Auger Generation as an Intrinsic Limit to Tunneling Field-Effect Transistor Performance

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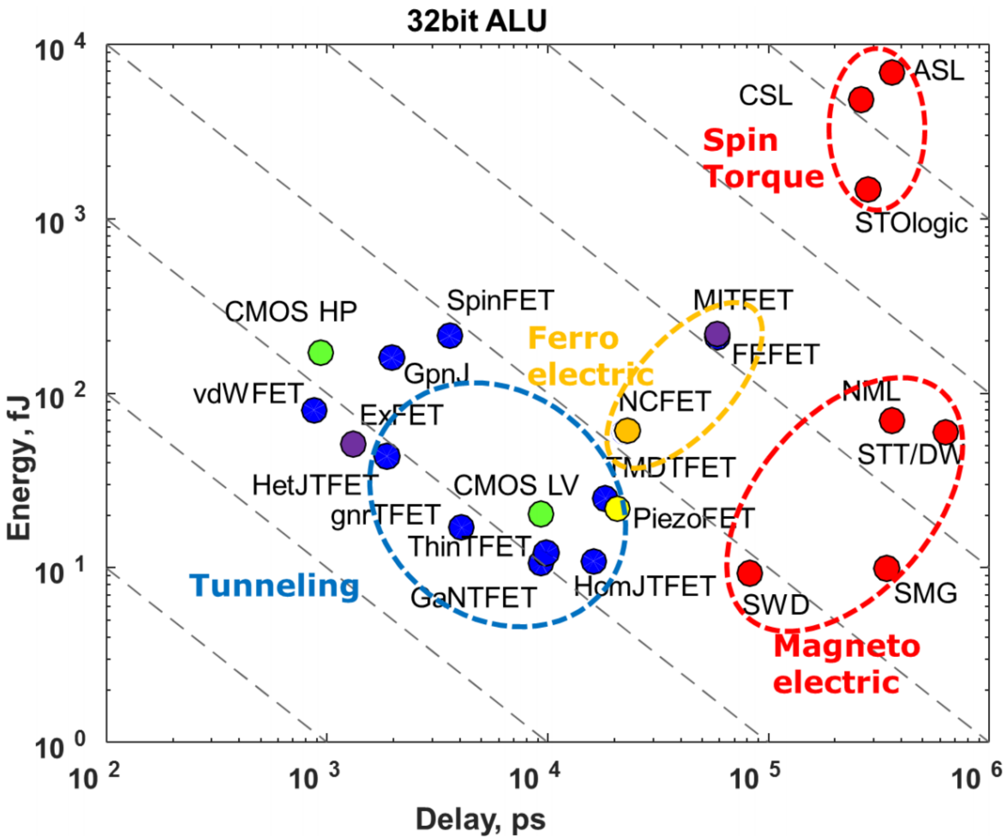
Outline

- Why TFETs?
- Brief Introduction to TFETs
- State-of-the-Field for TFETs
- Auger Generation
- Rate Equation
- Comparison to BTBT
- Commentary

Why TFETs?

- One of the most *promising* beyond-CMOS devicesa



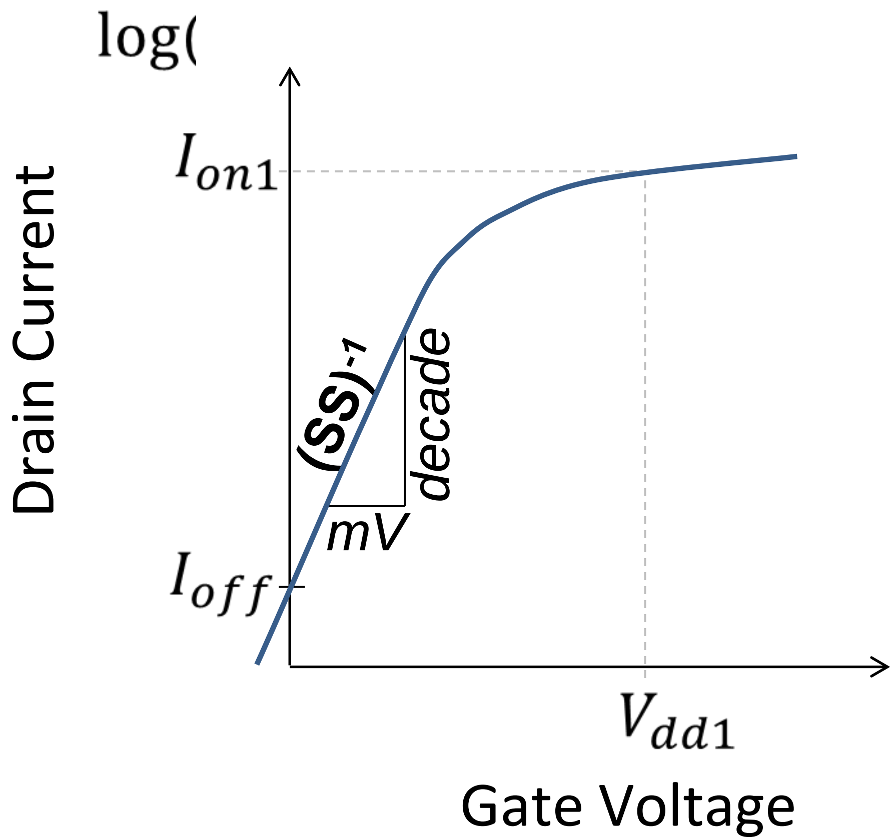
- Key potential advantages
  - looks like a MOSFET
  - drop-in replacement to existing CMOS productions lines
  - small energy-delay product

Nikonov and Young, “Benchmarking of Beyond-CMOS Exploratory Devices for Logic Integrated Circuits,” 2015.

Brief Introduction to TFETs

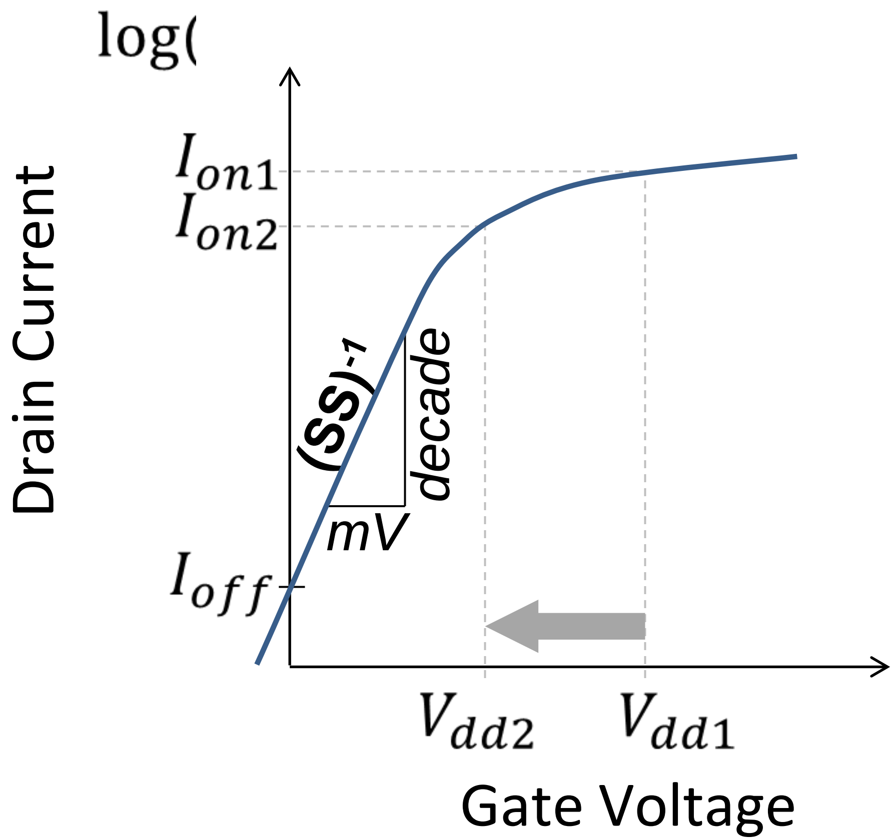
To explain TFETs, let’s begin with MOSFETs

Transfer characteristics for a MOSFET



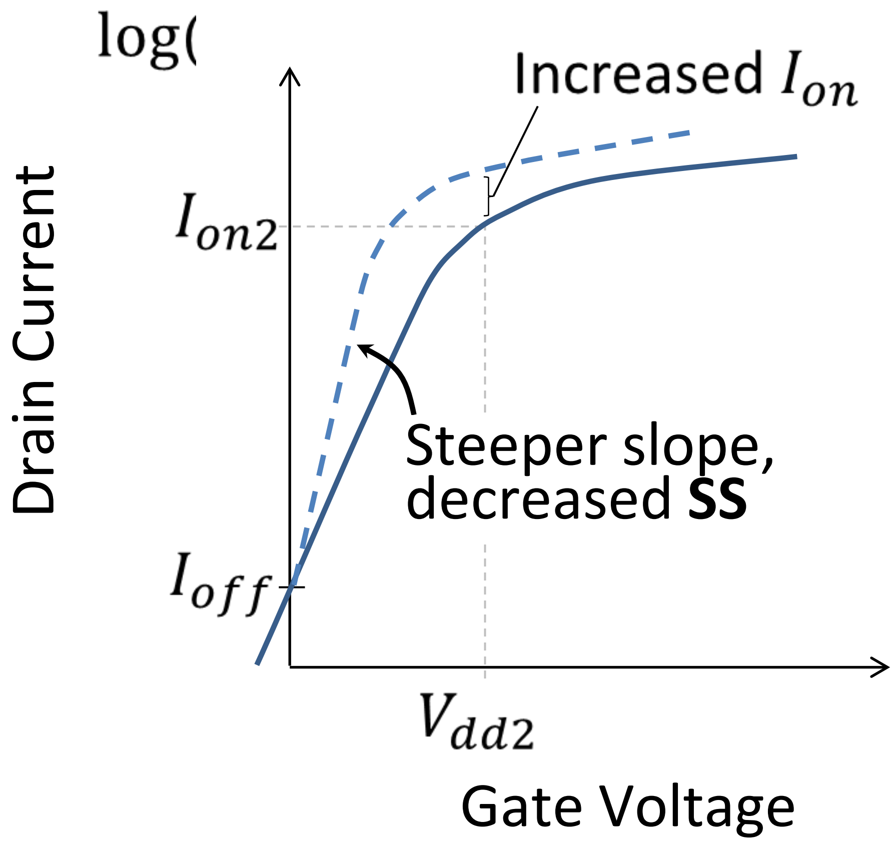
SS—subthreshold swing (mV/decade)

Reducing the voltage reduces the output current and switching speed



SS—subthreshold swing (mV/decade)

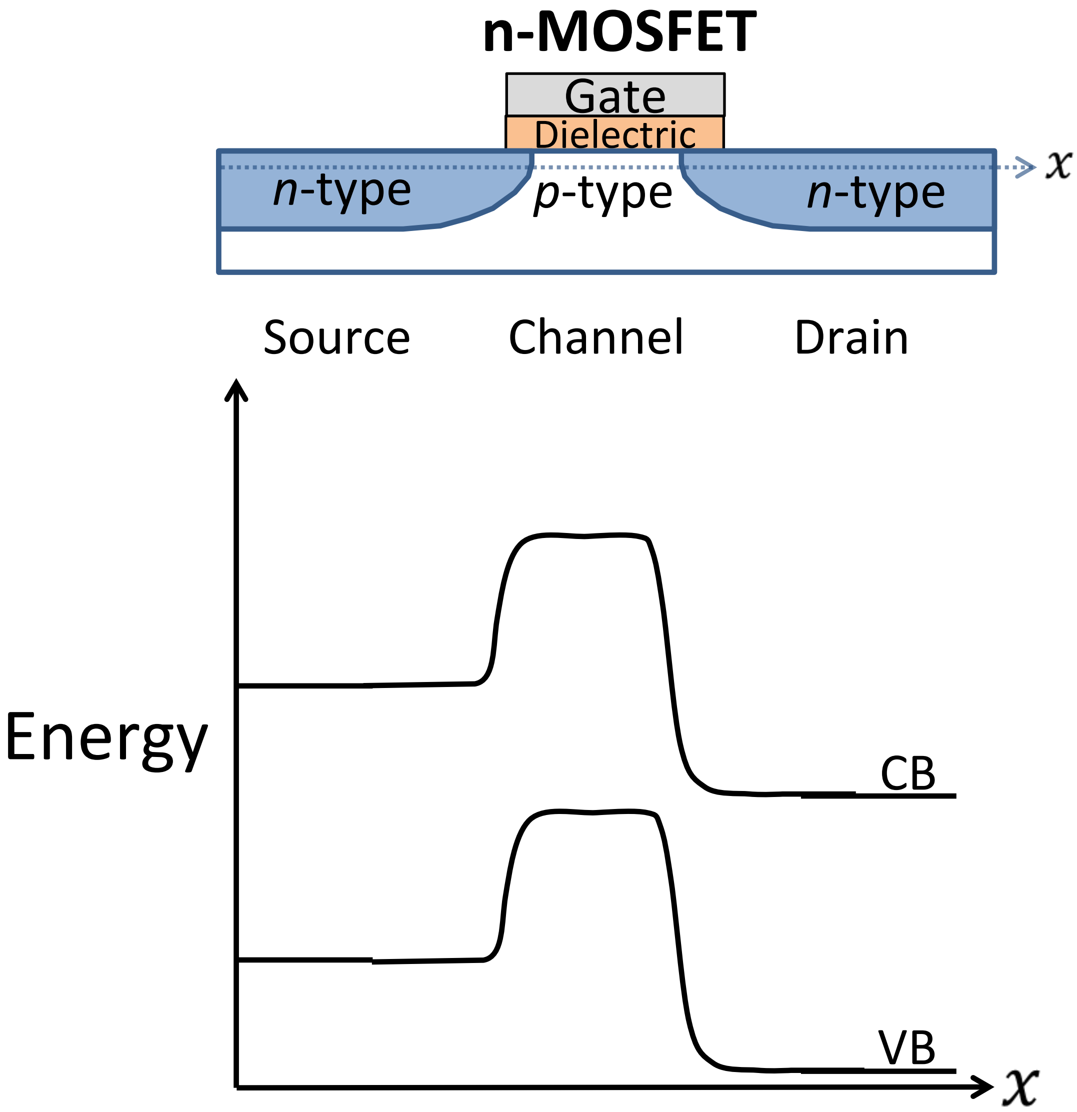
Decreasing the SS gives improved performance at a lower voltage



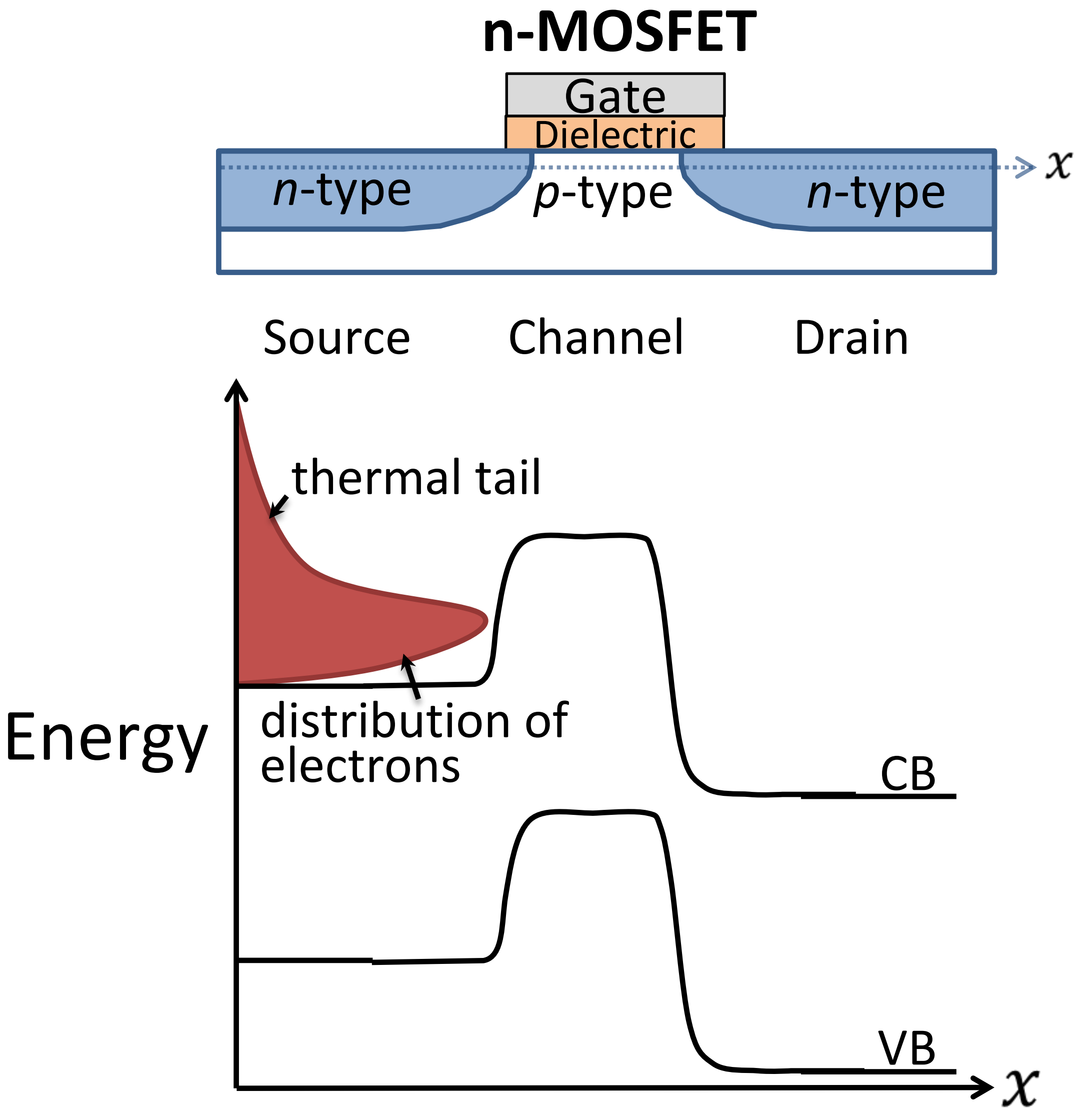
SS—subthreshold swing (mV/decade)

What limits the SS in MOSFETs?

