

September 16, 2013

Tunneling Transistors for Low Power Electronics

James Teherani, Tao Yu,
Dimitri Antoniadis, Judy Hoyt



Support from
NSF E3S Center

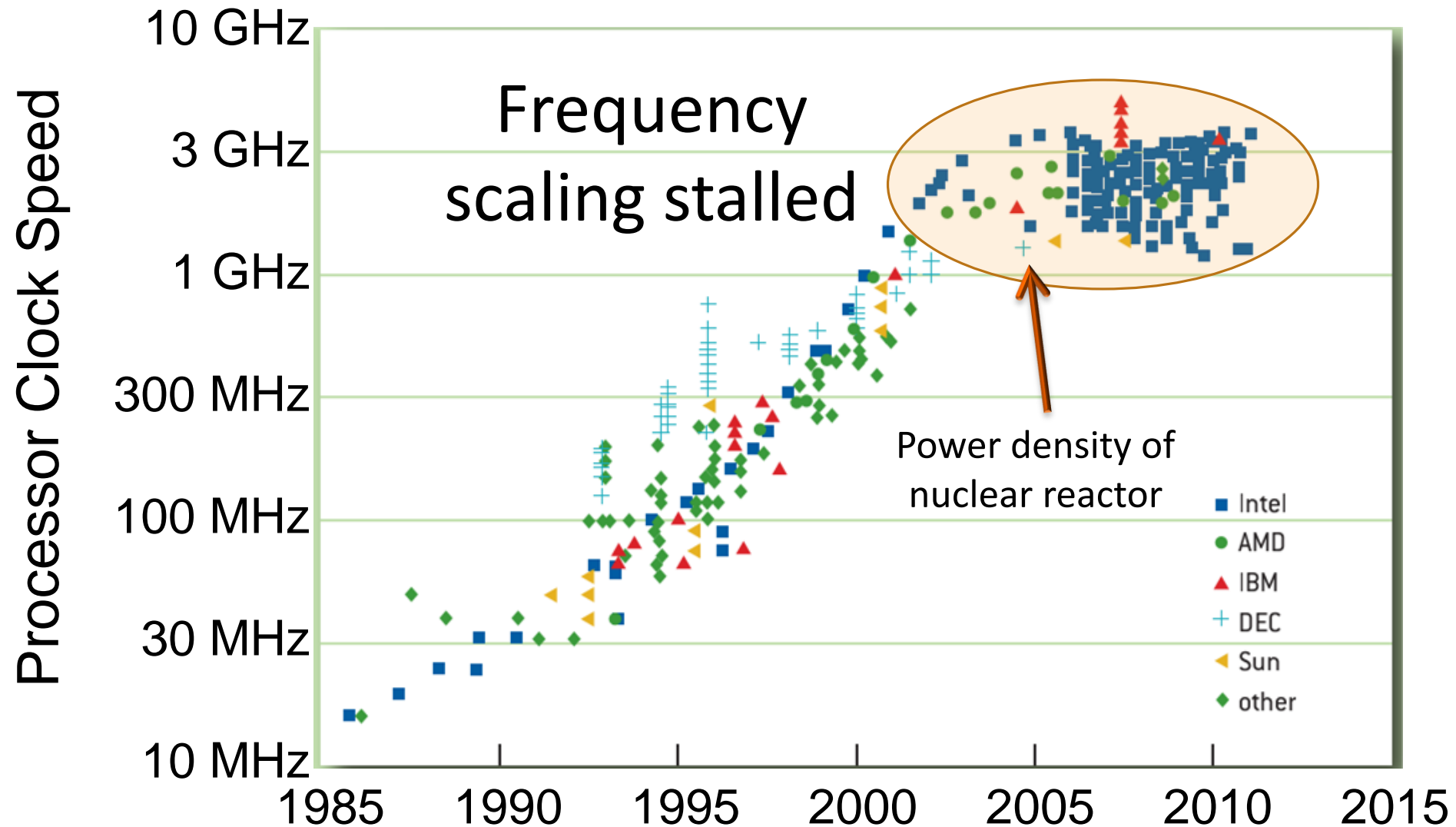




MOSFET

TFET
(tunneling transistor)

