Brandenburgische Technische Universität Cottbus

Quantum transport in ultra-short channel VLSI CMOS-Transistors

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A contribution to the
Leibniz-Konferenz 'Nanoscience 2012'
Lichtenwalde, 26. - 27.04.2012

Outline of the presentation

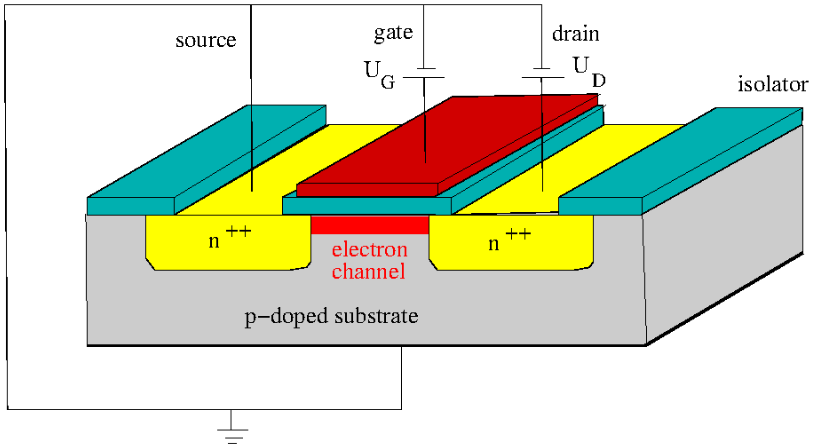
I. Scale-invariant one-dimensional effective model for quantum transport in nano-transistors

II. Qualitative comparison with experimental drain characteristics

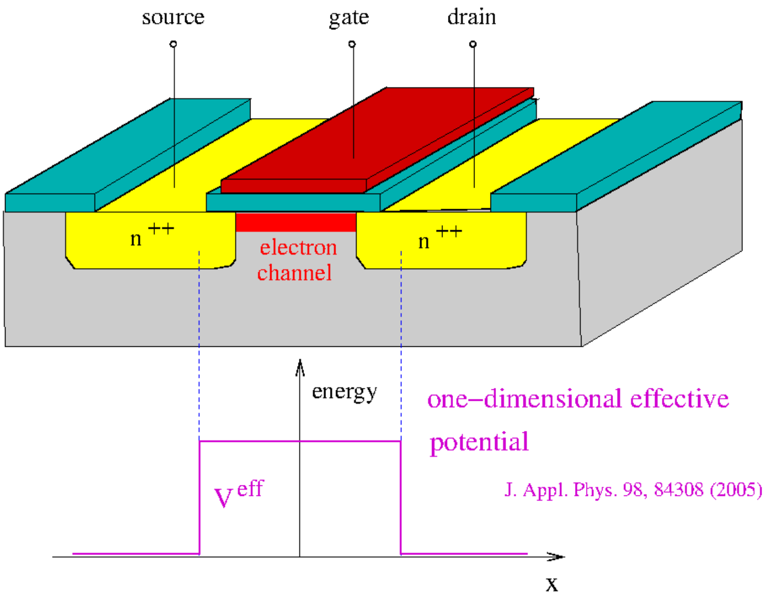
III. Calibration of the model parameters: towards quantitative understanding

IV. Three-parameter calibration for threshold- and subthreshold regime

I.1. One-dimensional effective potential



I.1. One-dimensional effective potential



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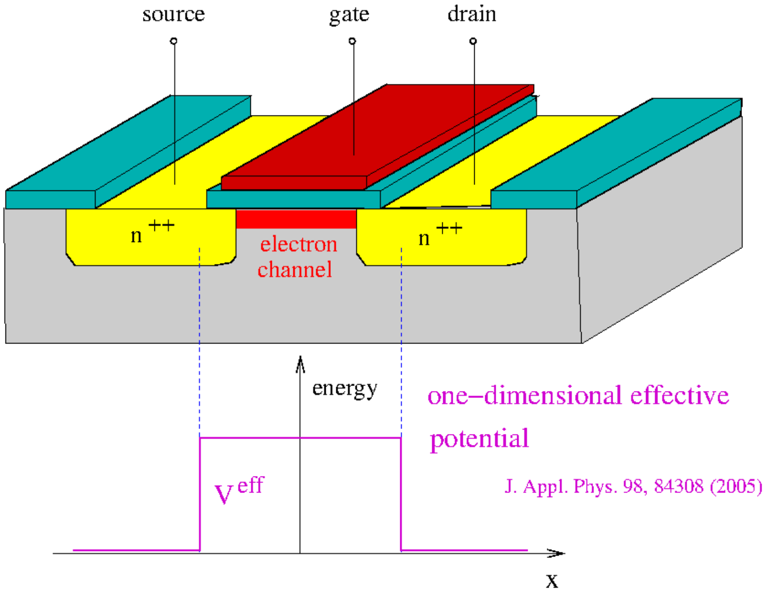

'SMAT'–approximation= single–mode–abrupt–transition

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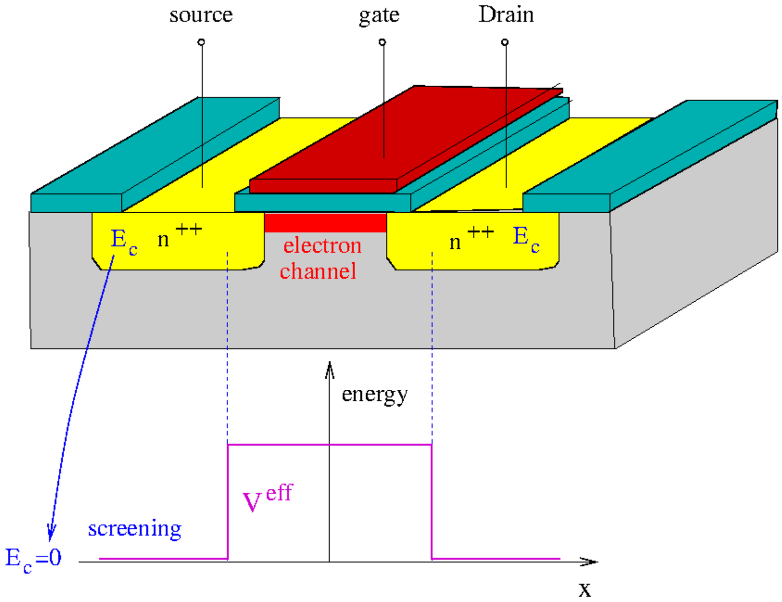

