Mission Statement:
To develop the device science and technology that will reduce energy consumption in electronic systems by orders of magnitude. To inspire and train a diverse generation of scientists, engineers, and technicians.

NSF, Arlington VA
Aug. 30, 2010

Eli Yablonovitch, Berkeley EECS Dept.

# NSF Center for E3S

Center for Energy Efficient Electronics Science

Major Research Universities

Historically Black University

Highly Diverse California Community Colleges
covering Northern and Southern California
that span the gamut from
high academic achievement to vocational education

Downtown Los Angeles
LATTC Campus
LOS ANGELES TRADE-TECH
LATTC
A Community College

# Electronics / network electricity use

Buildings Electricity: ~2,700 TWh

*Residential* | *Commercial*

Electronics

Network**ed**
~150 TWh ?

Net. Eqt.
~ 20 TWh

Tel.

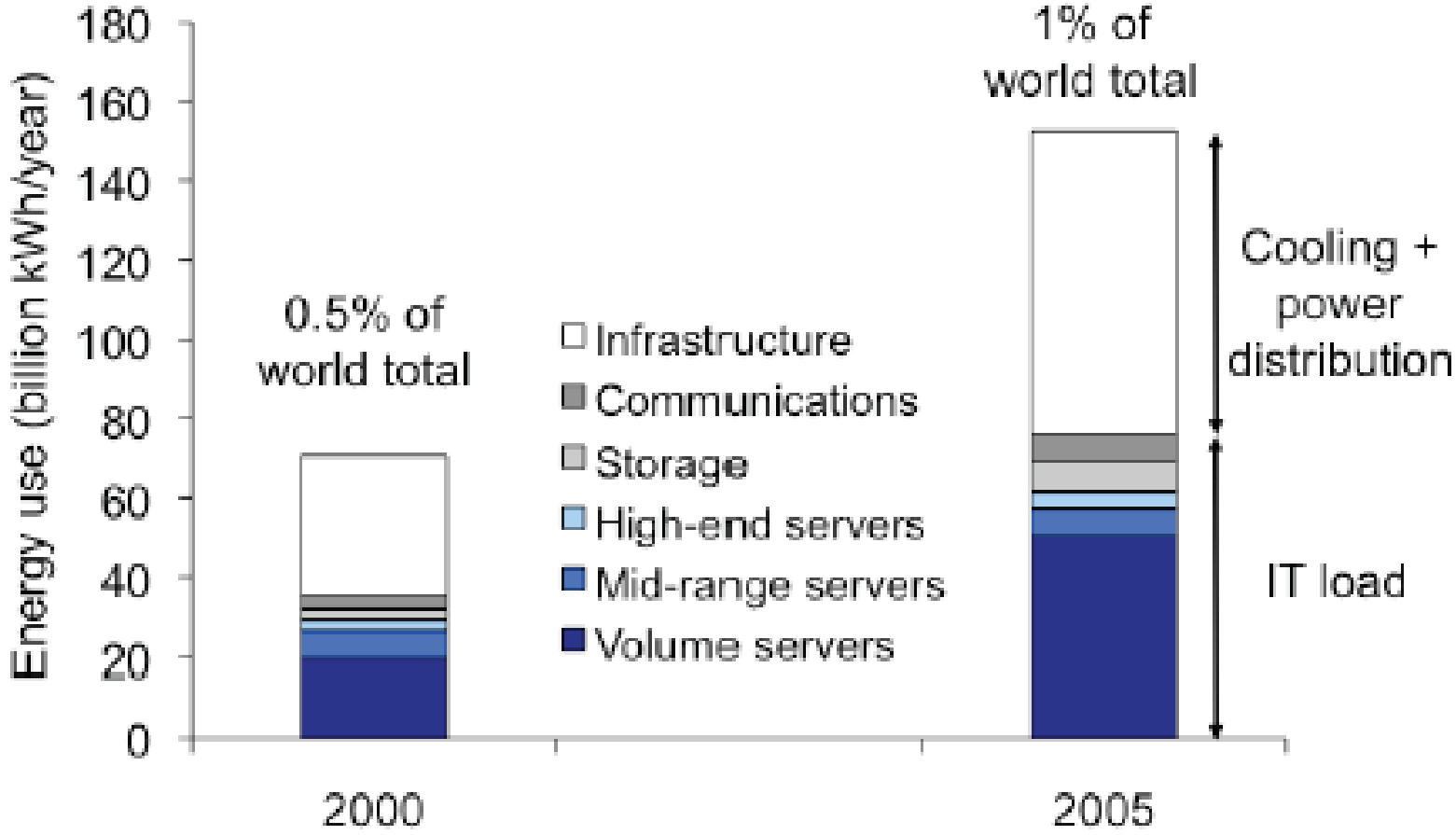
~290 TWh

One central baseload power plant (about 7 TWh/year)