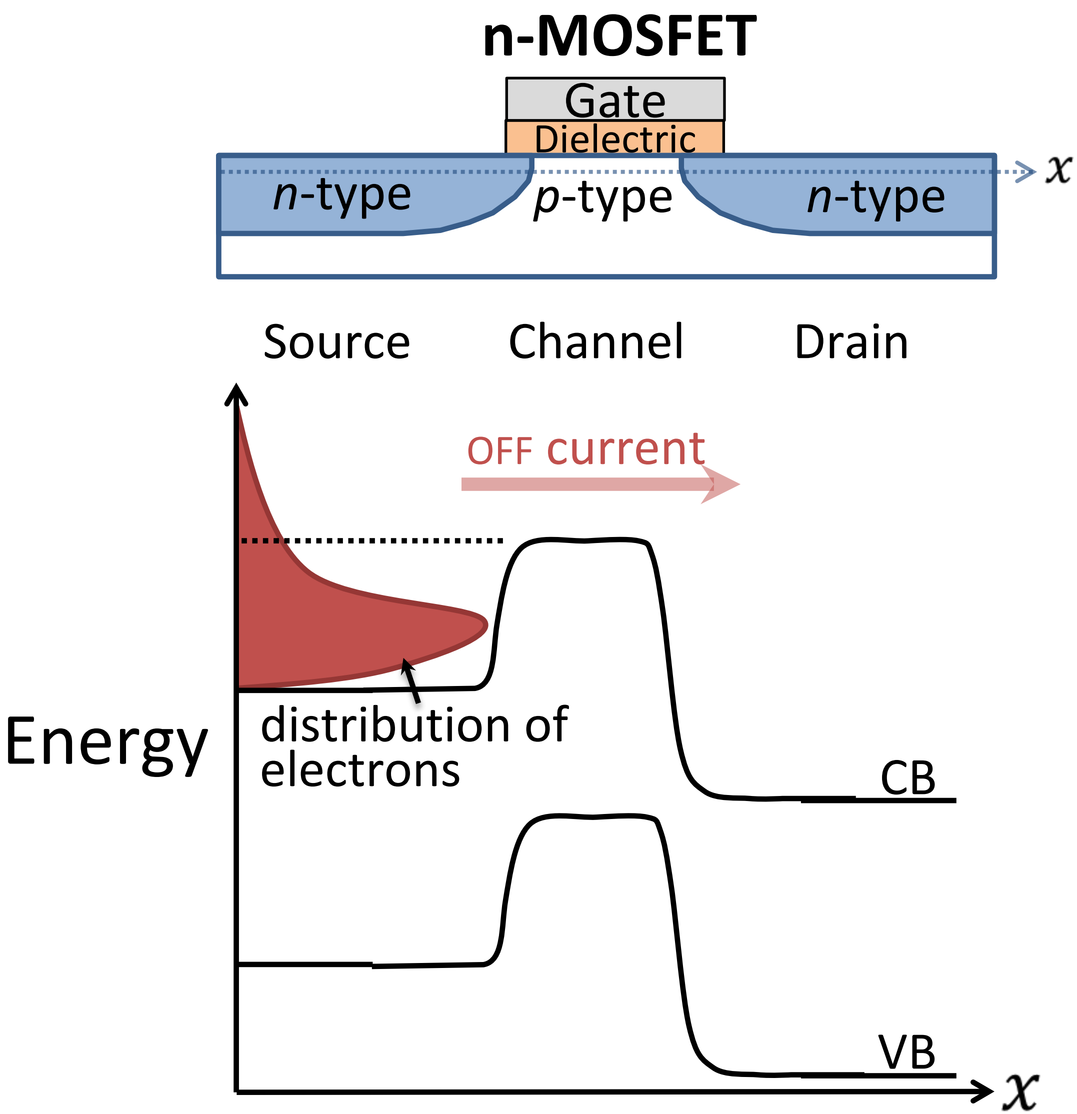
Band diagram for a MOSFET in the OFF-state



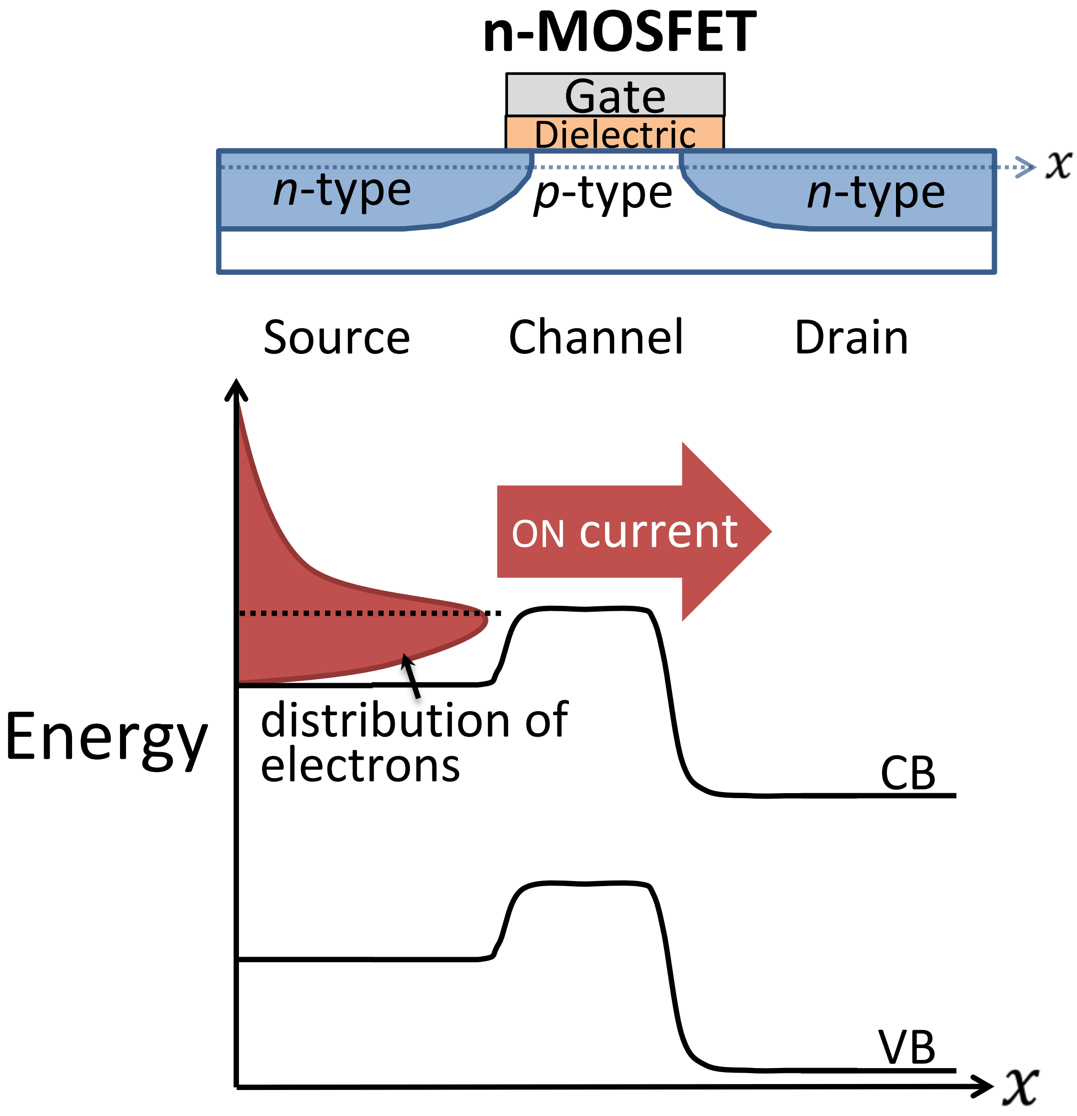
A thermal distribution of electrons exist in the source



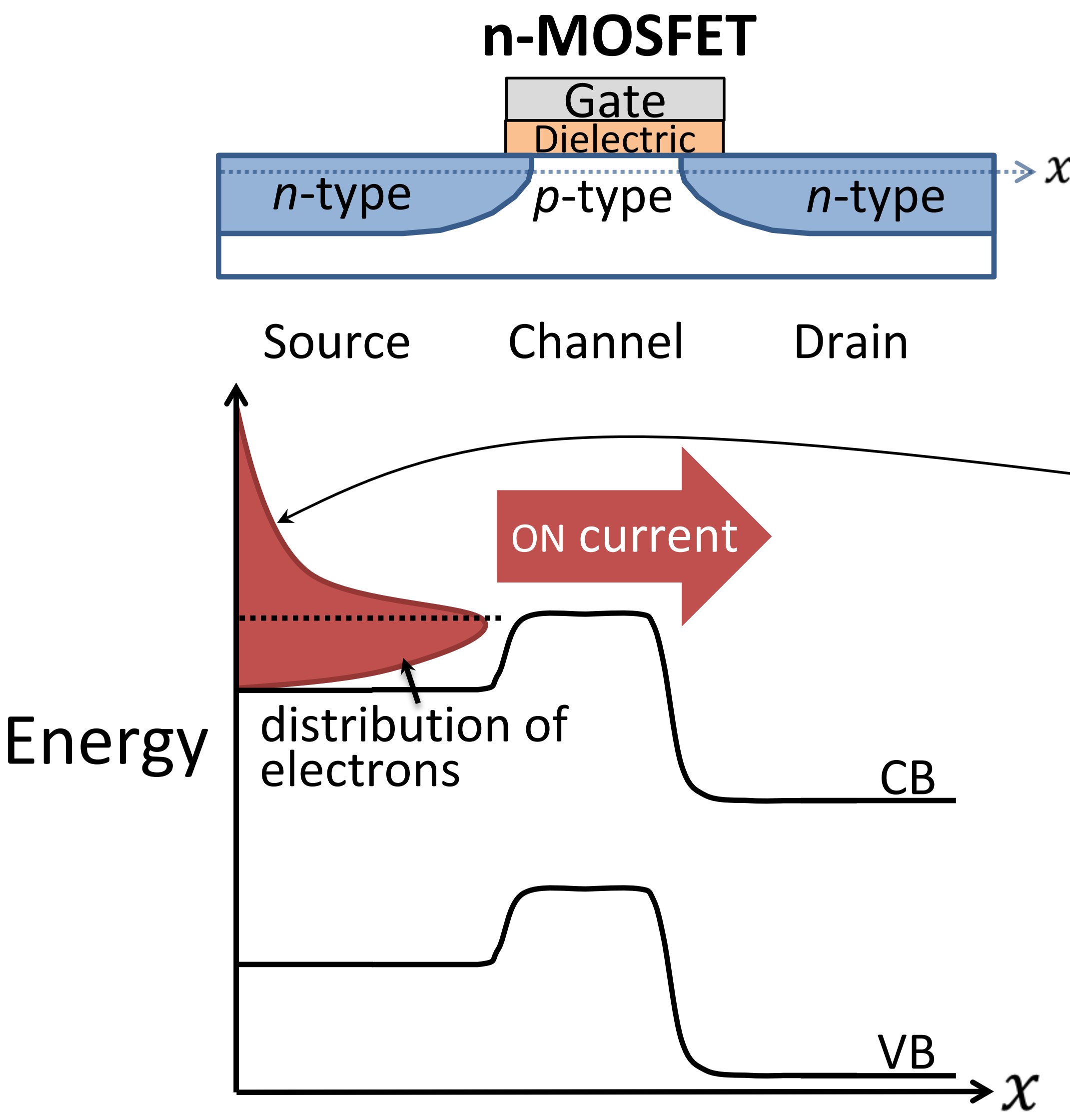
OFF current is limited by a thermal tail of electrons



Gate bias lowers the barrier for electrons and current increases



SS in a MOSFET is limited to 60 mV/decade



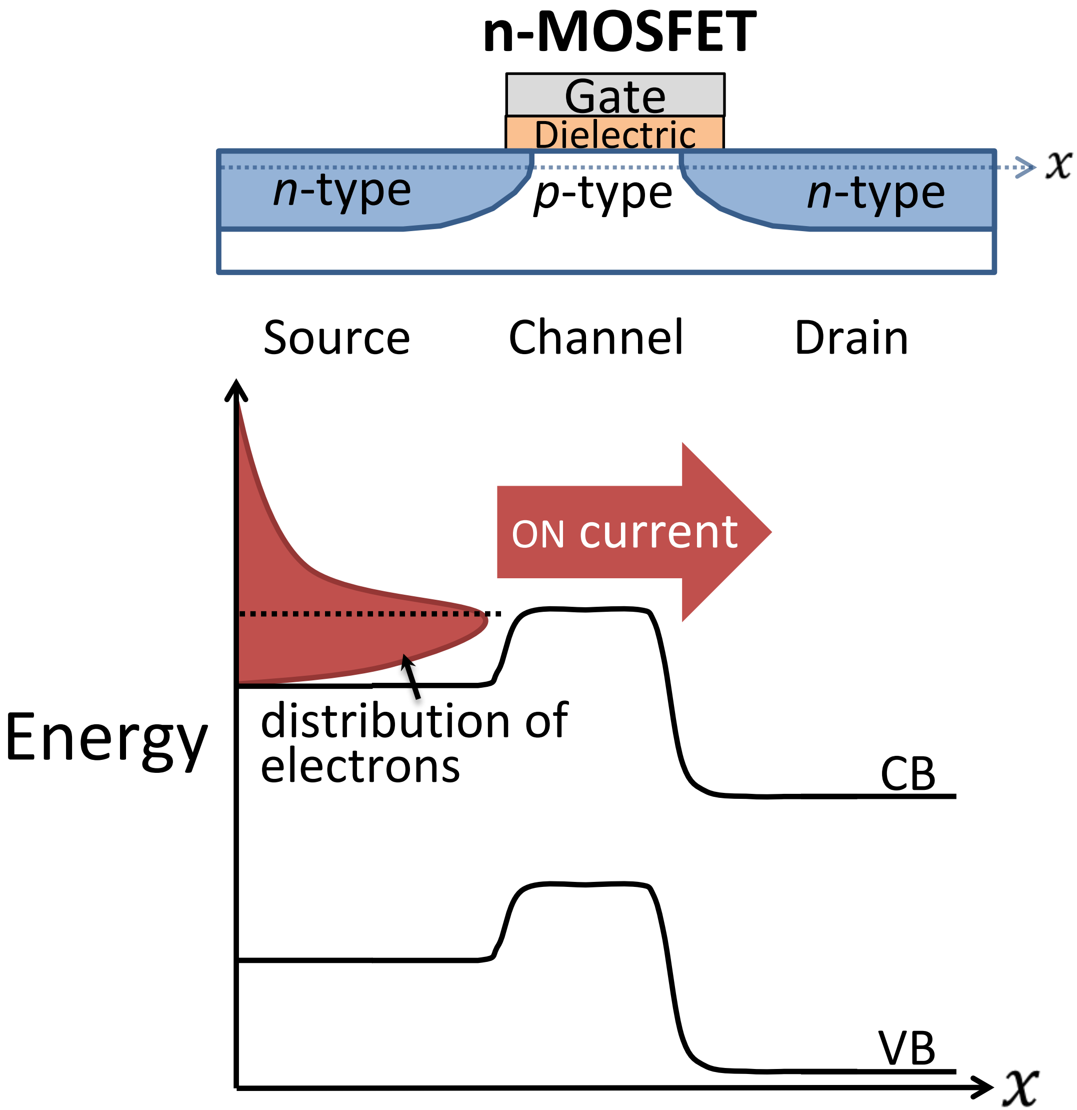
Fermi-Dirac Distribution

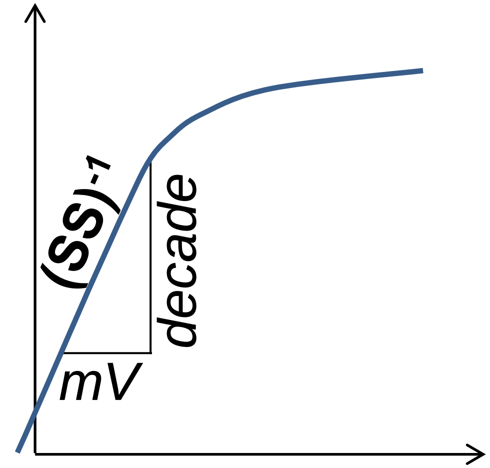
$$f(E) \approx \exp\left(\frac{E_f - E}{kT}\right)$$