MOSFET Scaling Crisis

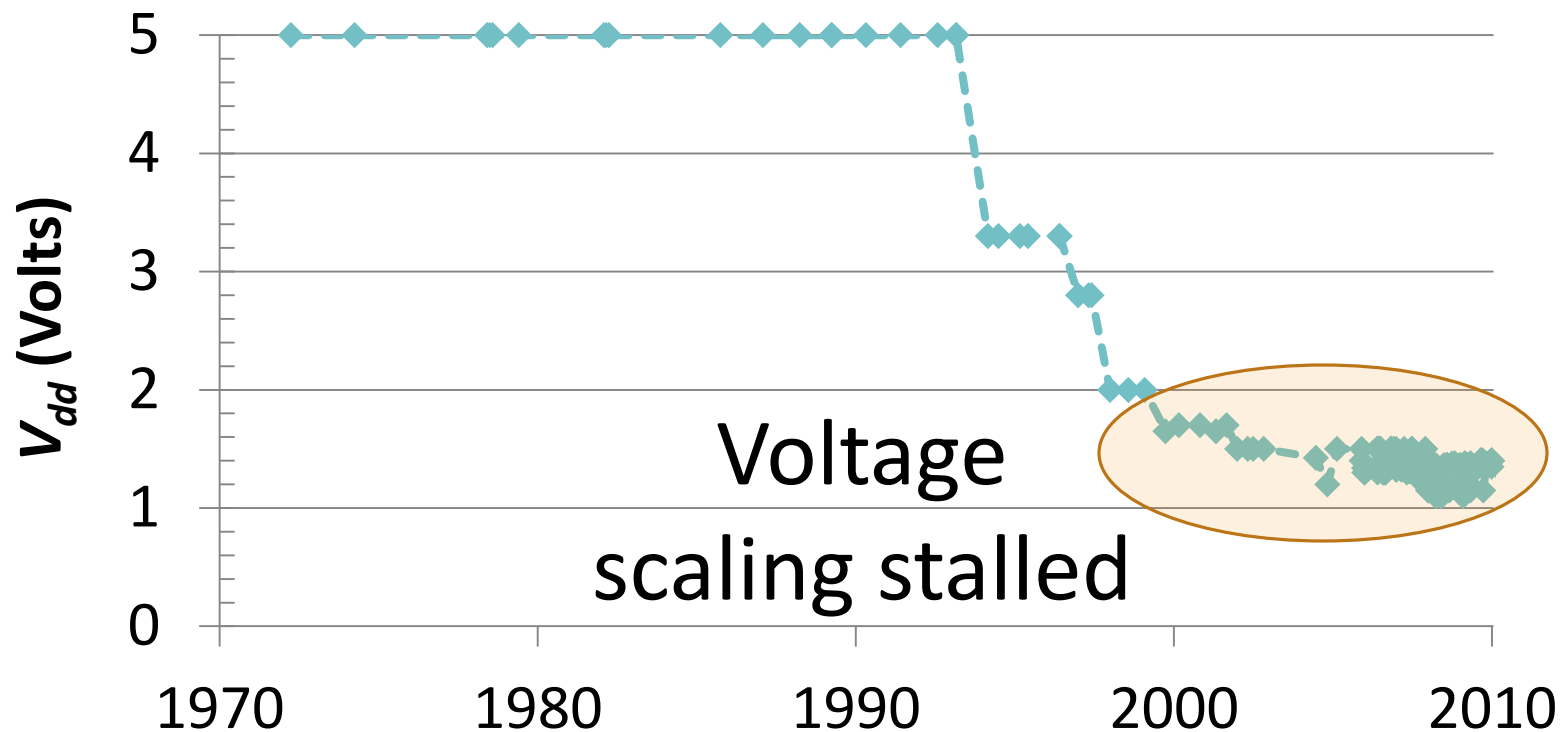


Power & Voltage Scaling

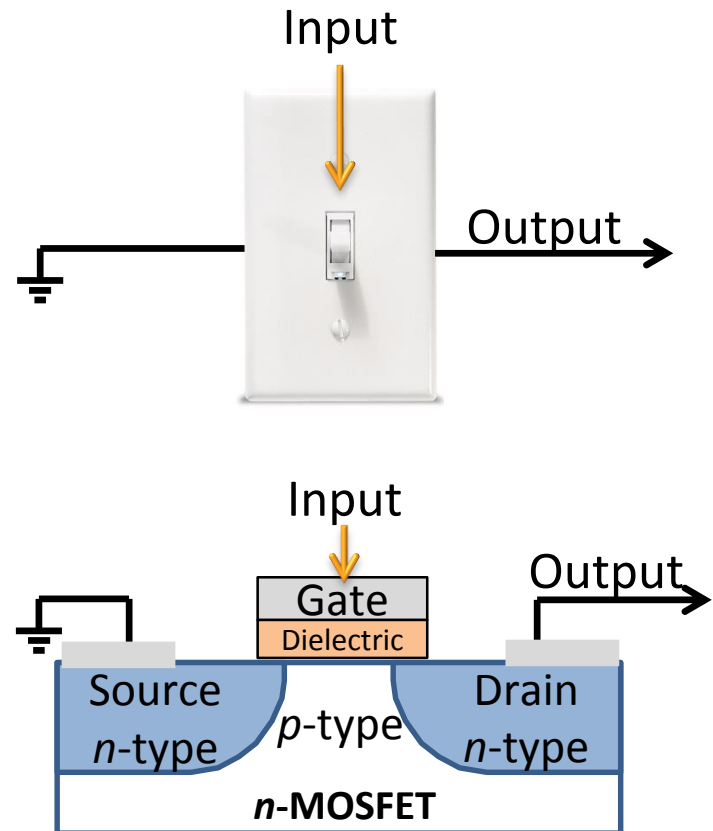
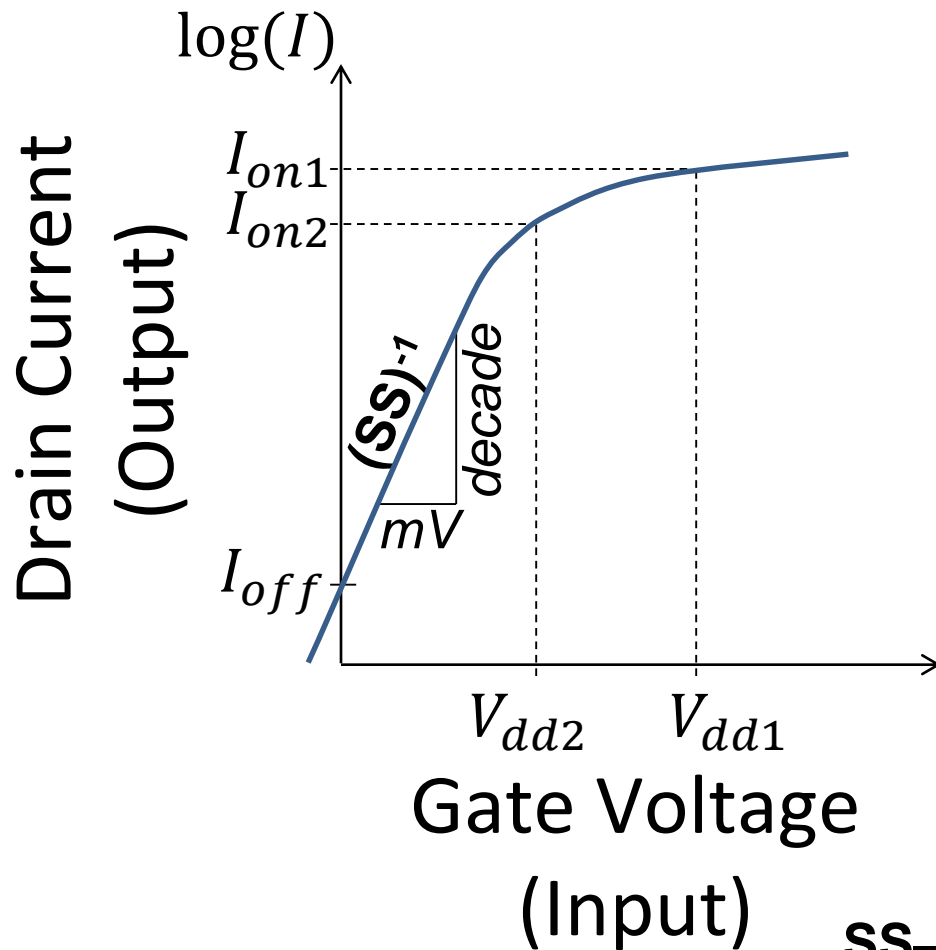
$$P_{active} = \alpha C V_{dd}^2 f$$