**Bruce Nordman, LBL**

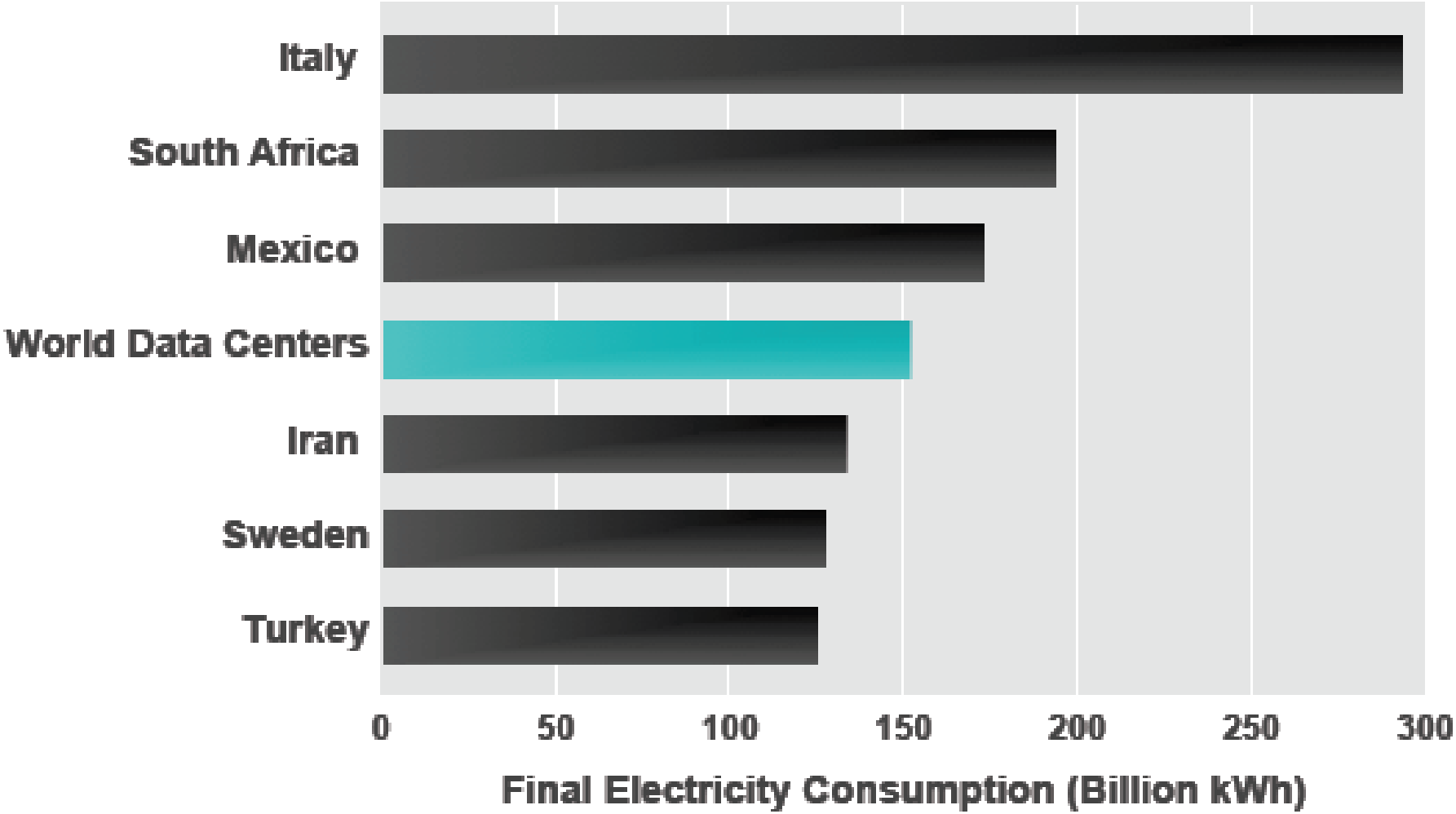
- U.S. only
- Annual figures circa 2006
- All approximate

