Auger effect limited performance in tunnel field effect transistors

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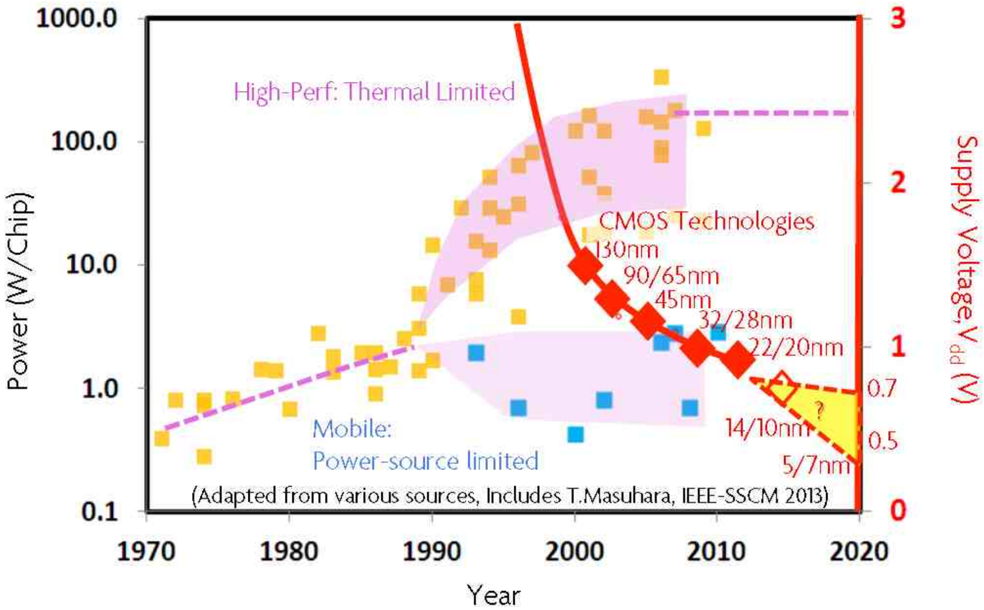
The Challenge of semiconductor industry

Power Crisis



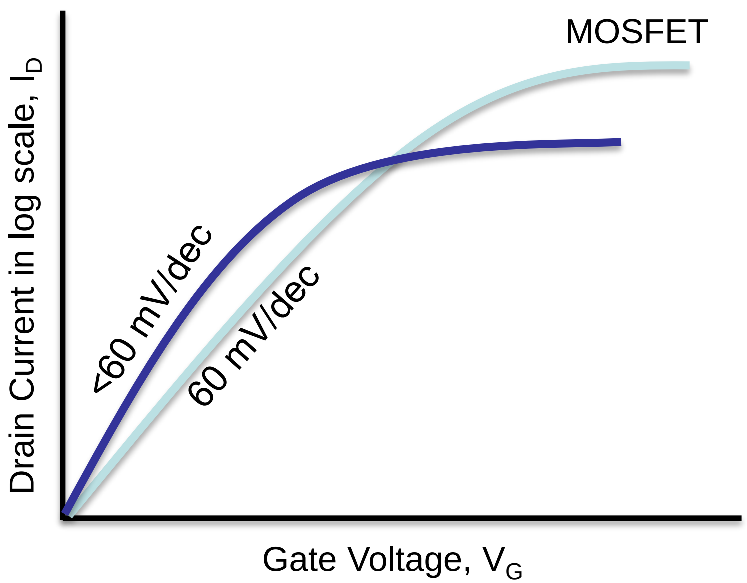
Scaling of V_{DD}

Low power transistors → low subthreshold swing

Lower Subthreshold Swing

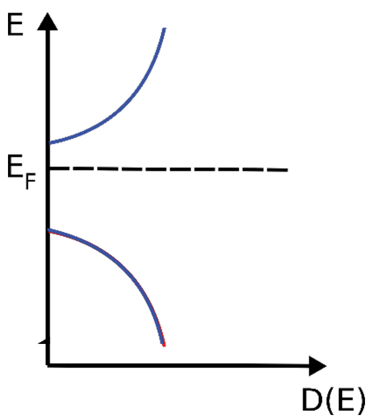
Applications:

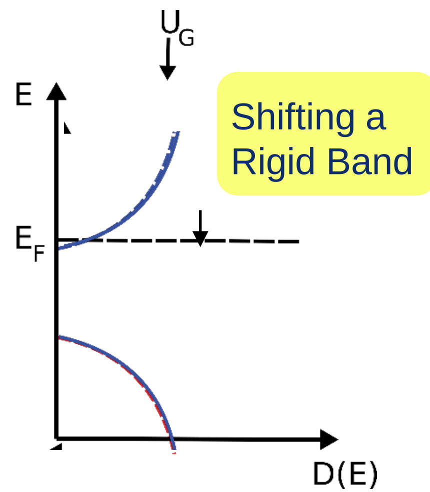
- Analog to Digital converters
- Neuromorphic Computing



How to achieve low Subthreshold Swing? Transmission Engineering

MOSFETs:





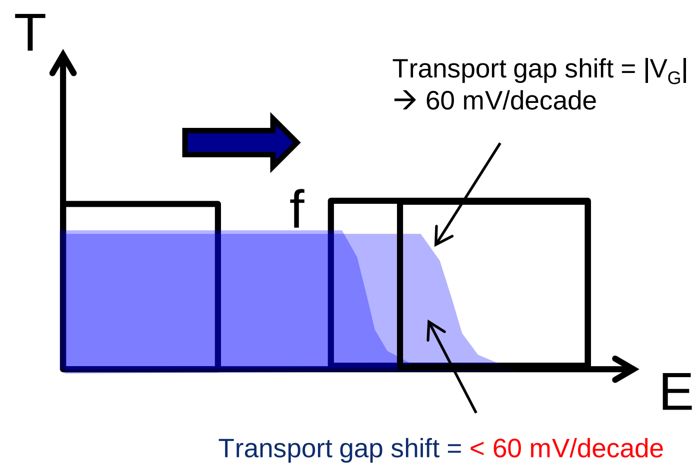
$$I = I_0 \int_{-\infty}^{+\infty} T\ (f_1 - f_2) dE$$

