Approaches for Analytical (Compact) Modeling of Tunneling Current in MOS Transistors

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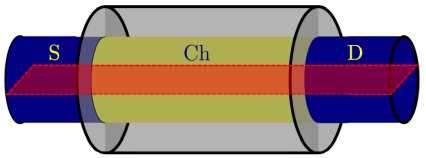
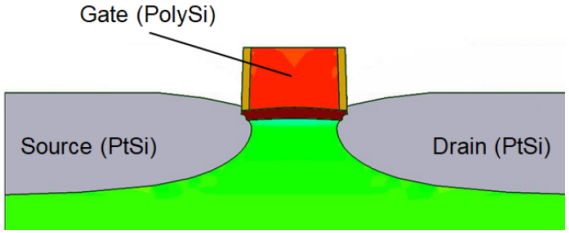
Motivation

Aggressive device scaling in new technologies: tunneling currents getting more important



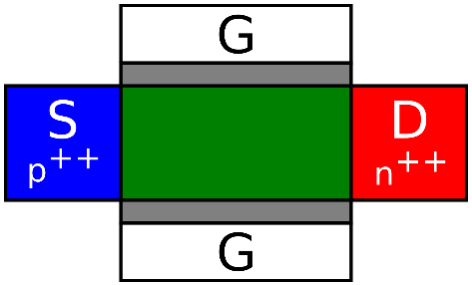
Leakage effects to avoid:

- Gate leakage
- Source-to-drain tunneling (L << 10 nm)
- …



New devices based on tunneling:

- Schottky barrier FET (SB-FET)
- Tunnel-FET (TFET)
- …



Compact modeling must provide solutions to describe tunneling currents in a physics-based and numerically efficient way!

Outline

1. Basics of Tunneling
2. Approaches:
   - WKB Approximation
   - Wavelet transform
3. Results for Device Modeling:
   - Compact model for TFET *(WKB)*
   - Ultra-Short Channel MOSFET *(WKB vs. Wavelet)*
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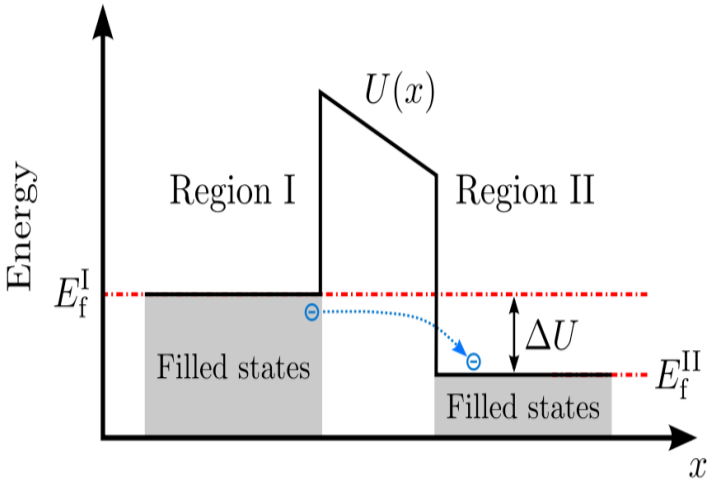
1. Basics of Tunneling

- Solution of (at least) 1D time-independent Schrödinger equation necessary:

$$-\frac{\hbar^2}{2m^*}\cdot\frac{\mathrm{d}^2\,\Psi(x)}{\mathrm{d}x^2}+U(x)\cdot\Psi(x)=E\cdot\Psi(x)$$

- T_{tun}: **tunneling probability**

- Analytical approximations possible?



