

**Low Energy Communication:
NanoPhotonic & Electrical**

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What is the energy cost of reading out your flash memory?



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

Units:

$\sim 40kT/\text{bit}$ of information

0.016 atto-Joules/bit of information

0.16 nano-Watts/Gbit/second

This is about 10^6 times better
than we are doing today!

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 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

.

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 natural voltage range for wired communication is rather low:

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

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

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

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

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

$V \approx 1 \text{ mVolt}$

The wire wants
1000 electrons at 1mVolt each.
(to fulfill the signal-to-noise
requirement $>1\text{eV}$ of energy)

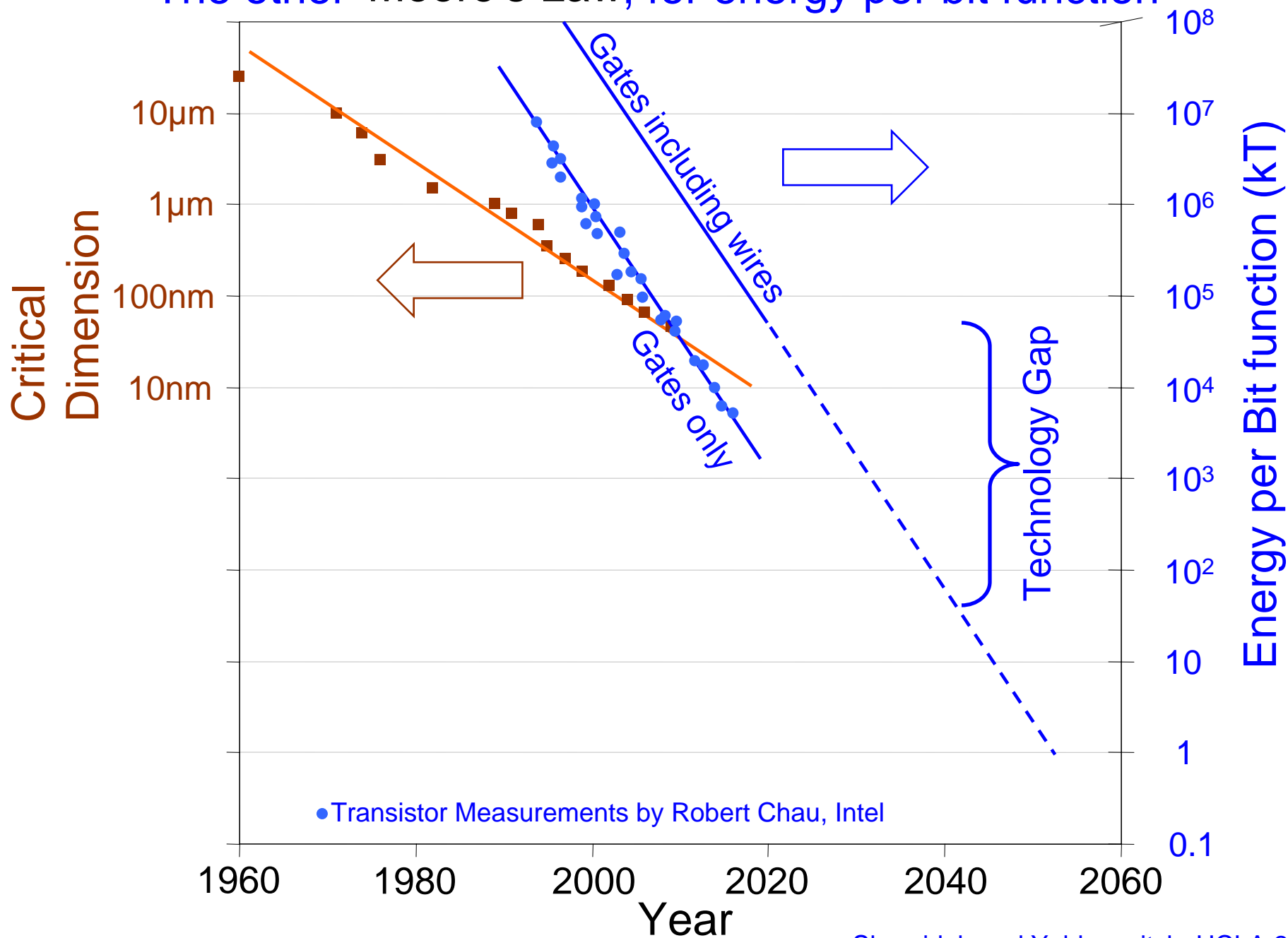
The natural voltage range for a thermally activated switch like transistors is $\gg kT/q$, eg. $\sim 40kT/q$
or about $\sim 1\text{Volt}$

**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 $\sim 1\text{Volt}$.

The other Moore's Law, for energy per bit function



The experts look ahead

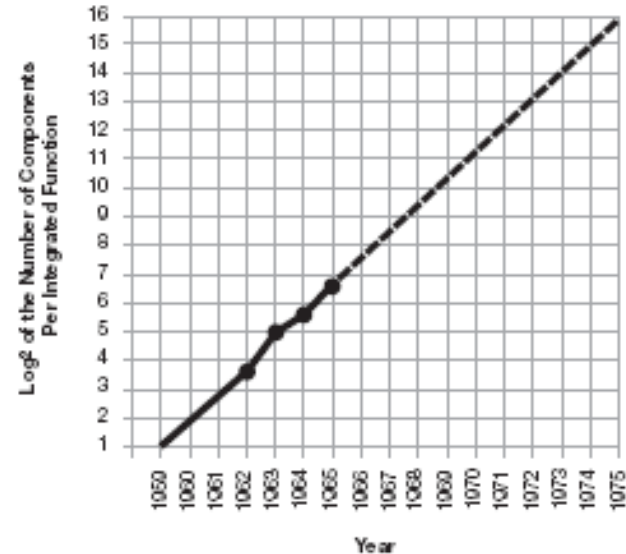
Cramming more components onto integrated circuits

With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip

By Gordon E. Moore

Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

Electronics, Volume 38, Number 8, April 19, 1965 p. 114



"In addition, **power is needed primarily to drive the various lines and capacitances associated with the system.** As long as a function is confined to a small area on a wafer, the amount of capacitance which must be driven is distinctly limited. In fact, shrinking dimensions on an integrated structure makes it possible to operate the structure at higher speed for the same power per unit area."



$$\text{Resistance, } R = \rho \frac{l}{a^2}$$

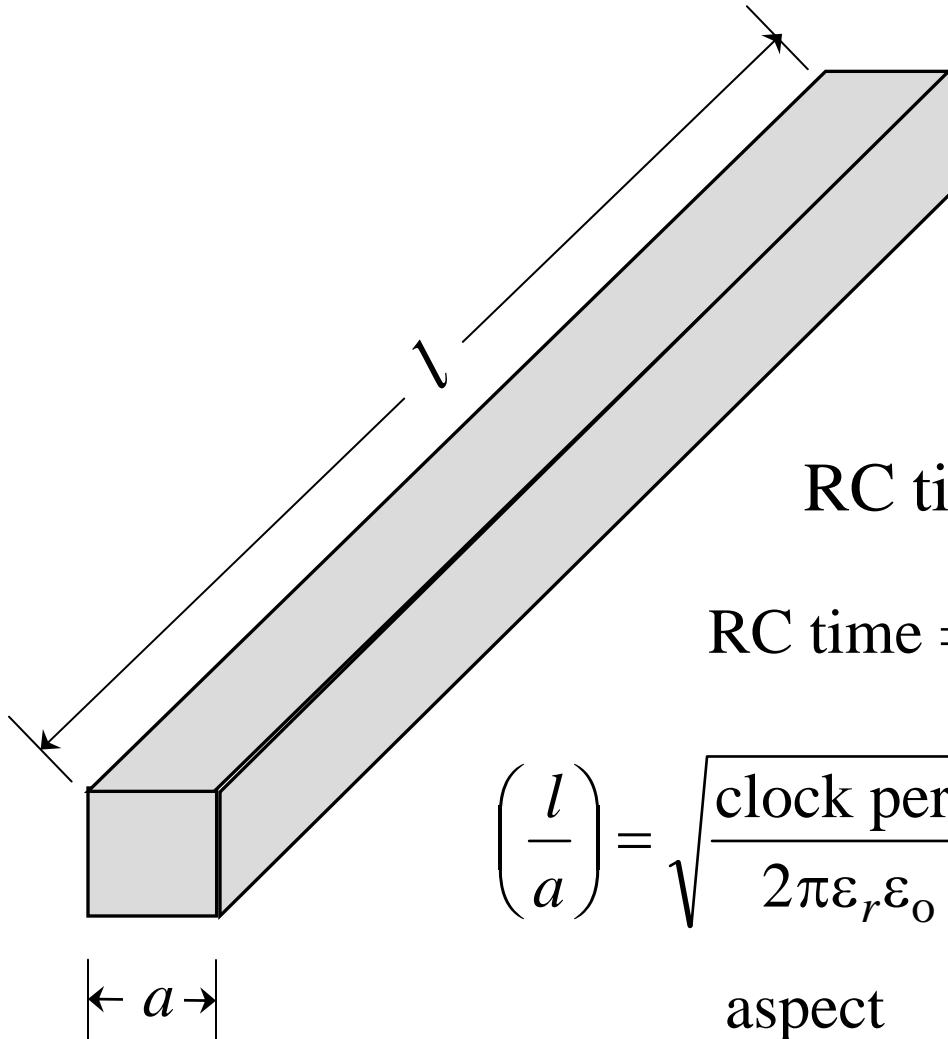
$$\text{Capacitance, } C \approx \epsilon_r \epsilon_o l$$