Landauer

$$S^{-1} = (q\alpha_G/k_BT + \overline{d\ln T/dV_G})/\ln 10$$

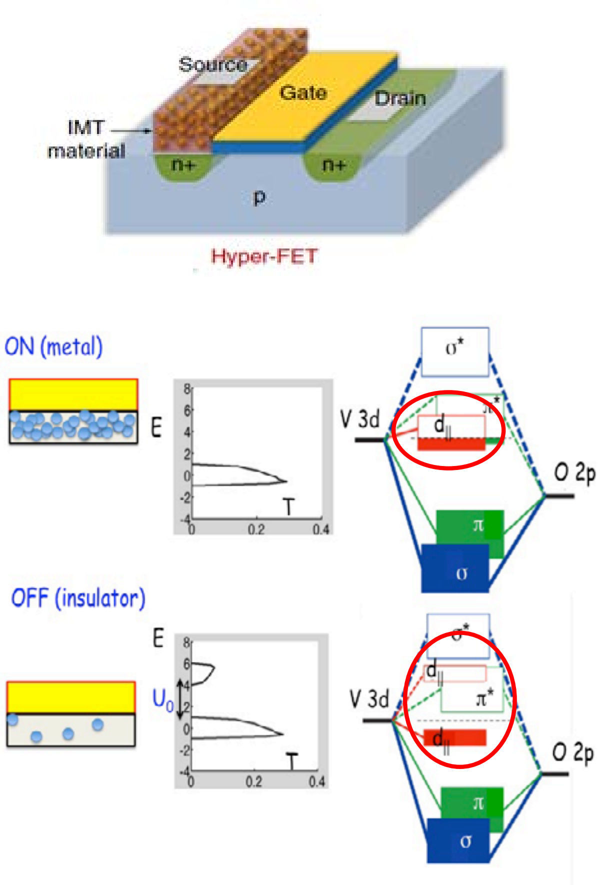
Electrostatic origin (60 mV/dec)

Quantum Origin



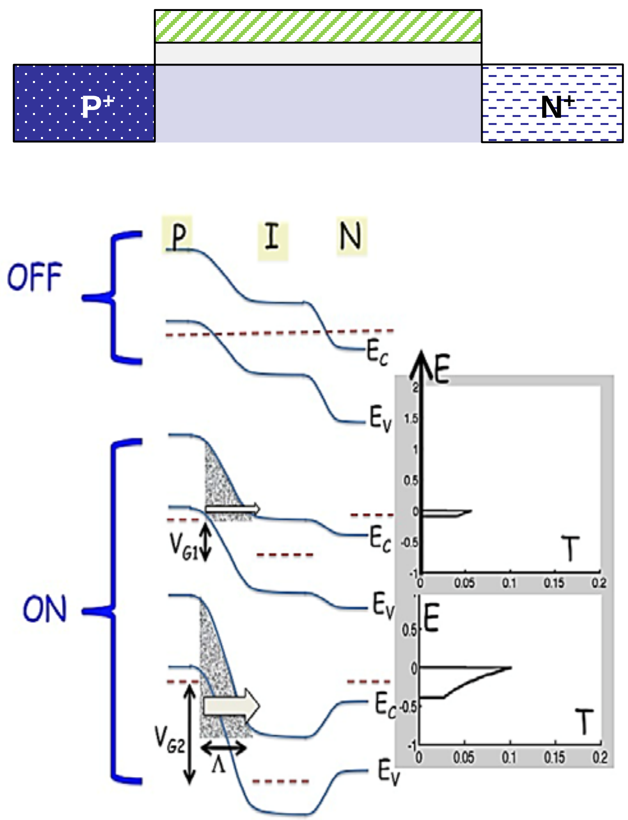
Examples: Transmission Engineering

MOTT FET



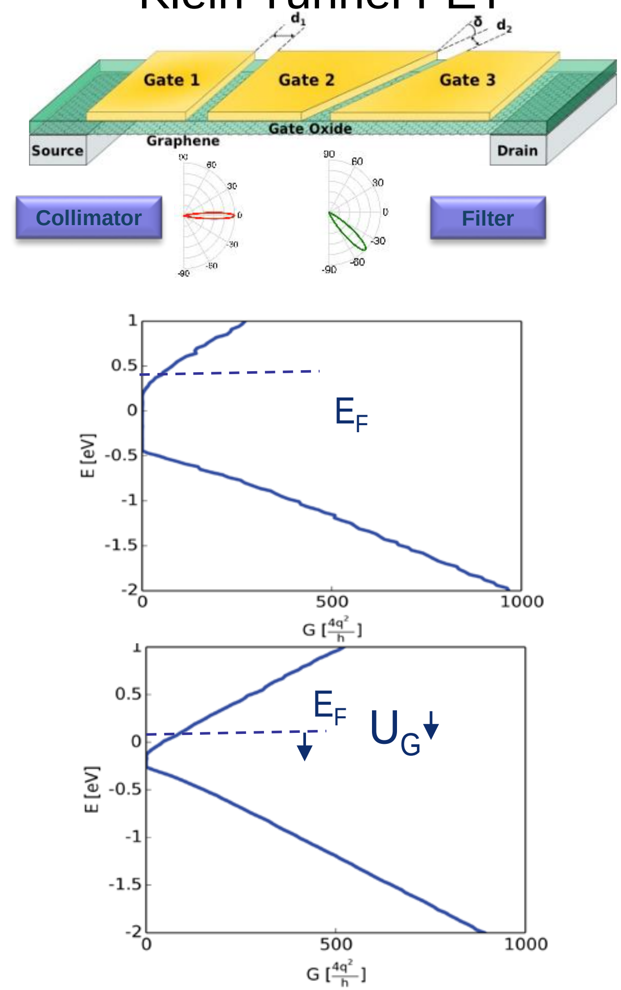
Band Modulation

Tunnel FET



Channel Modulation

Klein Tunnel FET



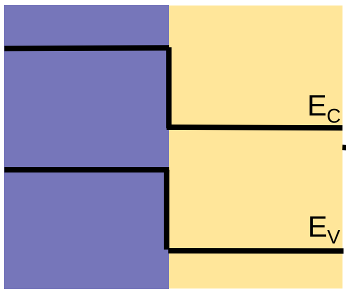
Transport Modulation

Shukla et al., *Nature Communications,* 2015.
Ghosh, *IEEE Journal of the Electron Devices Society*, 2015.

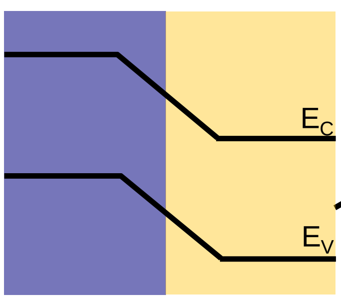
Ghosh, *IEEE Journal of the Electron Devices Society*, 2015.
Ghosh, *Nanoelectronics: A molecular view*, 2016.

