Scanned Current

\[ V_{ds} = -0.5 \, \text{V}, \quad V_{g} = -9 \, \text{V} \]
Sample 35  $T = 180\ K$

**Frenkel–Poole emission**

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

\[ R_P = 20\ G\Omega \]

\[ V_g = -10\ V \]
Sample 35 \( T = 160 \, \text{K} \)

\[ V_g = -20 \, \text{V} \]

Frenkel–Poole emission

\[ J \sim \xi \exp \left[ -\frac{q(\phi_B - \sqrt{\xi}/\pi\varepsilon_i)}{kT} \right] \sim V \exp(+2a\sqrt{V}/T - q\phi_B/kT) \]
Temperature, Poole-Frenkel

Sample 35 \( T = 140 \text{ K} \)

\[ J \sim e \exp \left[ -\frac{q\phi_B - \sqrt{q\varepsilon/\pi\varepsilon_i}}{kT} \right] \sim V \exp(+2a\sqrt{V}/T - q\phi_B/kT) \]

Frenkel–Poole emission

\( V_g = -20 \text{ V} \)
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, $\mu$ depends on $\nu$
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