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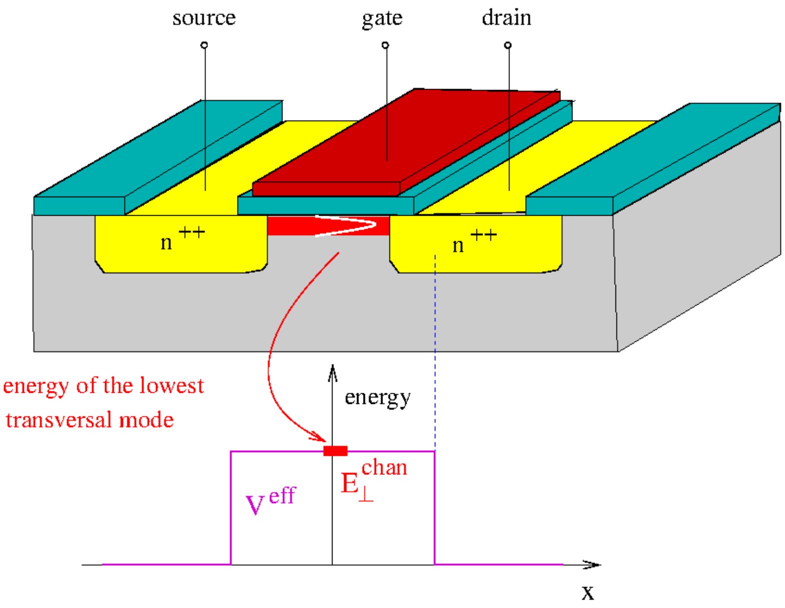

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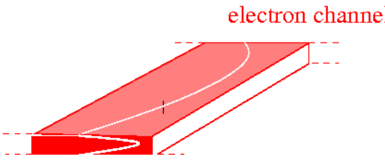
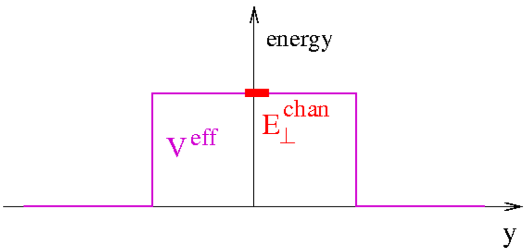
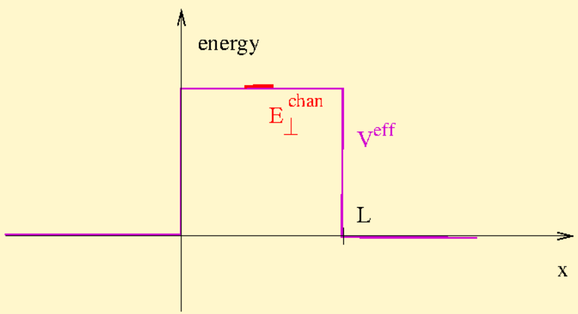


$E_\perp^{chan}$: corresponds to lowest energy with propagating waves in the 'electron wave–guide'



I.2. One-dimensional effective Schrödinger equation

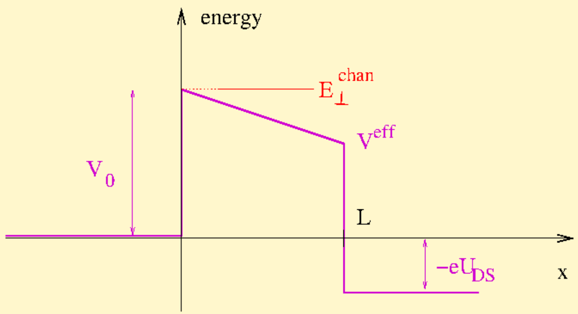
$$\left[-\frac{\hbar^2}{2m^*}\frac{d^2}{dx^2} + V^{eff}(x) - E\right]\psi(x) = 0,$$



I.3. One-dimensional effective problem with drain voltage

$$\left[-\frac{\hbar^2}{2m^*}\frac{d^2}{dx^2} + V^{eff}(x) - E\right]\psi(x) = 0,$$

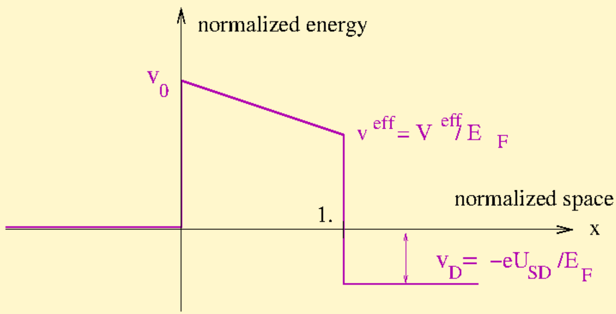
$$V^{eff}(y) = \begin{cases} 0, & \text{for } x < 0 \\ V_0 - \frac{x}{L}eU_{DS} & \text{for } 0 \le x \le L \\ -eU_{DS}, & \text{for } x > L. \end{cases}$$