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2. WKB Approach

Wentzel-Kramers-Brillouin Approximation:

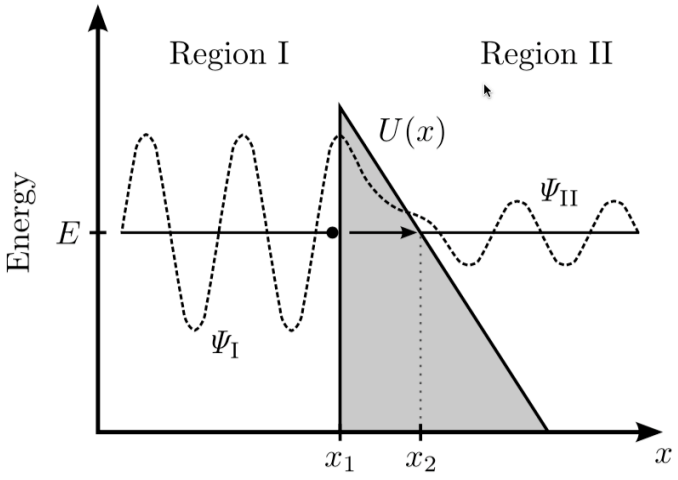
- Assumption: *U(x)* varies "slowly" with *x:*

$$T_{\text{tun}} = \exp\left(-2 \cdot \int_{x_1}^{x_2} \left| \sqrt{\frac{2m^* \cdot (U(x) - E)}{\hbar^2}} \right| \mathrm{d}x\right)$$

- Closed form for triangular barrier:

$$T_{\text{tun}} = \exp\left(-\frac{4}{3} \cdot \sqrt{\frac{2m^*}{\hbar^2} \cdot \frac{U(x_1) - E}{x_1 - x_2}} \cdot \left(x_2^{3/2} - x_1^{3/2}\right)\right)$$

- Kane's tunneling model:
  - based on WKB with const. field: $T \neq f(E)$
  - Integration w.r.t. energy replaced by effective DOS



[1] G. Wentzel, "Eine Verallgemeinerung der Quantenbedingungen für die Zwecke der Wellenmechanik," Zeitschrift für Physik, vol. 38, pp. 518–529, June 1926
[2] Evan O. Kane, „Theory of tunneling", Journal of Applied Physics 32, 83 (1961)

2. WKB Approach

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- Kane's tunneling model:
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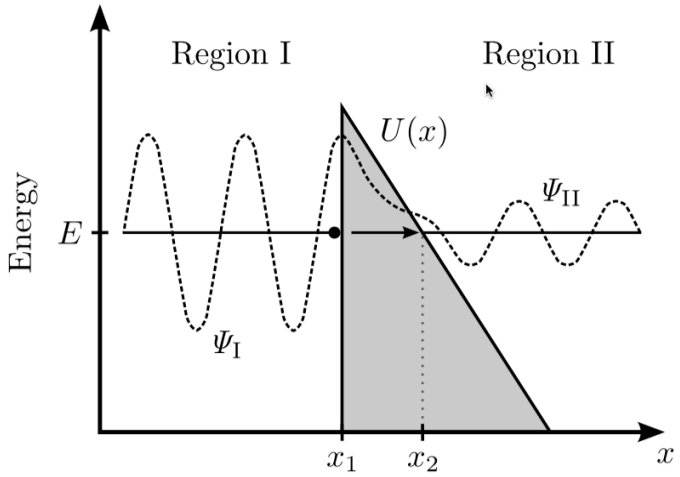
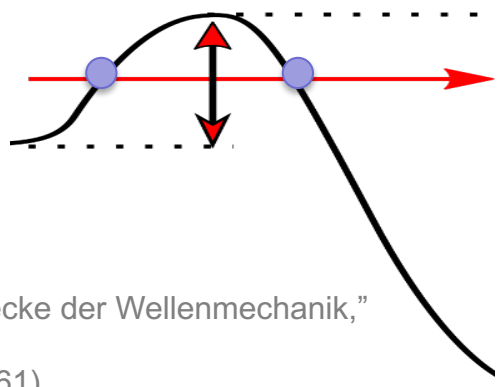
- Problem:
  at turning points *U(x)* can be very steep!