$$P_{passive} = I_{off} V_{dd} + I_G V_{dd}$$

$$P_{total} = P_{active} + P_{passive}$$

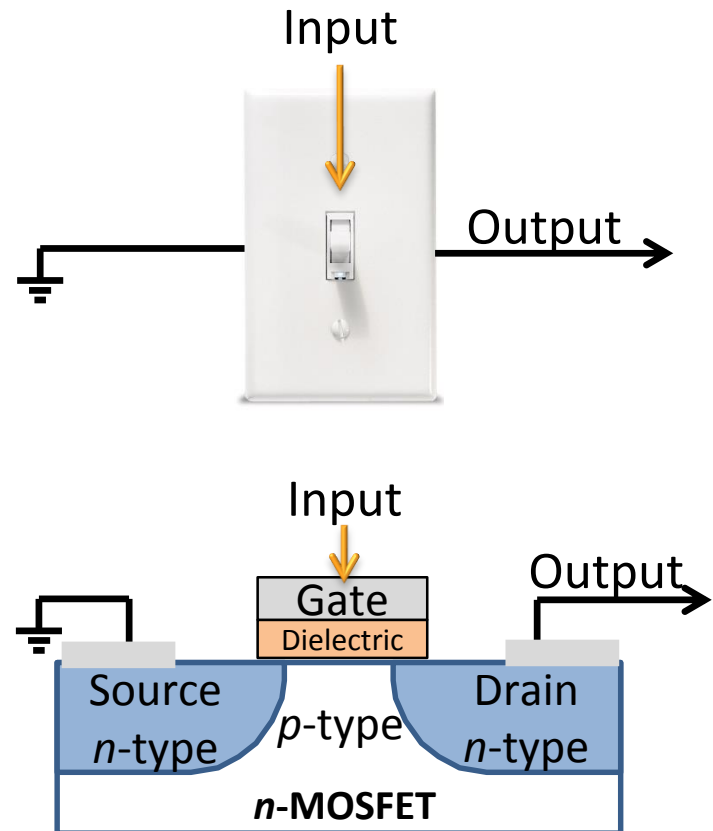
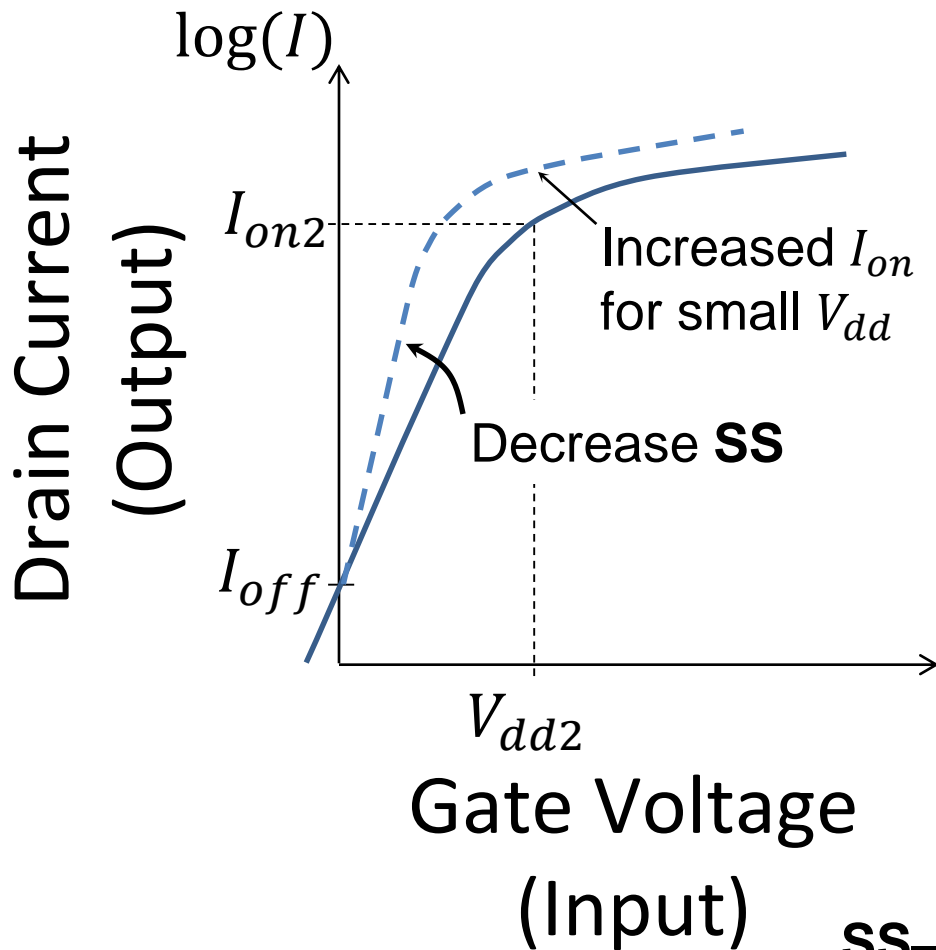