I.4. Scale-invariant representation of the Schrödinger equation

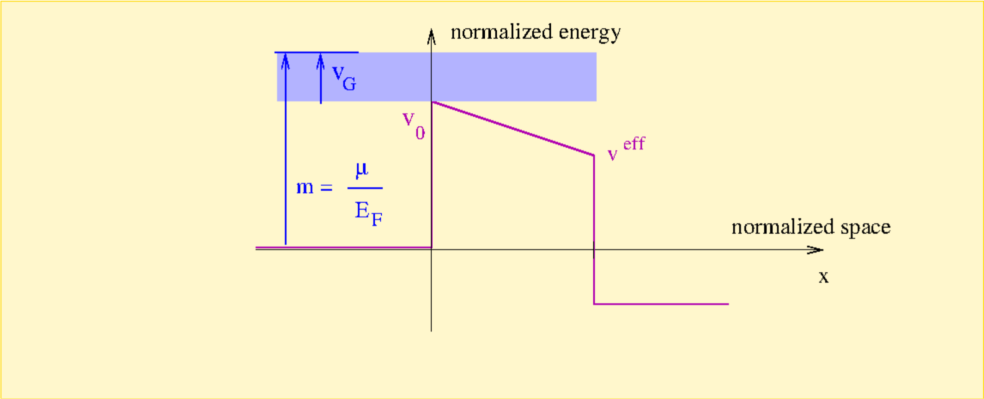
$$\left(-\frac{1}{l^2}\frac{d^2}{dx^2} + v^{eff}(x) - \epsilon\right)\psi(x) = 0$$

$$\frac{x}{L} \to x \qquad \frac{V^{eff}(x)}{E_F} \to v^{eff}(x) \qquad \epsilon = \frac{E}{E_F} \qquad l^2 = \frac{2m^* E_F L^2}{\hbar^2}$$



I.5. Introduction of the gate voltage parameter v_G

$$\left(-\frac{1}{l^2}\frac{d^2}{dx^2} + v^{eff}(x) - \epsilon\right)\psi(x) = 0$$



$$v_G = m - v_0$$

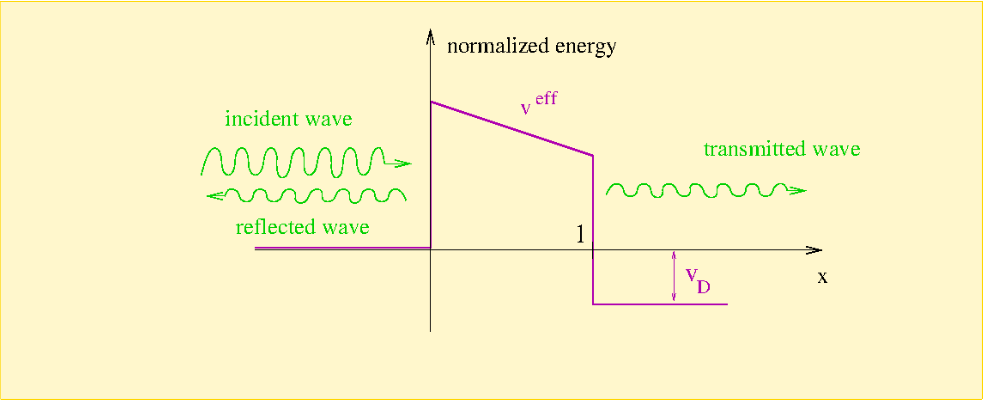
$v_G \gtrsim 0$: ON-state

$v_G \lesssim 0$: quasi-OFF-state

I.6. Scaled current transmission

$$\left(-\frac{1}{l^2}\frac{d^2}{dx^2} + v^{eff}(x) - \epsilon\right)\psi(x) = 0$$

- Source-emitted scattering state $\psi(x \geq 1, \epsilon) = t\exp(ik_D x)$
- Current transmission $T = k_D \mid t \mid^2 k_S^{-1}, \quad k_D = \sqrt{l^2(\epsilon + v_D)}$



I.7. The scale-invariant Tsu-Esaki formula for drain current

$$j = \frac{I_D}{W J_0} = \int_0^\infty d\epsilon \left[s\left(\epsilon - m\right) - s\left(\epsilon - m + v_D\right)\right] T(\epsilon)$$

- normalized chemical potential $m = \mu/\epsilon_F$ and $u = k_B T/E_F$

$$m(u) = u X_{\frac{1}{2}} \left(\frac{4}{3\sqrt{\pi}} u^{-3/2} \right),$$

$X_{\frac{1}{2}}$: inverse F.-D. integral

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- normalized supply function

$$s\left(\alpha\right) = \frac{1}{\sqrt{4\pi}} \sqrt{u} F_{-\frac{1}{2}} \left[\frac{\alpha}{u}\right],$$

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- scale-invariant expression for drain current

$$j = j(v_D, v_G, u, l)$$

$$v_D = eU_D/E_F, v_G = V_G/E_F, u = k_B T/E_F, l = L/\lambda \left(\lambda = \hbar/\sqrt{2m^* E_F}\right)$$

I.7. The scale-invariant Tsu-Esaki formula for drain current

$$j = \frac{I_D}{W J_0} = \int_0^\infty d\epsilon \, [s\,(\epsilon - m) - s\,(\epsilon - m + v_D)] \, T(\epsilon) = j(v_D, v_G, u, l),$$

