

There are Orders-of-Magnitude Power  
Advantages  
in Complementing the Transistor  
With a Milli-Volt Switch

MTO Symposium  
San Jose, CA, March 7, 2007

Eli Yablonovitch  
UCLA EE Dept.  
& UC Berkeley EECS Dept.

Read the current going through a resistor, in the presence of noise:

$$(\Delta i)^2 = 2q i \times \Delta f \dots\dots\dots \text{Shot Noise}$$

$$(\Delta i)^2 = \frac{4kT}{R} \times \Delta f \dots\dots\dots \text{Johnson Noise}$$

$$\text{Required voltage } V = iR \gg 2kT/q \sim 50\text{mVolts}$$

$$\text{Signal – to – Noise Ratio} = \frac{i}{\sqrt{2q i \Delta f}} = \sqrt{\frac{i}{2q \Delta f}}$$

$$i > 2q \times \Delta f$$

$$\text{Required power } iV > 2q \Delta f \times \frac{2kT}{q} = 4kT \times \Delta f$$

With a safety margin:

Energy Consumed  $\sim 40 kT$  per bit processed

What will be the energy cost, per bit processed?

1. Logic                      energy cost  $\sim 40kT$  per bit processed
2. Storage                    energy cost  $\sim 40kT$  per bit processed
3. Communications      currently  $> 100,000kT$  per bit processed

.

There are many type of memory possible:

1. Flash
  2. SRAM
  3. Dram
  4. Magnetic Spin
  5. Nano-Electro-Chemical Cells
  6. Nano-Electro-Mechanical NEMS
  7. Moletronic
  8. Chalcogenide glass (phase change)
  9. Carbon Nanotubes
- -

Similarly there are many ways to do logic.

But there are not many ways to communicate:

1. Microwaves (electrical)
2. Optical

What is the energy cost for electrical communication?

$$V_{noise}^2 = 4kT R \Delta f$$

$$\frac{V_{noise}^2}{R} = 4kT \Delta f$$

$$\text{Signal Energy} \geq \frac{\text{Noise Power}}{\text{per bit}} = 4kT \text{ per bit}$$

All information processing costs  $\sim 40kT$  per bit.

(for good Signal-to-Noise Ratio)

Great!

So what's the problem?

# The transistor will have to be replaced by a 1milli-Volt switch:

The natural voltage range for wired communication is rather low:

$$V_{\text{noise}}^2 = 4kTR \Delta f$$

$$V_{\text{noise}}^2 = 4kTR \frac{1}{RC}$$

$$V_{\text{noise}}^2 = 4kT \times \frac{1}{C}$$

$$V_{\text{noise}}^2 = \frac{4kT}{q} \times \frac{q}{C}$$

$$V_{\text{noise}} = \sqrt{\underbrace{4kT/q}_{100\text{mVolts}} \times \underbrace{q/C}_{10\mu\text{Volts}}}$$

$$V \approx 1 \text{ mVolt}$$

The wire wants  
1000 electrons at 1mVolt each.

(to fulfill the signal-to-noise requirement  $>1\text{eV}$  of energy)

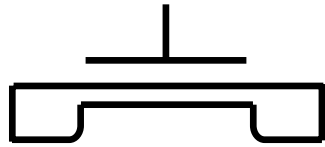
The natural voltage range for a thermally activated switch like transistors is  $\gg kT/q$ , eg.  $\sim 40kT/q$   
or about  $\sim 1\text{Volt}$

**Voltage Matching Crisis  
at the nano-scale!**

**If you ignore it the penalty will be  
 $(1\text{Volt}/1\text{mVolt})^2 = 10^6$**

The thermally activated device wants at least one electron at  $\sim 1\text{Volt}$ .