Transistor Transfer Characteristics



SS—subthreshold swing (mV/decade)

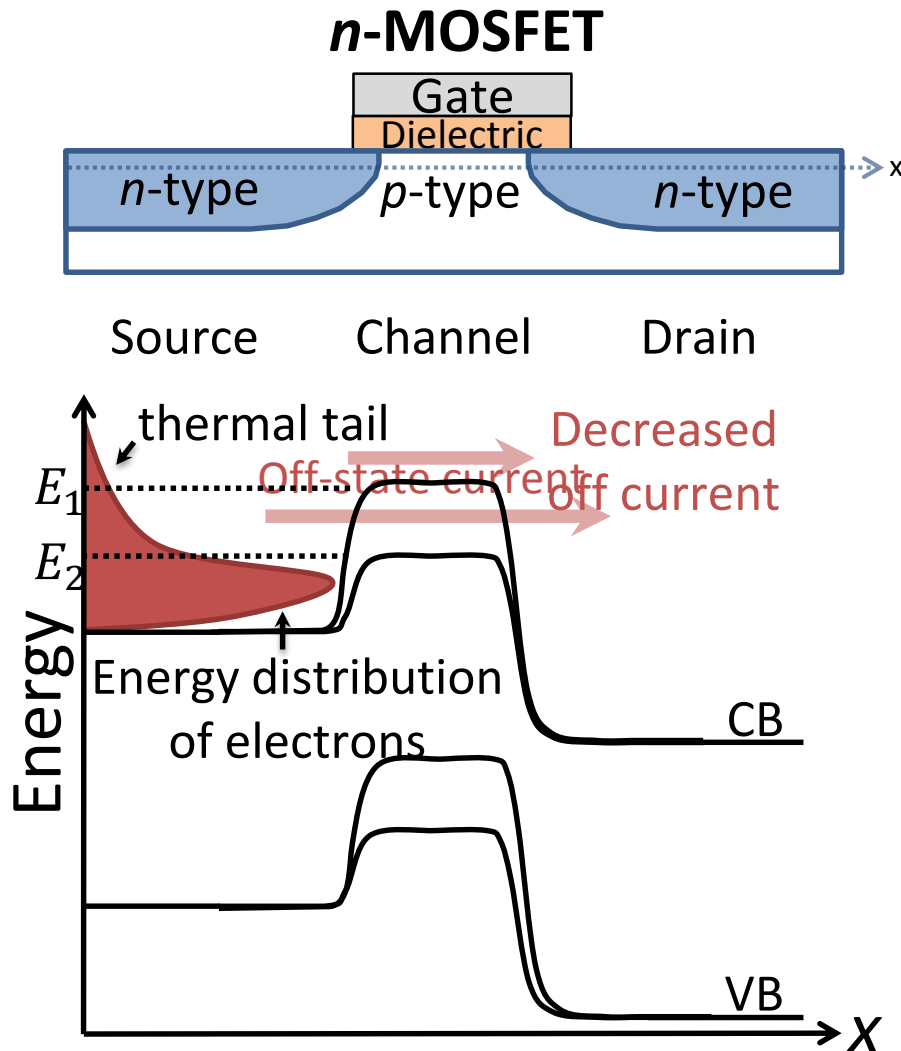
Transistor Transfer Characteristics



SS—subthreshold swing (mV/decade)

- If:
 - Reduce SS (subthreshold swing)
- Then:
 - $\downarrow V_{dd}$
 - $\downarrow P_{total}$

SS–Subthreshold Swing (MOSFET)



SS limited to
60 mV/decade

Distribution of Electrons

$$n(E) = f(E) \cdot g_{DOS}(E)$$

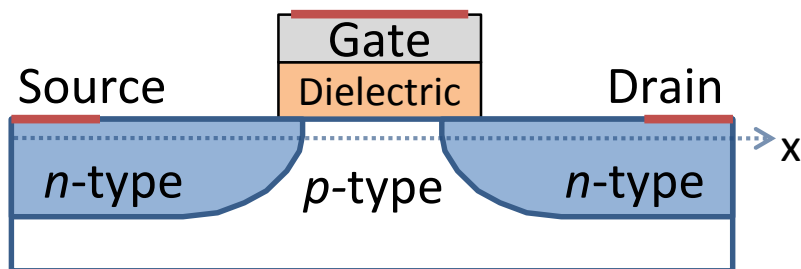
Fermi-Dirac Distribution

$$f(E) \approx \frac{1}{\exp\left(\frac{E - E_f}{kT}\right)}$$

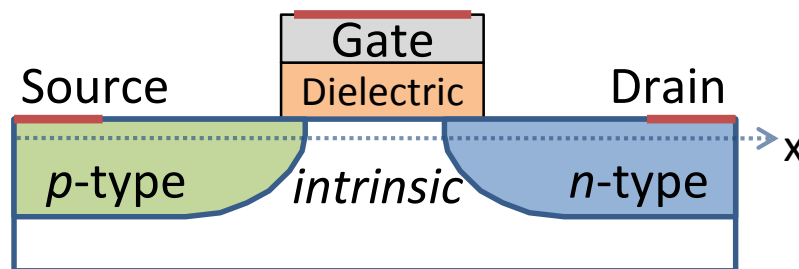
$$f(E) \Rightarrow 60 \text{ mV/decade}$$