$$\text{RC time} \equiv RC \approx \epsilon_r \epsilon_o \rho \frac{l^2}{a^2} = \epsilon_r \epsilon_o \rho \left(\frac{l}{a} \right)^2$$

$$\text{RC time} = (\text{clock period}) / 2\pi$$

$$\left(\frac{l}{a} \right) = \sqrt{\frac{\text{clock period}}{2\pi \epsilon_r \epsilon_o \rho}} \approx \sqrt{\frac{10^{-10} \text{ sec}}{2 \times 10^{-12} \text{ F/cm } 2 \times 10^{-6} \Omega \text{cm}}}$$

$$\text{aspect ratio} \equiv \left(\frac{l}{a} \right) \approx 4800$$



$$\text{aspect ratio of wire} \equiv \left(\frac{l}{a} \right) \approx 4800$$

$$\begin{aligned} \text{Resistance, } R &= \rho \frac{l}{a^2} = \frac{\rho}{a} \left(\frac{l}{a} \right) = 4800 \frac{\rho}{a} \\ &= \frac{4800 \times 2 \times 10^{-6} \Omega \text{cm}}{45 \text{nm}} \\ &= 2000 \Omega \end{aligned}$$

$$\text{Capacitance, } C \approx \epsilon_r \epsilon_0 l = \epsilon_r \epsilon_0 a \left(\frac{l}{a} \right)$$

$$C = \epsilon_r \epsilon_0 a \times 4800$$

$$C \approx 7 \text{ femto-Farads}$$

$$\langle V^2 \rangle = 4kT R \Delta f$$

$$V_{\text{signal}} = 0.56 \text{ milli-Volts}$$

$$\langle I^2 \rangle = 4(kT/R) \Delta f$$

$$I_{\text{signal}} = 0.25 \mu\text{Amps}$$

What about very short wires?

Johnson Noise:

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

$$V_{noise}^2 = 4kT R \frac{1}{RC}$$

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

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

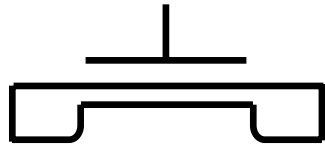
$$\text{If } \frac{4kT}{q} \approx \frac{q}{C},$$

then the signals could be large enough
to be efficiently amplified.

$$\text{If } C \leq \frac{q^2}{kT} \equiv \begin{array}{l} \text{The Coulomb} \\ \text{Blockade Capacitance.} \end{array} \approx 10 \text{ atto-Farads,}$$

For wires less than $1\mu\text{m}$, a conventional transistor amplifier
configuration may be adequate.

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

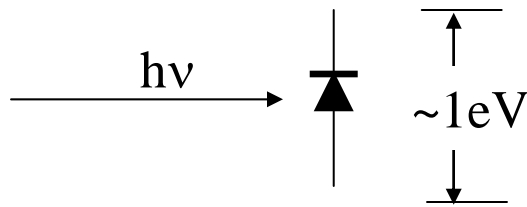
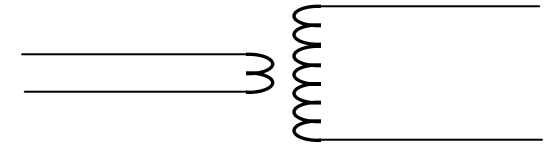


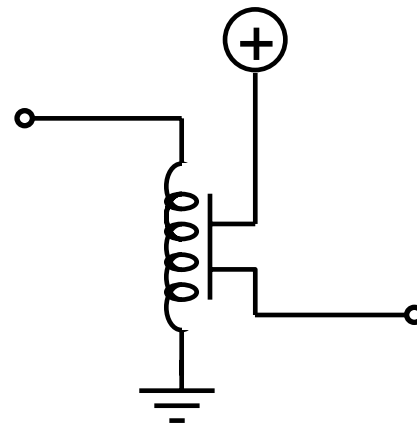
photo-diode



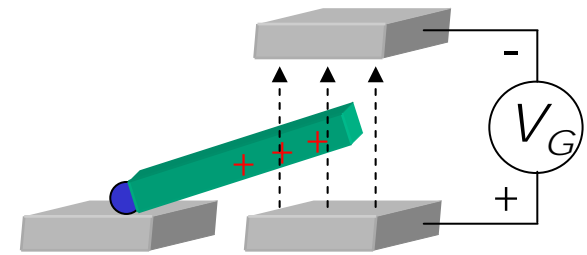
nano-transformer



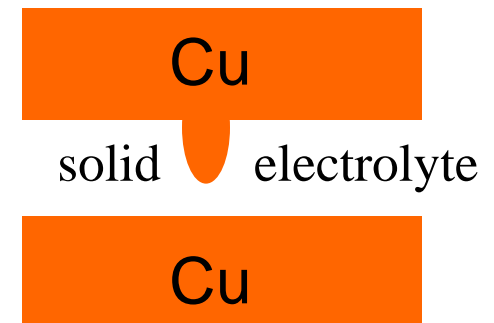
Cryo-Electronics
 $kT/q \sim q/C$



giant magneto-resistance
spintronics

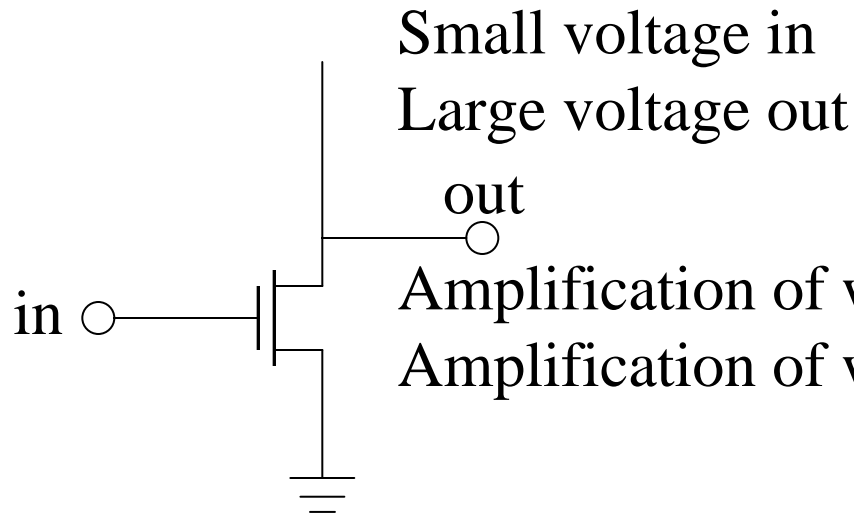


MEM's switch



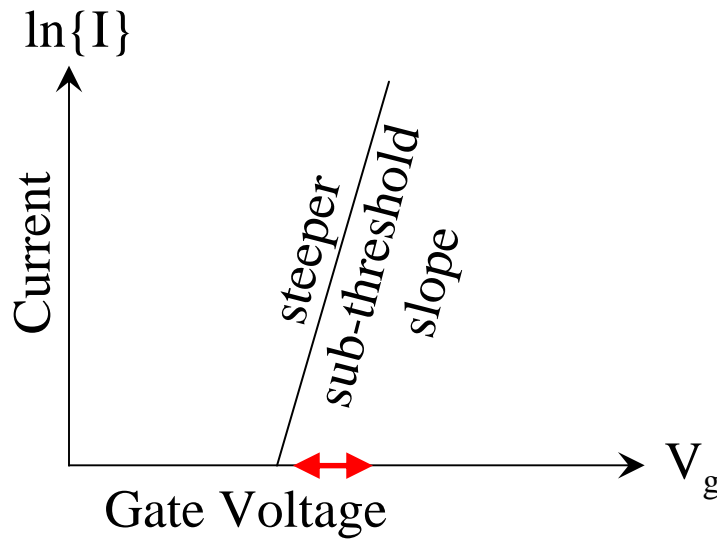
Electro-Chemical Switch

An amplifying transistor as a voltage matching device:



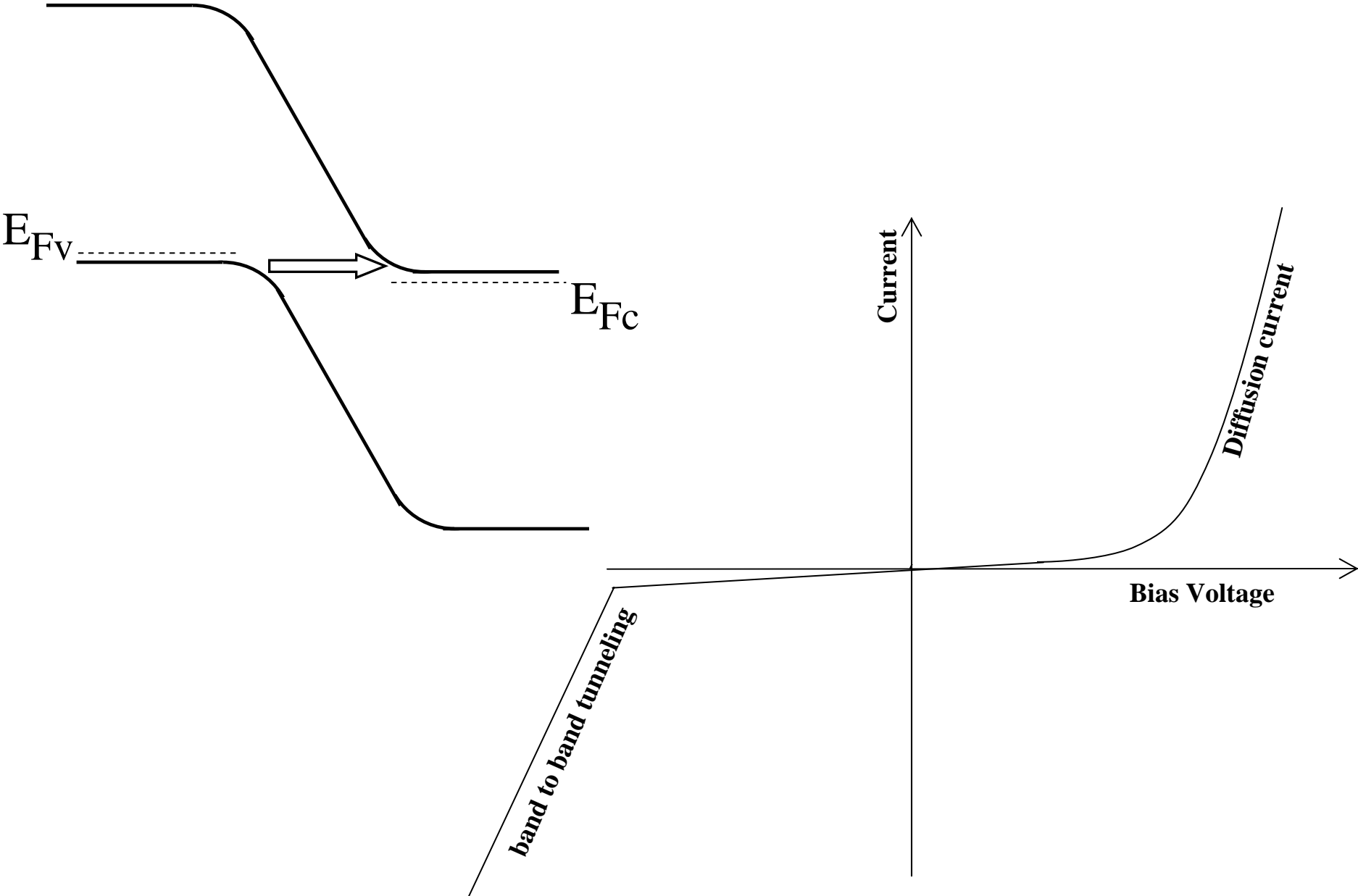
Small voltage in
Large voltage out

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

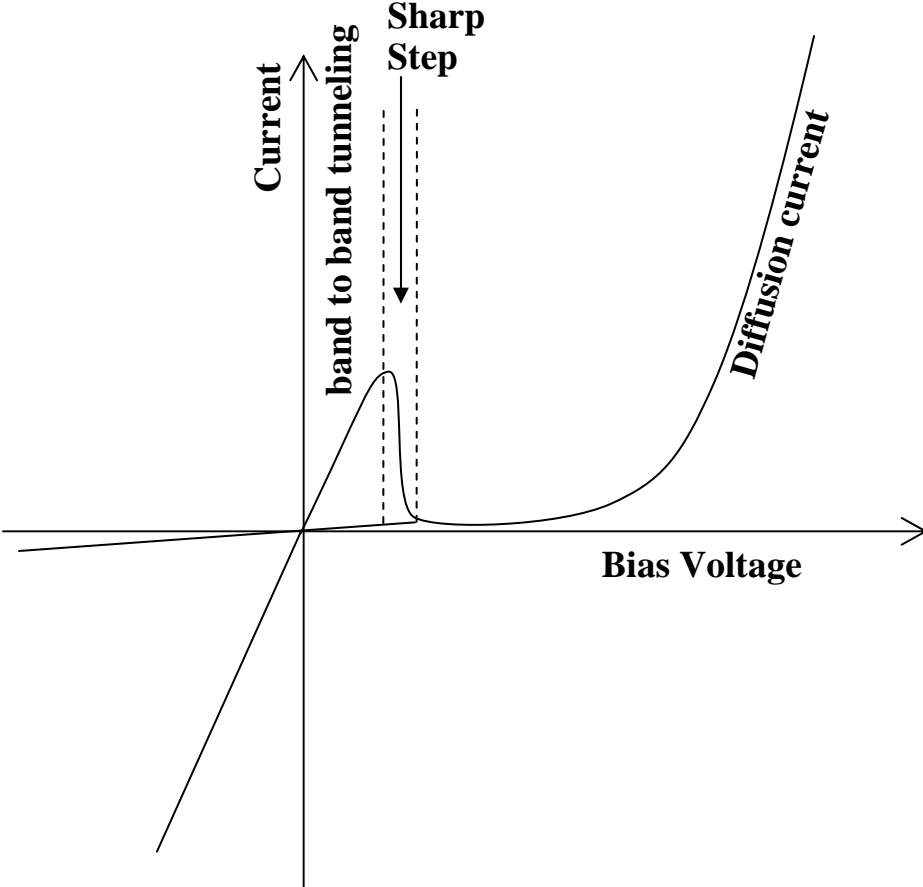
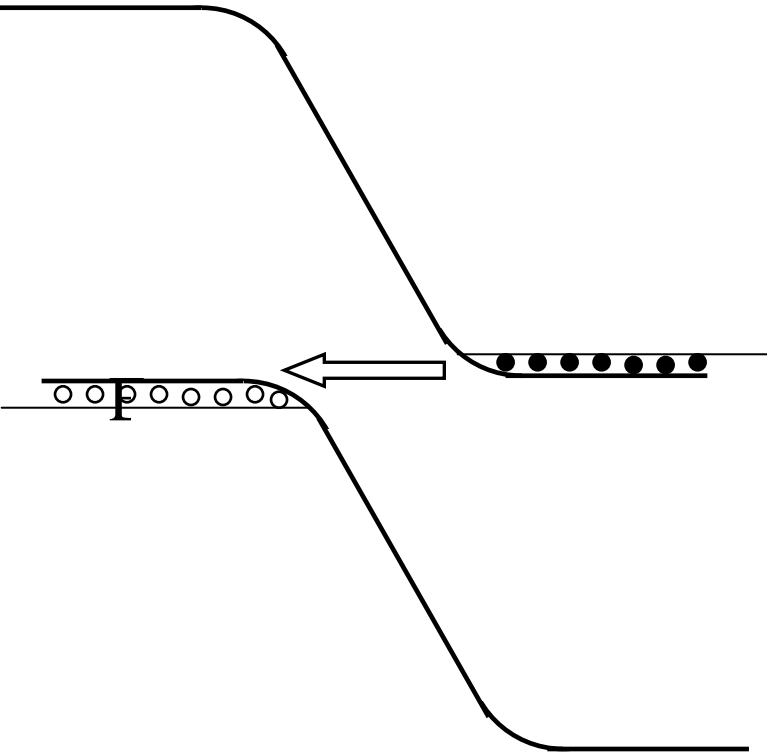


correlated electron motion?