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2. Wavelet Approach

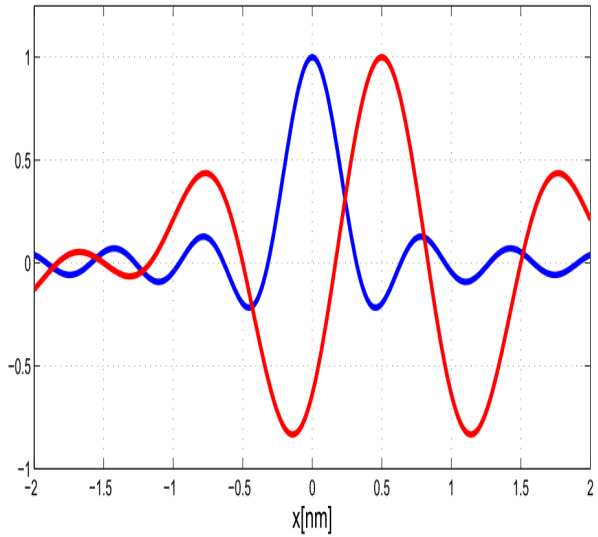
Wavelet Approach:

- Considering the Schrödinger equation:

$$\frac{d^2\psi}{dx^2} - k^2\psi(x) = 0 \qquad K = k^2 = \frac{2m^* \cdot (U(x) - E)}{\hbar^2}$$

- Solution is approximated by *Shannon wavelet family*:

$$\psi(x) = \alpha\varphi(x) + \overline{\alpha\varphi}(x) + \beta\eta(x) + \overline{\beta}\overline{\eta}(x)$$

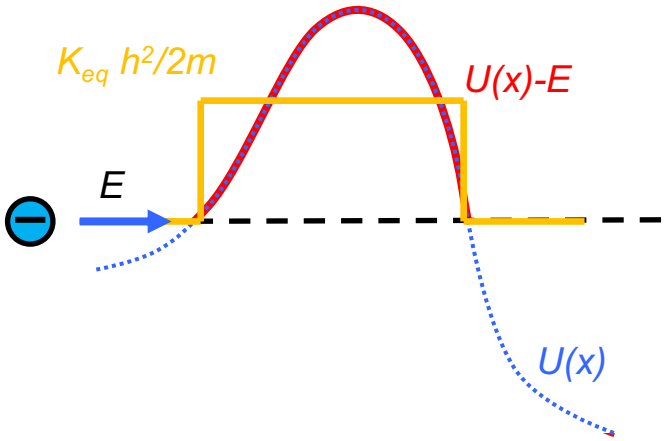


2. Wavelet Approach

- By projection of Schrödinger equation an equivalent rectangular barrier is derived:

$$K_{eq}(x) = \frac{1}{2\pi} \int_{-2\pi}^{2\pi} \hat{K}(\omega) d\omega$$

- Equivalent barrier results in approx. same T_{tun} as *U(x)*
- Implementation requires FFT of potential barrier



[3] A. Farokhnejad, M. Graef, A. Kloes: Wavelet-Based Calculation of the Transmission Coefficient for Tunneling Events in Tunnel-FETs, MIXDES 2015, Torun, Poland