$$\frac{f(E_1)}{f(E_2)} \approx \exp\left(\frac{E_2 - E_1}{kT}\right)$$

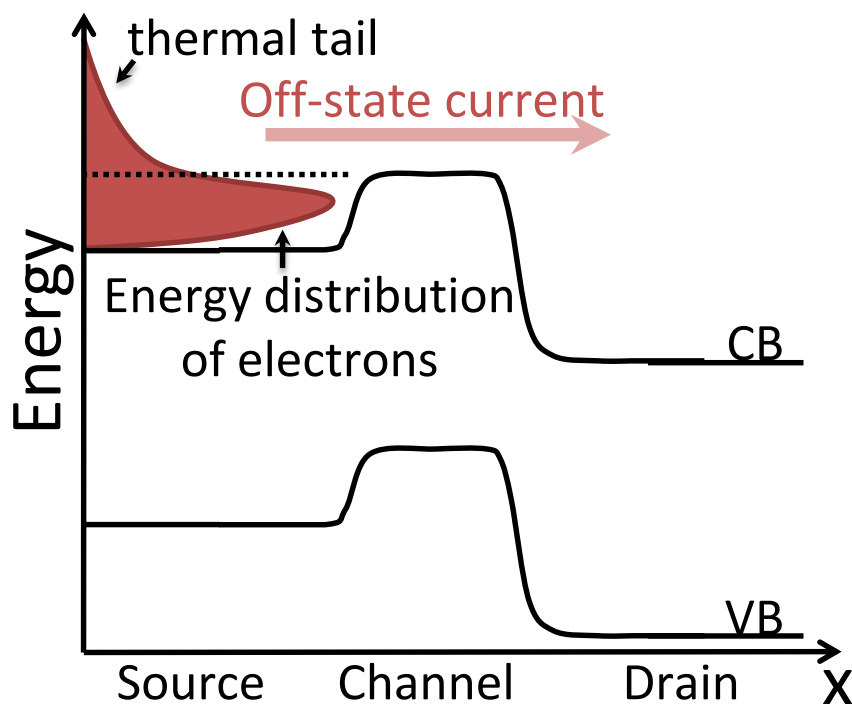
MOSFET and TFET Structures



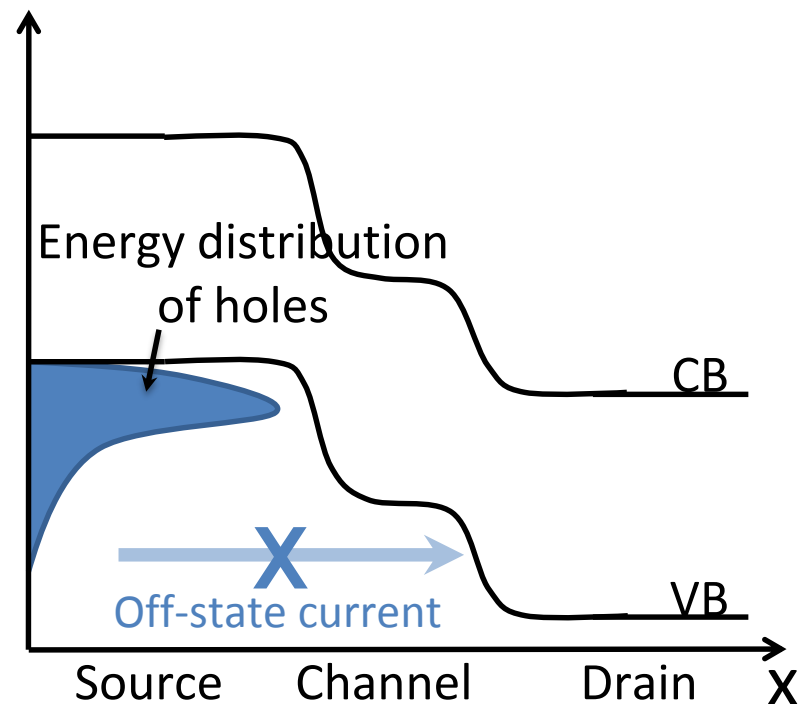