A low-voltage technology, or an impedance matching device, needs to be invented/discovered at the Nano-scale:



transistor amplifier with steeper sub-threshold slope

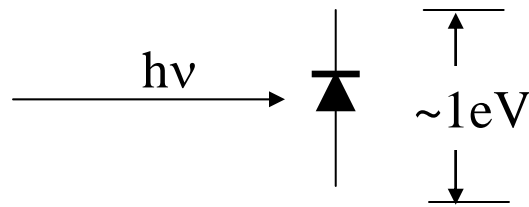
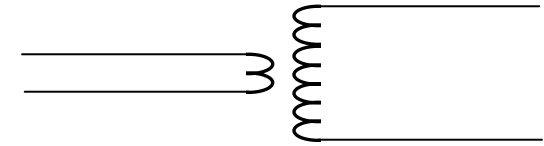


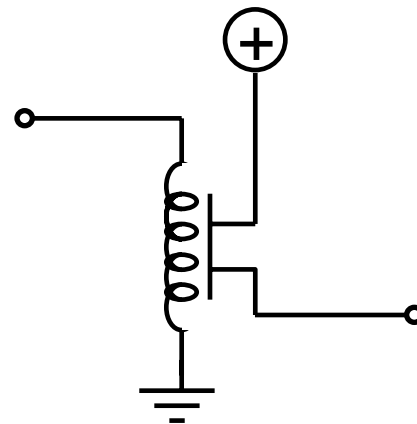
photo-diode