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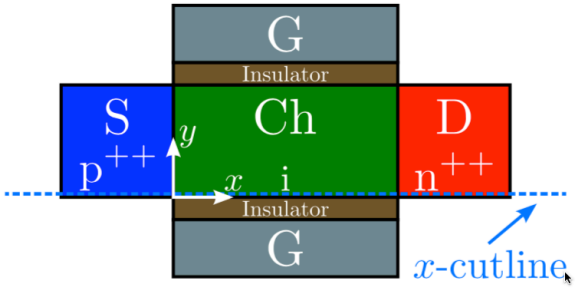
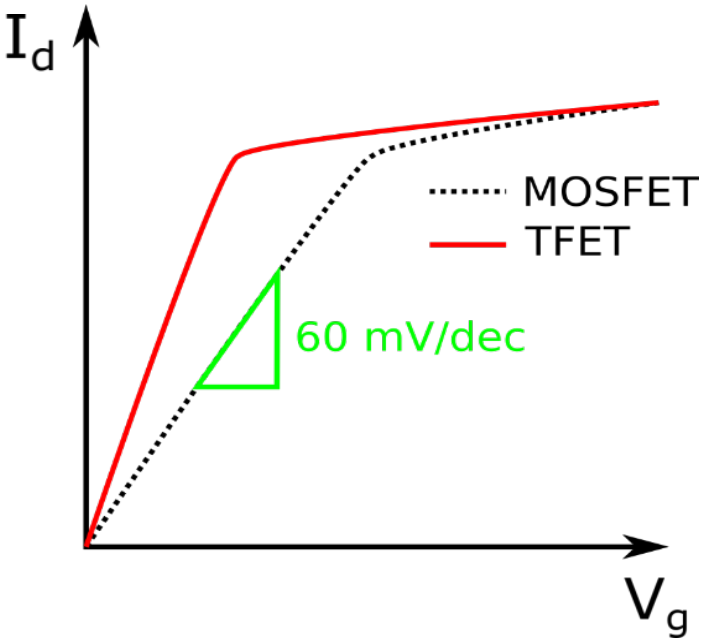
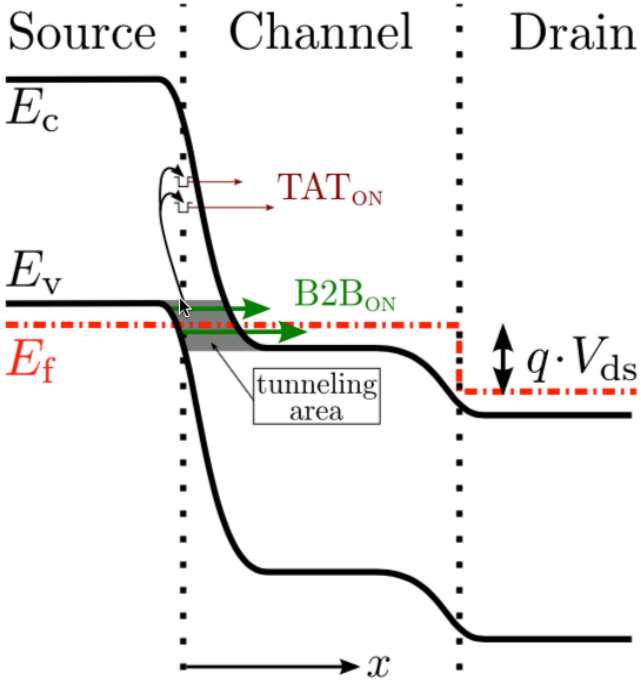
3. Compact Model for TFET

Tunnel-FET:

- Swing < 60 mV/dec possible
- Band-to-band tunneling at source junction



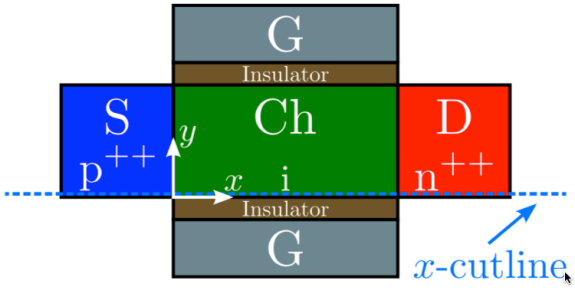


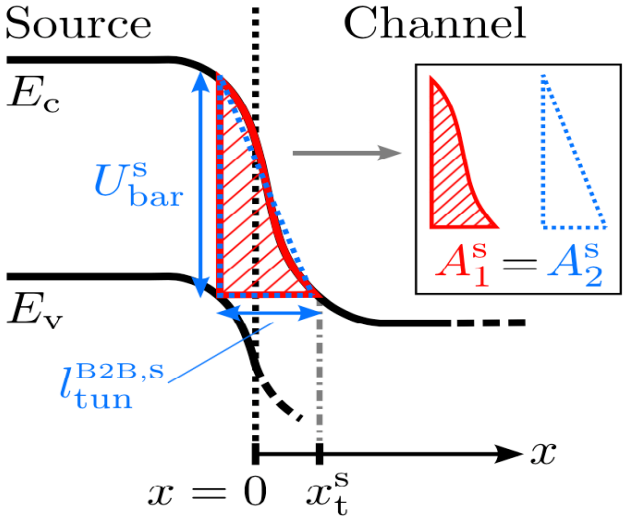


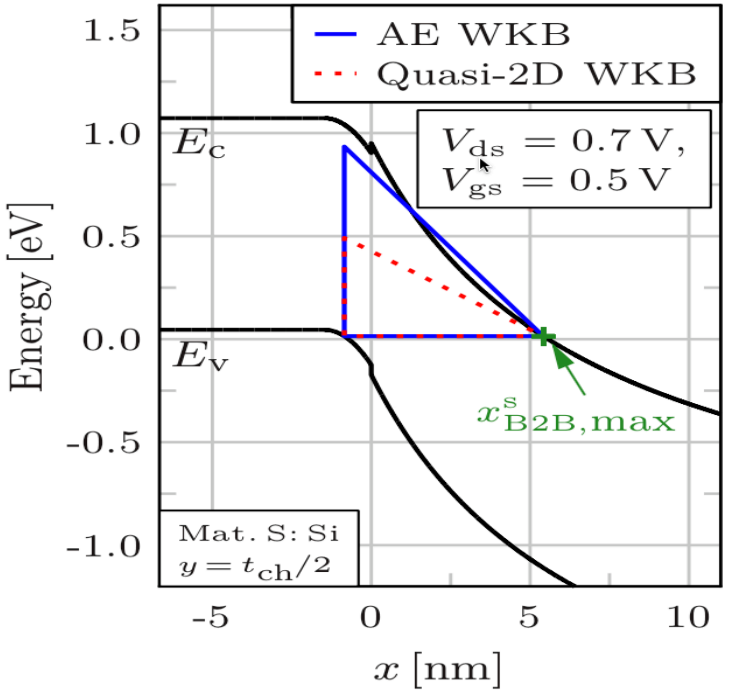
3. Compact Model for TFET

Area-equivalent WKB approximation:

- Improved representation of barrier
- Not relying on electric field in single point