***n*-MOSFET**



***n*-TFET**

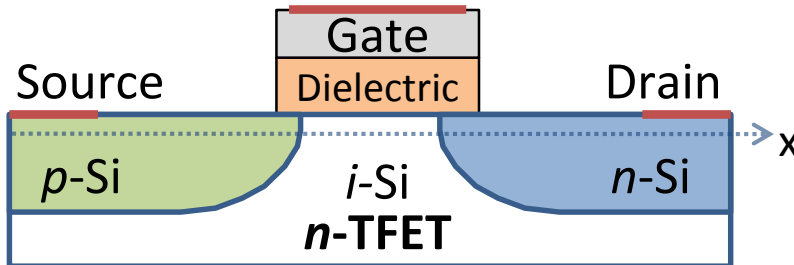


Limited SS of 60 $mV/decade$

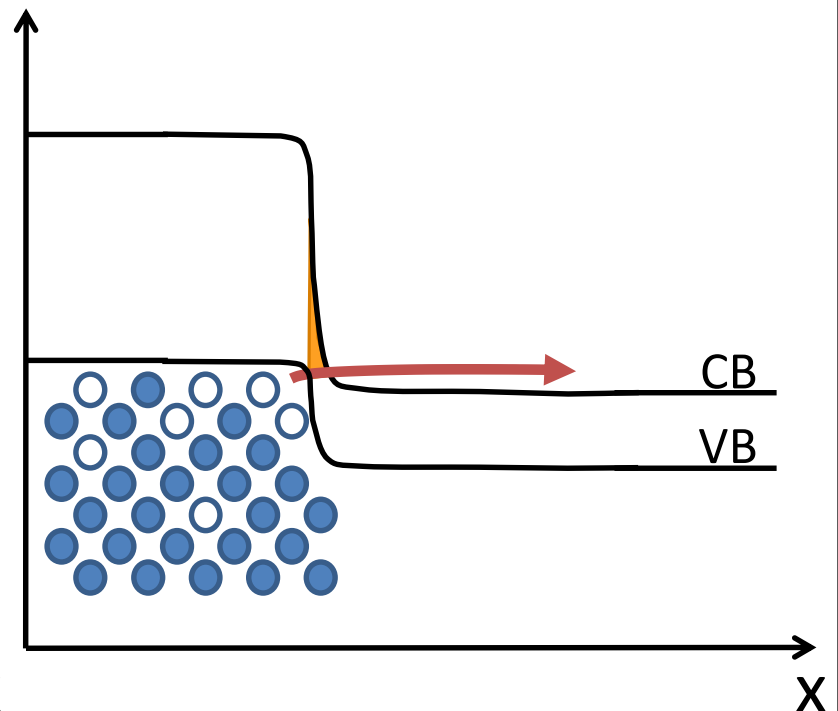
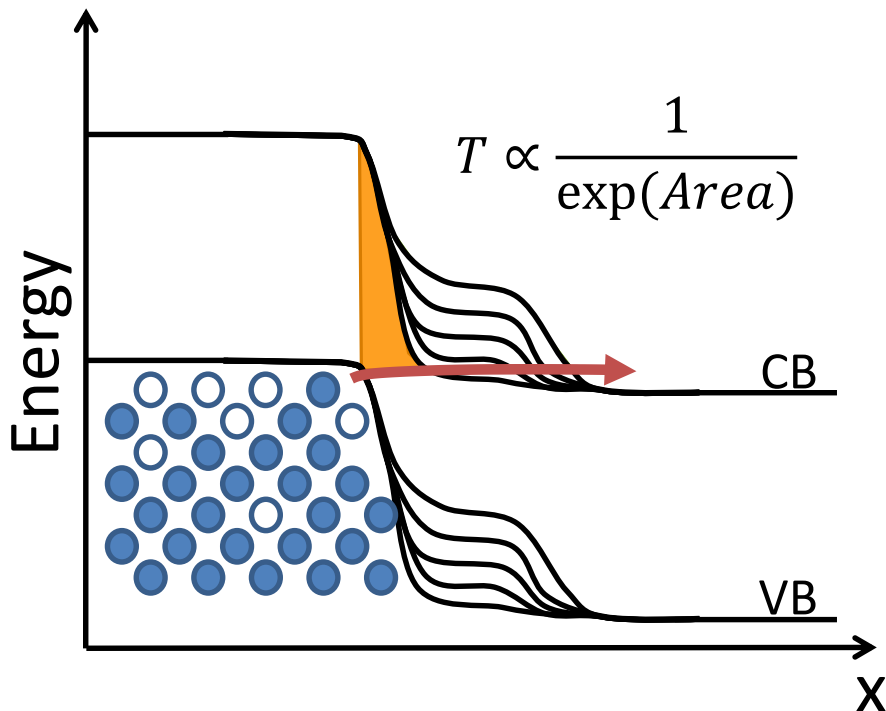
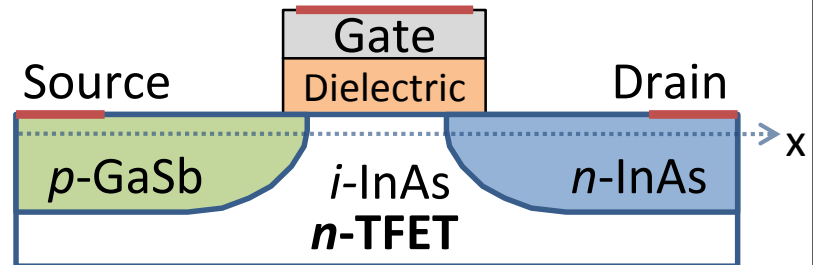