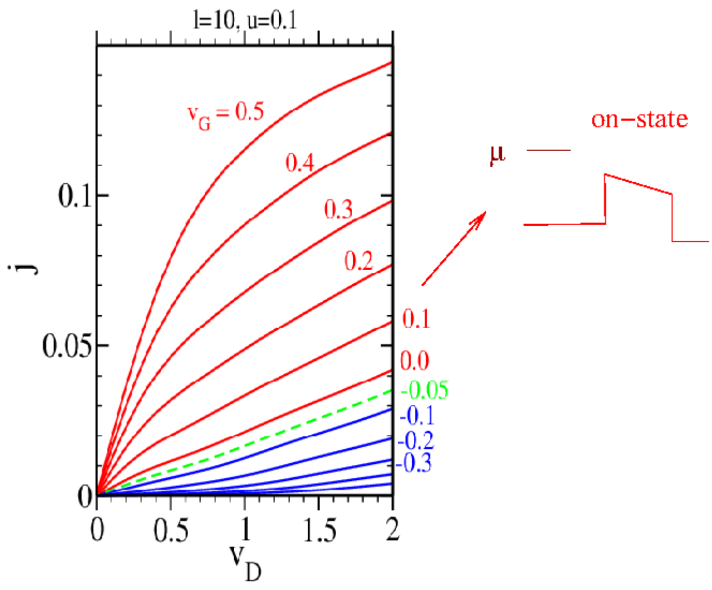
with

$$v_D = eU_D/E_F, \;\; v_G = V_G/E_F, \quad u = k_B T/E_F, \quad l = L/\lambda$$

For a wide transistor with strong doping in source/drain contact:

- $E_F = 0.35eV \Rightarrow u \sim 0.1$ at room temperature
- scaling length $\lambda \sim 1nm$
- current unit $J_0 = 5.4 \times 10^{-2} A/\mu m$

II.1. Theoretical drain characteristics ∼ room temperature



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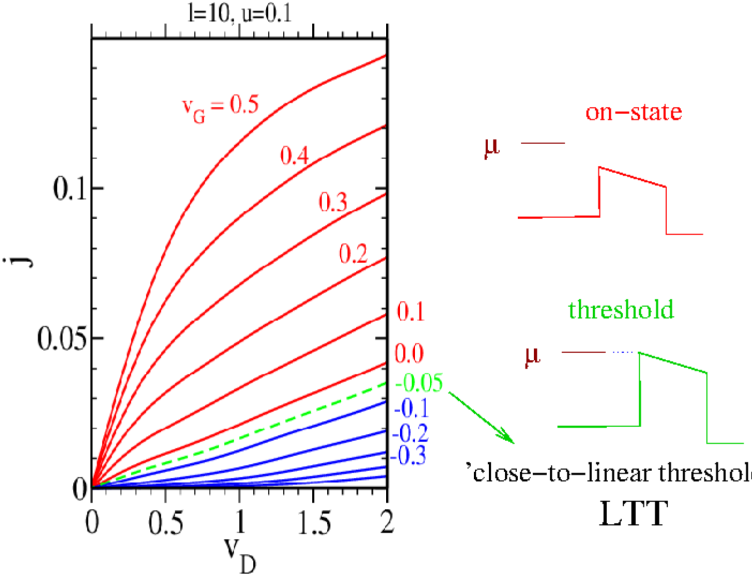

'close−to−linear threshold trace'

LTT

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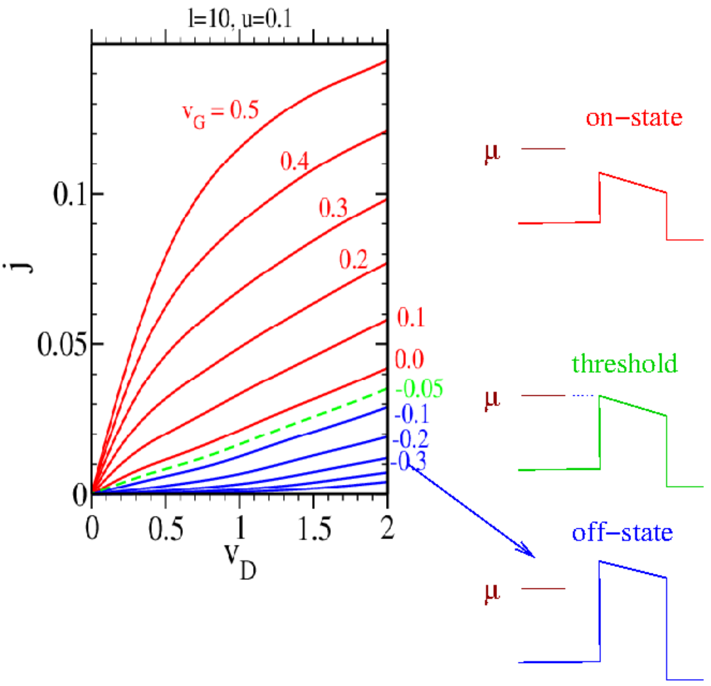
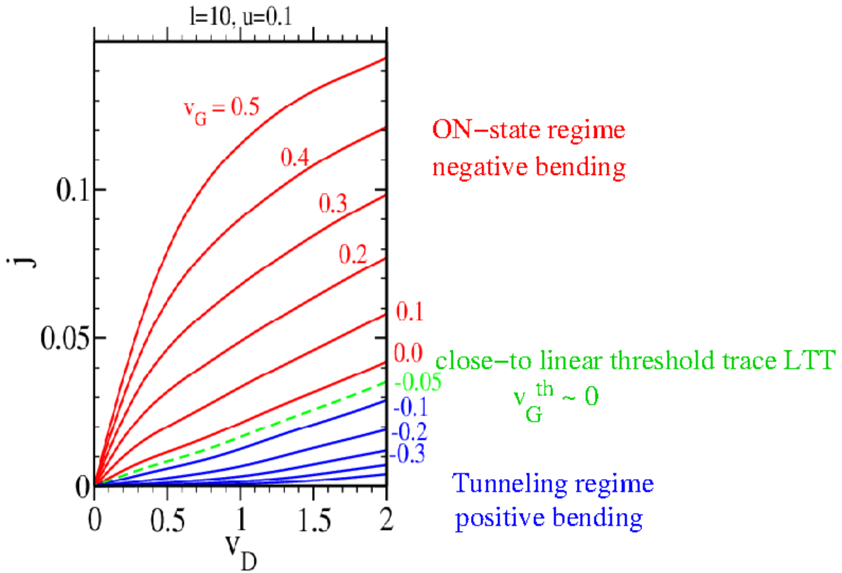
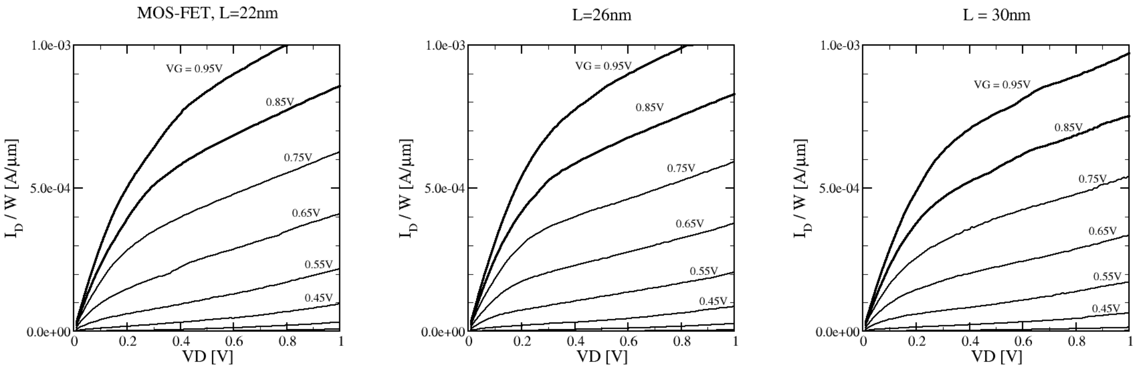