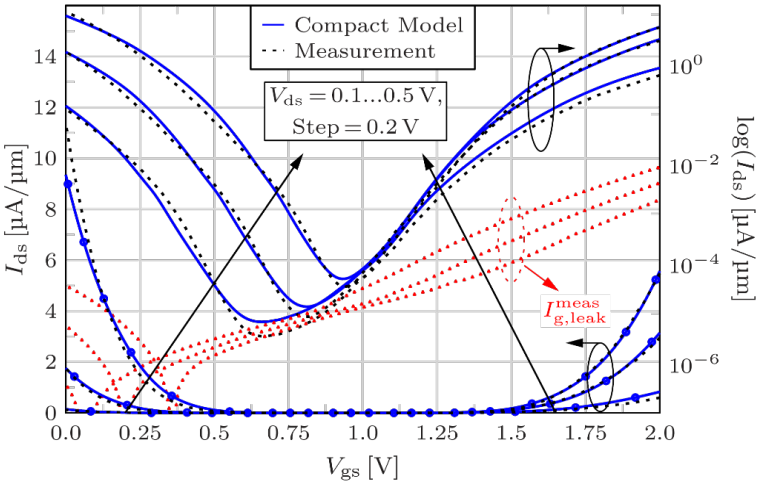


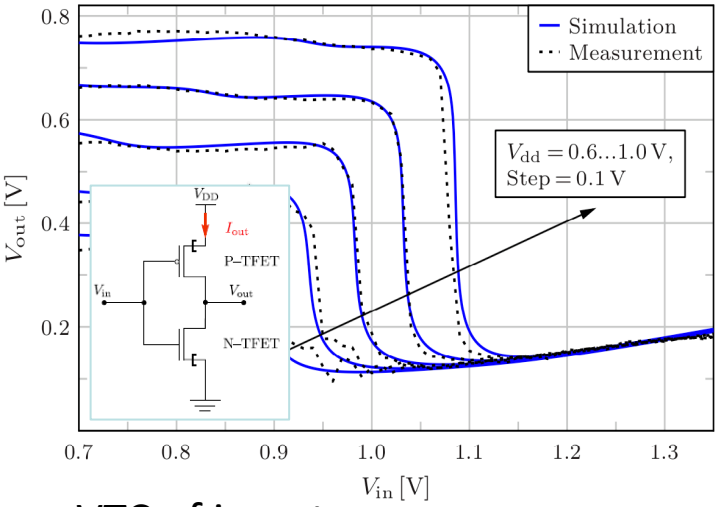


3. Compact Model for TFET

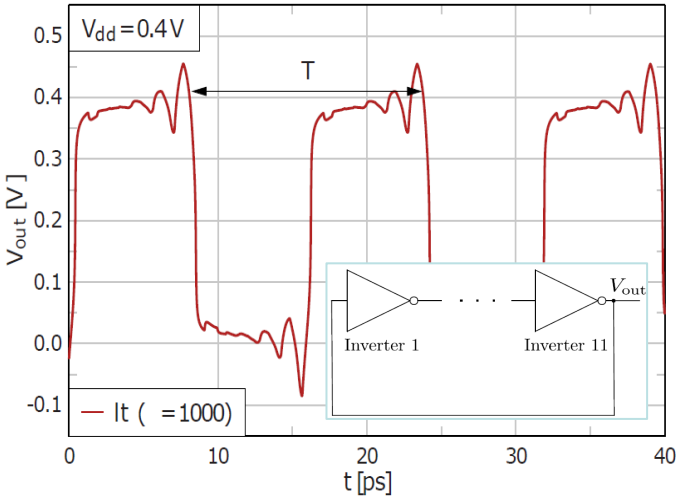
DC/AC compact model in VerilogA:

- Verified by TCAD and meas. (FZ Juelich)
- Soon available on nanohub.org





VTC of inverter



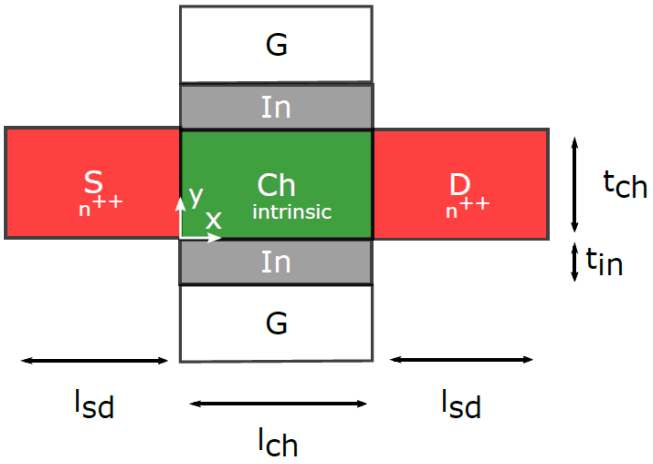
Simulation of ring oscillator

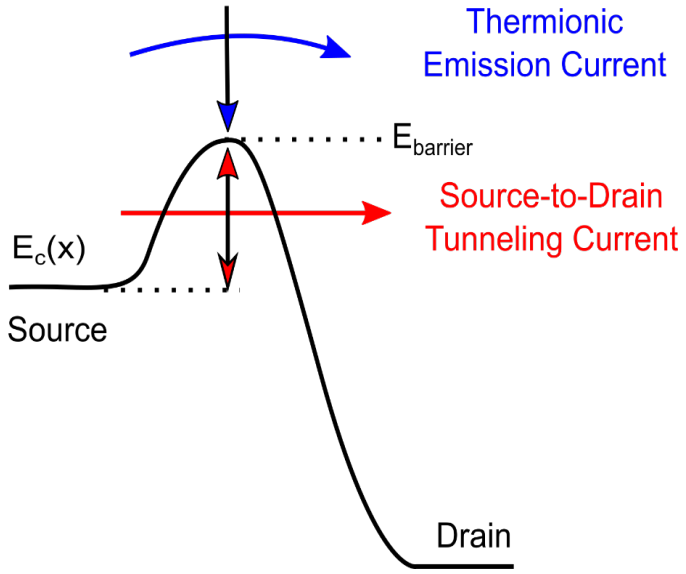
[4] A. Farokhnejad, F. Horst, B. Iñíguez, F. Lime, and A. Kloes, “Evaluation of Static/Transient Performance of TFET Inverter Regarding Device Parameters Using a Compact Model,” Proc. ESSDERC, pp. 202-205, 2019