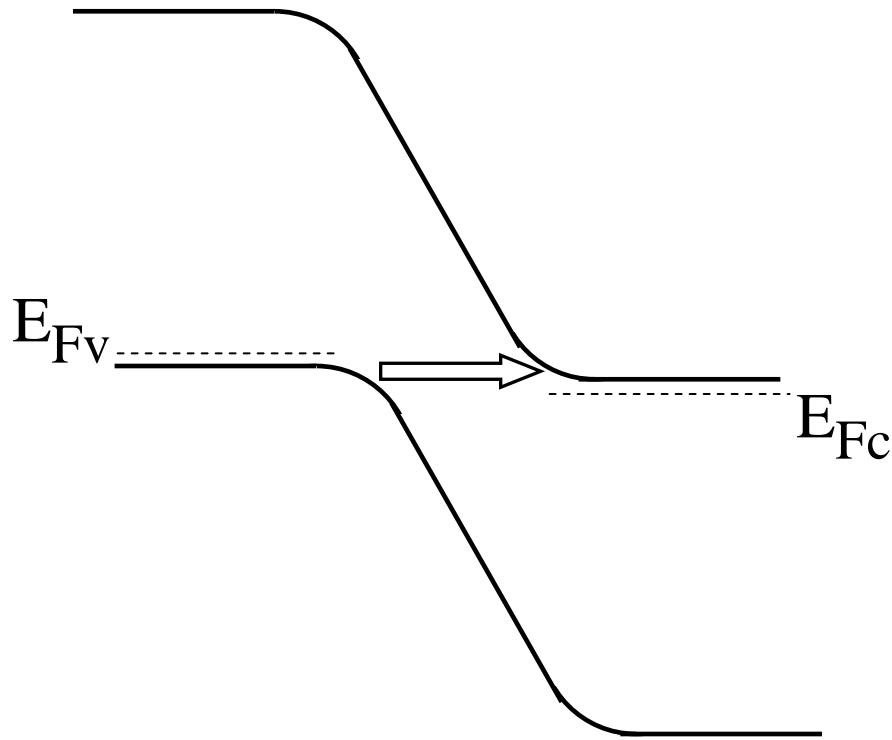
The Zener Diode:



The Esaki Diode:

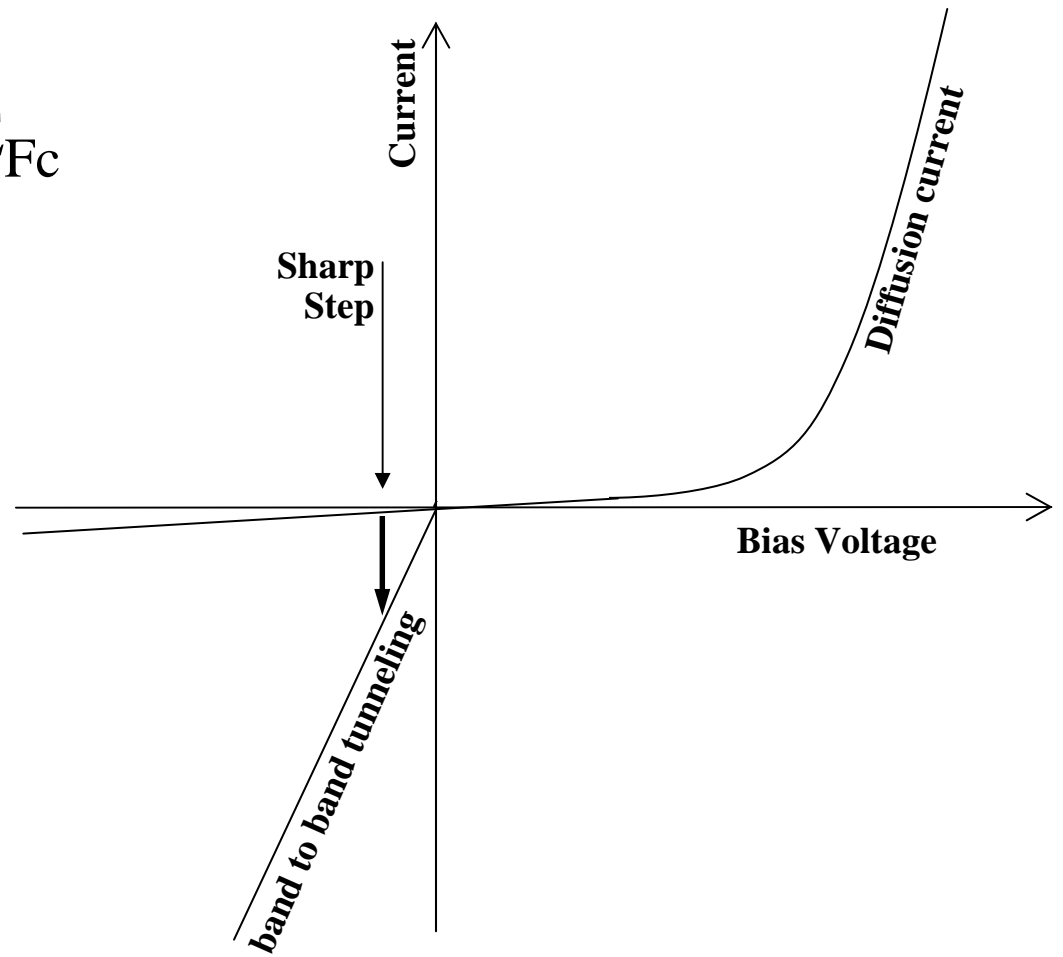


The Backward Diode as a Switch:

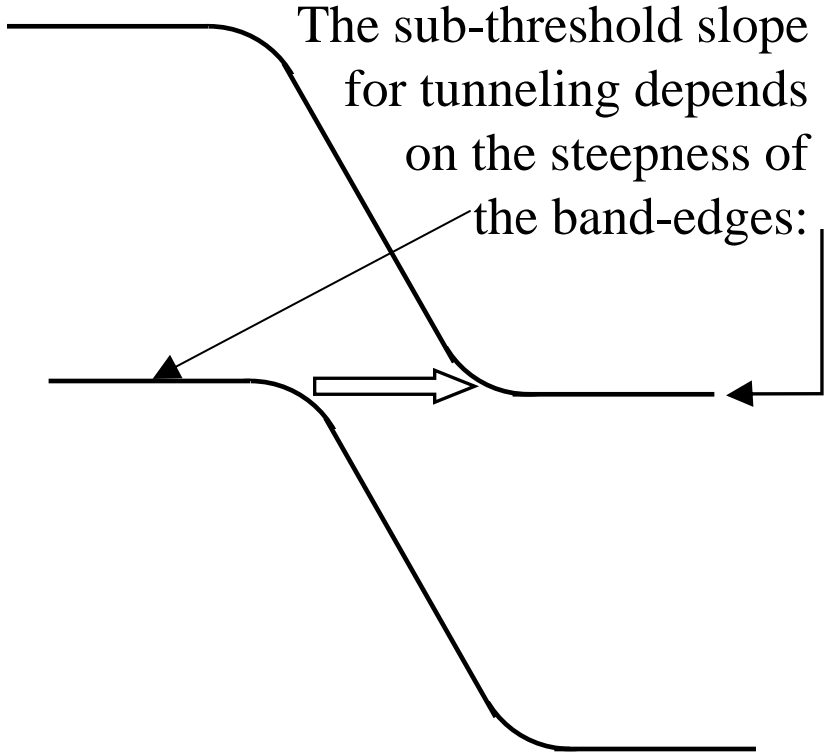


The Backward Diode:

These have been routinely made in Ge homo-junctions, since the 1960's.