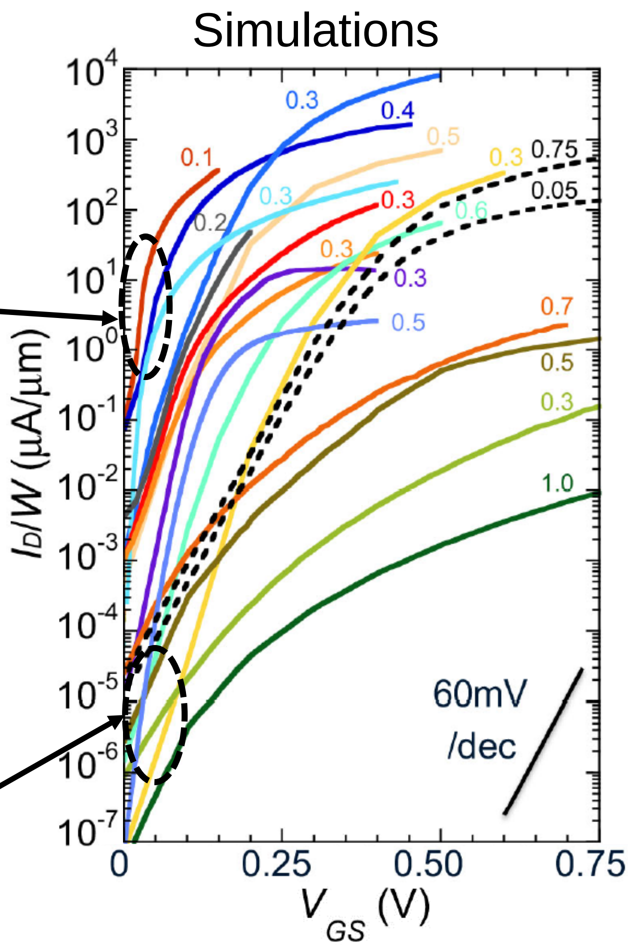
Sajjad, Ghosh, ACS Nano, 2013

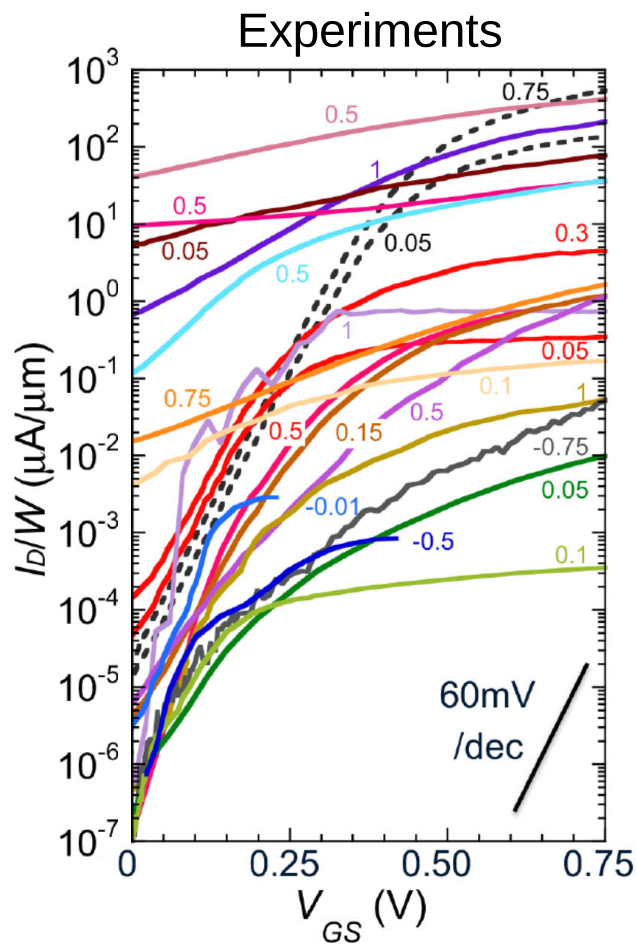
High E-field, smaller width



Low E-field, larger width

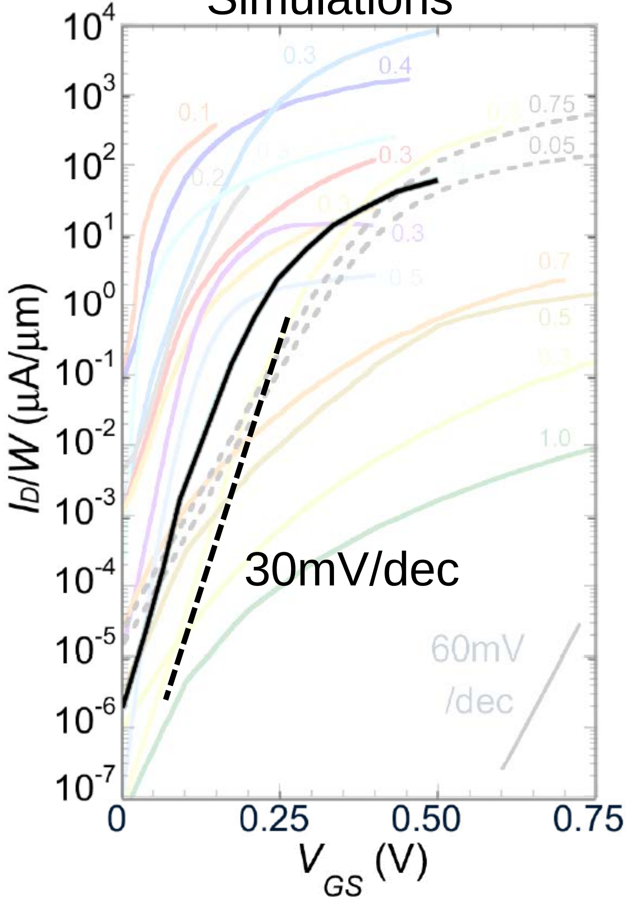




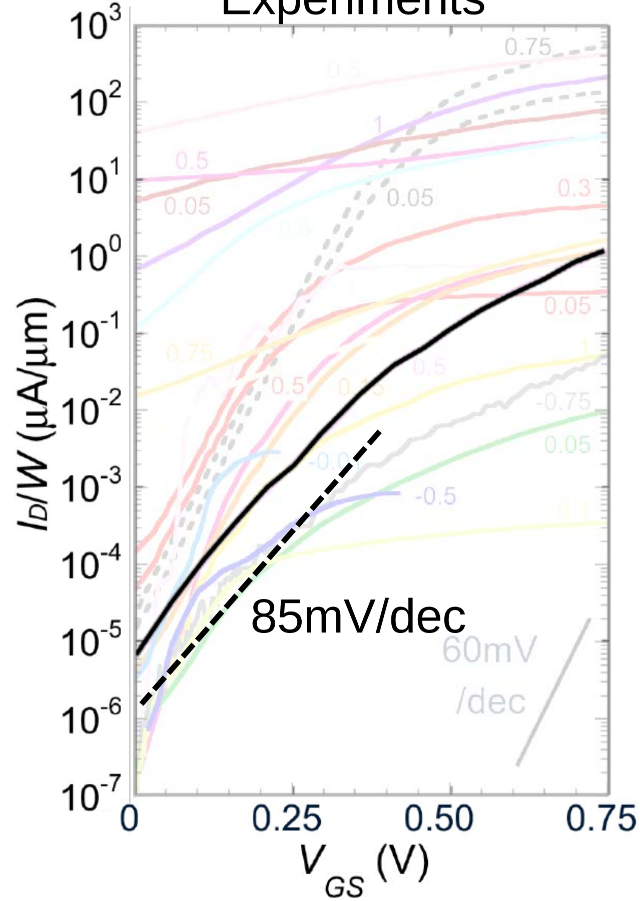


Lu and Seabaugh, *IEEE Journal of the Electron Devices Society*, 2015

Simulations



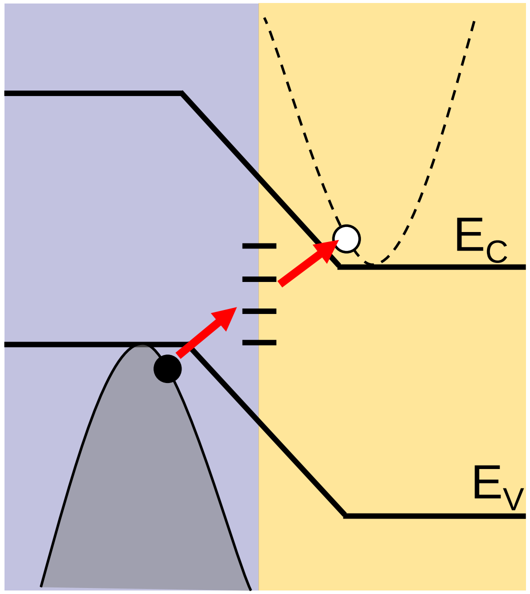
Experiments



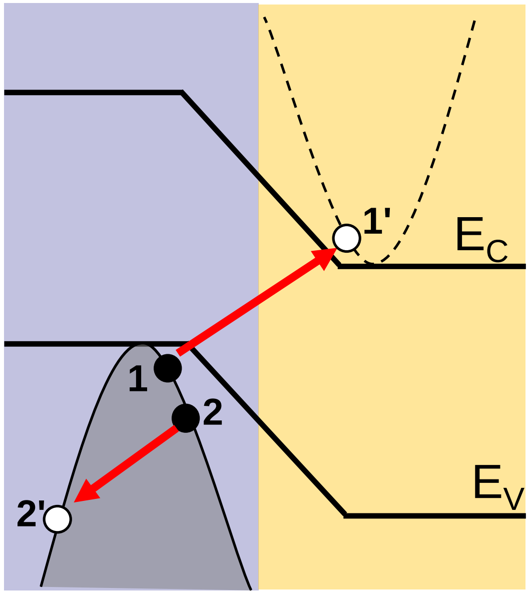