3. Ultra-SC MOSFET: WKB vs. Wavelet

Ultra-short channel MOSFET:

- Calculation of S/D tunneling
- For verification, potential extracted from TCAD





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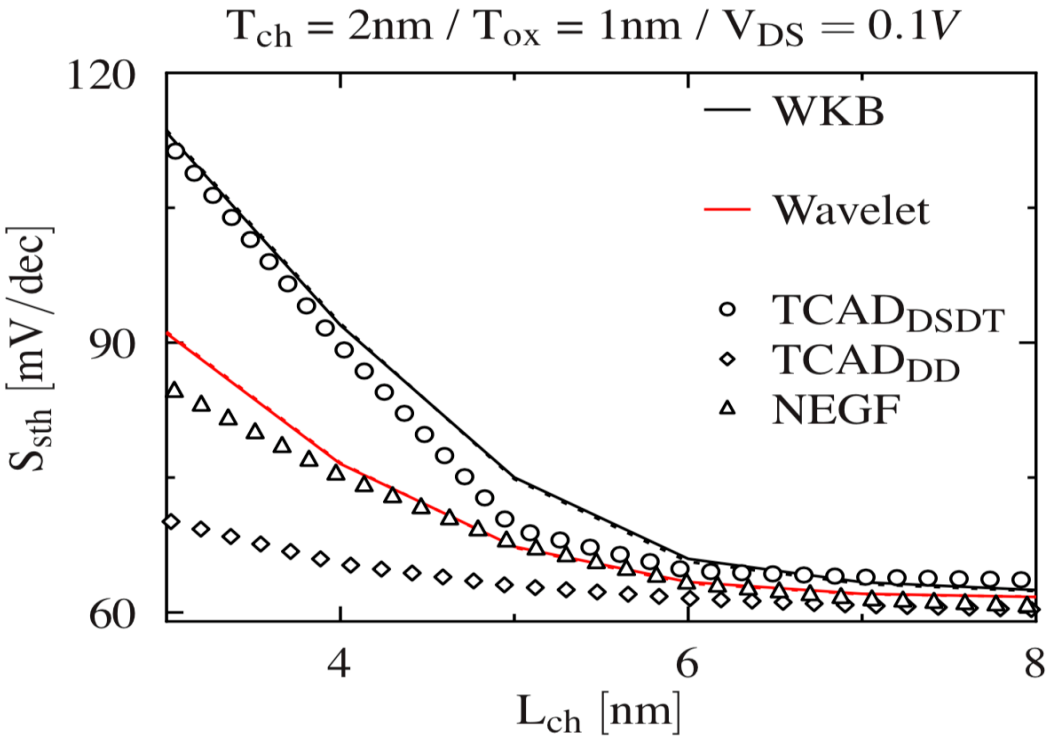

- WKB approximation overestimates tunneling current
- Wavelet approach in good agreement to NEGF

[5] K. Yilmaz, A. Farokhnejad, F. Criado, B. Iñíguez, F. Lime, and A. Kloes, "Direct Source-to-Drain Tunneling Current in Ultra-Short Channel DG MOSFETs by Wavelet Transform," LAEDC, Escazu, Costa Rica, 2020

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- Tunneling currents are getting more important in new devices
- Compact modeling must provide numerically efficient solutions

- **WKB:**
  - analytical solution for single energy level (triangular approximation)
  - Kane's model: effective DOS (instead of integration *dE*)
  - can be improved by „area equivalent" WKB
  - fails if steep barrier profile

- **Wavelet approach:**
  - promising (better than WKB even for steep profile)
  - numerically more expensive: FFT of barrier for each energy level (-> analytical approximations?)

Acknowledgements

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