# World data center electricity use, 2000 and 2005

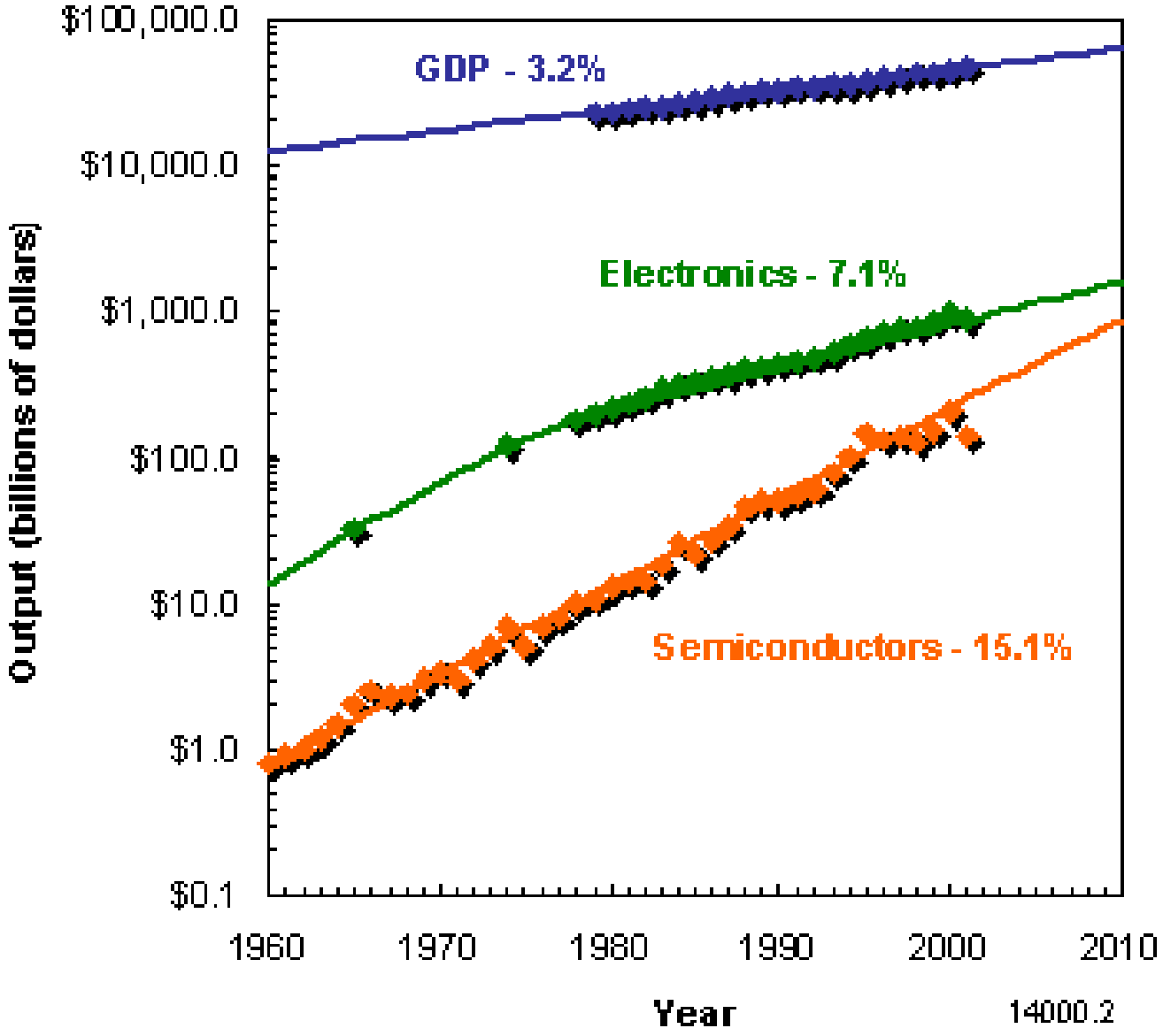



Source: Koomey 2008

# How much is 152B kWh?




Source for country data in 2005: International Energy Agency, *World Energy Balances* (2007 edition)


$100,000.0
$10,000.0
$1,000.0
$100.0
$10.0
$1.0
$0.1
Output (billions of dollars)
GDP - 3.2%
Electronics - 7.1%
Semiconductors - 15.1%
1960
1970
1980
1990
2000
2010
Year
14000.2