TFET: simulations predict lower SS than experiments.

What are the possible reasons?

What contribute to the off-current in reality?



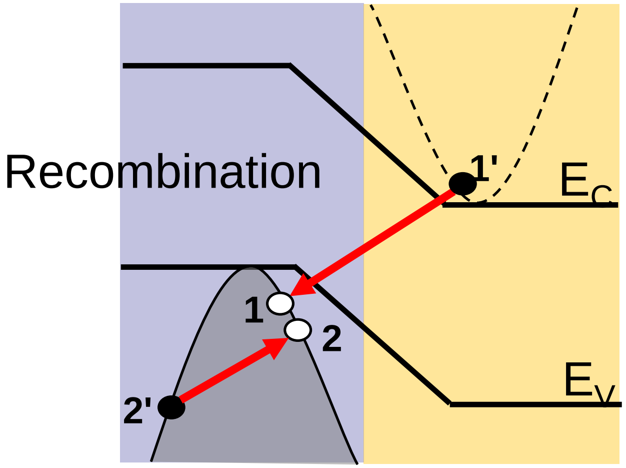
Trap Assisted Tunneling (TAT)

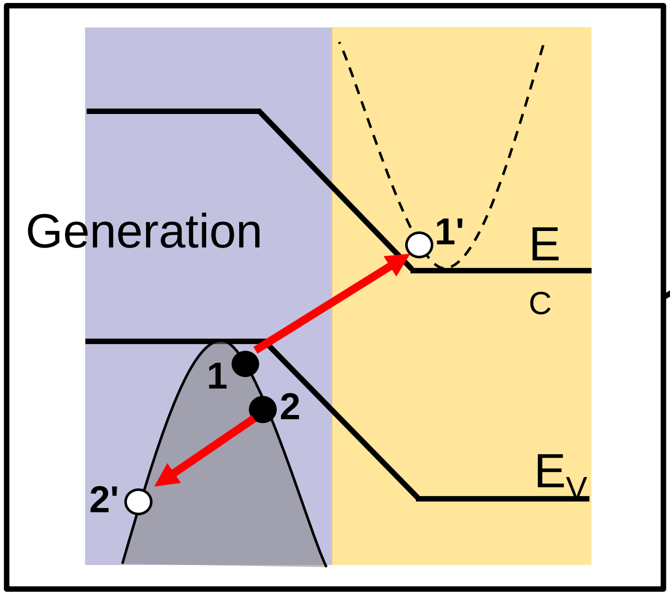


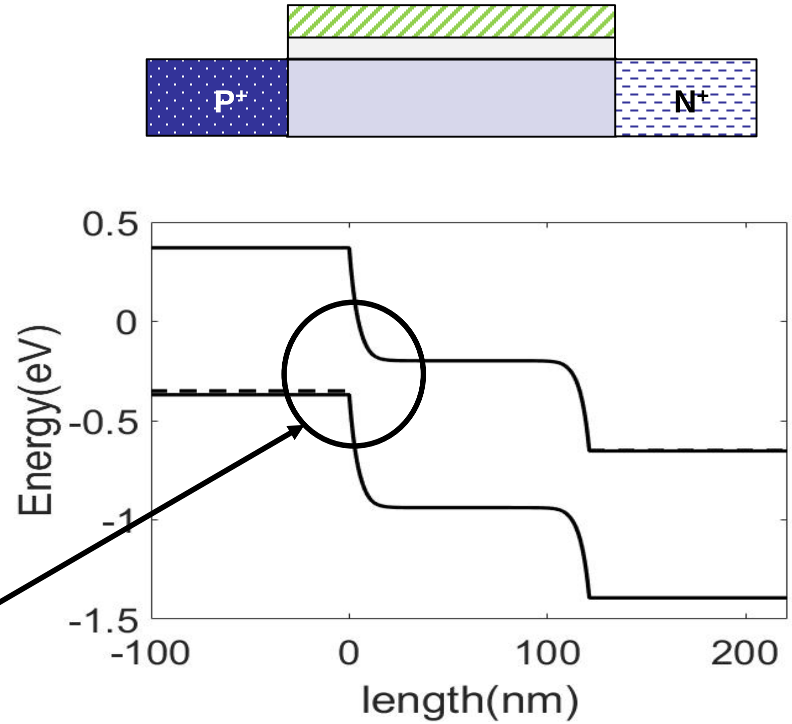
e-e interactions like Auger

Auger effect introduces extra off-current even if traps/defects are eliminated

Why auger is important?