No 60 $mV/decade$ limit

Tunneling in Homostructure



Heterostructure



Experimental Results

Appenzeller: Carbon Nanotubes for High-Performance Electronics

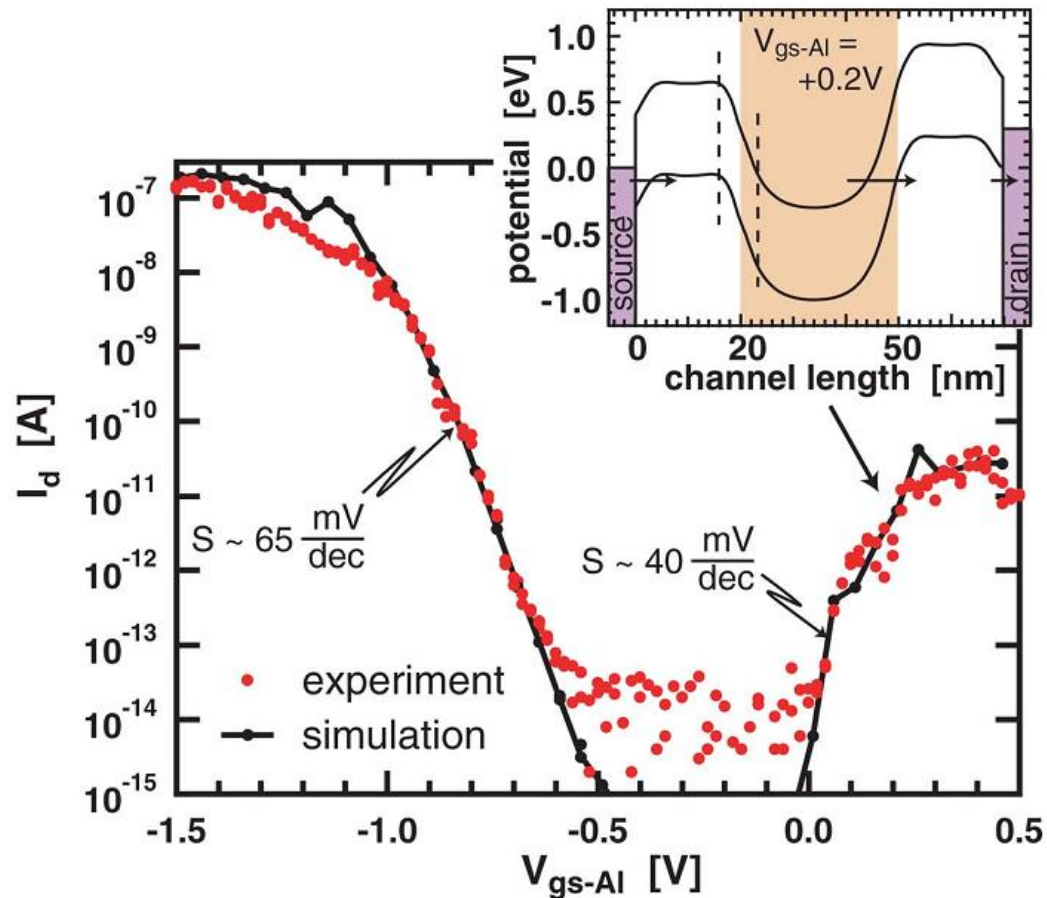
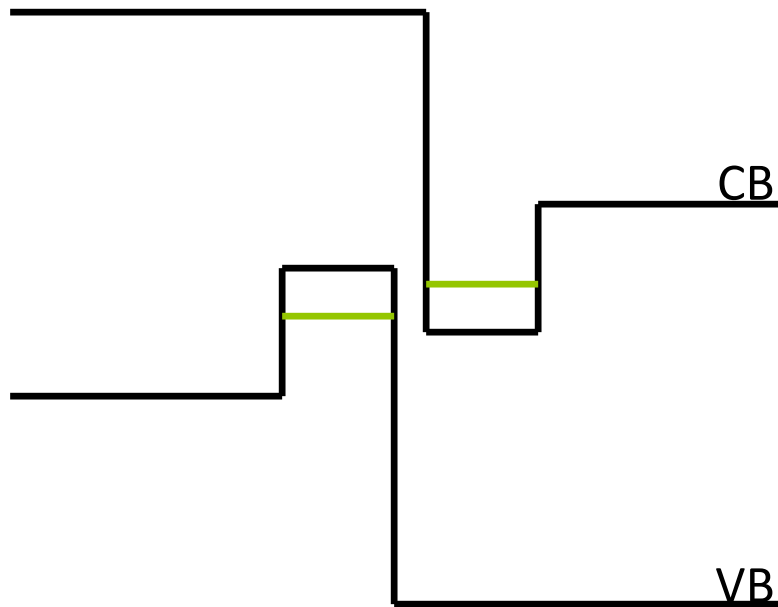


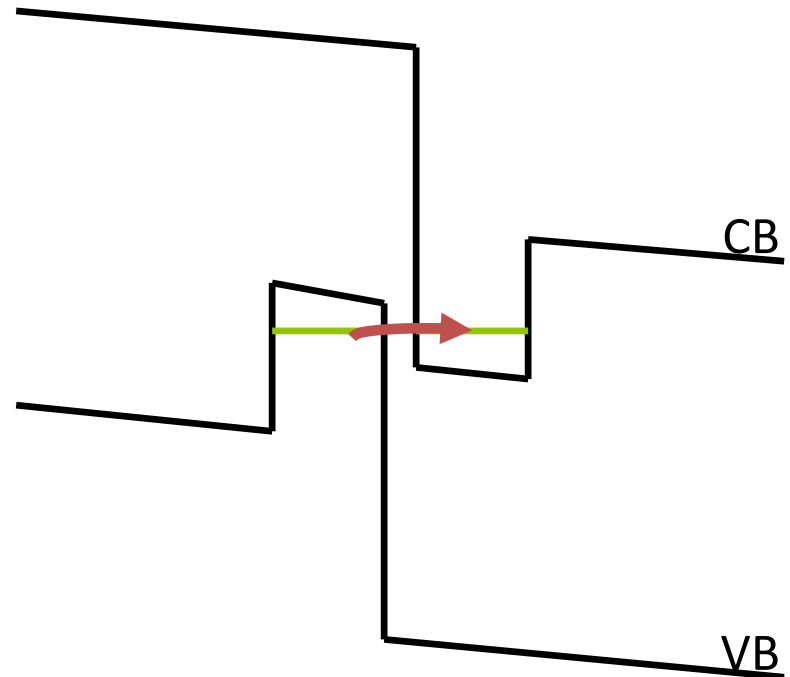
Fig. 12. Experimental and simulated $I_d(V_{gs-Al})$ for a drain voltage of $V_{ds} = -0.5$ V and $V_{gs-Si} = -3$ V. The upper inset shows the band bending situation under tunneling conditions from the simulation.