# Power Usage Rising Faster Than Past Trend

- **Because power consumption $\propto V_{dd}^2$ and $V_{dd}$ (operation voltage) scaling has slowed after 0.13μm node.**

| *Technology Node* | | | 0.25 μm | 0.18 μm | 0.13 μm | 90 nm | 65 nm | 45 nm | 32 nm | 22 nm | 16 nm |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{dd}$ | | | 2.5 V | 1.8 V | 1.3 V | 1.2 V | 1.1 V | 1.0 V | 0.9 V | 0.8 V | 0.7 V |

*High Performance ITRS Roadmap*

The natural voltage range for wired communication is rather low:

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

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

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

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

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

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

The wire wants
1000 electrons at 1mVolt each.

(to fulfill the signal-to-noise requirement >1eV of energy)

The natural voltage range for a thermally activated switch like transistors is >>kT/q, eg. ~ 40kT/q or about ~1Volt

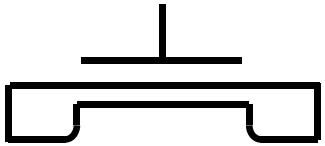
Voltage Matching Crisis
at the nano-scale!

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 ~1Volt.

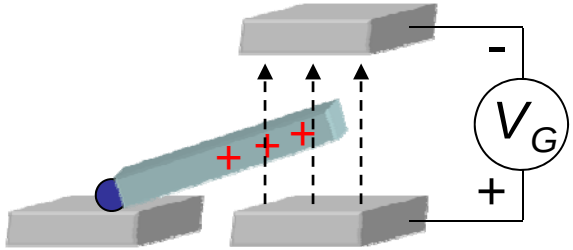
# This Center will address the Electronics Energy Efficiency by Four Interconnected Approaches:

## Theme 1:



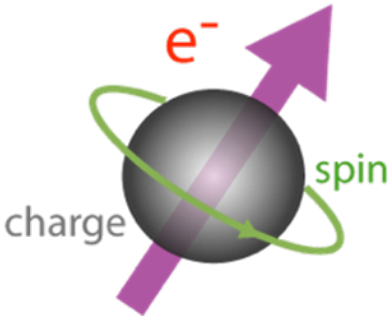
Nanoelectronics:
Solid-State Milli-Volt Switching

## Theme 2:



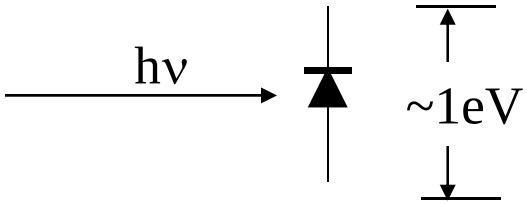

Nanomechanics:
Zero-Leakage Switching

## Theme 3:




Nanomagnetics:
Surmounting the Landauer Limit

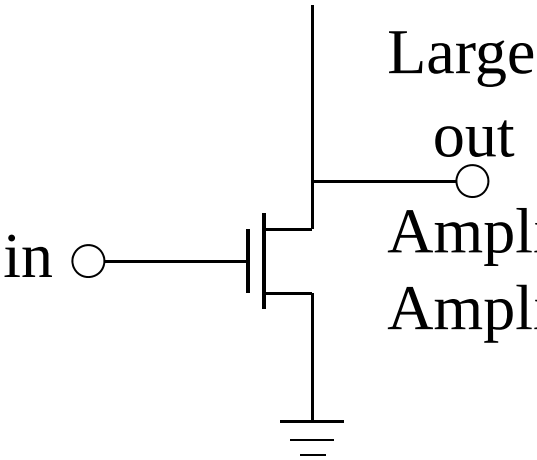
## Theme 4:




Nanophotonics for Ultra-Low Energy Communication

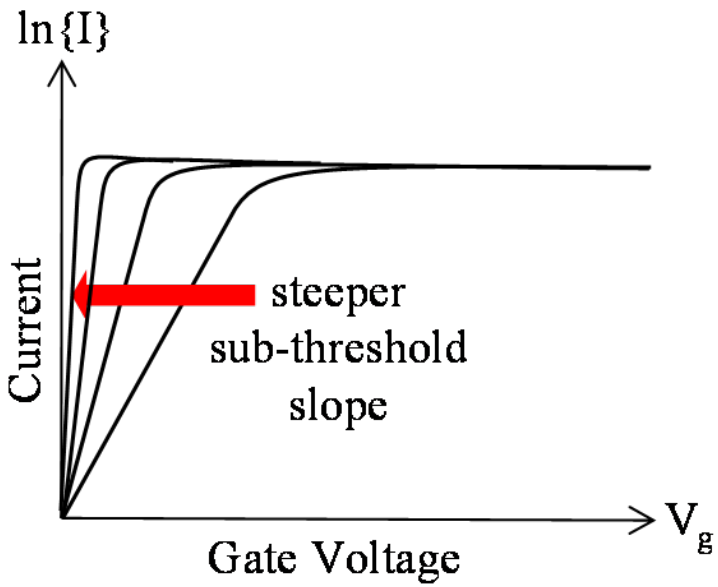
# Theme 1 - Nanoelectronics: Solid-State Milli-Volt Switching

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!



# Key Scientific Questions

- New examples of Type III Energy band offsets need to be discovered.
- Fundamental band edge abruptness is very poorly understood.

This is high risk/high payoff scientific research.

After all, we are trying to replace the transistor with a more sensitive device.

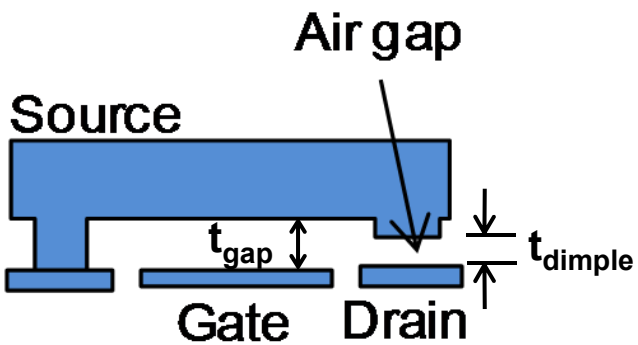
# Theme 2 - NanoMechanics: Solid-State Milli-Volt Switching

# Why Mechanical Switches?

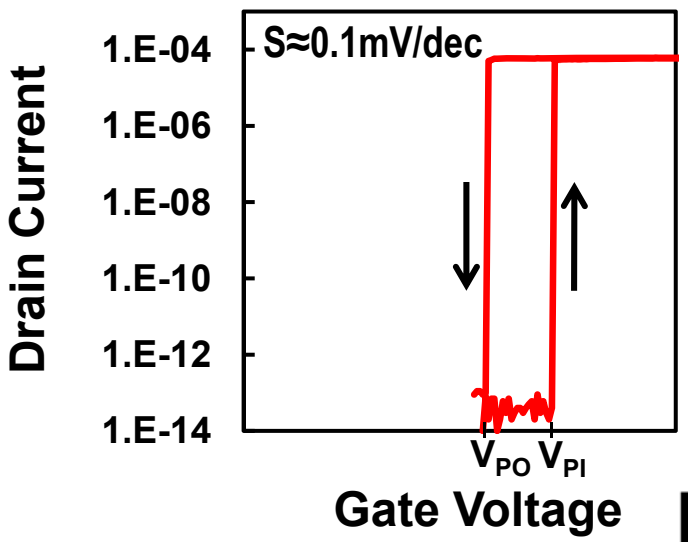
- **Relays have zero off-state leakage**
  → **zero static energy**

- **Relays switch on/off abruptly**
  → **allows for aggressive $V_{DD}$ scaling (ultra-low dynamic energy)**