Auger generation is important for low SS TFETs.

$$U_{aug} \propto p\,(np - n_0 p_0)$$

Outline

Material parameters

Compact model of TFET

Auger effect in TFET

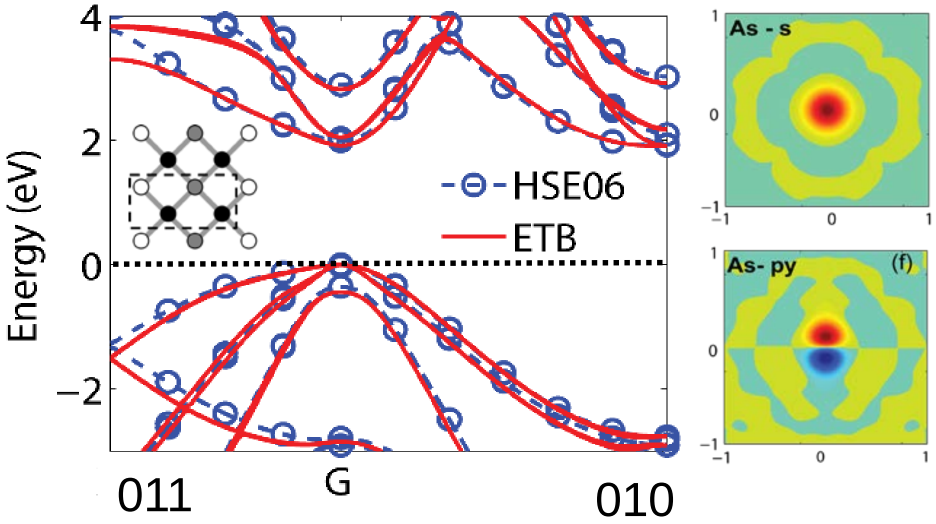
How to get correct material parameters? Modified tight binding

What we need

m*, bandedge	**Compact model of TFT**
Wave function overlaps	**Auger effect in TFET**

ETB model:
- Calibrated with DFT band structures
- Calibrated with **DFT wave functions**
- **Match experiments**

ETB with explicit basis functions



AlInAs	Experiment	ETB
6ML	**1.27 eV**	**1.24 eV**
8ML	**1.16 eV**	**1.17 eV**

Modified tight binding is used to extract material parameters

Alternate: Extended Huckel Theory (Ghosh)

Tan et al., *Physical Review B*, 2016.

Outline

Material parameters

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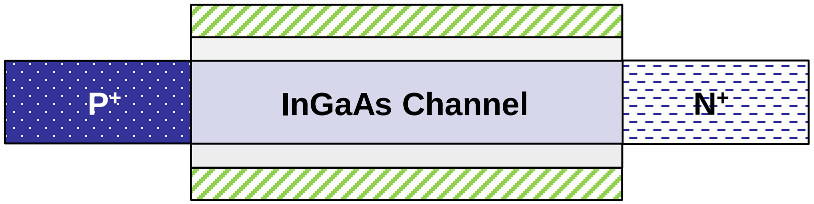
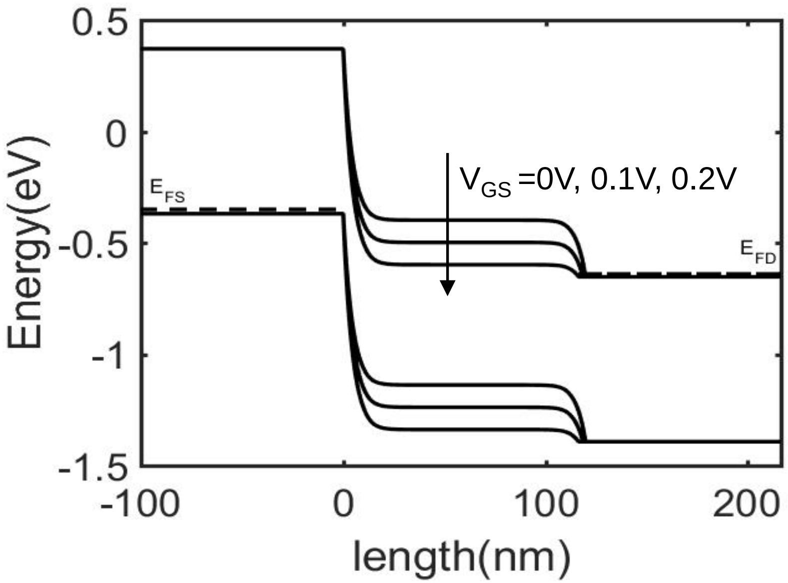
Chemistry Based Analytical Model: Using Simmons Equation





- ➢ Potential Model
  - ❑ Solving Laplace Equation
- ➢ Two band model:
  - ❑ Band-to-band tunneling

$$H(\mathbf{k}) = \begin{bmatrix} E_c(\mathbf{k}_{||}) & Ak_z \\ Ak_z & E_v(\mathbf{k}_{||}) \end{bmatrix} \quad \frac{A^2}{E_c - E_v} = \frac{\hbar^2}{2m^*}$$

- ➢ Current:
  - ❑ WKB+k-space integration

$$I = \int dE dk_{||} T_{WKB}\left(E, k_{||}\right)\left[f_S(E) - f_D(E)\right]$$

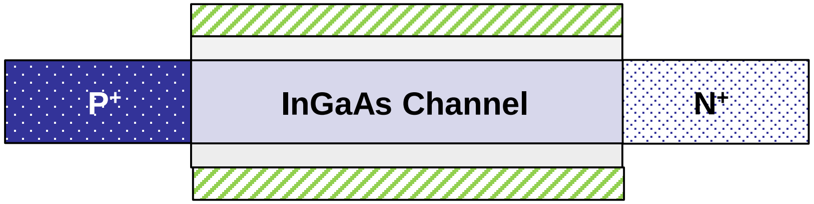
Ballistic model for TFETs: Modified Simmons Equation using two band model

Bardon et al., *IEEE Transactions on electron Devices,* 2010.
Simmons, *Phys. Rev. Letters, 1953*.