The Backward Diode as a Switch:



Sb-Heterostructure Interband Backward Diodes

J. N. Schulman and D. H. Chow

Abstract—Backward diodes are a version of Esaki tunnel diodes that are useful for mixing and detection. Ge backward diodes in particular have been used as temperature insensitive, zero bias square law detectors, capable of translating low level rf power into dc voltage or current with extreme linearity and low noise. However, Ge diodes are difficult to reproducibly manufacture and are physically fragile. Here we demonstrate specially designed Sb-heterostructure-based backward diodes grown by molecular beam epitaxy. These diodes have superior figures of merit compared to Ge diodes, especially the current density and junction resistance, and are reproducible and physically rugged. In addition, the flexibility of MBE growth allows easy tailoring of the layer structure to maximize the desired figure of merit for a given application.

Index Terms—Millimeter wave detectors, millimeter wave diodes, millimeter wave imaging, millimeter wave mixers, semiconductor heterojunctions, tunnel diodes, tunneling.

I. INTRODUCTION

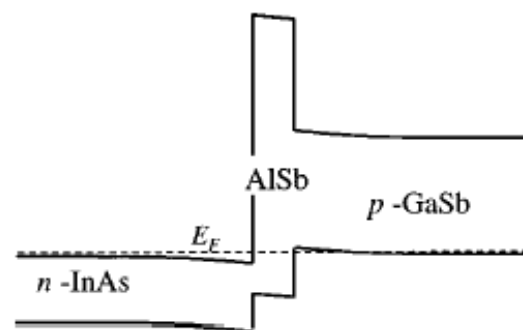


Fig. 1. Band diagram of InAs/AlSb/GaSb diode.

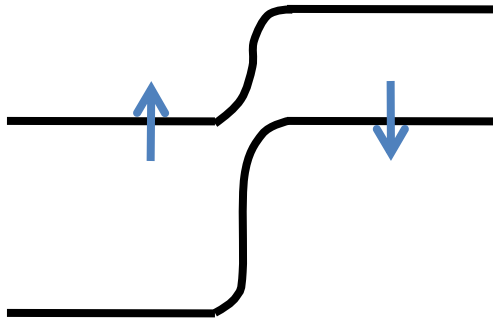
technology is relatively primitive and reproducibility is a challenge [2] as modern epitaxial growth techniques have not been sufficiently developed for Ge. Perhaps as serious a problem is that Ge diodes cannot withstand ordinary soldering processes making packaging difficult. Modern epitaxial growth technology has provided new avenues for exploring substitutes for Ge, including GaAs/AlGaAs [3] and InGaAs [4] alternatives.

I:	II:	III:
Steepness, Low Operating Voltage	On/Off Ratio $>10^5$	On-State Current Drive Capability, $\text{mA}/\mu\text{m}$ or better: $\text{mS}/\mu\text{m}$

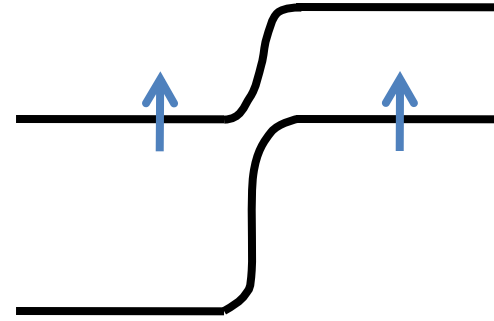
With tunneling alone, you can pick any
two out of the three above,
but you can't get all three!



Engineer Bands to Move Together



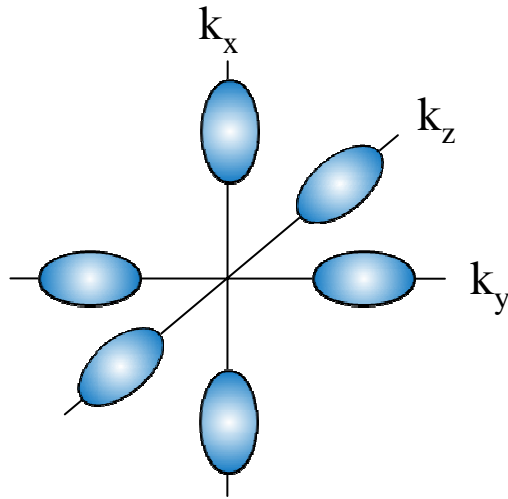
Un-Engineered



Engineered

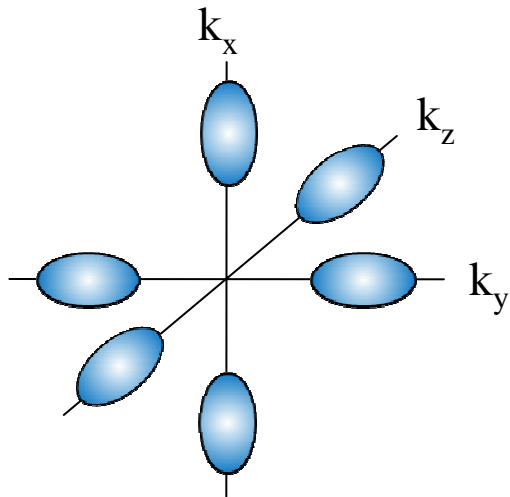
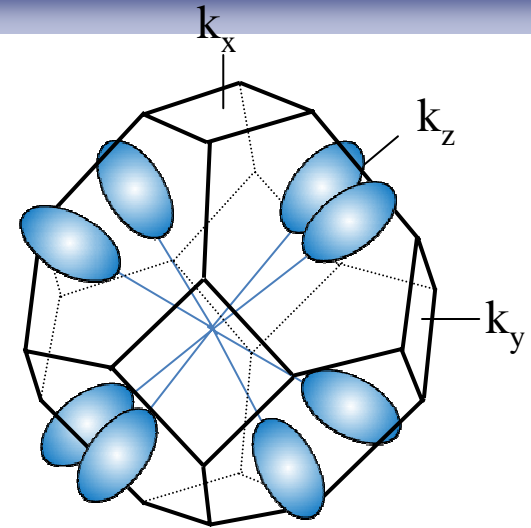


Consider Thermal Vibrations



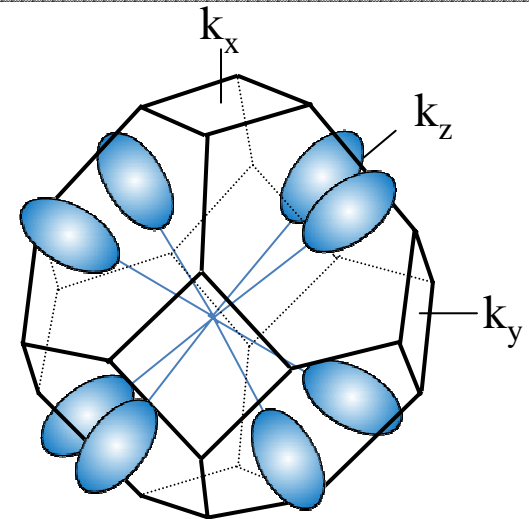
Uniaxial Strain

$$\epsilon_{xx}$$



Shear Strain

$$\epsilon_{xy}$$

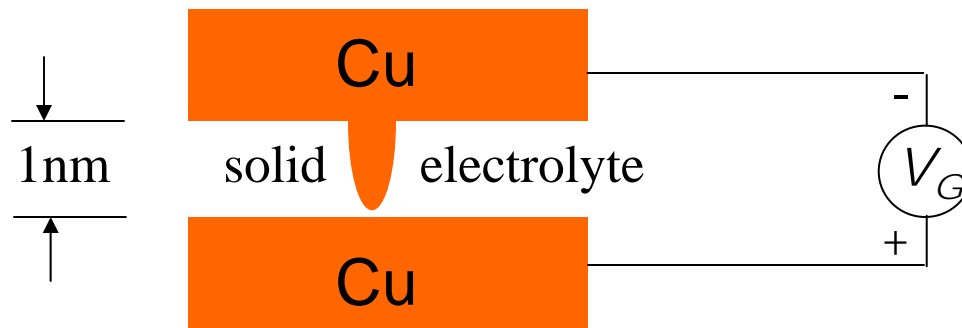


Silicon

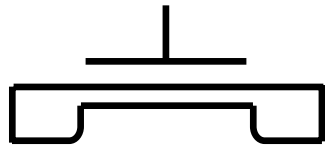
Germanium



Electro-Chemically Driven Metallic Switch:



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

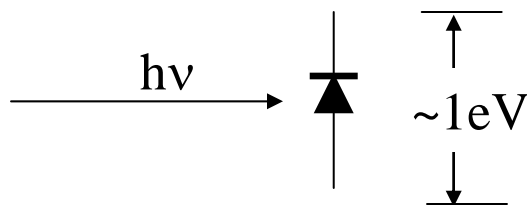
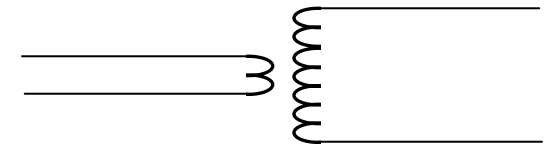


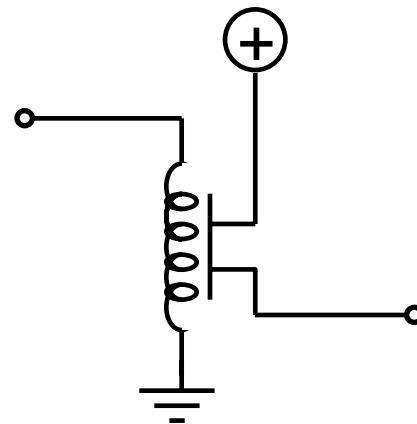
photo-diode



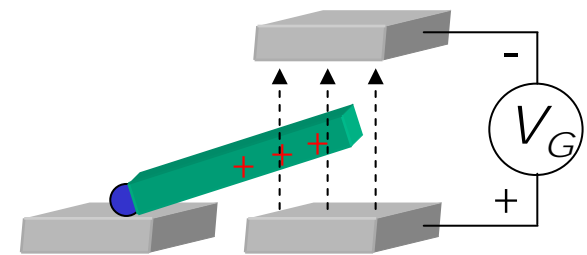
nano-transformer



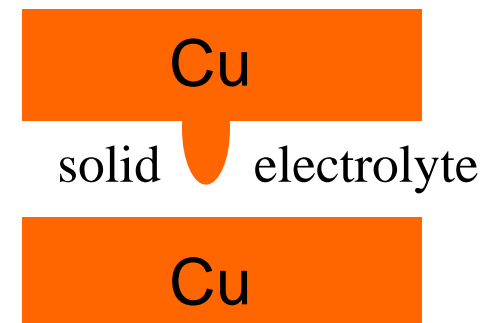
Cryo-Electronics
 $kT/q \sim q/C$



giant magneto-resistance
spintronics



MEM's switch



Electro-Chemical Switch

That was Electrical Communication.

For longer distances,

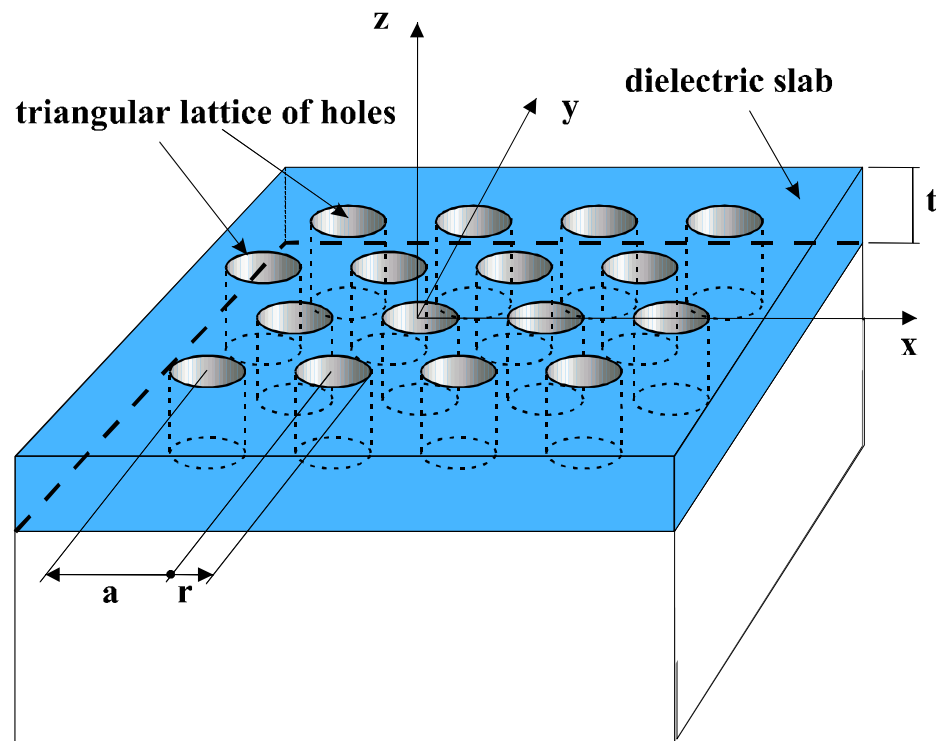
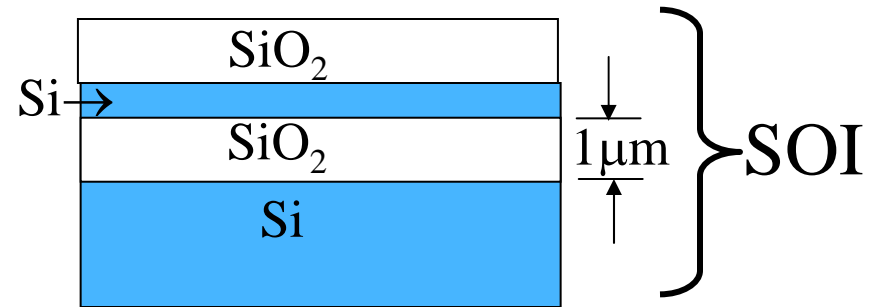
Optical Communication is needed;
How efficient can that be?

How many photons are needed?

This is mainly determined by the photodetectors.

Two-Dimensional
Thin Film
Photonic Crystals

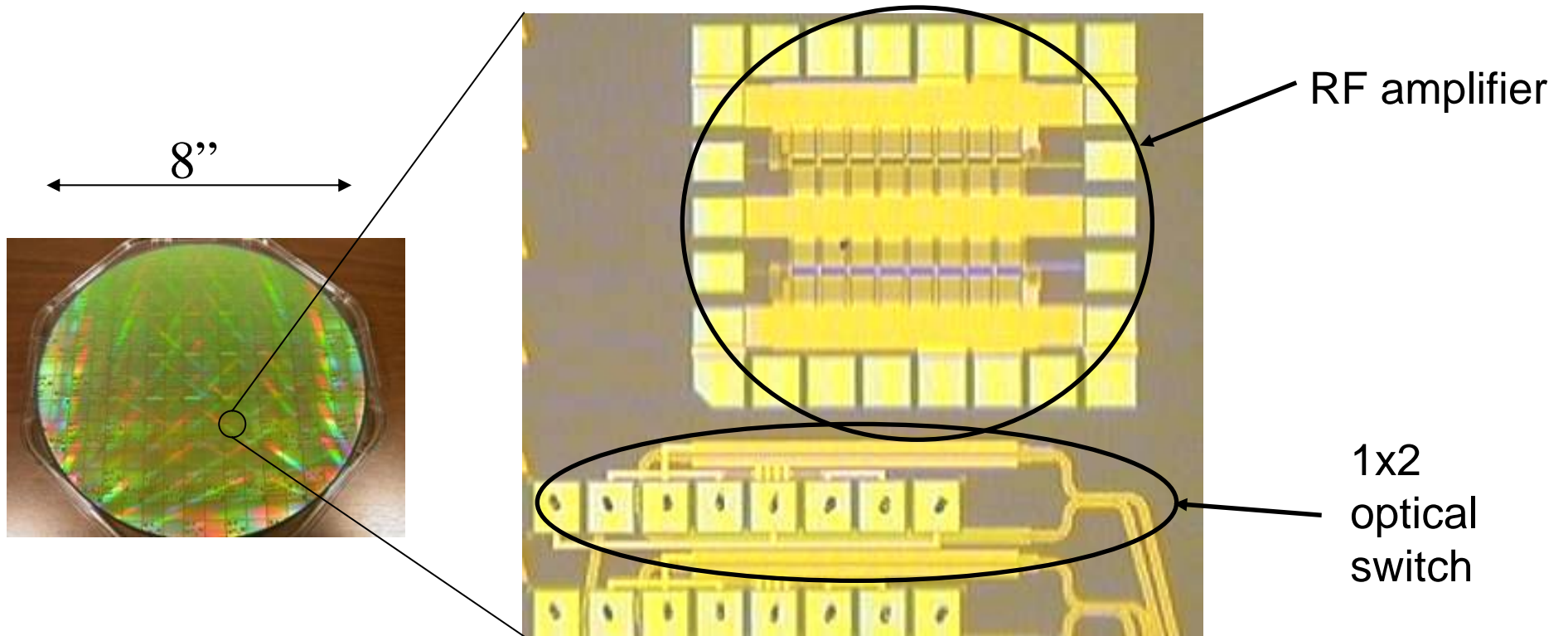
Cross-
Section:



Si/SiO₂ SOI



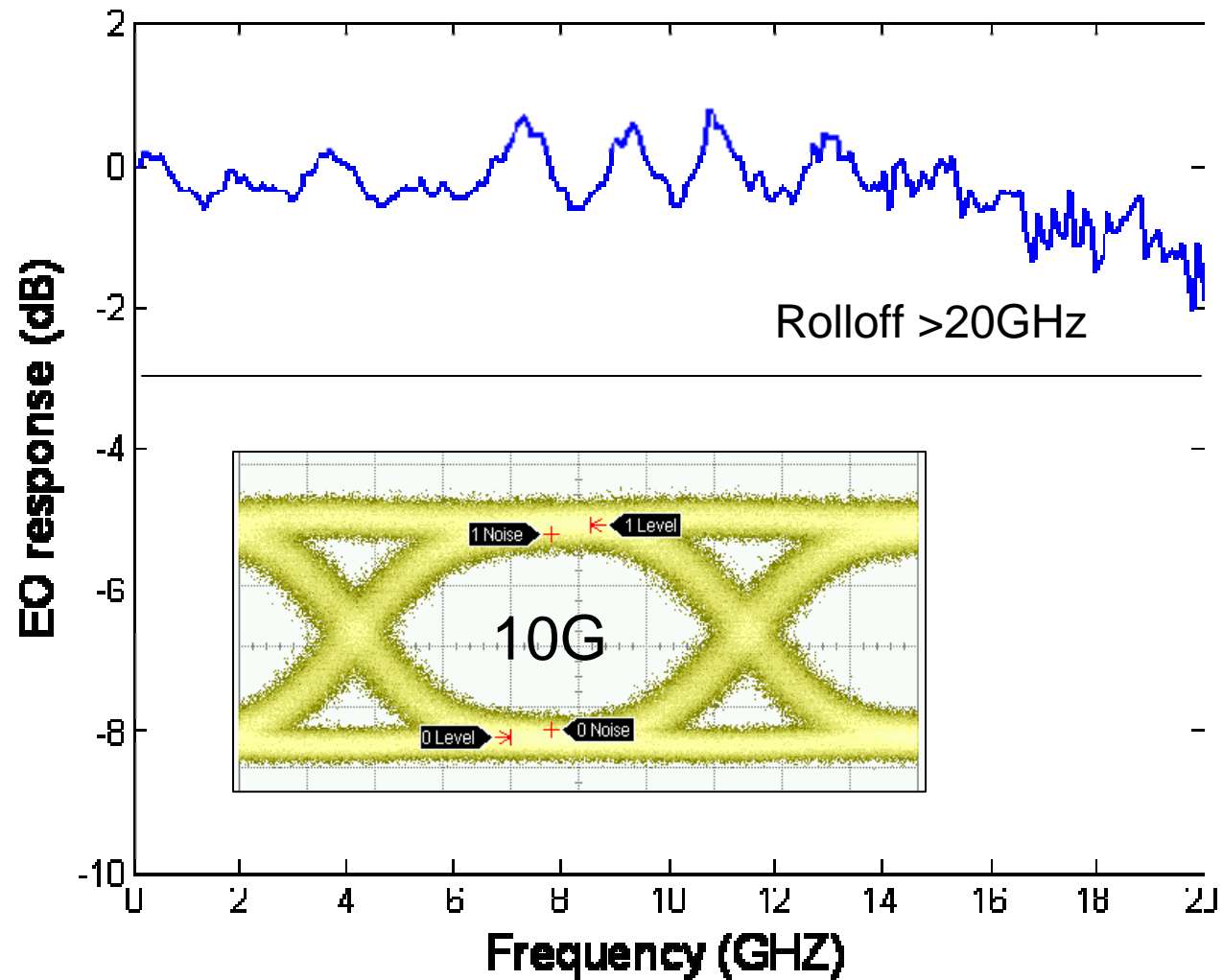
Monolithic Integration of Optics and Electronics



Optical devices and transistors are constructed side-by-side monolithically in the silicon



CMOS Optical Modulator Performance



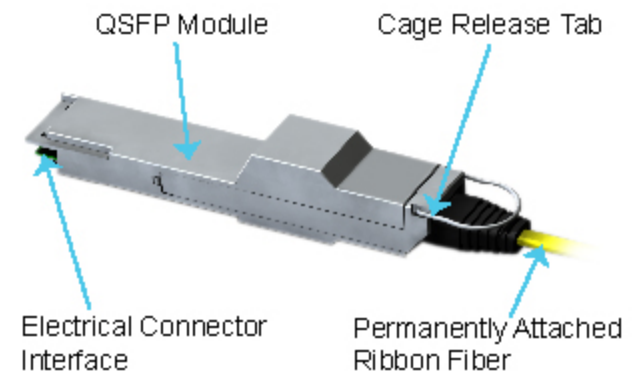


Blazar LUX5010

Multirate 4x10G Optical Active Cable

Typical Applications

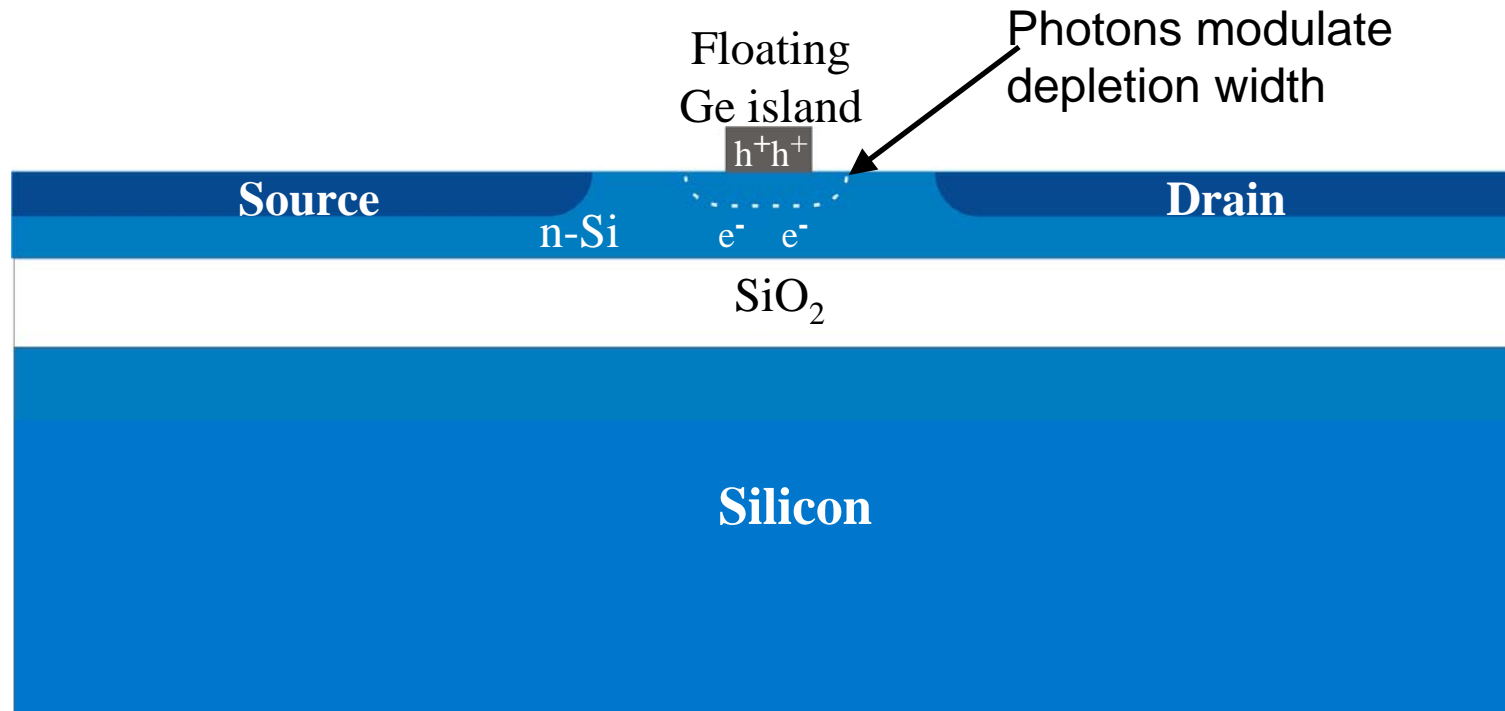
- InfiniBand Connectivity SDR/DDR/QDR
- 10/40 Gigabit Ethernet
- 2 / 4 / 8 / 10 Gbps Fibre Channel
- Proprietary Cluster Interconnect
- Ethernet Local Area Network (LAN)
- Storage Area Network (SAN)
- 2.5G / 5G PCI-Express Extension
- Storage Arrays
- Optical Backplanes
- Rack-to-Rack, Shelf-to-Shelf Interconnect
- Test Equipment