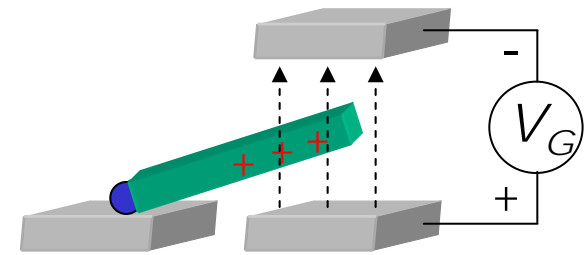
nano-transformer



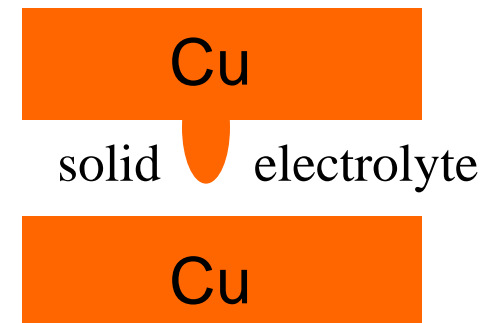
Cryo-Electronics  
 $kT/q \sim q/C$



giant magneto-resistance  
spintronics



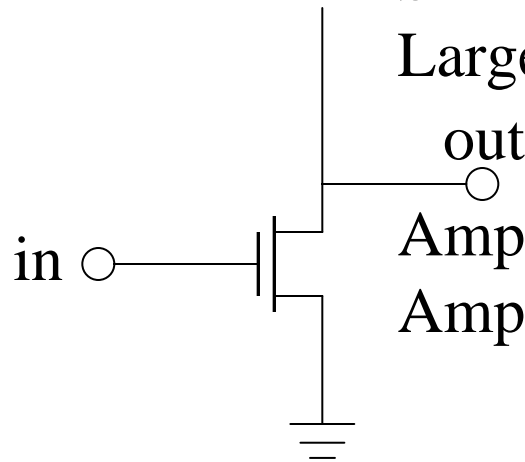
MEM's switch



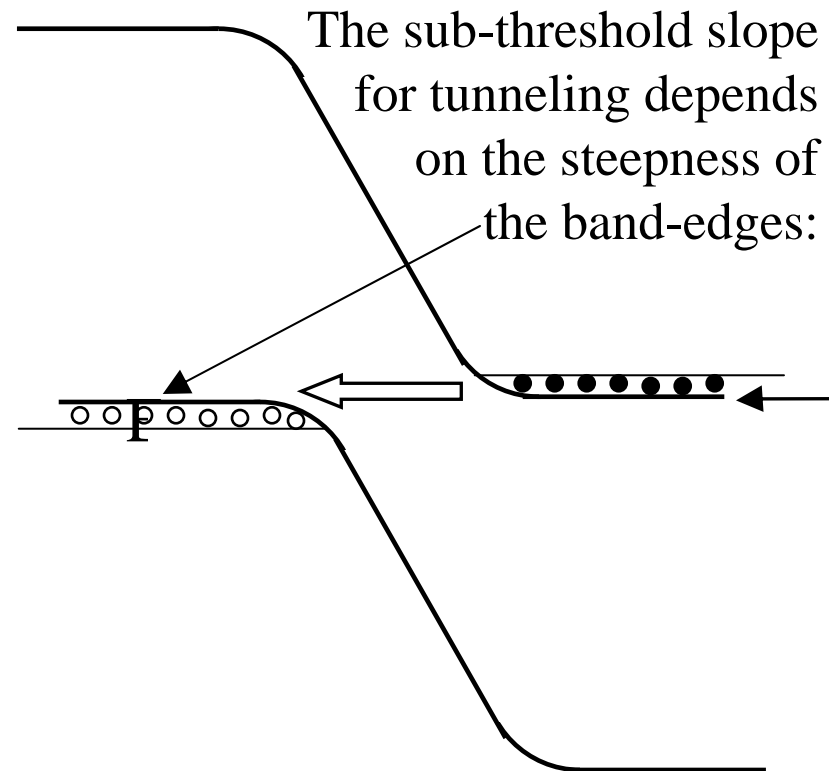
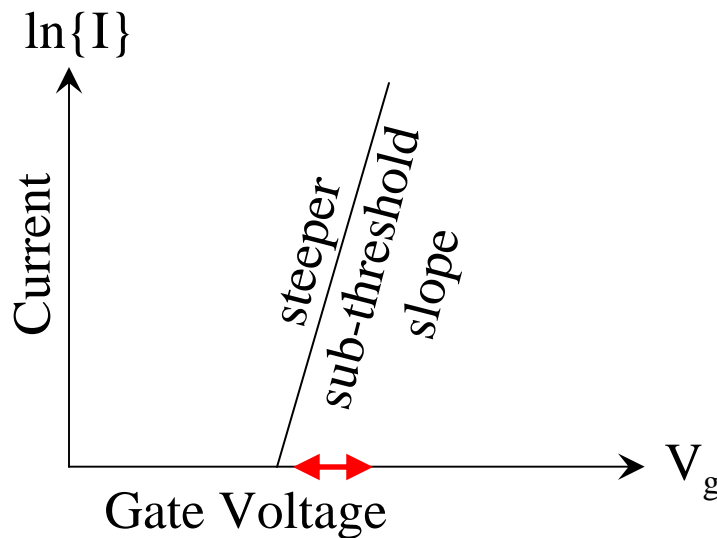
Electro-Chemical Switch