Calibration: Homojunction and Heterojunction

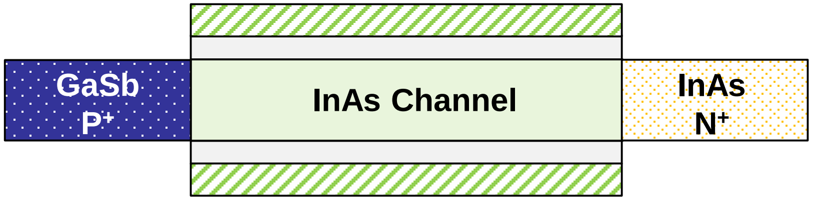
Homojunction

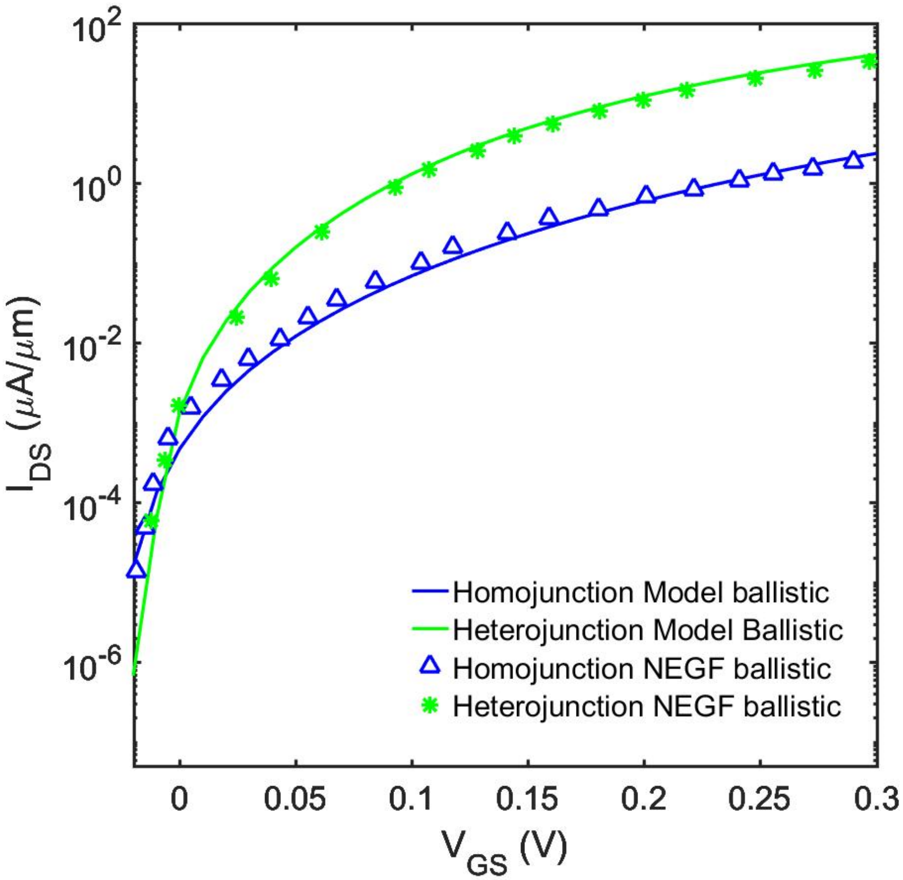
$L_{channel}$ = 100nm



Type II Heterojunction

$L_{channel}$ = 30nm



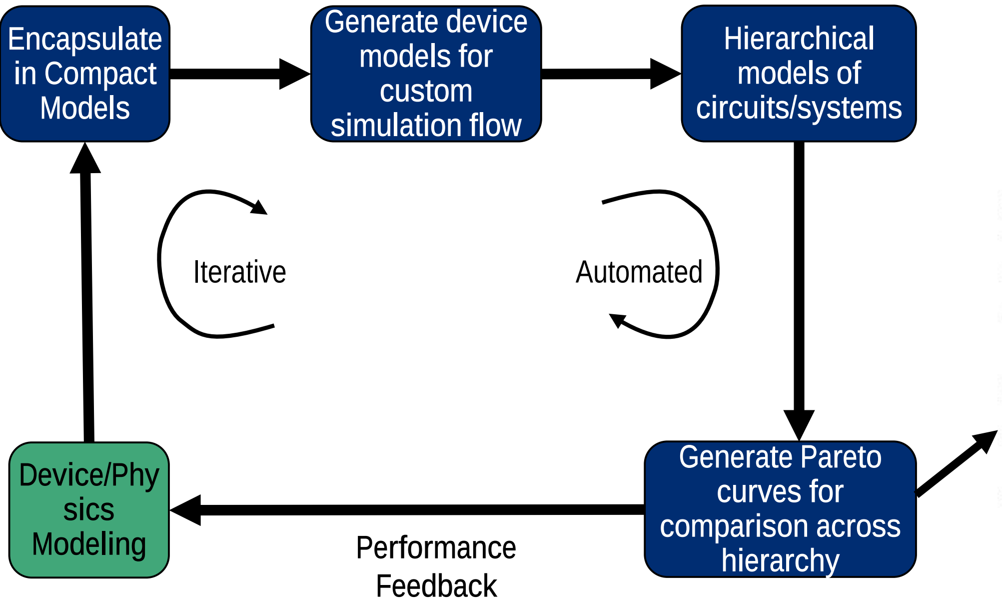


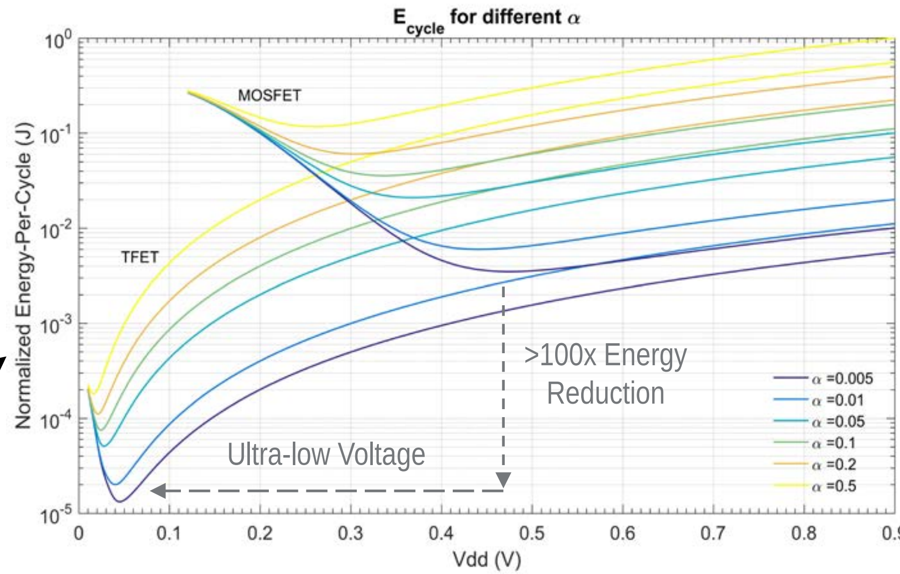
Compact model match NEGF calculations (single Hetero TFET)

Avci, *VLSIT*, 2012.
Long, *IEEE Electron Device Letters*, 2016.