II.2. Theoretical drain characteristics - qualitative features

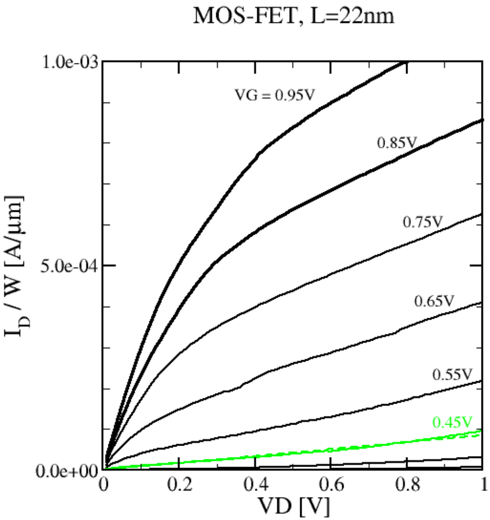


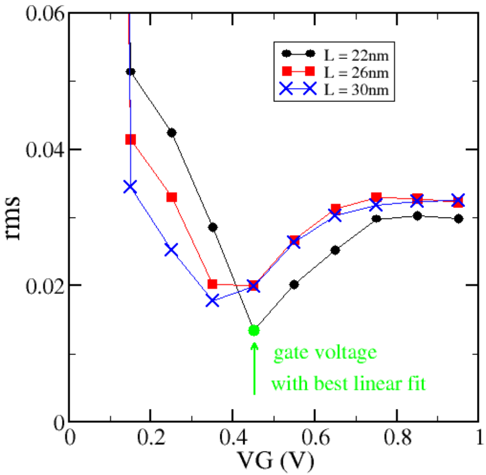
II.3. Experimental drain characteristics



- Transistor data provided by GLOBALFOUNDRIES, Dresden
- $\lambda = 1nm \Rightarrow L = 22nm, 26nm, 30nm$ corresponds to $l = 22,\ 26,\ 30$
- $E_F = 0.35eV \Rightarrow$ room temperature corresponds to $u \sim 0.1$

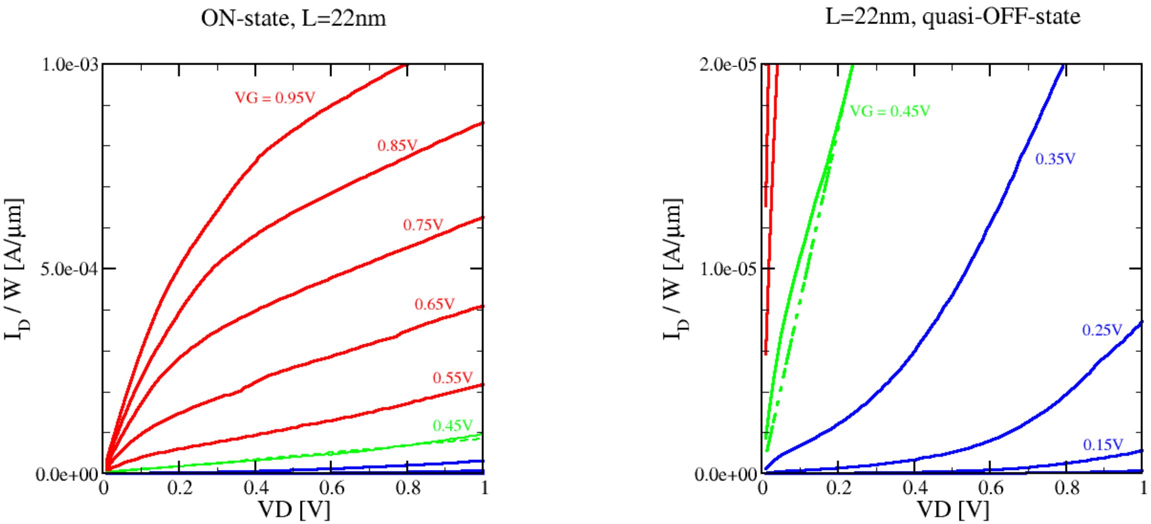
II.4. Experimental close-to-linear threshold trace (LTT)