Density of States Switch

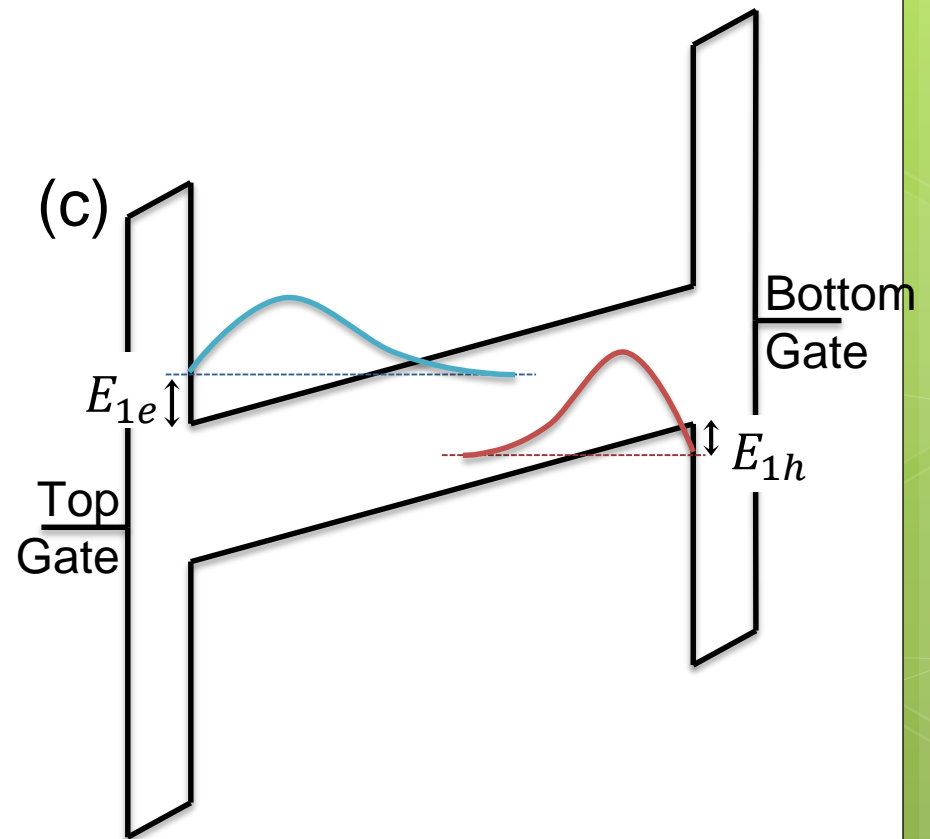
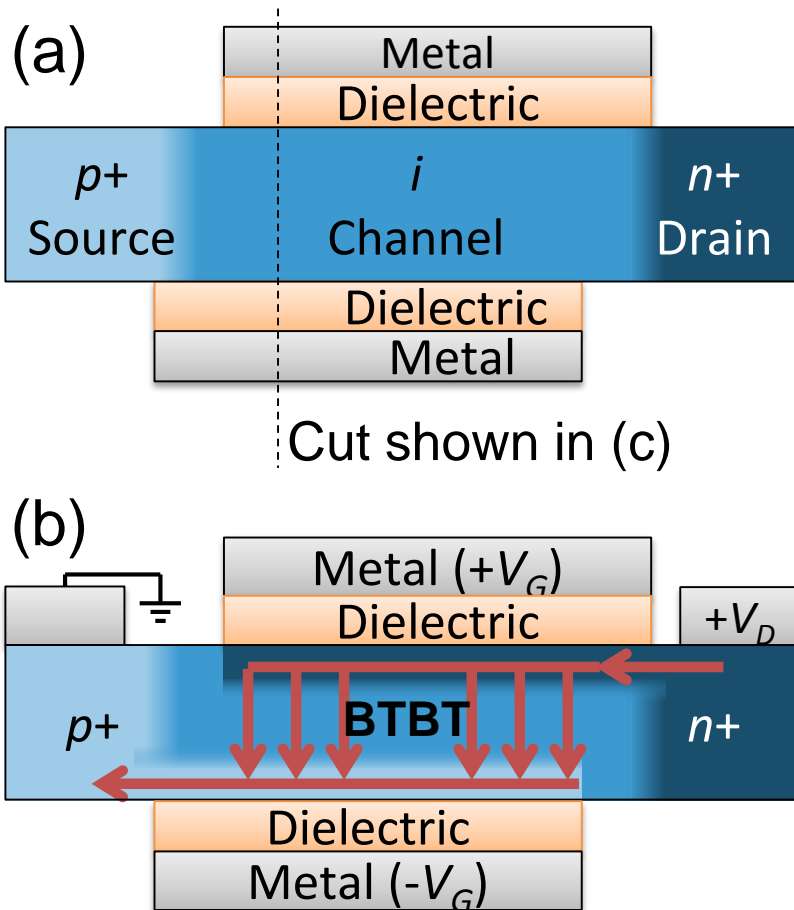
OFF-State



ON-State



Bilayer TFET Structure



Challenges Limiting TFET Performance

- Fundamental
 - Phonon effects
 - Band edge abruptness
- Technological
 - Interface states
 - Complex geometries, design
 - Junction abruptness
 - Thickness variation with thin body structures
 - Work function engineering

Summary

- Frequency and voltage scaling of MOSFETs have stalled due to power constraints
- Substantial voltage scaling requires new switching physics
- TFETs employ tunneling to overcome 60 mV/decade limit
 - Experimental results have shown $SS < 60 \text{ mV/decade}$, albeit at low currents
 - Much work is still needed in matching theory to experiment
- Heterojunctions and density-of-states switching designs may lead to better TFET performance
- We're currently exploring the bilayer TFET, which utilizes an interesting device geometry to create electron and hole quantum wells