$$f(E) \Longrightarrow \; 60\, mV/decade$$

SS limited to 60 mV/decade

SS in a MOSFET is limited to 60 mV/decade





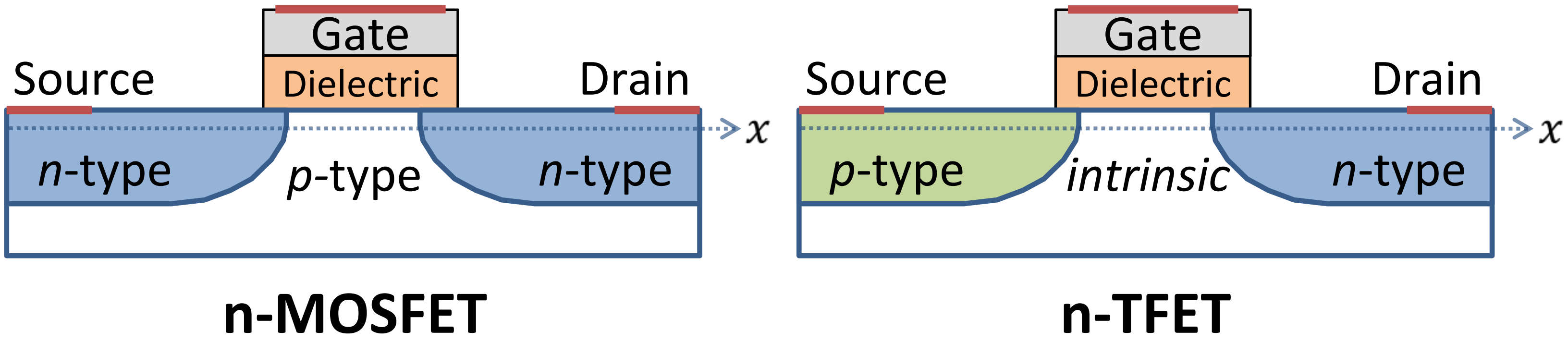
Fermi-Dirac Distribution

$$f(E) \approx \exp\left(\frac{E_f - E}{kT}\right)$$

$$f(E) \Longrightarrow \ 60\ mV/decade$$

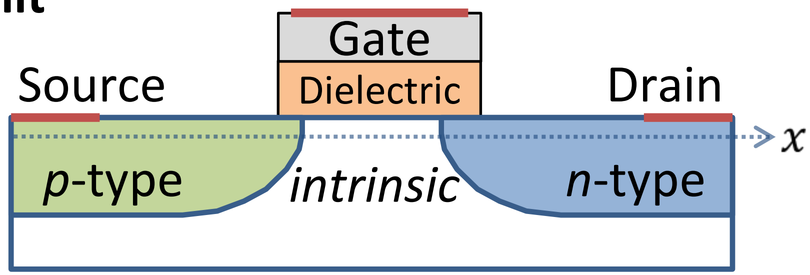
SS limited to
60 mV/decade

TFET structure is similar to a MOSFET

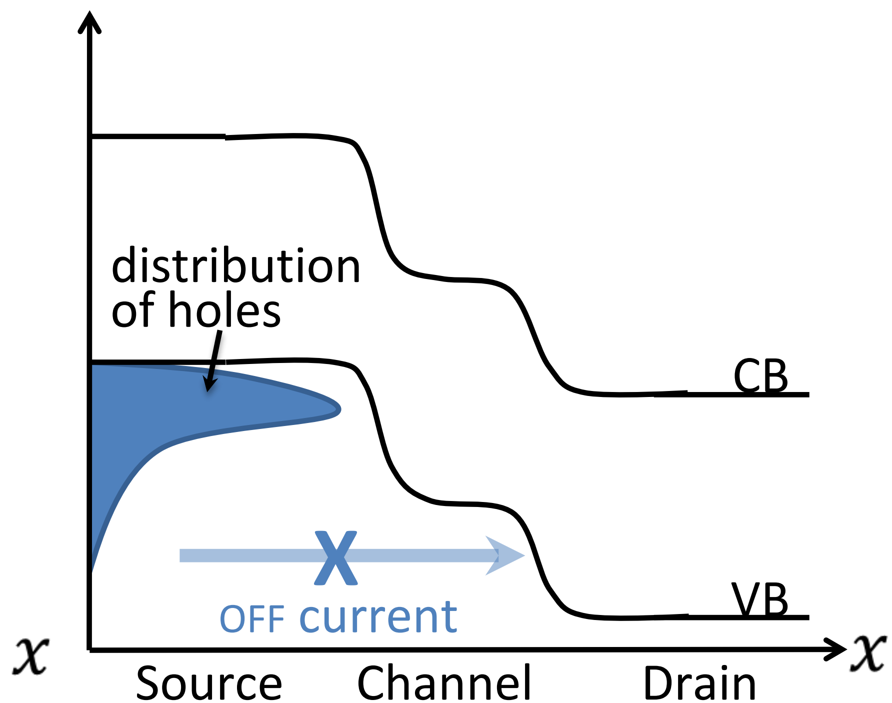


TFET design prevents OFF current from thermal tail

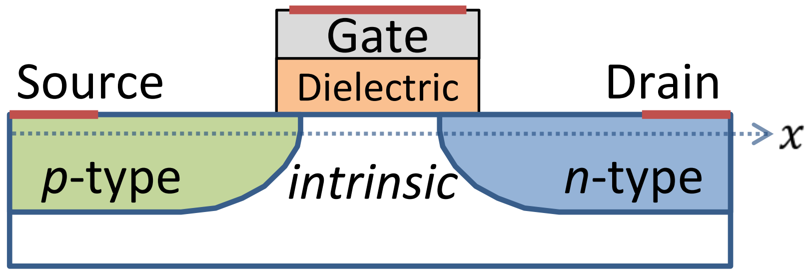
→ no 60 mV/decade limit

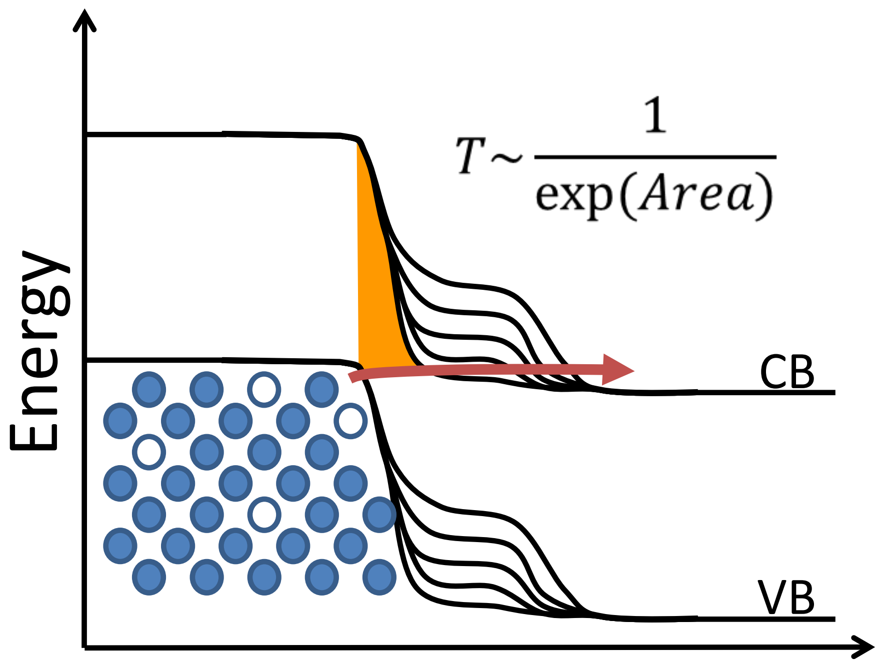


n-TFET

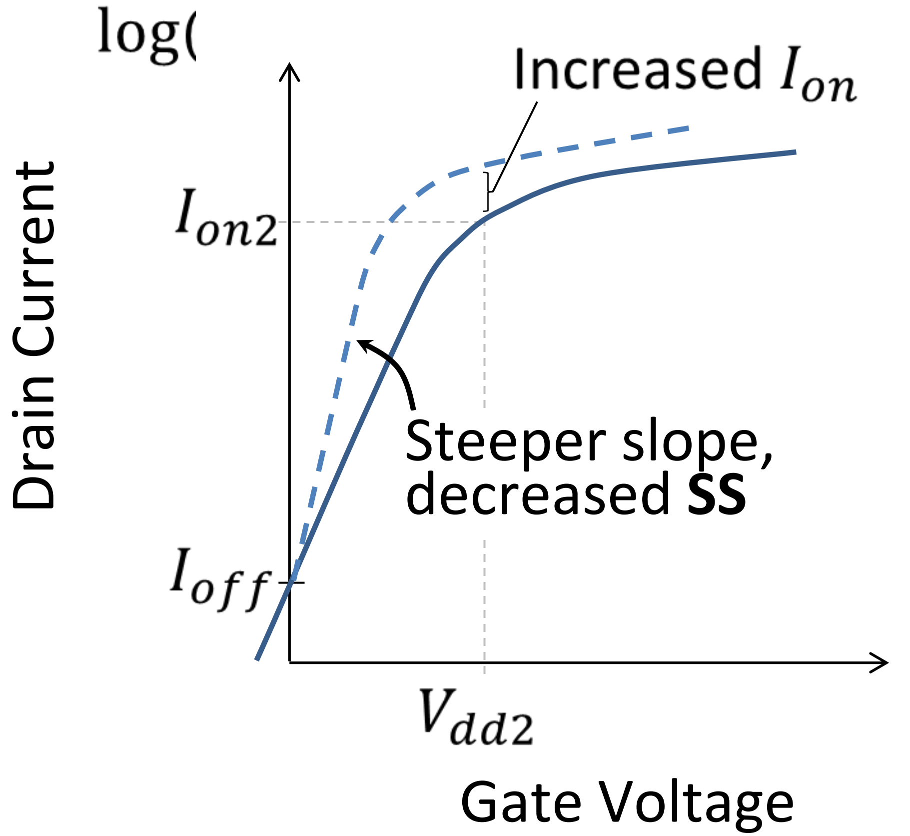


TFETs turn-on by modulating the tunneling path





Since TFETs are governed by different device physics, SS can be < 60 mV/decade



SS—subthreshold swing (mV/decade)

State-of-the-Field for TFETs

TFET simulations suggest superior results

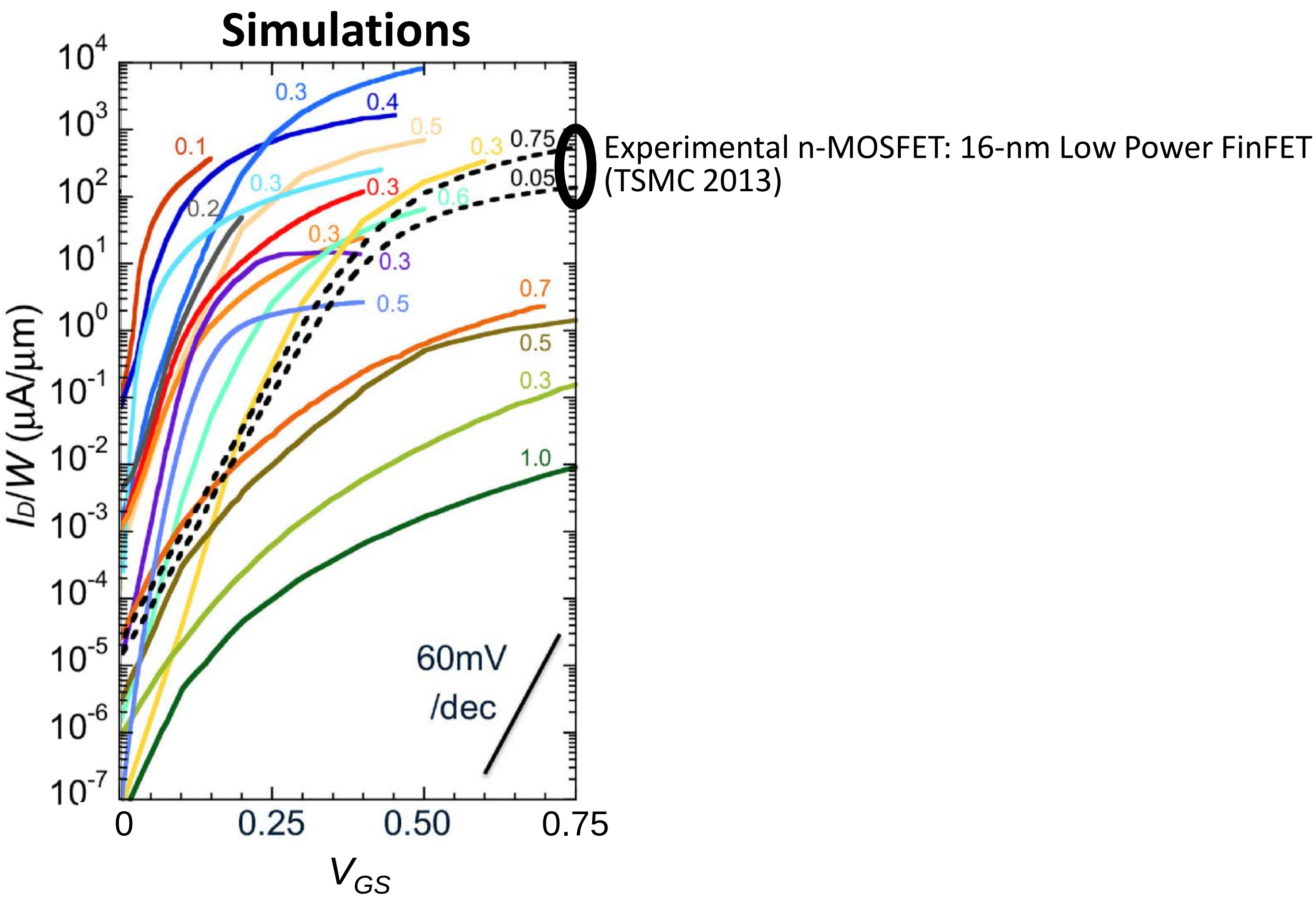


Figure adapted from Lu and Seabaugh's *Tunnel Field-Effect Transistors: State-of-the-Art*, 2014

Many TFET simulations are in sharp contrast to experimental results

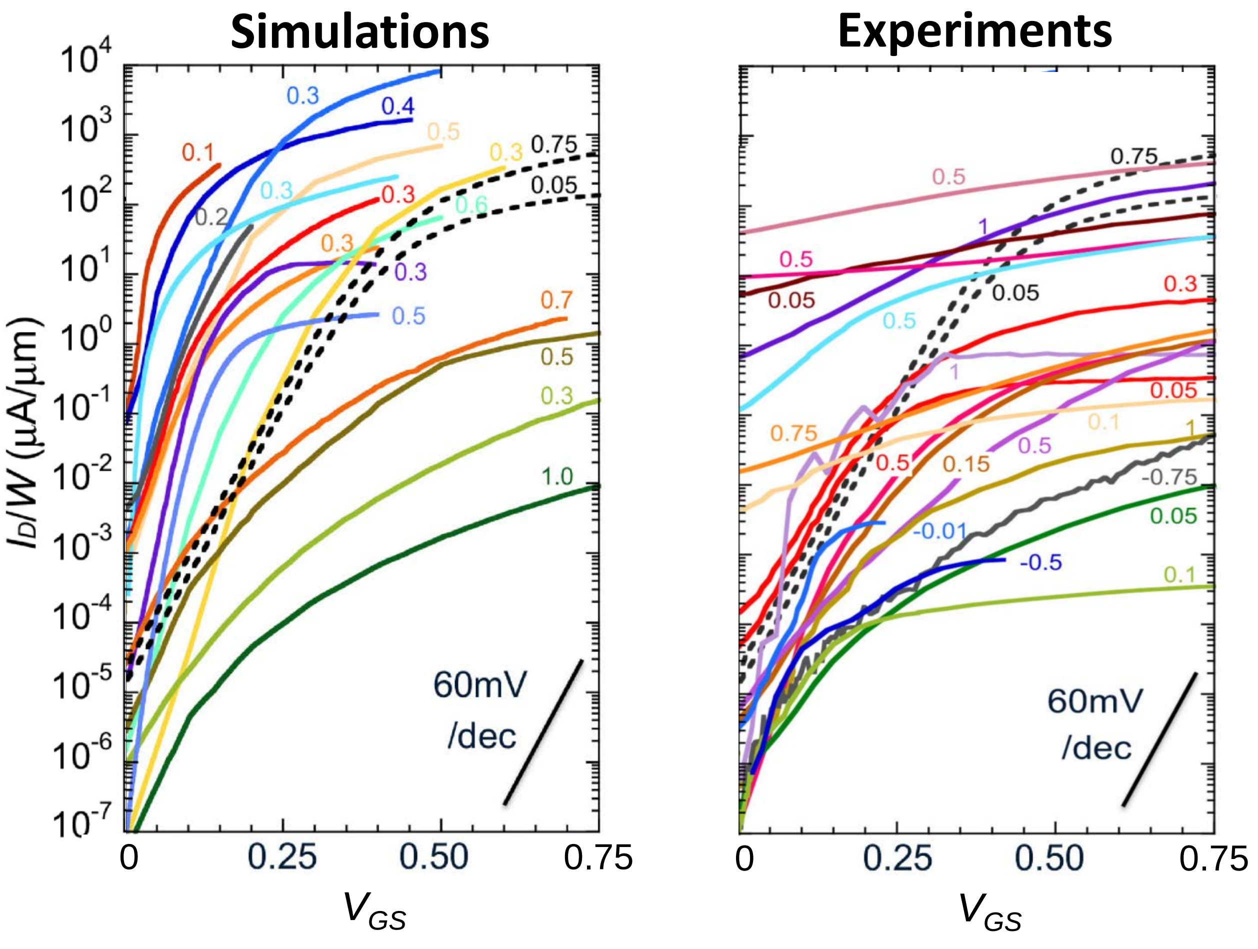


Figure adapted from Lu and Seabaugh's *Tunnel Field-Effect Transistors: State-of-the-Art*, 2014