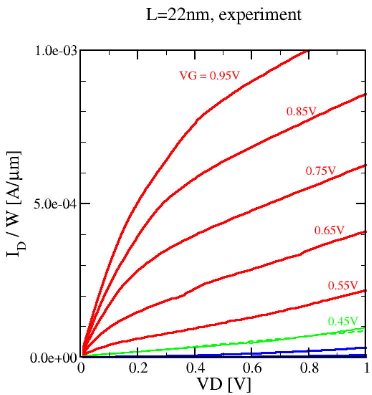
$$\mathrm{rms}(V_G) = \mathrm{Min}_\sigma \left\{ \sqrt{\sum_{VD} \frac{[I_D(VD,VG) - \sigma VD]^2}{I_D(VD,VG)^2}} \right\}$$

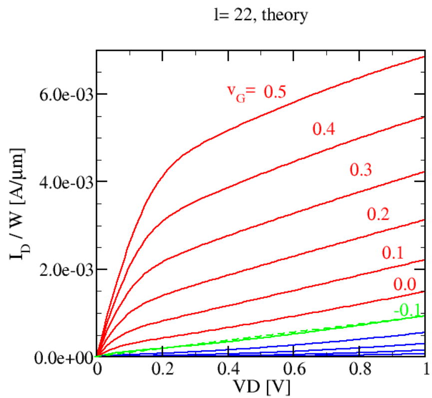
II.5. Experimental ON-state and quasi-OFF-state regime



- ON-state negative bending, quasi-OFF-state positive bending

II.6. Comparison theory - experiment without calibration



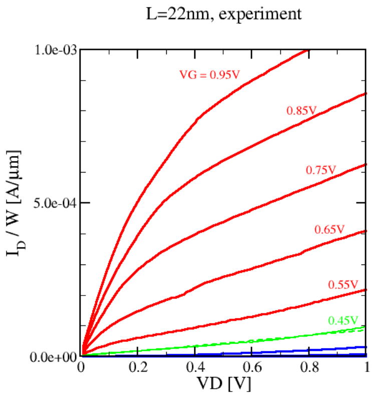


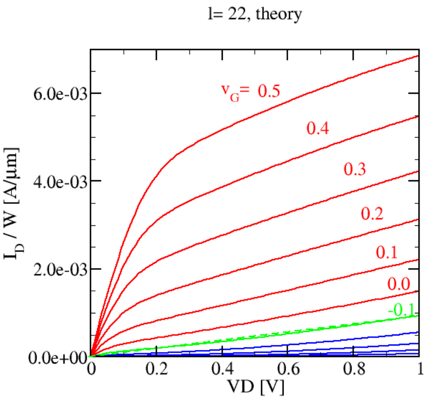
1. Theoretical LTT-current is bigger than the experimental one

2. For large gate voltages the experimental trace is much smoother

3. No relation between the theoretical v_G and experimental VG

III.1. Calibration parameters





1. Theoretical LTT-current is bigger than the experimental one
   $\Rightarrow$ current calibration function $I_{cal}(VG)$: $I_D/W = J_0 j \rightarrow I_{cal} J_0 j$
2. For large gate voltages the experimental trace is much smoother
   $\Rightarrow$ heating: temperature calibration function $u(VG)$ is introduced
3. No relation between the theoretical v_G and experimental VG
   $\Rightarrow$ gate calibration function $v_G(VG)$