**3-Terminal Relay**




**Measured *I-V***

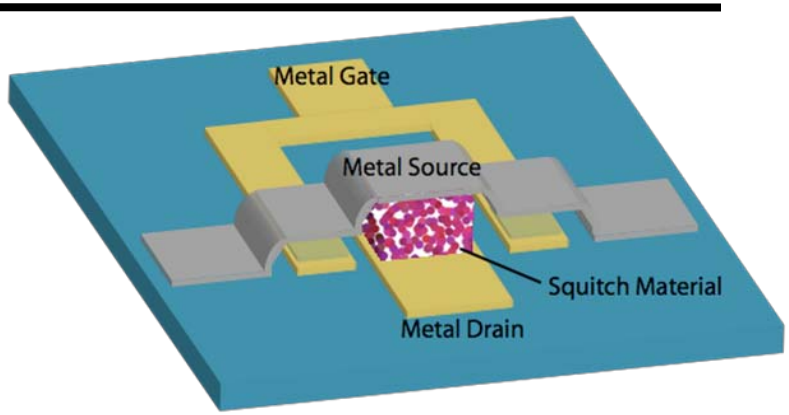


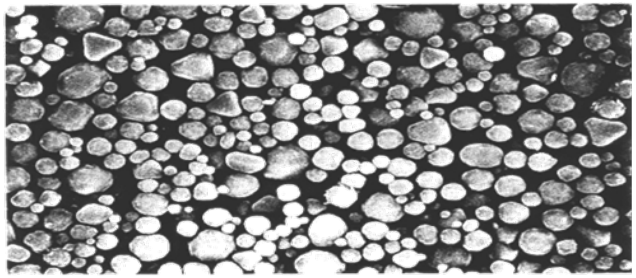
Bulovic / Lang (MIT)

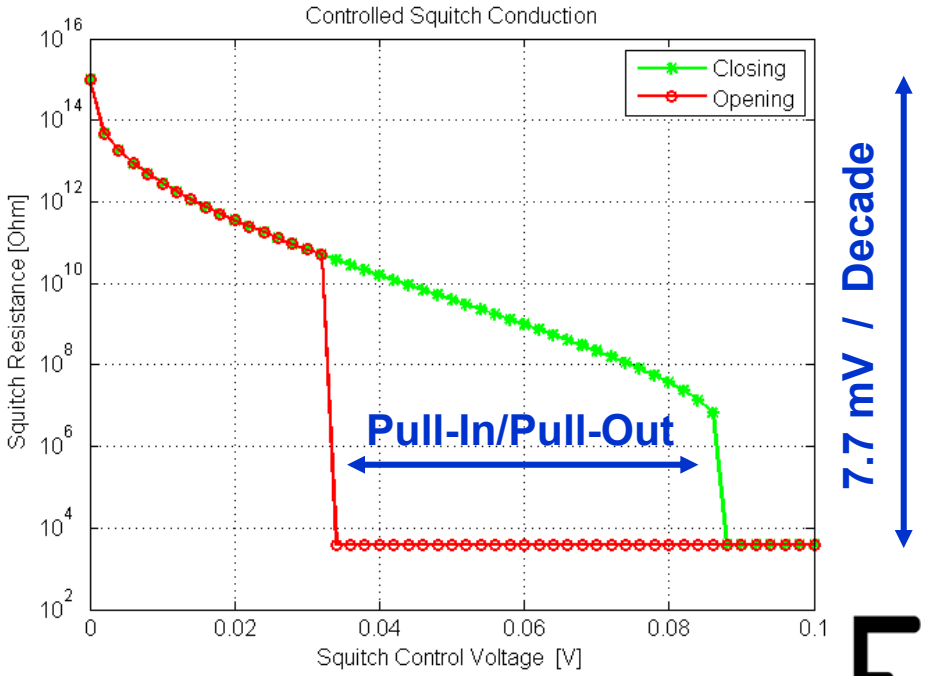
# Tunneling Nanoswitch

## Device Operating Principle:

- Electrostatic actuation of electrode
- Conduction via tunneling
  - nanoconductors embedded in a deformable matrix






## Advantages:

- ease of fabrication and packaging
- better device reliability

# Theme 4 – NanoPhotonics for Ultra-Low Energy Communication

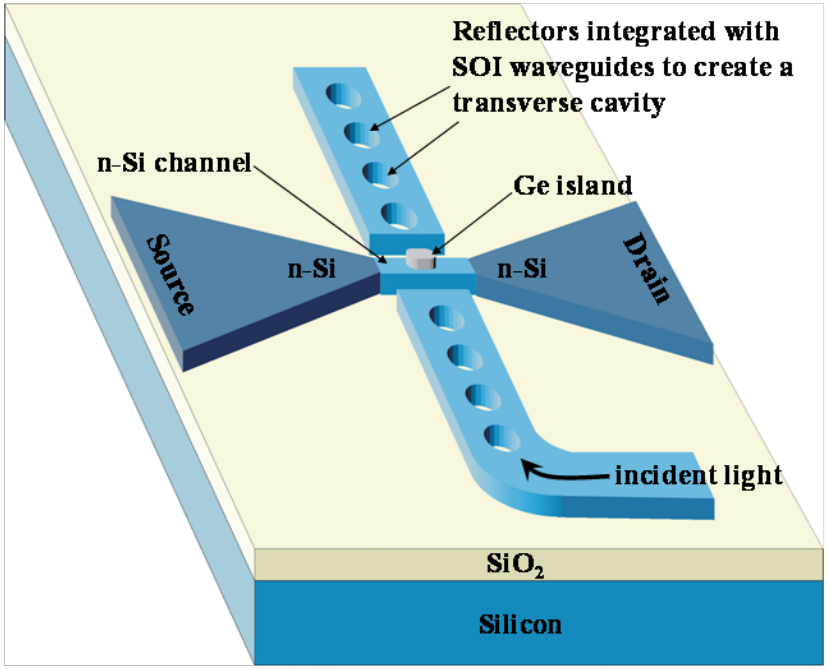
We want to from go from ~10,000 photons/bit