Compact model based circuit simulation

Rapid Circuit Simulation Flow for TFET Models





Circuit design/analysis based on compact model

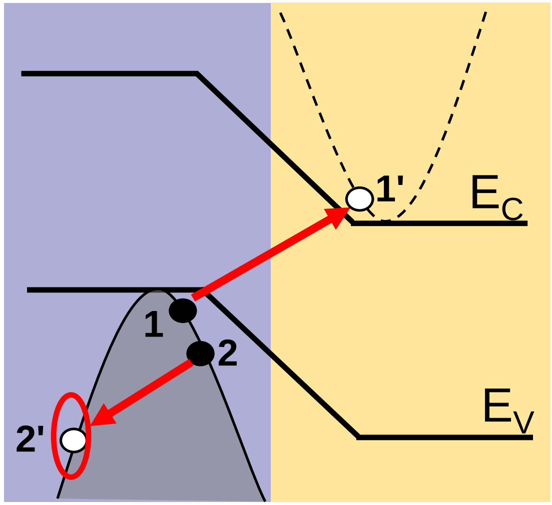
Collaborators: Daniel Truesdell, Ben Calhoun (UVA)

Huang et al, *IEEE Transactions on Electron Devices*, 2016

Outline

- **Material parameters**
- **Compact model of TFET**
- **Auger effect in TFET**

Physics of Auger process: basics



Auger generation

- Dominates in the OFF state;
- Energy and momentum conserved;
- Depends on hole density p and wave function overlaps $|\langle\psi_1|\psi_{1'}\rangle|^2$

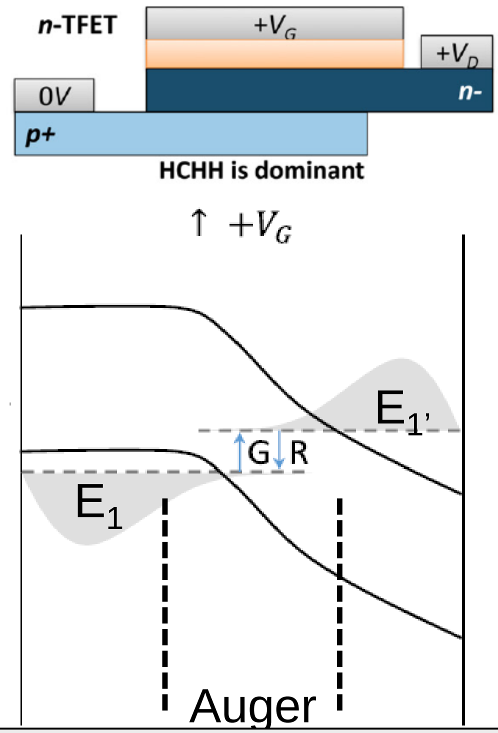
$$U \approx \frac{2\pi}{\hbar} \sum_{1,1',2,2'} P(1,1',2,2') |M|^2 \delta(E_1 - E_{1'} + E_2 - E_{2'})$$

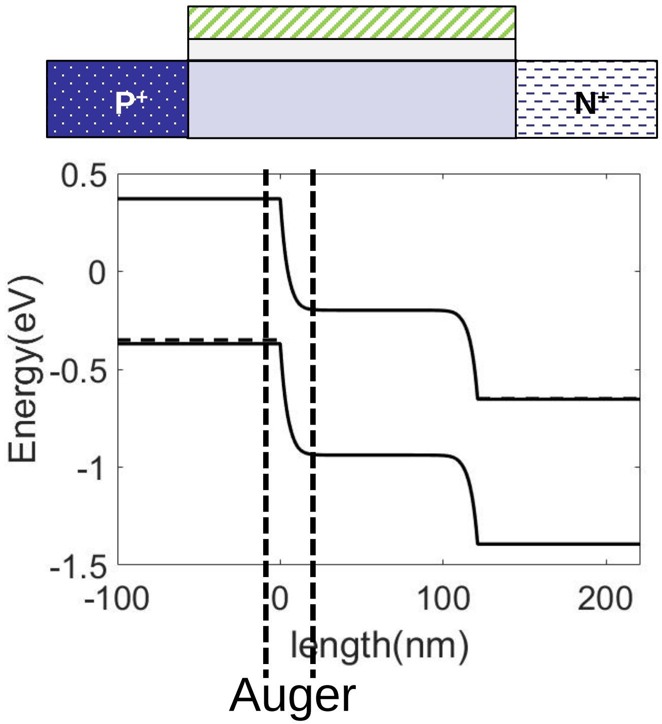
$$(1 - f_c(E_{1'}))D_c(E_{1'})\, D_v(E_1)\, D_v(E_2)\, p(E_{2'})$$

$$|\langle\psi_1|\psi_{1'}\rangle|^2$$

- **Auger generation generate extra off current;**
- **Depends on the hole density and overlaps of CB and VB**

Physics of Auger process: Auger in different device structures





Auger in 2D:

- In a 2D plane
- **Discrete** E_1 and $E_{1'}$ in quantum wells

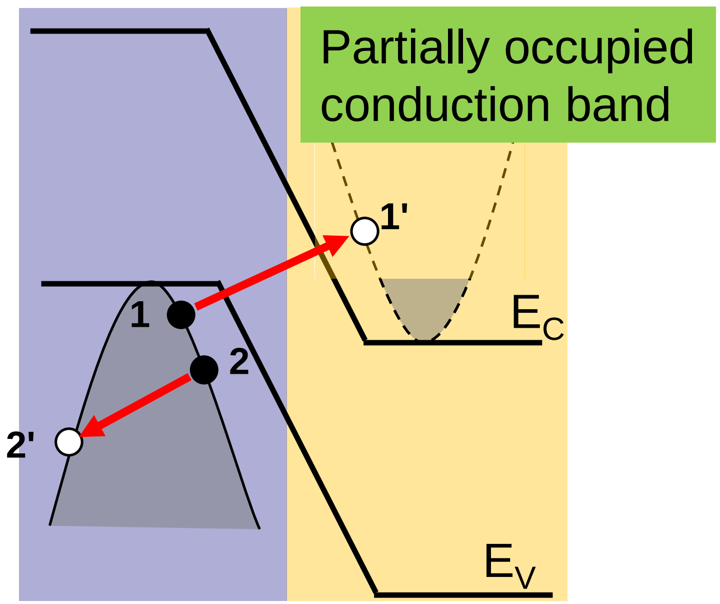
Auger in Quasi 3D:

- In a 2D plane
- **Continuous** E_1 and $E_{1'}$

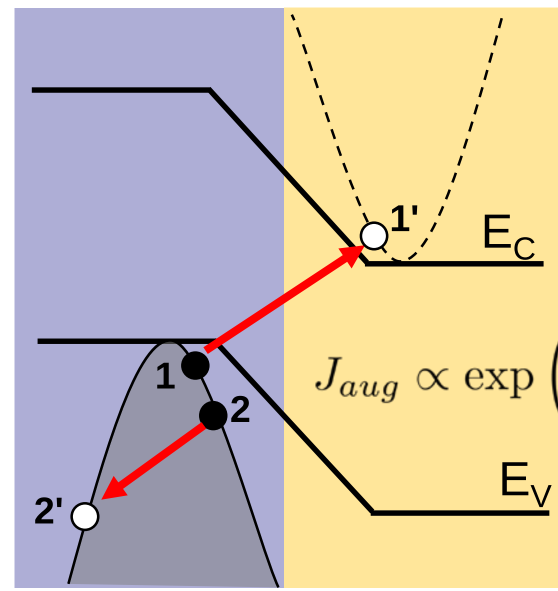
Auger process in 2D and quasi 3D: Slightly different density of states

Teherani, *Journal of Applied Physics*, 2016.

Auger generation in the ON-state



Auger generation in the OFF-state



Empty conduction band

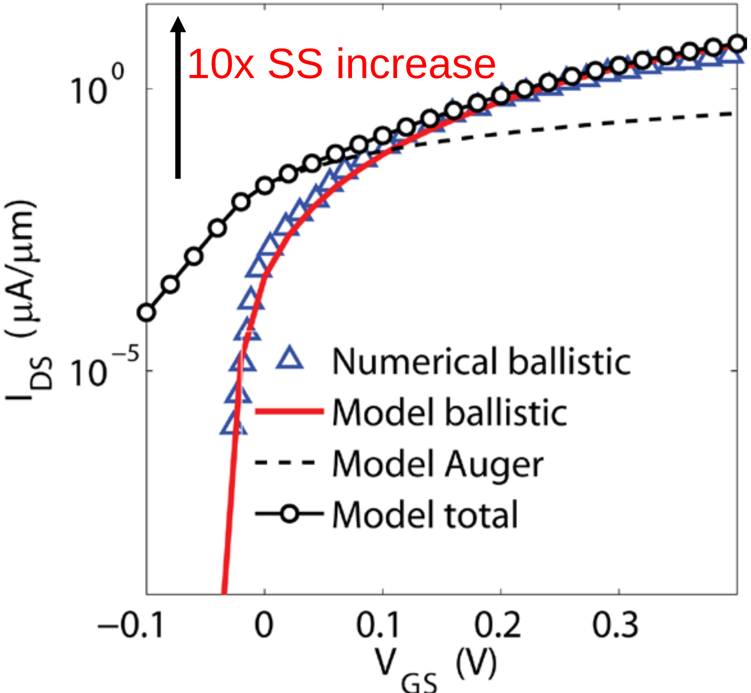
$$J_{aug} \propto \exp\left(-\frac{2\mu^{-1}+1}{\mu^{-1}+1}\frac{\Delta E}{kT}\right)$$

$$\mu = \frac{m_c}{m_v}$$

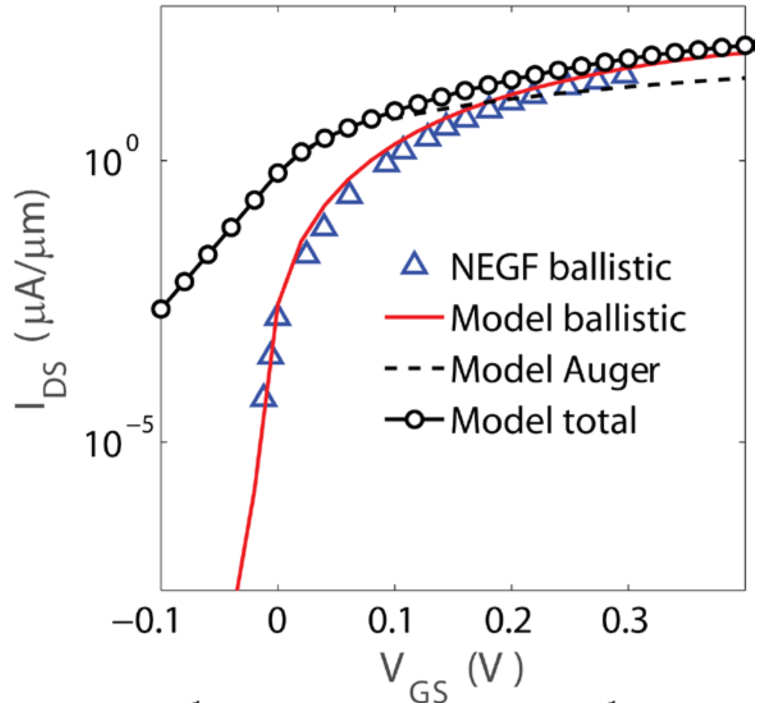
Limits the Subthreshold swing

Occupancy of the conduction bands affect the Auger generation rates.

Homojunction TFETs



Single heterojunction TFETs



$$J_{aug} \propto \exp\left(-\frac{2\mu^{-1}+1}{\mu^{-1}+1}\frac{\Delta E}{kT}\right) \Rightarrow SS = \frac{\mu^{-1}+1}{2\mu^{-1}+1}\frac{kT}{q}\log 10 \approx \frac{\mu^{-1}+1}{2\mu^{-1}+1}60\mathrm{mV/dec}$$

$$\mu = \frac{m_c}{m_v}$$

TAT increases SS by a 2x (Sajjad, 2016)

Auger Effect limit the SS and off-current.

➢ Compact model of TFET

- Compact model developed and benchmarked
- For both homojunction and heterojunction

➢ Auger effect in TFET

- Auger effect is calculated
- Auger effect limit the SS

$$SS \approx \frac{\mu^{-1}+1}{2\mu^{-1}+1} 60\mathrm{mV/dec}$$

➢ TAT + Auger can explain discrepancy between simulation and experiment

Acknowledgement

Daniel Truesdell (University of Virginia)

Professor Benton Calhoun (University of Virginia)

Funded by: Energy-Efficient Computing: from Devices to Architectures(E2CDA)

Thank You