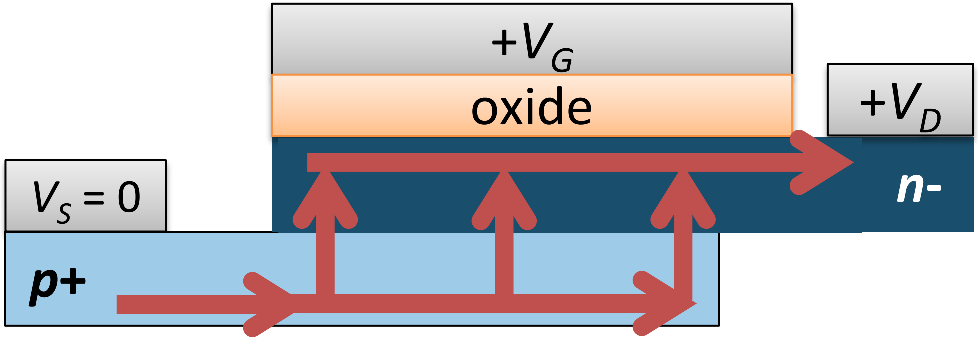
Traps and defects are certainly a big concern...

My question:

Are there <u>intrinsic</u> mechanisms that limit TFET performance?

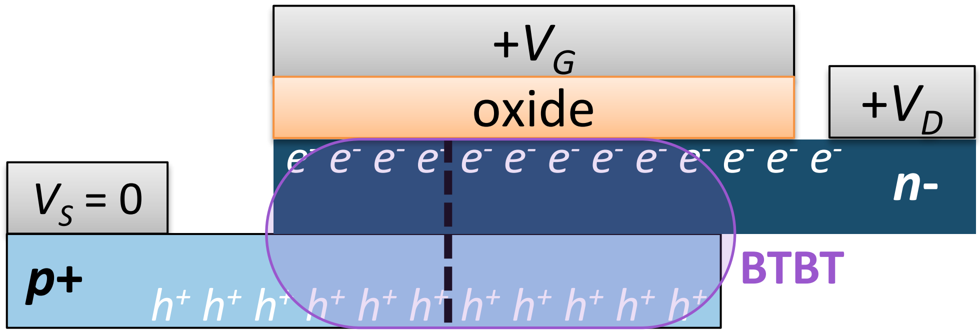
We’ll study an ideal TFET:

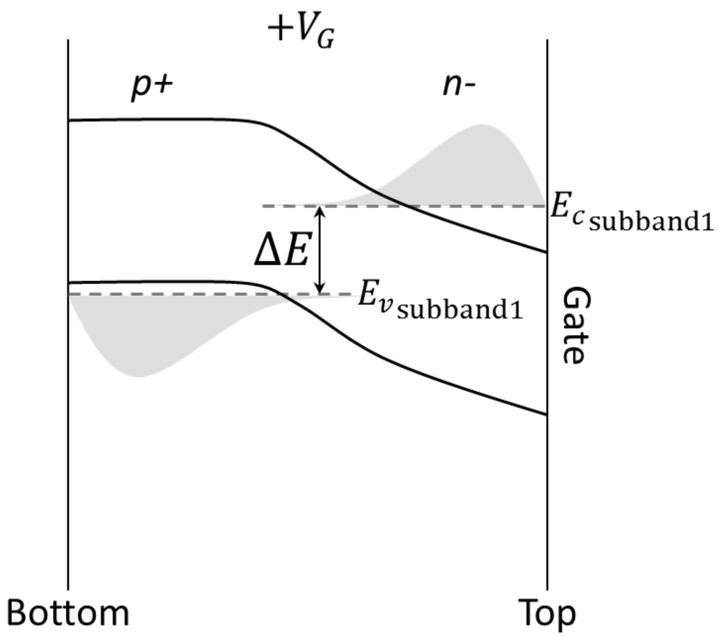
“Perpendicular TFET”
“Line TFET”
“In-line TFET”
“Vertical TFET”



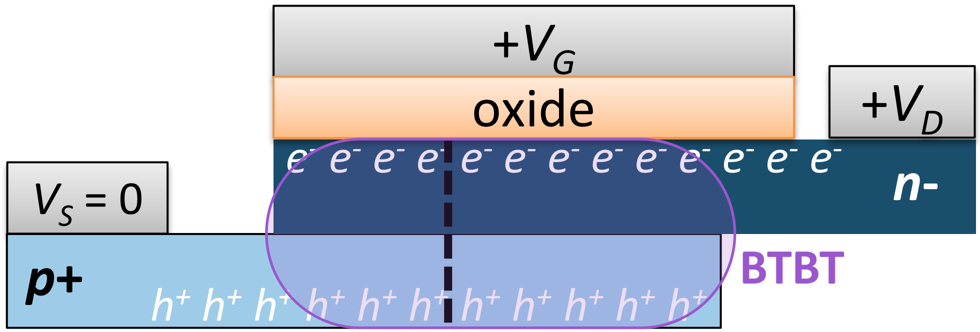
The concept is general and can be applied to other designs

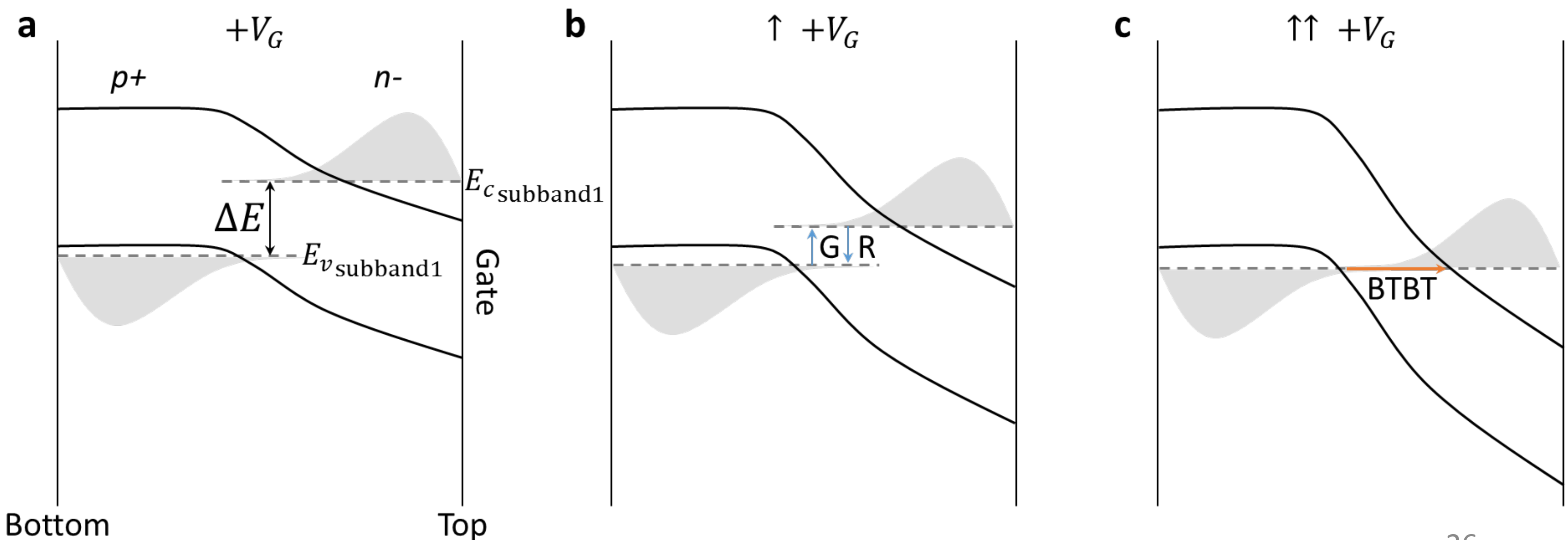
Band-to-band tunneling occurs vertically across the channel





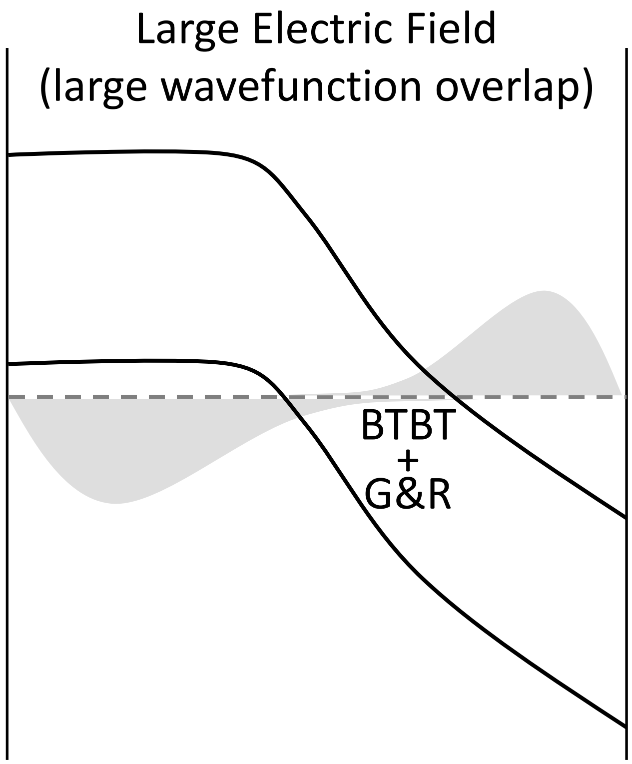
We turn the TFET on by ↑ V_G to ↓ ΔE

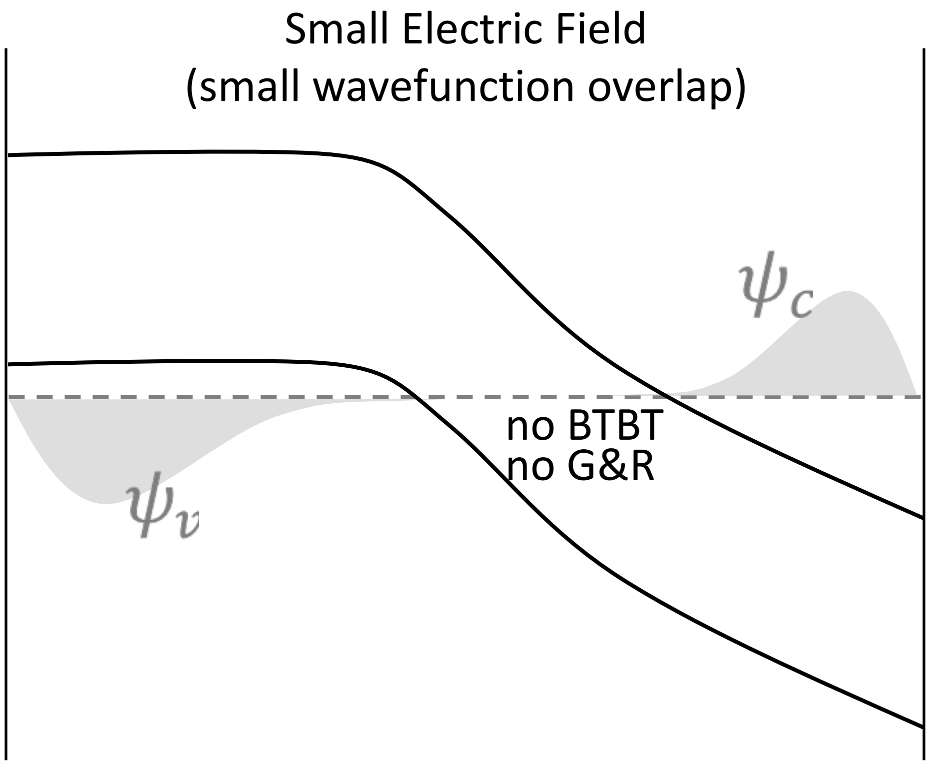


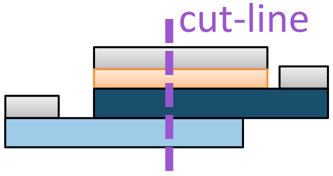


BTBT and G&R are fundamentally linked through the **wavefunction overlap**

$$\langle \psi_v | \psi_c \rangle$$



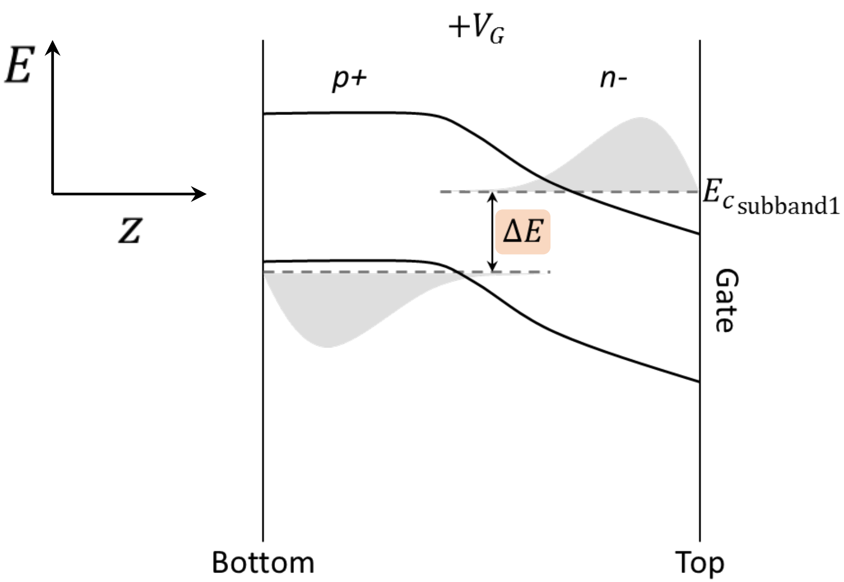




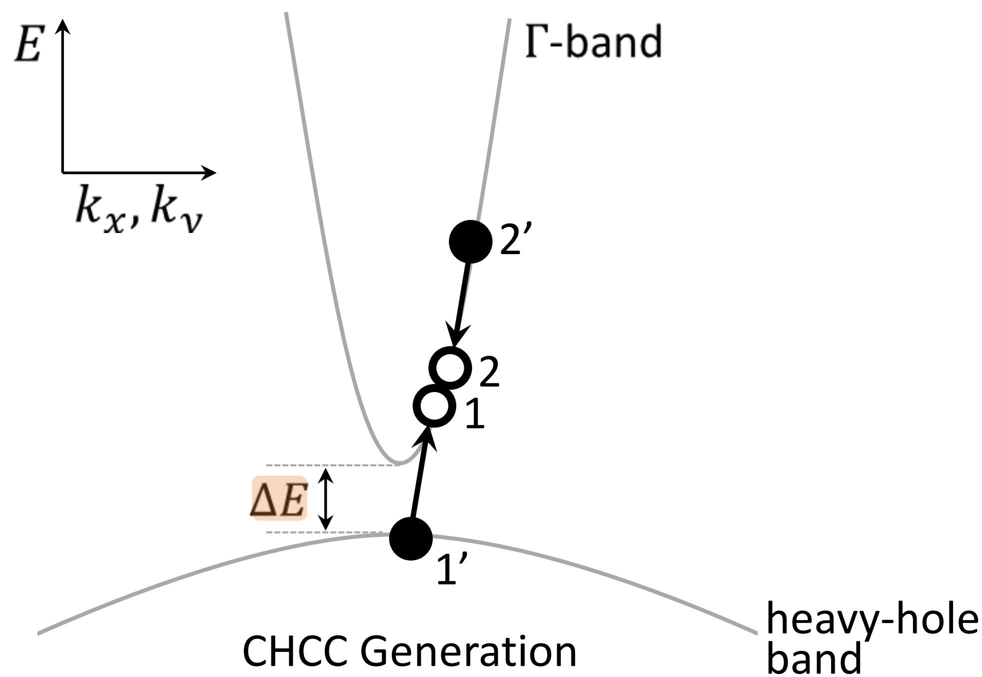
Proposed mechanism, **Auger generation** (also called impact ionization):