# An amplifying transistor as a voltage matching device:

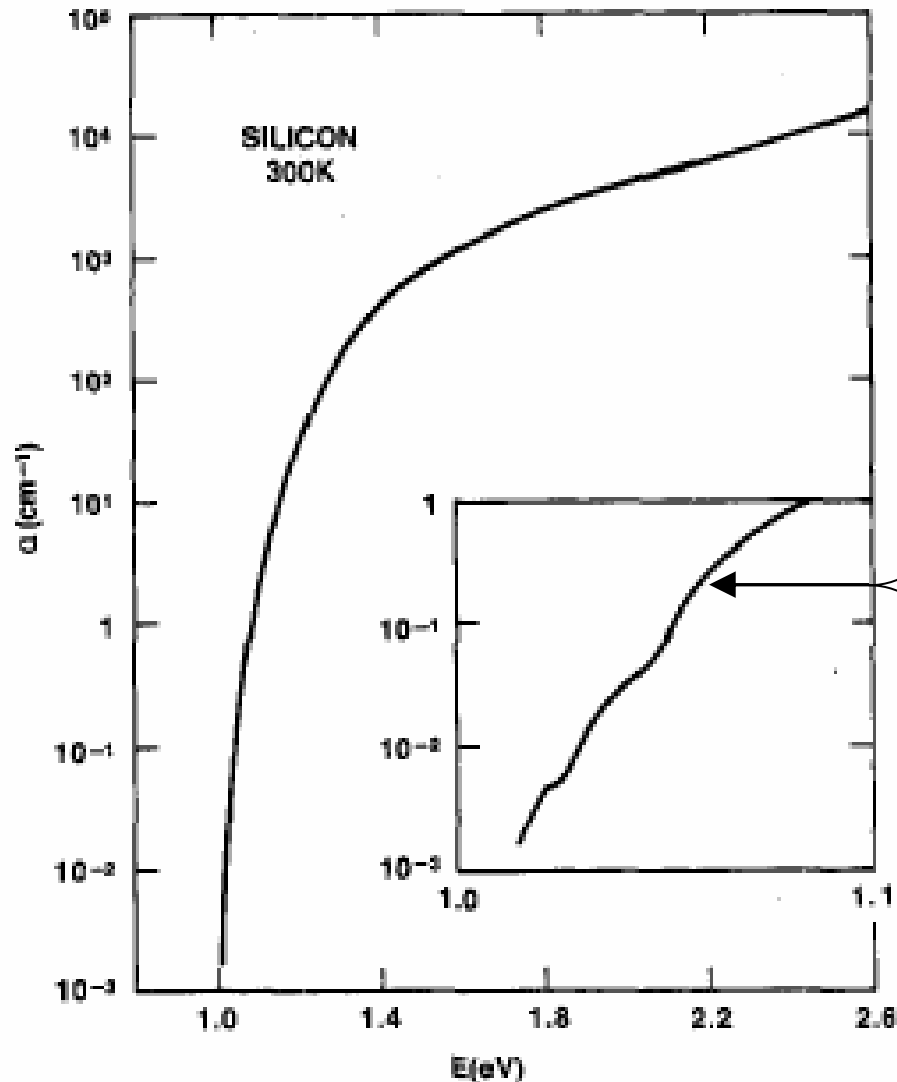
Small voltage in  
Large voltage out



Amplification of weak signals has an energy cost!  
Amplification of weak signals has a speed penalty!



The optical absorption coefficient,  $\alpha(h\nu)$ , of Si at 300K, in the vicinity of the band edge.



The Urbach edge  
grows as:

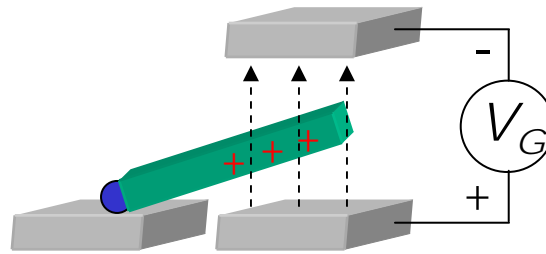
$$\alpha(h\nu) \sim \exp\{(h\nu - E_g)/E_o\},$$

where the  $E_o$  parameter is a  
type of sub-threshold slope.

$$E_o \sim 10\text{meV for Silicon}$$

It's good, but it should be better.  
We need to search for materials  
with steeper band-edges!

# Nano-Mechanical Switch:



$$I \sim \exp(-3qV_G/kT)$$

for 3 charges on the MEM's tip

## Recommendations:

1. Medium and long-range internal communication is beset by a Voltage Matching problem, leading to severe energy inefficiency.
2. The transistor will have to be replaced by a 1milli-Volt switch:
3. Metallic or semi-metallic switches are likely to be more radiation hard.
4. Band edge steepness is poorly known, and should be investigated for a number of semiconductors and semi-metals.
5. How will the world change if the energy/bit-function drops by six orders of magnitude?