III.2. Calibration of fit-parameters I_{cal}, u, and v_G

- Fit of the calibrated theoretical current

$$J = \frac{I_D}{W} = I_{cal} J_0 j(v_D, v_G, u, l)$$

to the experimental trace

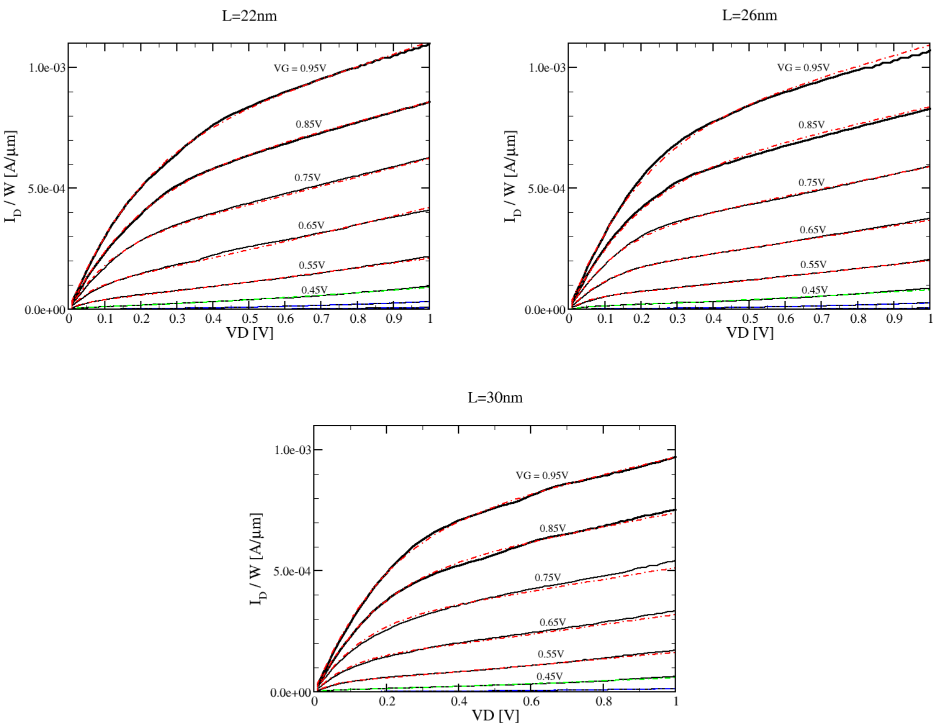
$$J^{exp}(VD, VG, L)$$

at given VG, L, and $l = L/\lambda$, $\lambda = 1nm$

- Minimization of the root mean square sum

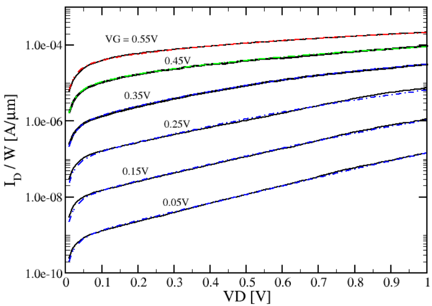
$$\mathrm{rms}(I_{cal}, u, v_G) = \sum_{VD} \frac{\left[J^{exp}(VD, VG, L) - I_{cal} J_0 j(VD/E_F, v_G, u, L/\lambda)\right]^2}{J^{exp}(VD, VG, L)^2}$$

III.3. Theory vs. experiment with calibration in ON-state

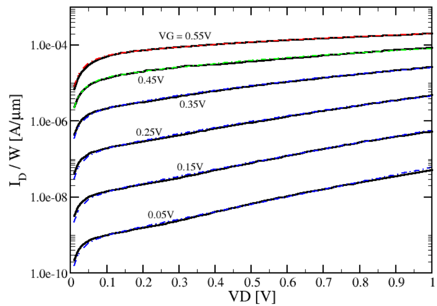


III.4. Theory vs. experiment in quasi-OFF-state

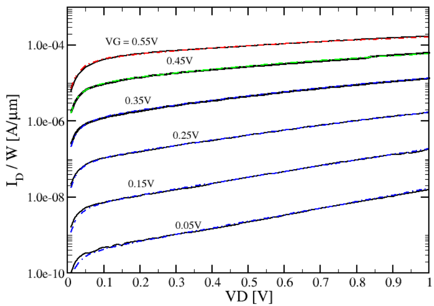
L = 22nm



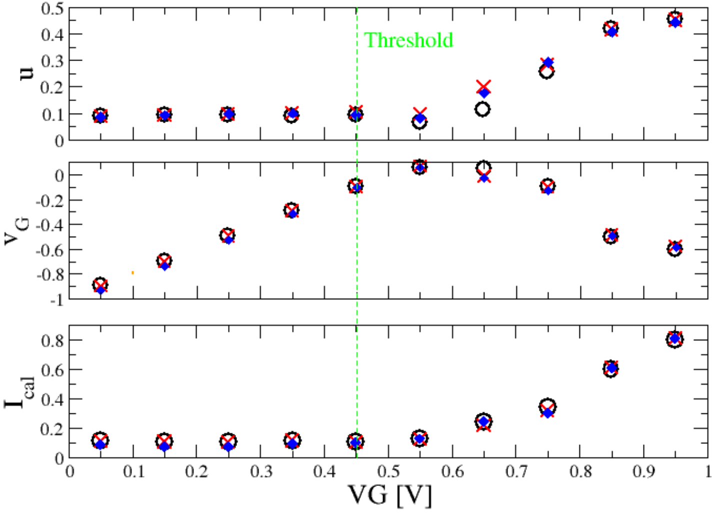
L = 26nm



L = 30nm



III.5. Results for the calibration functions



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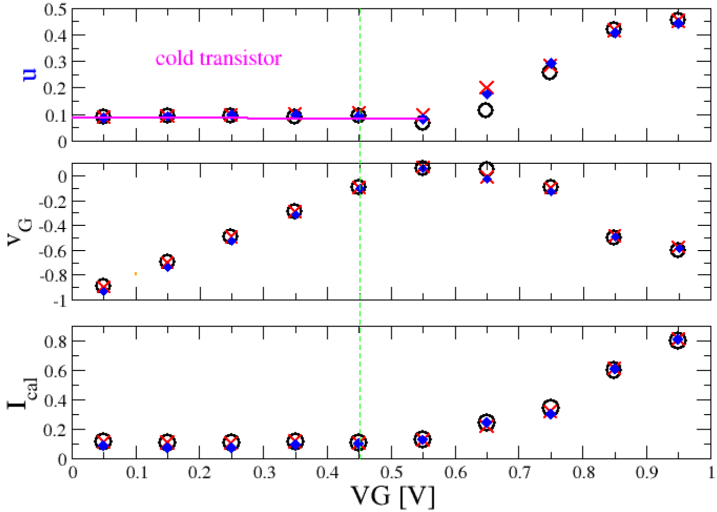
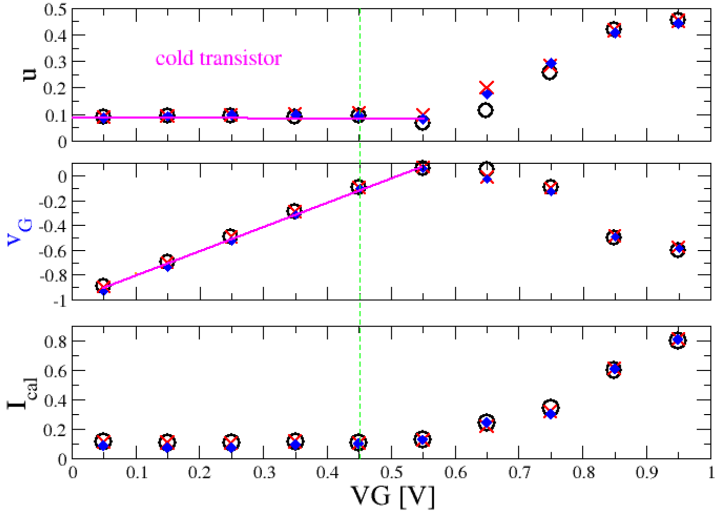