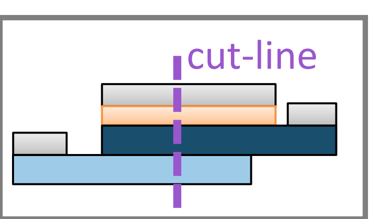
High-energy electron (2’) knocks valence electron (1’) into the conduction band

real space



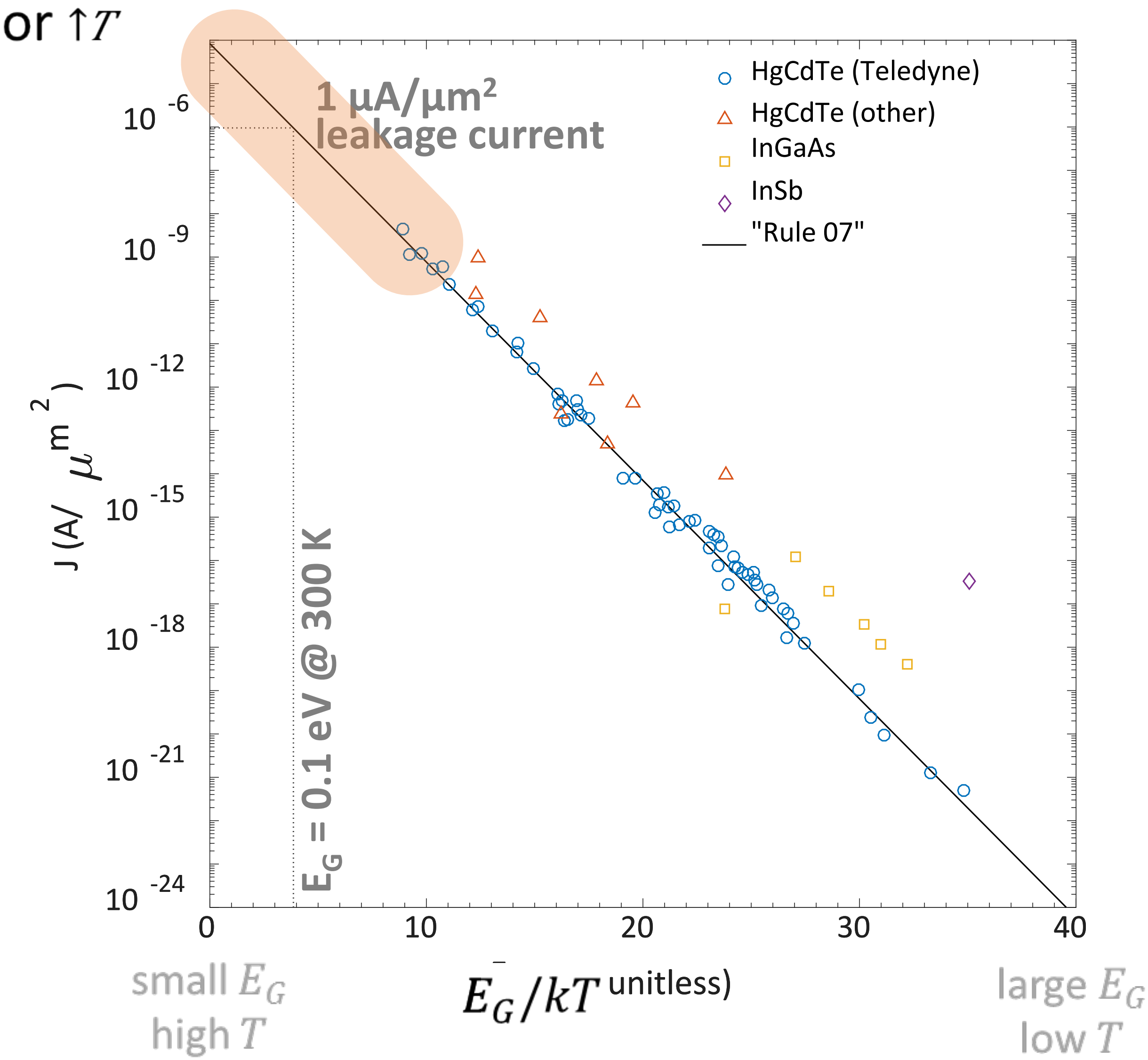
k-space





Auger leakage current in experimental photodectors

↑↑ Auger as ↓E↓G or ↑T

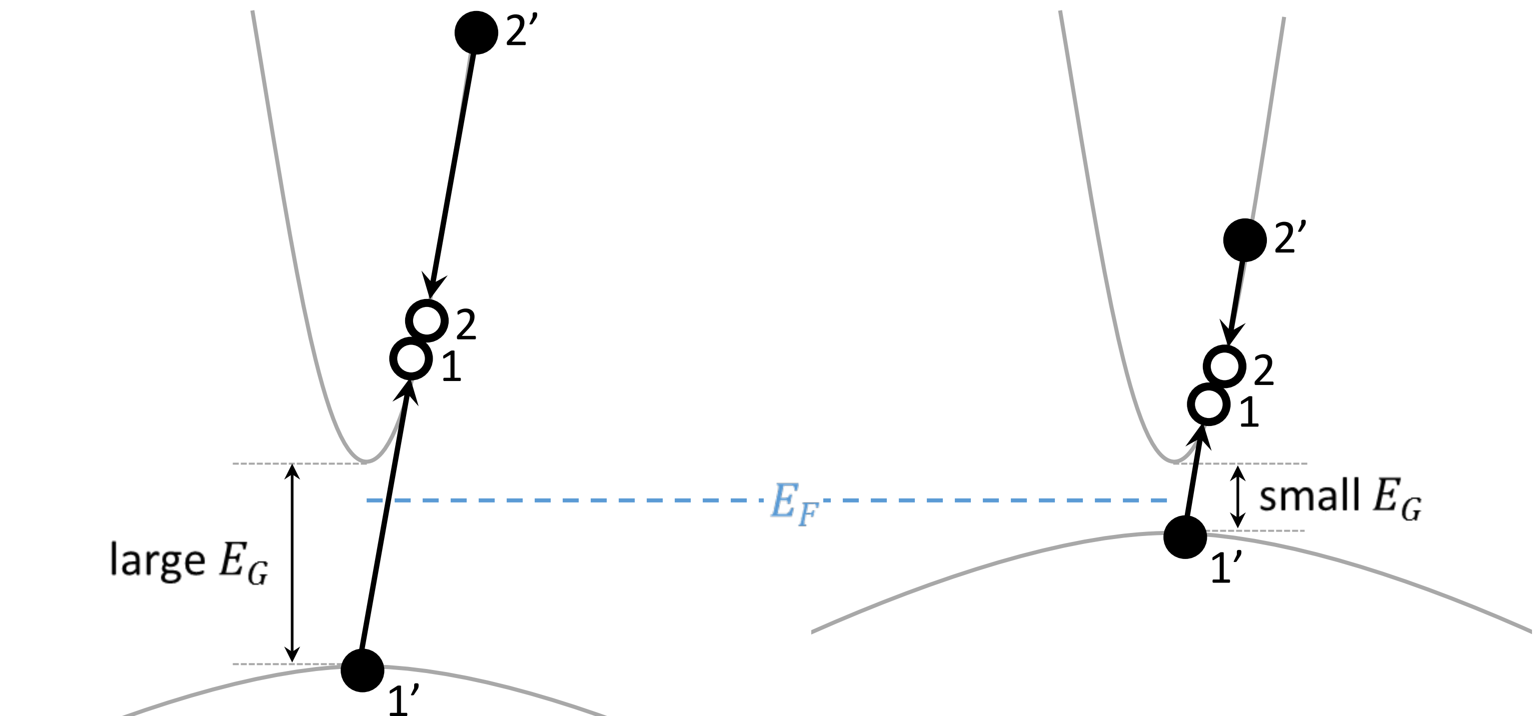


Tennant et al., "MBE HgCdTe Technology: A Very General Solution to IR Detection…," 2008.

Tennant, "'Rule 07' Revisited: Still a Good Heuristic Predictor…," 2010.

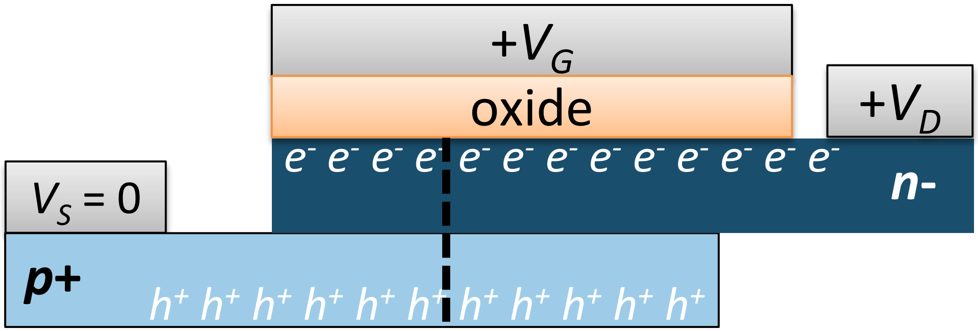
To understand the photodiode results, review Auger transition

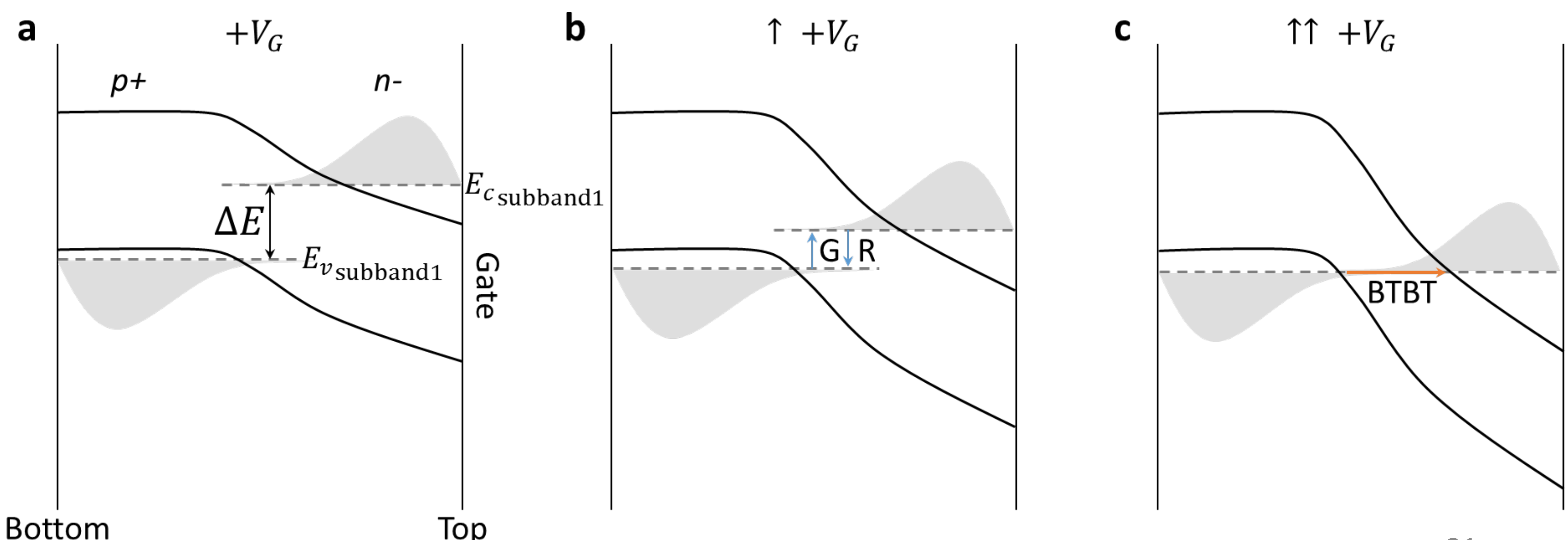
As ↓ E_G, higher likelihood of *hot electron* with energy needed for generation



In TFET structure, ↓ ΔE instead of E_G

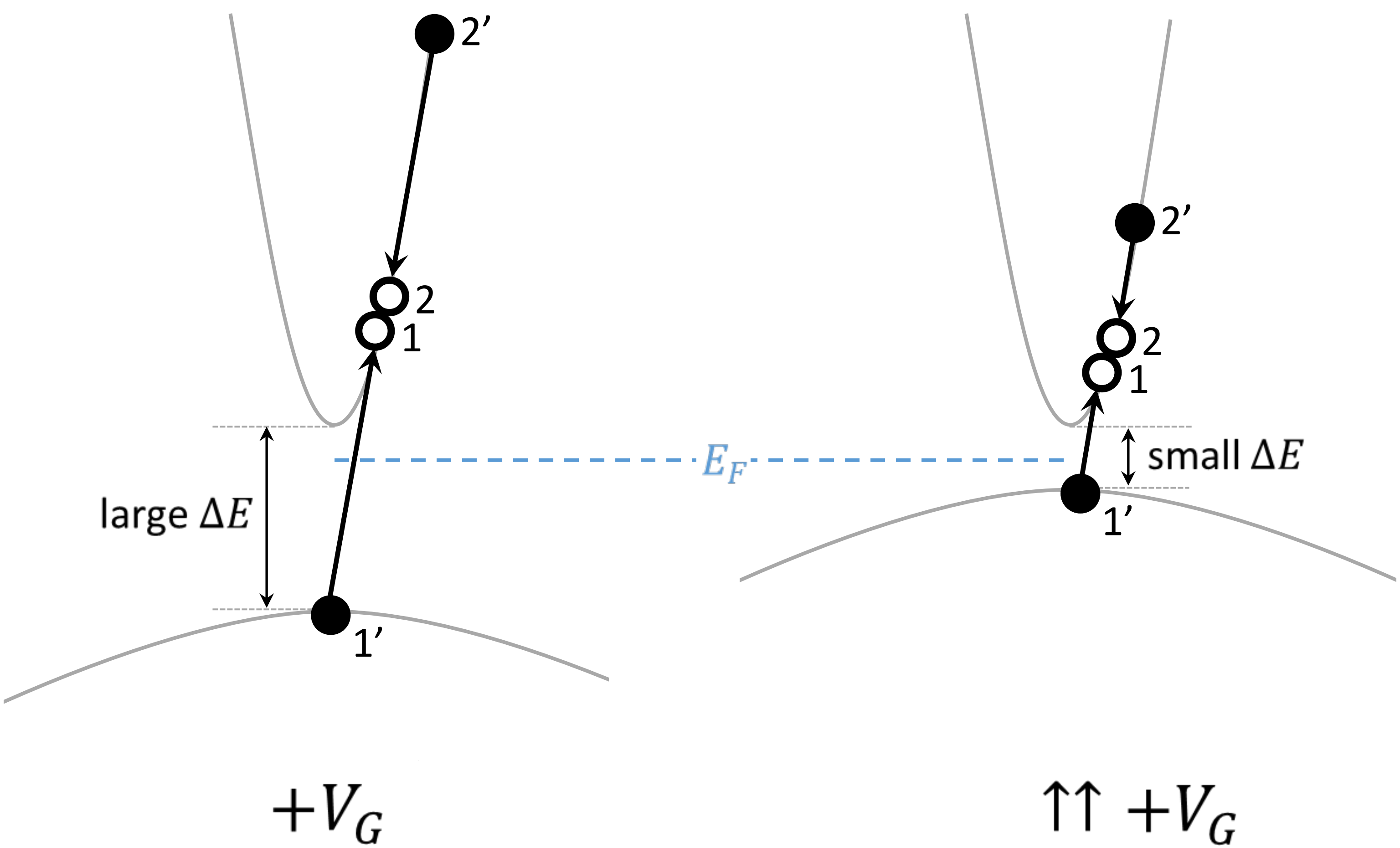
↑↑ Auger as ↓ ΔE





In TFET structure, ↓ ΔE instead of E_G

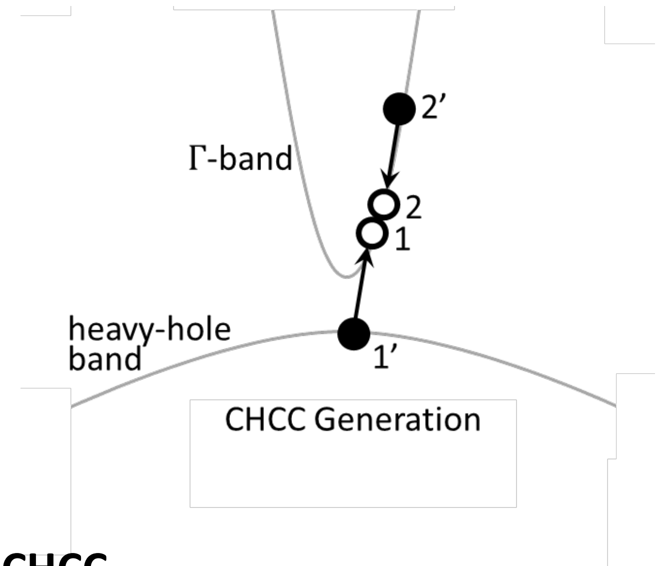
↑↑ Auger as ↓ ΔE

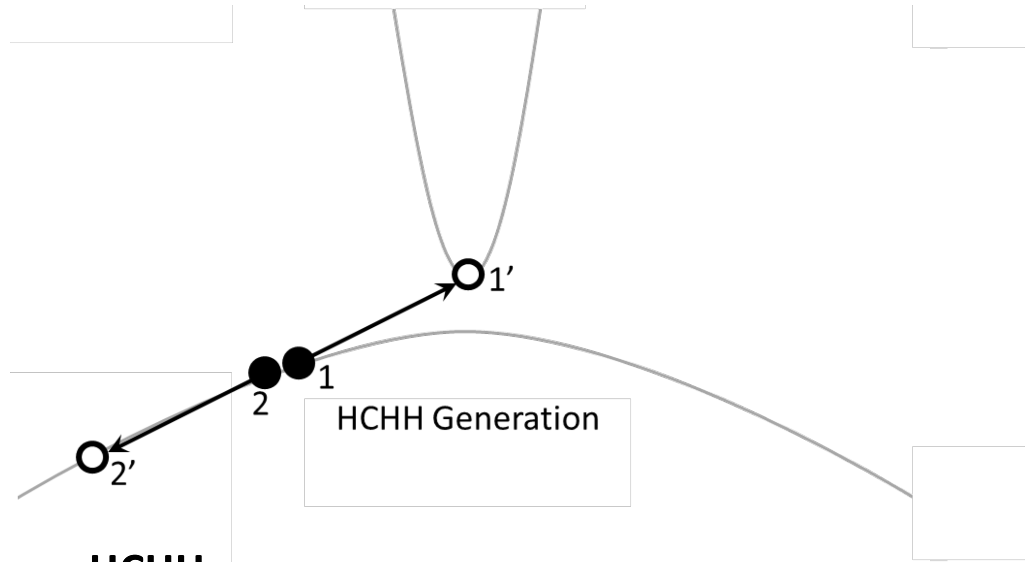


Several types of Auger generation:

CHCC dominates for large electron concentrations

HCHH dominates for large hole concentrations





CHCC

Dominant for large n-type doping

Dominant in **p-TFETs**

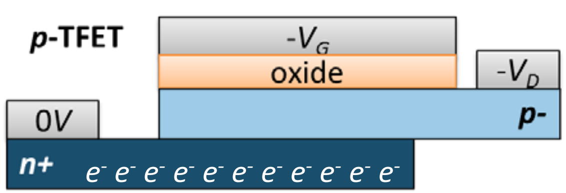
Depends on $\mu = \frac{m_c}{m_v}$

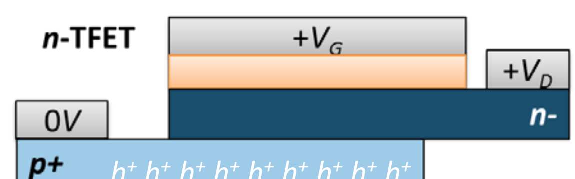
HCHH

Dominant for large p-type doping

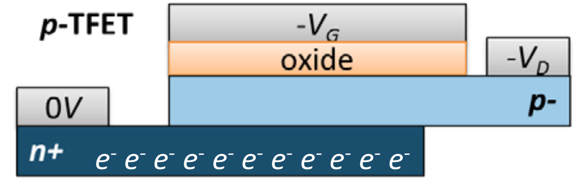
Dominant in **n-TFETs**

Depends on $\mu^{-1} = m_v / m_c$





For CHCC, probability of an electron at $E_{2'}$ limits gen. rate



Energy and momentum conservation

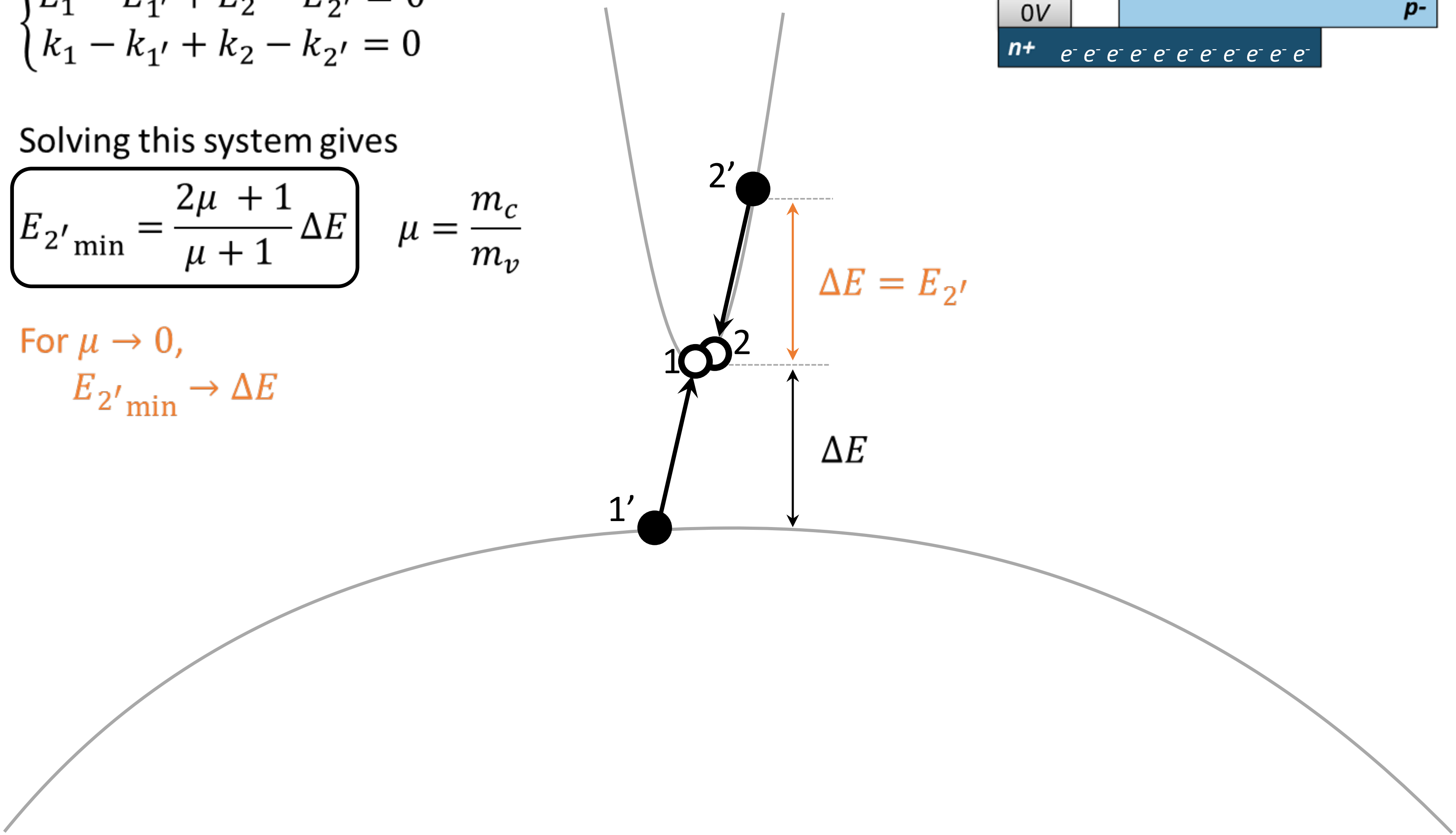
$$\begin{cases} E_1 - E_{1'} + E_2 - E_{2'} = 0 \\ k_1 - k_{1'} + k_2 - k_{2'} = 0 \end{cases}$$

Solving this system gives

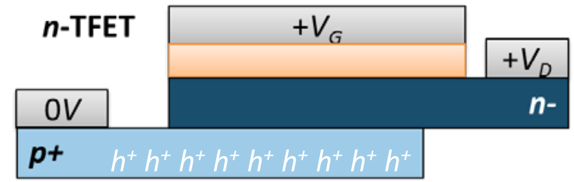
$$\boxed{E_{2'\,\mathrm{min}} = \frac{2\mu + 1}{\mu + 1}\Delta E} \qquad \mu = \frac{m_c}{m_v}$$

For $\mu \to 0$,

$$E_{2'\,\mathrm{min}} \to \Delta E$$



For HCHH, probability of a hole at $E_{2'}$ limits gen. rate

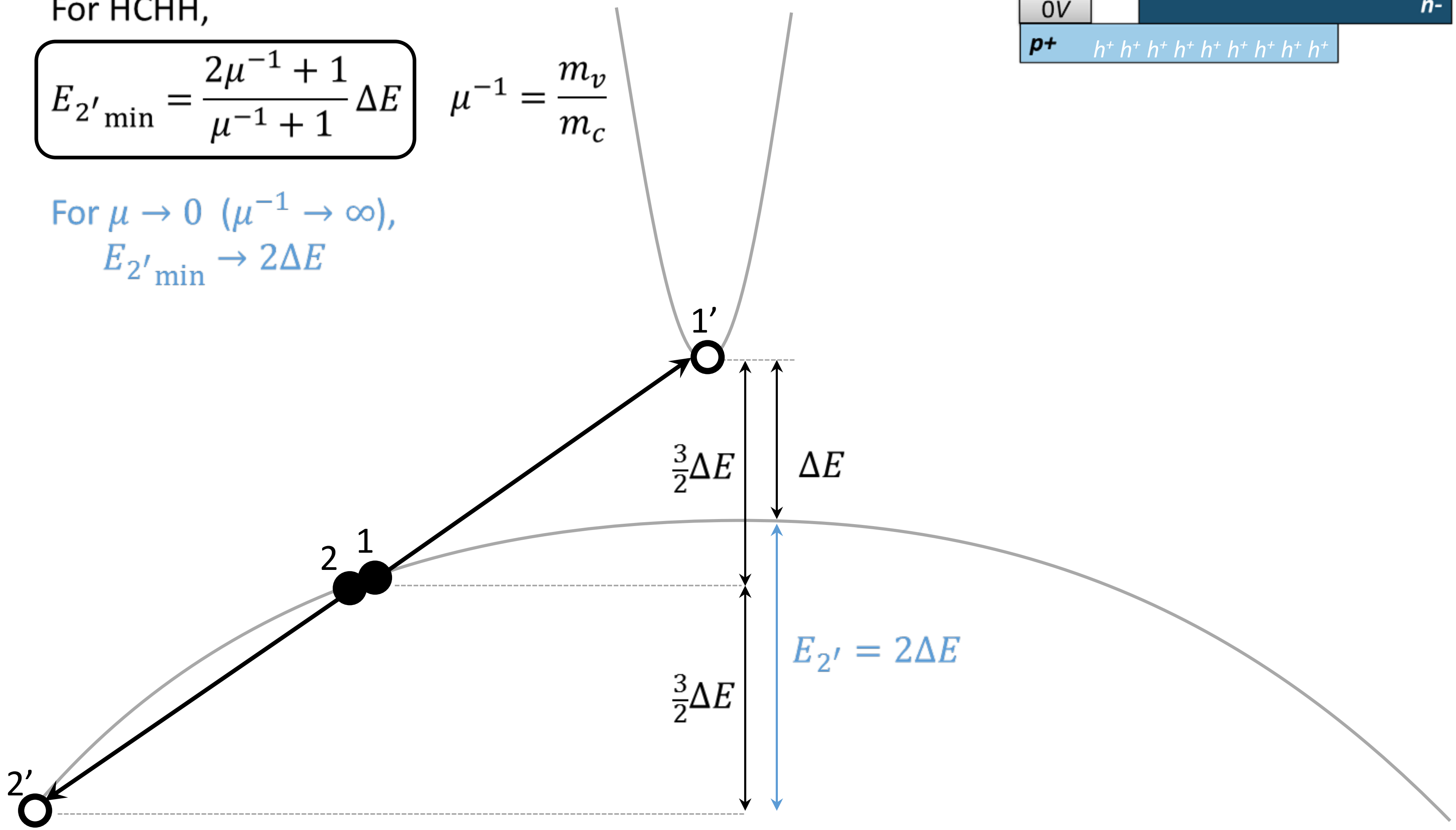


For HCHH,

$$E_{2'\,\mathrm{min}} = \frac{2\mu^{-1}+1}{\mu^{-1}+1}\Delta E \qquad \mu^{-1} = \frac{m_v}{m_c}$$

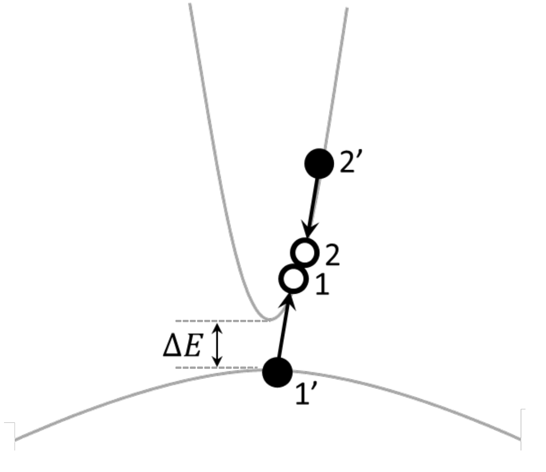
For $\mu \to 0$ $(\mu^{-1} \to \infty)$,

$E_{2'\,\mathrm{min}} \to 2\Delta E$



Net Auger transition rate is determined by Fermi's Golden Rule:

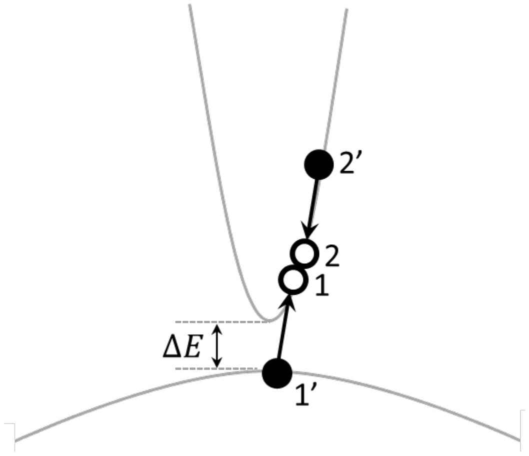
$$U = R - G = \frac{1}{A}\frac{2\pi}{\hbar}\sum_{1,1',2,2'} P(1,1',2,2')\,|M|^2\,\delta(E_1 - E_{1'} + E_2 - E_{2'}) \quad \left[\frac{\#\ \text{transition}}{\text{s} \cdot \text{cm}^2}\right]$$



Counting all possible states:

Total rate is the sum of all the possible transitions

$$U = R - G = \frac{1}{A}\frac{2\pi}{\hbar}\sum_{1,1',2,2'} P(1,1',2,2')\,|M|^2\,\delta(E_1 - E_{1'} + E_2 - E_{2'}) \quad \left[\frac{\#\text{ transition}}{\text{s}\cdot\text{cm}^2}\right]$$



Probability of vacant/occupied states:

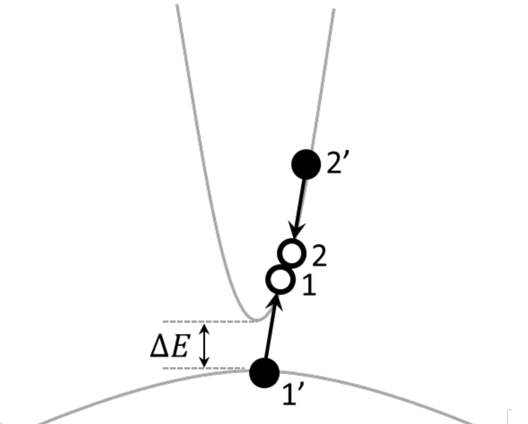
Weights the transition rate by the probability that particles needed for the transition are present

$$U = R - G = \frac{1}{A}\frac{2\pi}{\hbar}\sum_{1,1',2,2'} P(1,1',2,2')\,|M|^2\,\delta(E_1 - E_{1'} + E_2 - E_{2'}) \quad \left[\frac{\#\ \text{transition}}{\text{s}\cdot\text{cm}^2}\right]$$

For the transition pictured:

State 1 must be vacant
State 2 must be vacant
State 1’ must be occupied
State 2’ must be occupied

$$P = (1 - f_1)(1 - f_2) f_{1'} f_{2'}$$
$$\approx f_{2'}$$



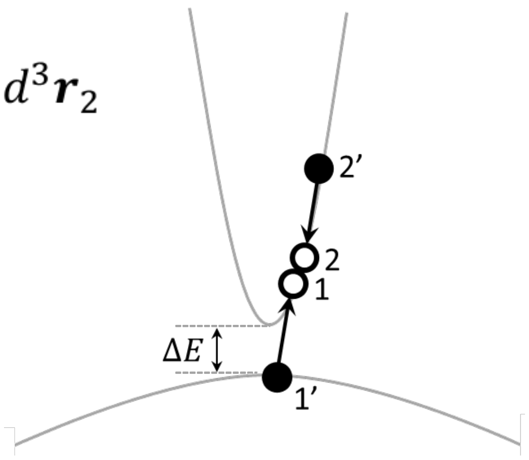
Perturbation that causes the transition:

Coulomb interaction acting on the initial and final wavefunctions

$$U = R - G = \frac{1}{A}\frac{2\pi}{\hbar}\sum_{1,1',2,2'} P(1,1',2,2')\,|M|^2\,\delta(E_1 - E_{1'} + E_2 - E_{2'}) \quad \left[\frac{\#\ \text{transition}}{\text{s}\cdot\text{cm}^2}\right.$$

$$M = \iint \Psi_{1'}^*(\boldsymbol{r}_1)\Psi_{2'}^*(\boldsymbol{r}_2)\frac{q^2}{4\pi\epsilon|\boldsymbol{r_1} - \boldsymbol{r_2}|}\Psi_1(\boldsymbol{r}_1)\Psi_2(\boldsymbol{r}_2)d^3\boldsymbol{r}_1 d^3\boldsymbol{r}_2$$

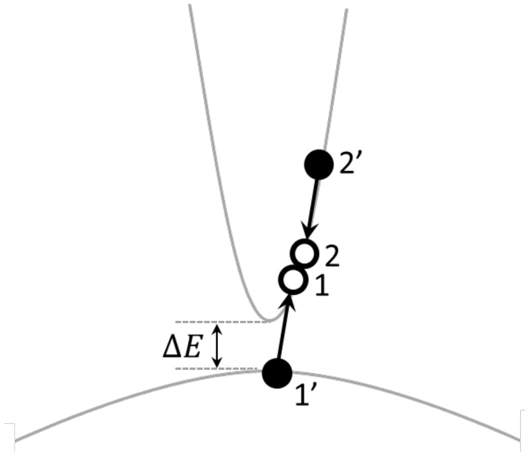
Coulombic potential



Conservation of energy:

We can't create or destroy energy in the transition

$$U = R - G = \frac{1}{A}\frac{2\pi}{\hbar}\sum_{1,1',2,2'} P(1,1',2,2')\,|M|^2\,\delta(E_1 - E_{1'} + E_2 - E_{2'}) \quad \left[\frac{\#\text{ transition}}{\text{s}\cdot\text{cm}^2}\right]$$

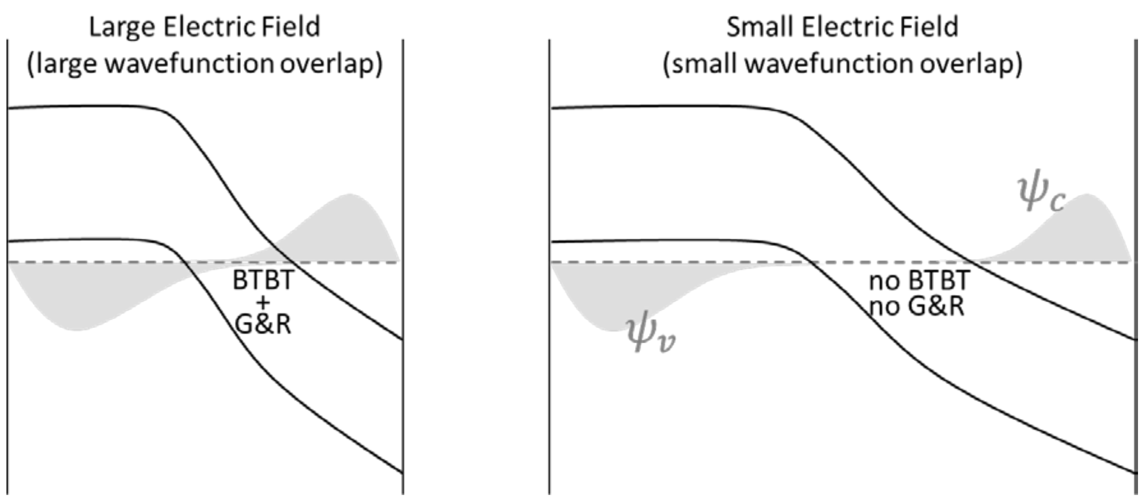


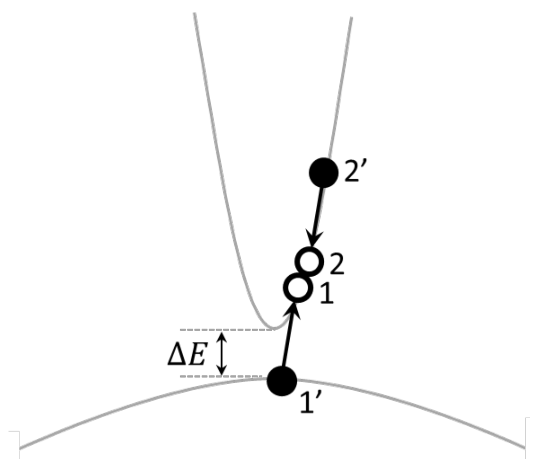
After a lot of math (and a few approximations), we arrive at the generation rate per unit area

$$G_{CHCC} \approx \frac{q^4 {m_c}^3 (kT)^2 c_u^2}{4\pi^2 \hbar^7 \epsilon^2} \frac{(\mu+1)}{(2\mu+1)^2} |\langle \psi_{1'} | \psi_1 \rangle|^2 \frac{n}{N_c} \exp\left(-\frac{(2\mu+1)}{(\mu+1)} \frac{\Delta E}{kT} \right) \quad \left[\frac{\text{\# transition}}{\text{s} \cdot \text{cm}^2} \right.$$

Constants

Wavefunction overlap





After a lot of math (and a few approximations), we arrive at the generation rate per unit area

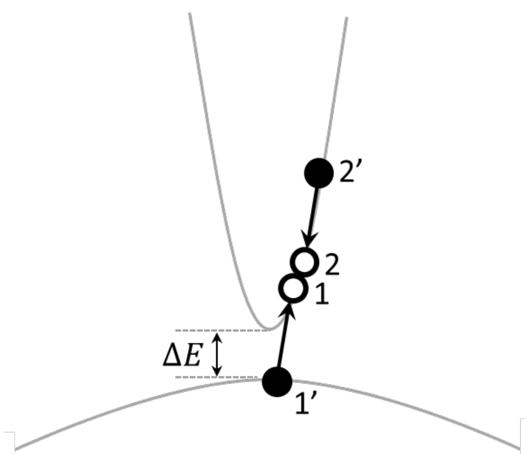
Probability of an electron at $E_{2'_{\min}}$

$$G_{CHCC} \approx \frac{q^4 m_c{}^3 (kT)^2 c_u^2}{4\pi^2 \hbar^7 \epsilon^2} \frac{(\mu+1)}{(2\mu+1)^2} |\langle \psi_{1'} | \psi_1 \rangle|^2 \frac{n}{N_c} \exp\left(-\frac{(2\mu+1)}{(\mu+1)} \frac{\Delta E}{kT} \right) \quad \left[\frac{\#\ \text{transition}}{\text{s} \cdot \text{cm}^2} \right]$$

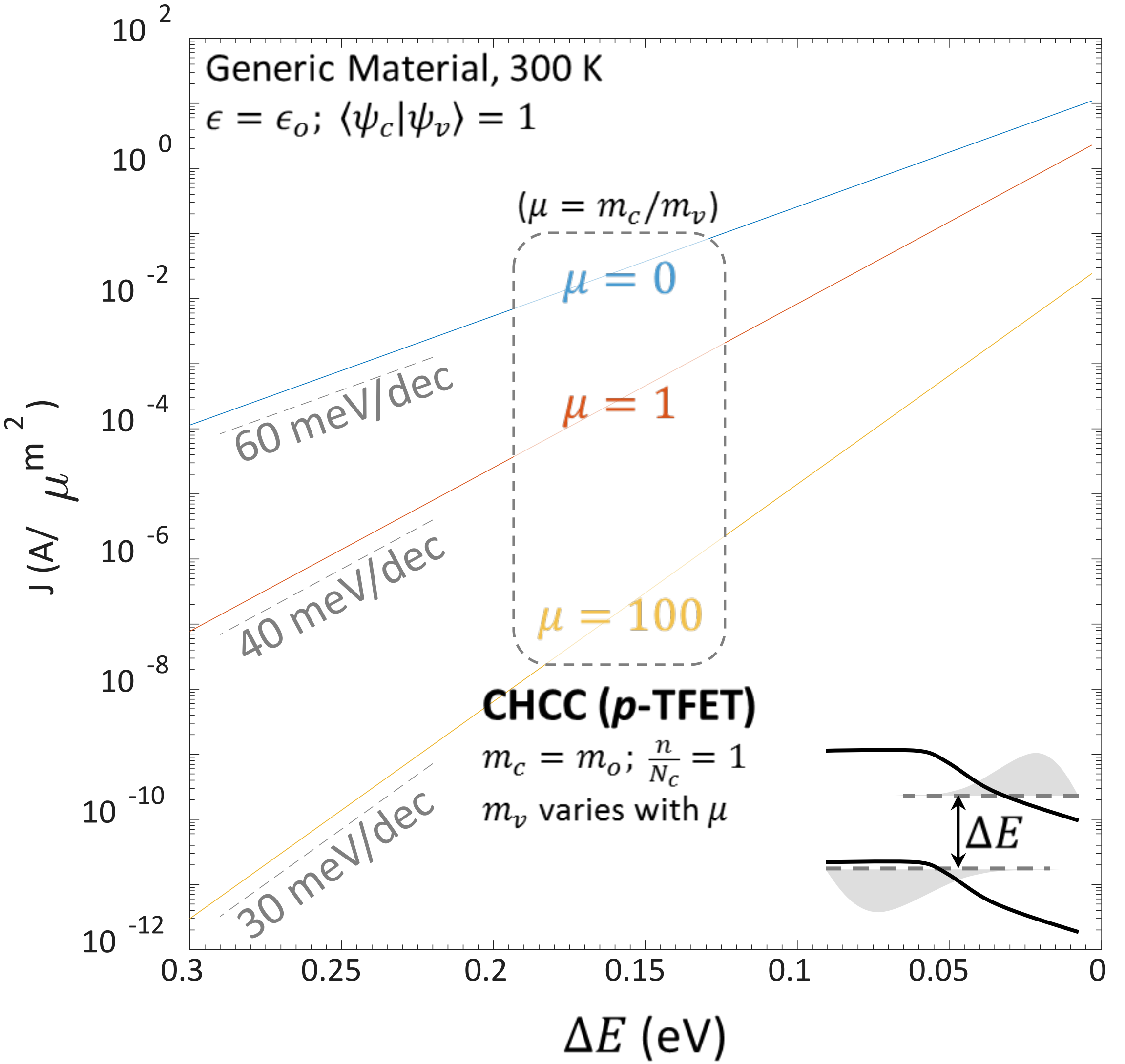
Constants

Wavefunction overlap

$E_{2'_{\min}}$

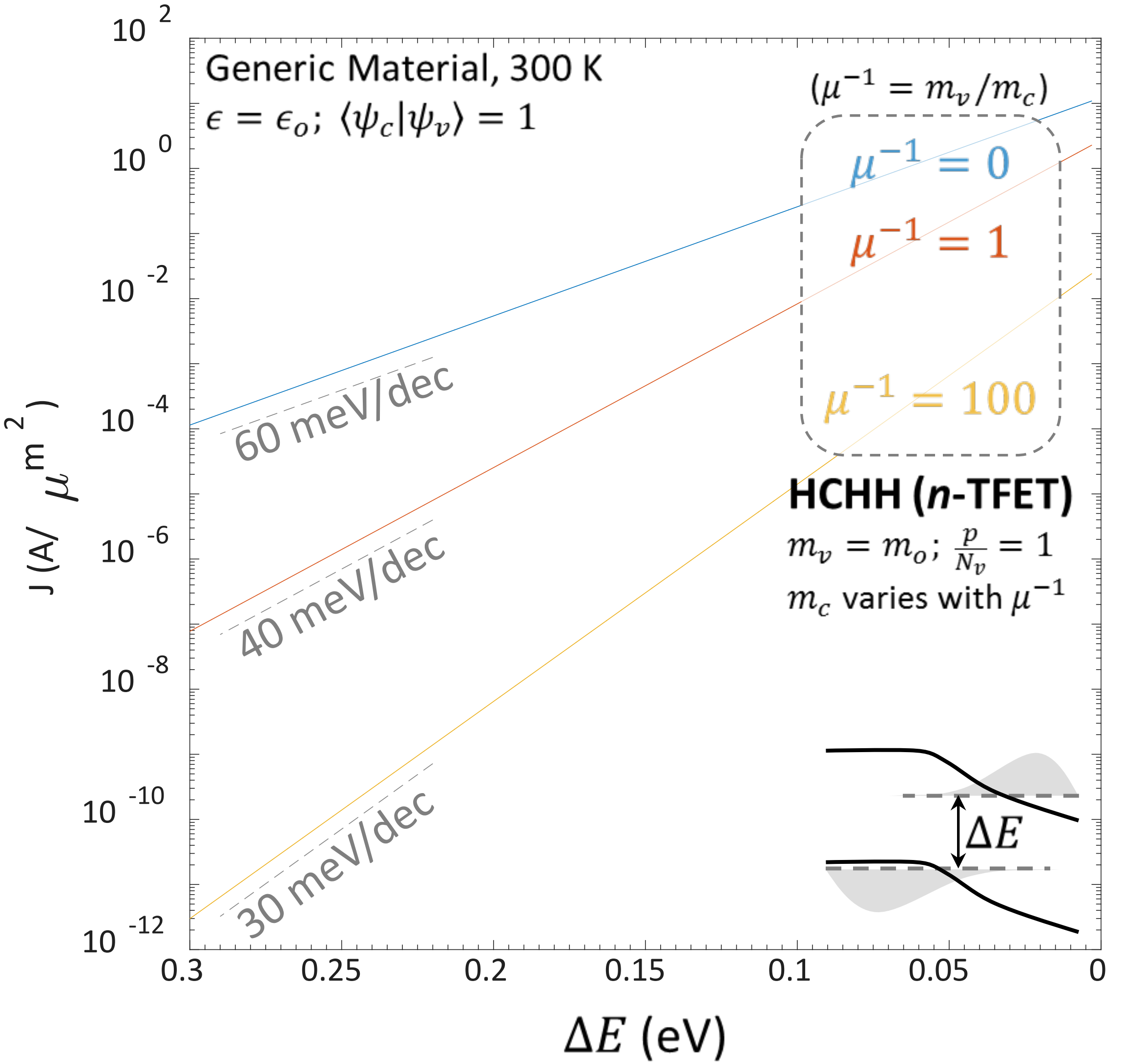


Auger current density calculated from the generation rate



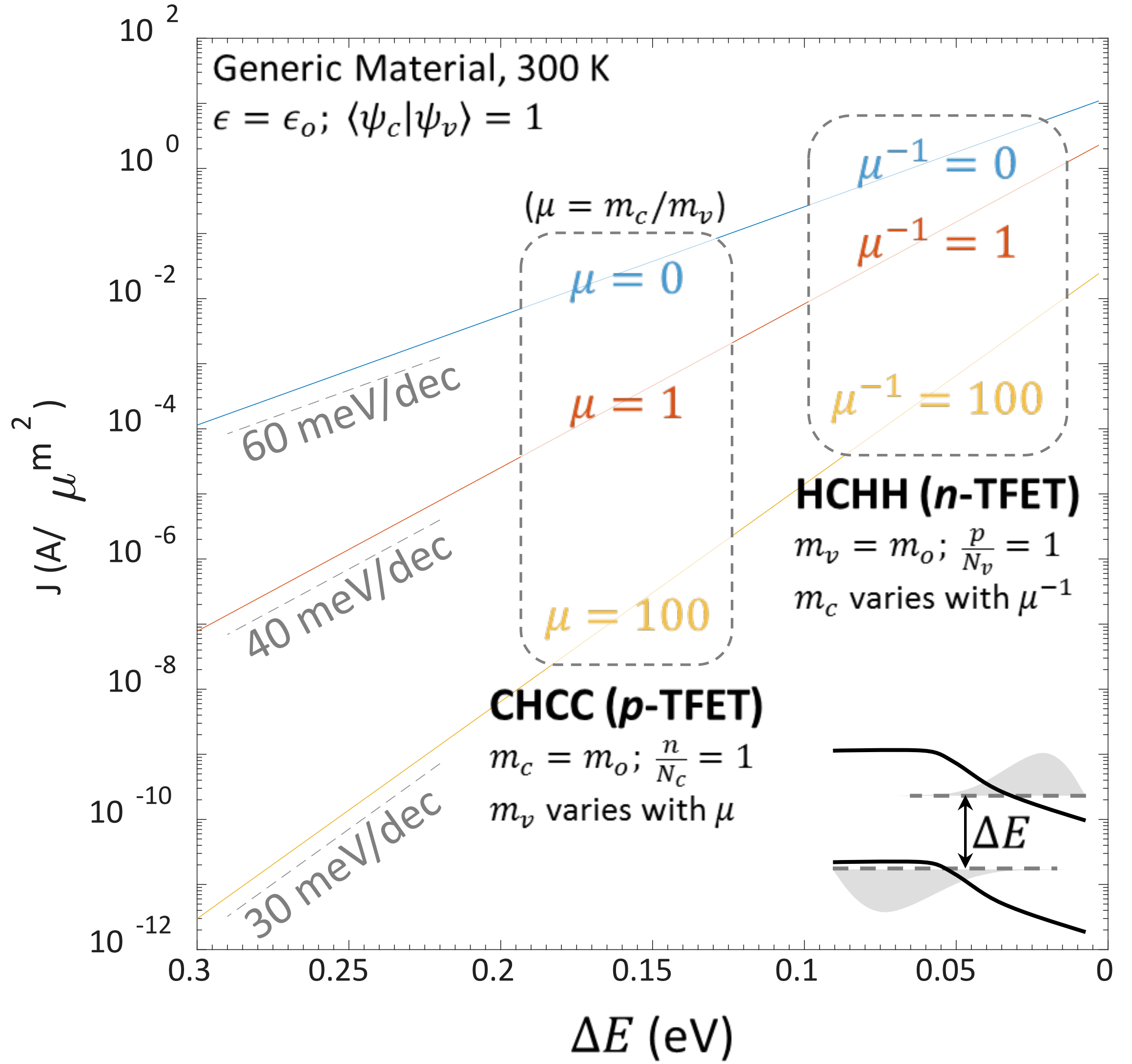
$$J = qG_{CHCC} \approx \frac{q^4 m_c{}^3 (kT)^2 c_u{}^2}{4\pi^2 \hbar^7 \epsilon^2} \frac{(\mu+1)}{(2\mu+1)^2} \left|\langle\psi_{1'}|\psi_1\rangle\right|^2 \frac{n}{N_c} \exp\left(-\frac{(2\mu+1)}{(\mu+1)}\frac{\Delta E}{kT}\right)$$