The problem is that optical communications
As it is currently practiced uses
 >10,000 photons/bit
 of information communicated

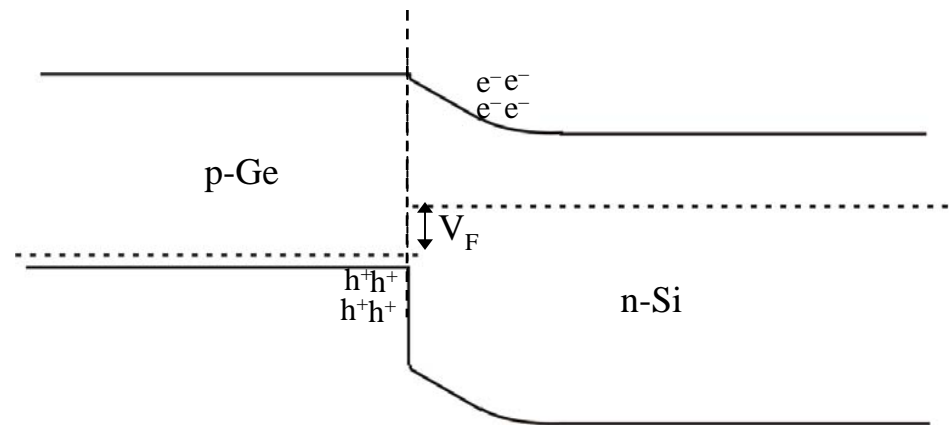
This is mainly determined by the photodetectors.

Photo-hetero-JFET concept:

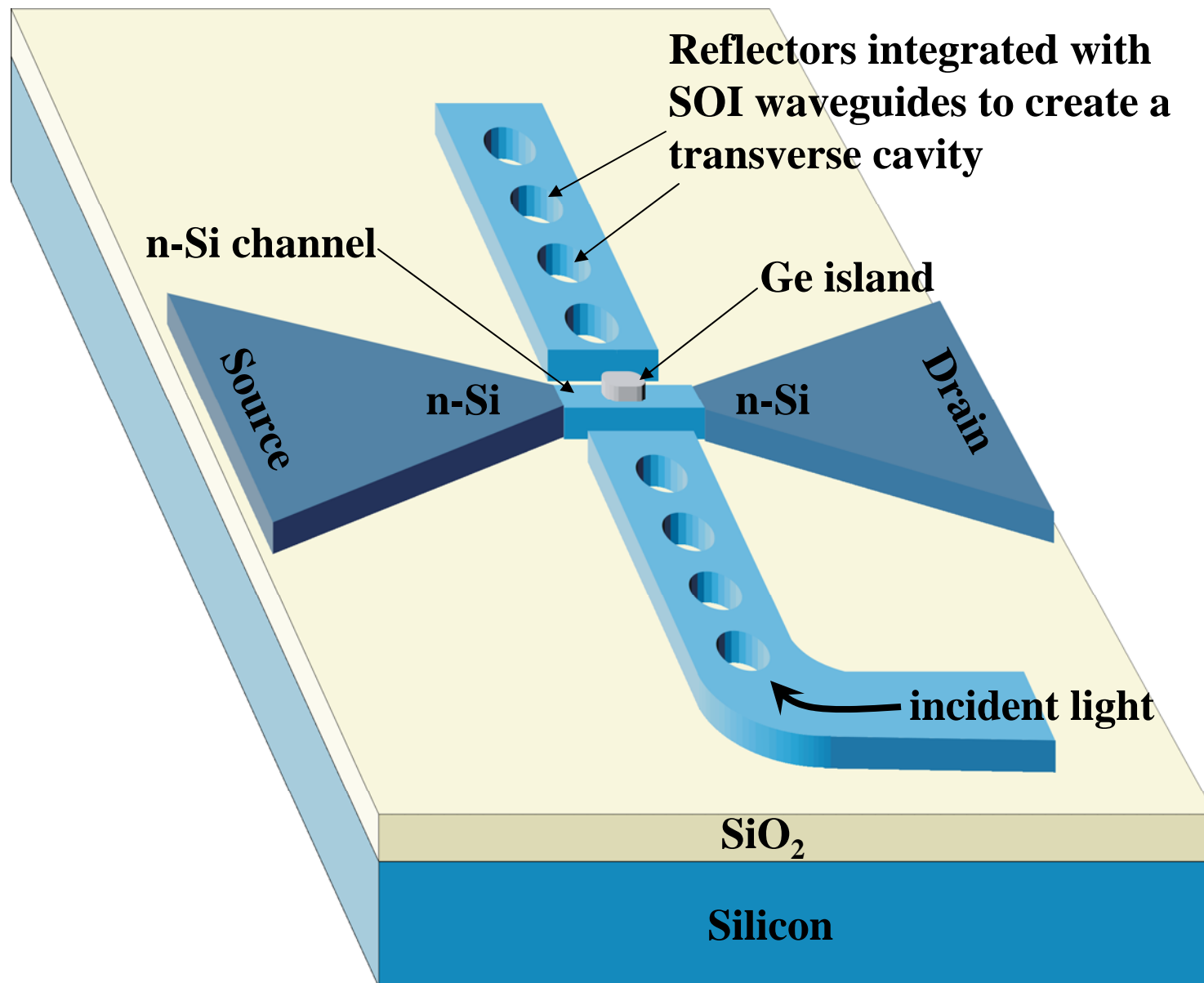


This is one of many types of photo-transistors!

Design Principle: Transistor with a Floating Gate



- Excess photo-holes attract electrons in the Silicon and change its conductance
- Open Ge/Si junction gets forward biased by an amount dependant on the light intensity



The problem is that optical communications

As it is currently practiced uses

>10,000 photons/bit

of information communicated

If the photodetector is small enough,

and preamp is sensitive enough,

we can anticipate getting this down to:

~15 photons/bit

of information communicated

For a $\sim 10^3$ times improvement

The experts look ahead

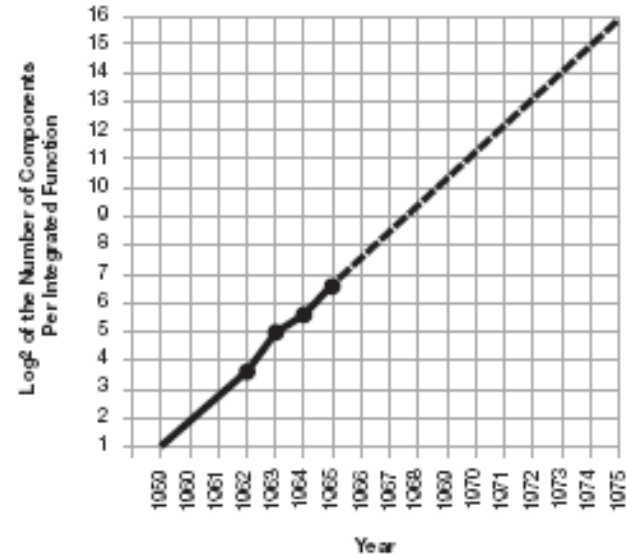
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Conclusions:

1. Communications is a big bottleneck for reducing power consumption in information processing.
2. The powering voltage for circuits is close to 1 Volt,
but it could be reduced to ~ 1 milli-Volt,
for a 10^6 reduction in power.
3. Optical communications uses $>10,000$ photons/bit of information,
but with more nanoscopic photodetectors this could
be reduced to ~ 15 photons/bit for a 10^3 reduction in power.

Reversible and Adiabatic Computing:

Energy/bit function $\ll kT$



Charles Bennett, IBM

The other Moore's Law, for energy per bit function