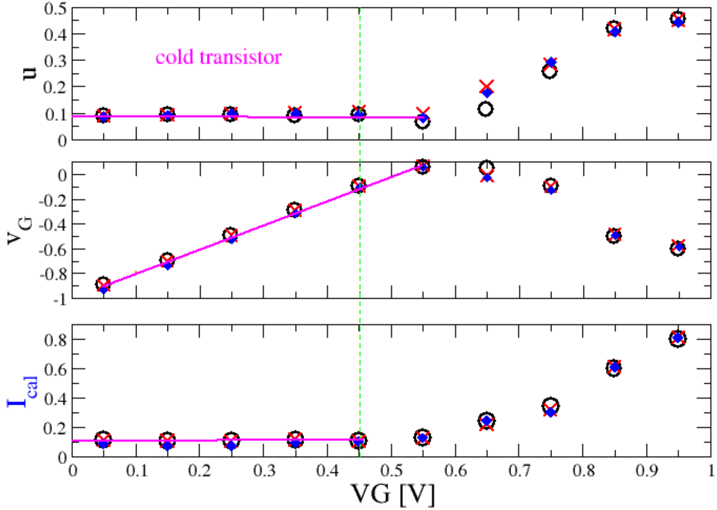
- subthreshold- and threshold regime: small drain current ⇒ room temperature ('cold transistor'). ON-state: increased drain current ⇒ dissipation and heating. Traces more rounded than at room temperature

III.5. Results for the calibration function



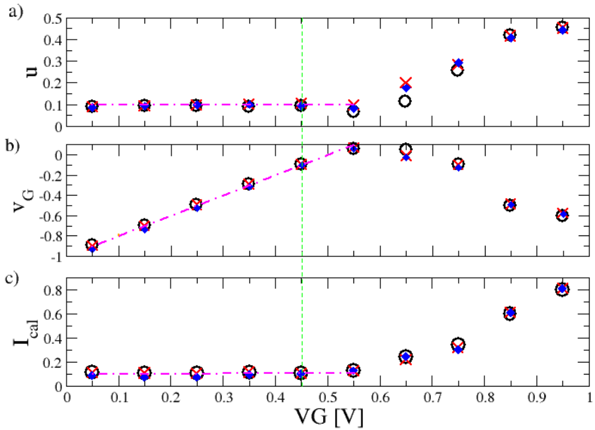
- cold transistor: $\mu \sim E_F \Rightarrow v_G = m - v_0 \sim E_F - v_0 \Rightarrow$ changes in v_0 translate directly into v_G. Constant capacitance $\Rightarrow v_G(VG)$ is linear. hot transistor: chemical potential and v_G drops.

III.5. Results for the calibration function



- Relatively big current calibration constant I_{cal} is to be expected given the simplicity of the model. It depends on the coupling of the contacts to the electron channel.

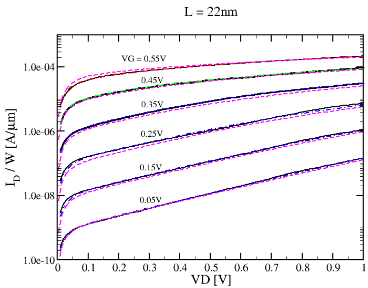
IV.1 Simple three-parameter calibration in quasi-OFF-state

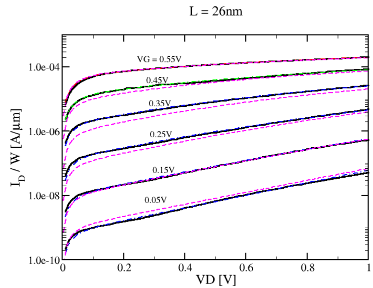


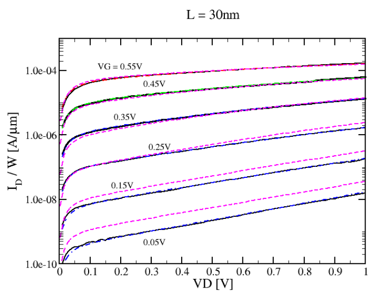
$$v_G(VG < 0.55V) = \alpha(VG - VG_T) + v_T$$

In magenta: $u = 0.09$ (room temperature), $\alpha = 2.0$ (constant capacitance of the electron channel), and $I_{cal} = 0.1$.

IV.2 Three-parameter calibration comparison with experiments







In magenta: $u = 0.09$, $\alpha = 2.0$, and $I_{cal} = 0.1$.

V. Conclusion

- Presentation of a scale-invariant one-dimensional effective model for quantum transport in nano-transistors
- Qualitative comparison with experimental drain characteristics: ON-state regime (traces with negative bending), close-to linear threshold characteristic (LTT), quasi-OFF-state tunneling regime (traces with positive bending)
- Calibration of the model parameters yields quantitative description
  - temperature calibration $\Rightarrow$ heating of transistor in ON-state
  - gate voltage calibration $\Rightarrow$ capacitance model of nanotransistor
  - current calibration $\Rightarrow$ optimization of transition of wave functions between contacts and transistor channel
- Simple three-parameter calibration for threshold- and subthreshold regime is possible