Auger current density calculated from the generation rate



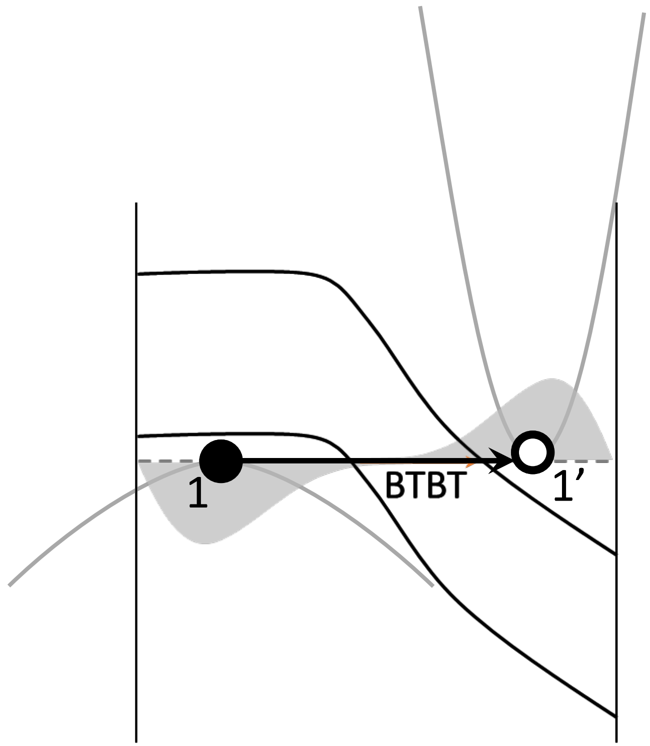
$$J = qG_{HCHH} \approx \frac{q^4 m_v{}^3 (kT)^2 c_u{}^2}{4\pi^2 \hbar^7 \epsilon^2} \frac{(\mu^{-1}+1)}{(2\mu^{-1}+1)^2} \left| \langle \psi_{1'} | \psi_1 \rangle \right|^2 \frac{p}{N_v} \exp\left(-\frac{(2\mu^{-1}+1)}{(\mu^{-1}+1)} \frac{\Delta E}{kT} \right)$$

Auger current density calculated from the generation rate



$$J = qG_{CHCC} \approx \frac{q^4 m_c{}^3 (kT)^2 c_u{}^2}{4\pi^2\hbar^7\epsilon^2} \frac{(\mu+1)}{(2\mu+1)^2} \left|\langle\psi_{1'}|\psi_1\rangle\right|^2 \frac{n}{N_c} \exp\left(-\frac{(2\mu+1)}{(\mu+1)}\frac{\Delta E}{kT}\right)$$

Visualization of band-to-band tunneling in terms of energy band diagram and E-k diagram

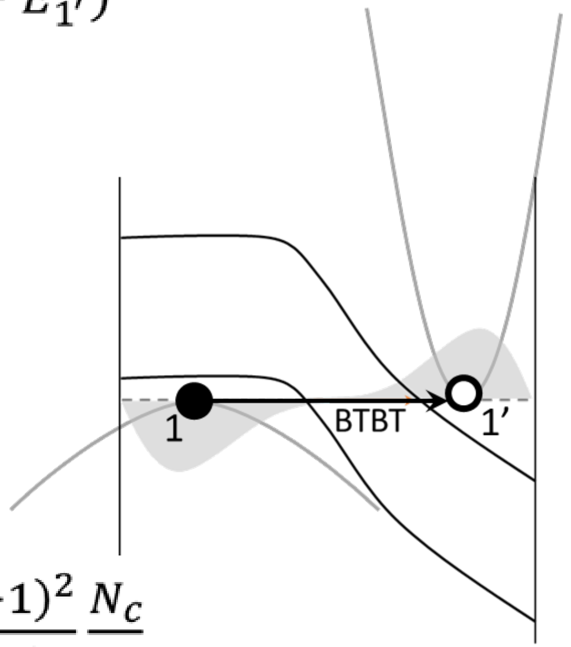


Ideal band-to-band tunneling can only take place when $\Delta E = 0$

Band-to-band tunneling has key similarities to Auger

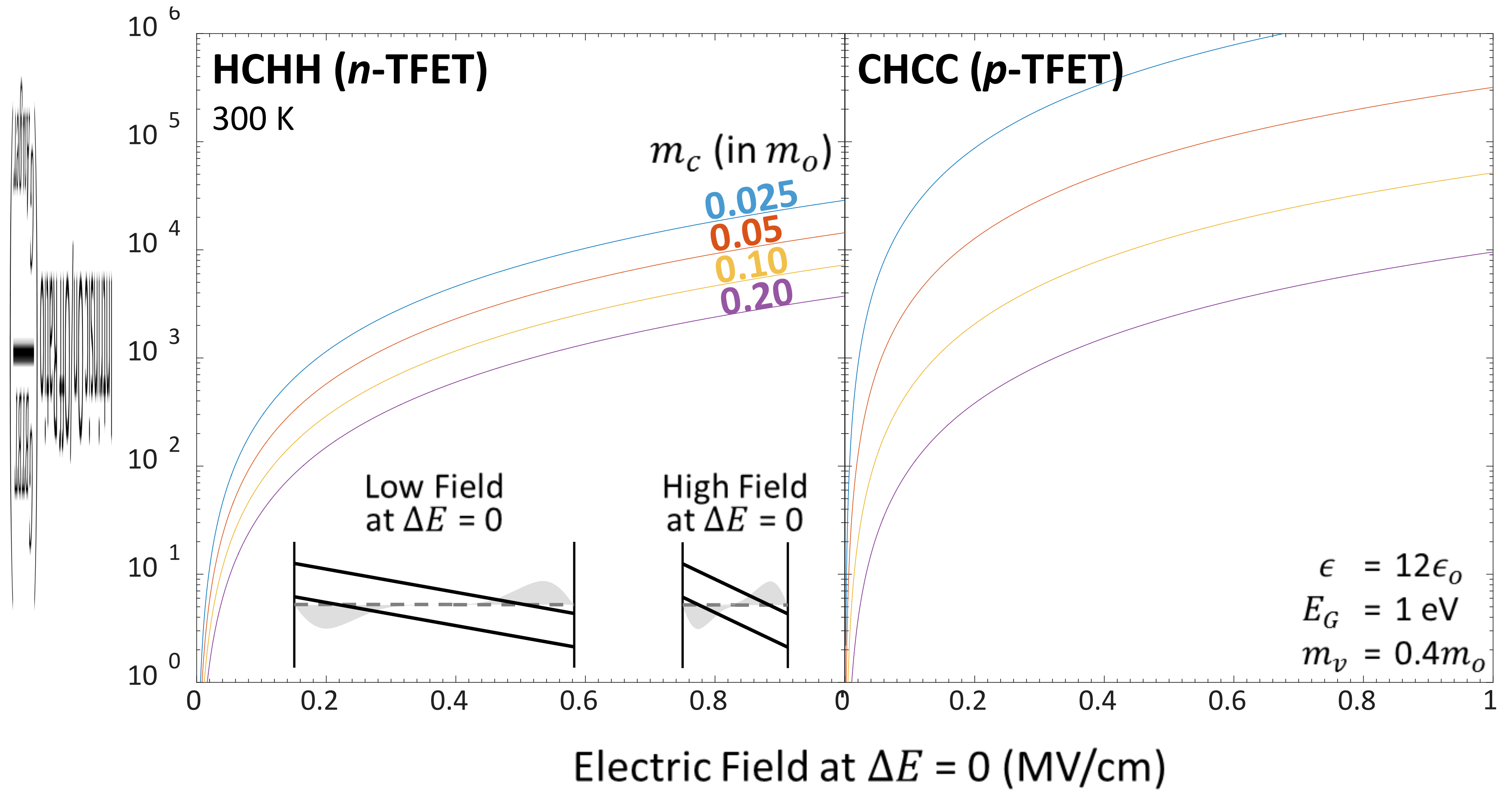
- Both can be viewed as generation and recombination events
- Fermi's Golden Rule can be used to calculate transition rate
  - $U_{Auger} = R - G = \frac{1}{A}\frac{2\pi}{\hbar}\sum_{1,1',2,2'} P(1,1',2,2')\,|M|^2\,\delta(E_1 - E_{1'} + E_2 - E_{2'})$
  - $U_{BTBT} = R - G = \frac{1}{A}\frac{2\pi}{\hbar}\sum_{1,1'} P(1,1')\,|M|^2\,\delta(E_1 - E_{1'})$
- $M_{Auger} = \frac{q^2}{2\epsilon A} c_u \delta_{\boldsymbol{k}_{\perp 1} - \boldsymbol{k}_{\perp 1'} + \boldsymbol{k}_{\perp 2} - \boldsymbol{k}_{\perp 2'}} \langle \psi_{1'} | \psi_1 \rangle$
- $M_{BTBT} = \int \Psi_{1'}^*(\boldsymbol{r})\, q\phi(z)\, \Psi_1(\boldsymbol{r})\, d^3\boldsymbol{r}$

  $= (qF) z_{cv} \delta_{\boldsymbol{k}_{\perp 1} - \boldsymbol{k}_{\perp 1'}} \langle \psi_{1'} | \psi_1 \rangle$



- At $\Delta E = 0$: $\frac{G_{BTBT}}{G_{CHCC}} = \frac{(qF)^2}{E_G} \frac{2\pi^2\hbar^6\epsilon^2}{q^4 m_c{}^3 (kT)^2 c_u{}^2} \frac{(2\mu+1)^2}{(\mu+1)} \frac{N_c}{n}$

Intrinsic on/off ratio (at turn-on) for TFETs due to Auger generation



At $\Delta E = 0$: $\frac{G_{BTBT}}{G_{CHCC}} = \frac{(qF)^2}{E_G} \frac{2\pi^2\hbar^6\epsilon^2}{q^4 {m_c}^3 (kT)^2 {c_u}^2} \frac{(2\mu+1)^2}{(\mu+1)} \frac{N_c}{n}$

Some remarks

Auger is intrinsic, no easy way to reduce it

—Decreasing doping decreases Auger, but also reduces field and hence BTBT

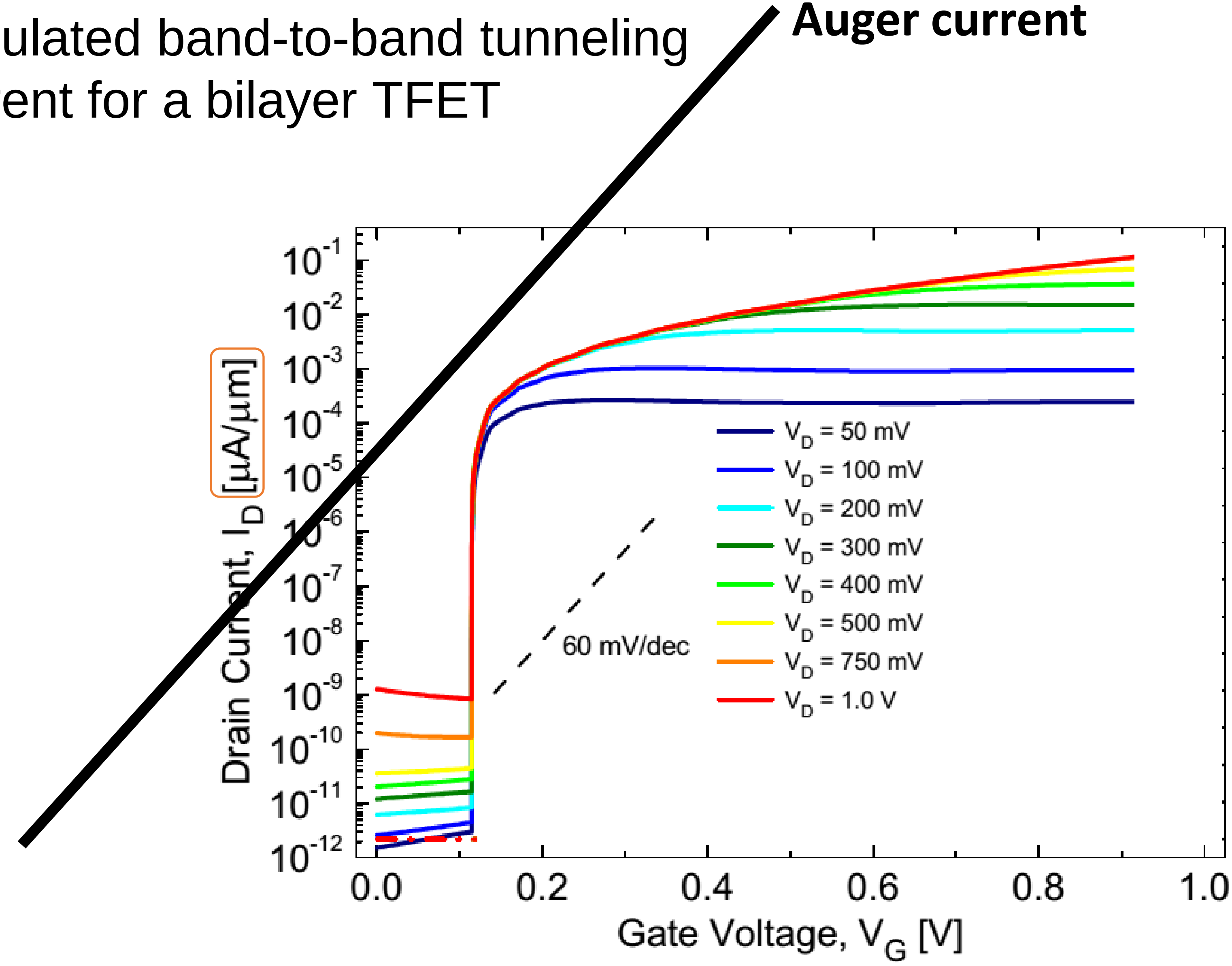
—Problematic for steep slope device because of Arrhenius dependence on ΔE

Auger and BTBT are both *generation* phenomena, and are tightly linked

—Decreasing Auger likely decreases BTBT as well

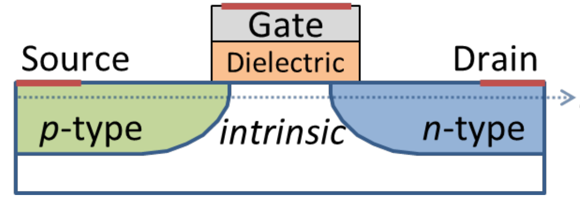
Simulated band-to-band tunneling current for a bilayer TFET

Auger current

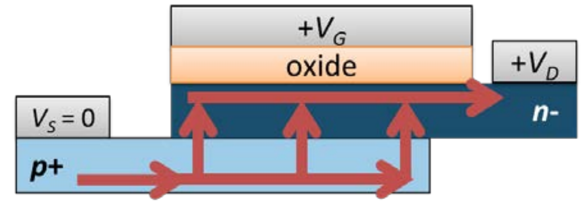


EDL 2011.

Future Work



Point TFET



Perpendicular TFET

- Extending the analysis to different device geometries
  - Point TFET
- Experimental verification of Auger phenomenon
  - Vary doping with electrostatic gating
- Demonstration of an Auger FET with sub-60 mV/decade SS

Summary

- Experimental TFETs have not lived up to *ideal* simulations
- We need to understand the reasons for the discrepancies
- Auger can be especially problematic for small E_G or ΔE
  - leads to significant off-state currents that may dictate subthreshold behavior
- Future TFET work must include non-ideal effects such as Auger