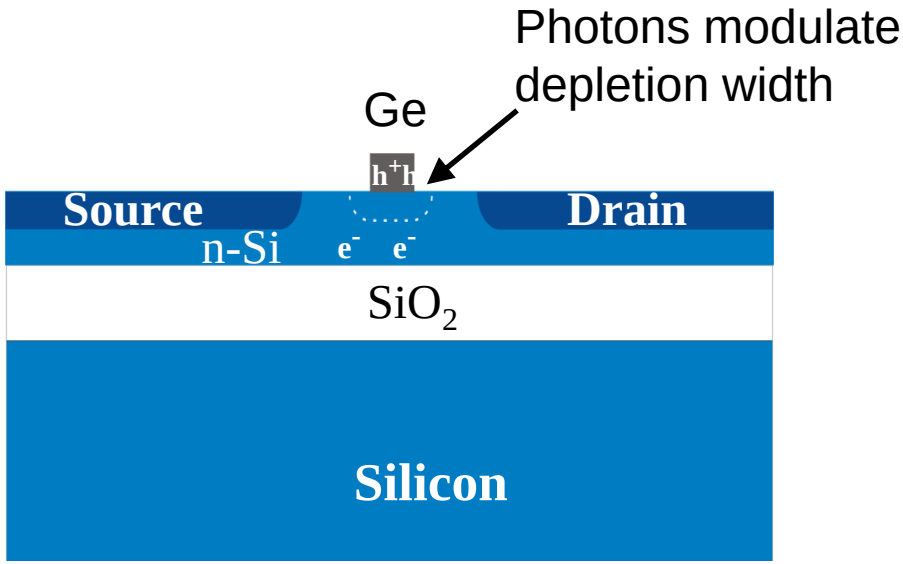
→ 17 photons/bit

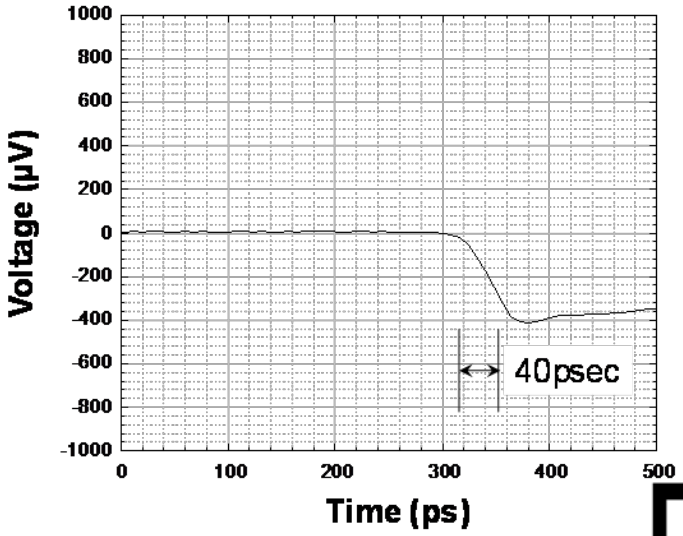
But this is insufficient, since we cannot afford to consume very much energy in amplifying the weak signal.

We need an ultra-sensitive low energy photodetector too!

# Ultra-sensitive Floating Gate photodetector:




- Eliminate wire capacitance between photodetector and amplifier
- Transistor with a floating Ge-island
- Photonic crystal cavity with 1000× efficiency improvement.

# Theme 3 – NanoMagnetics: Surmounting the Landauer Limit

# Fundamental Limits of Computing

**Von Neumann-Landauer limit (1961):**

**Energy lost in a logic operation in which 1 bit is lost is $E \geq kT \ln 2$**

**Bennett (1973):**

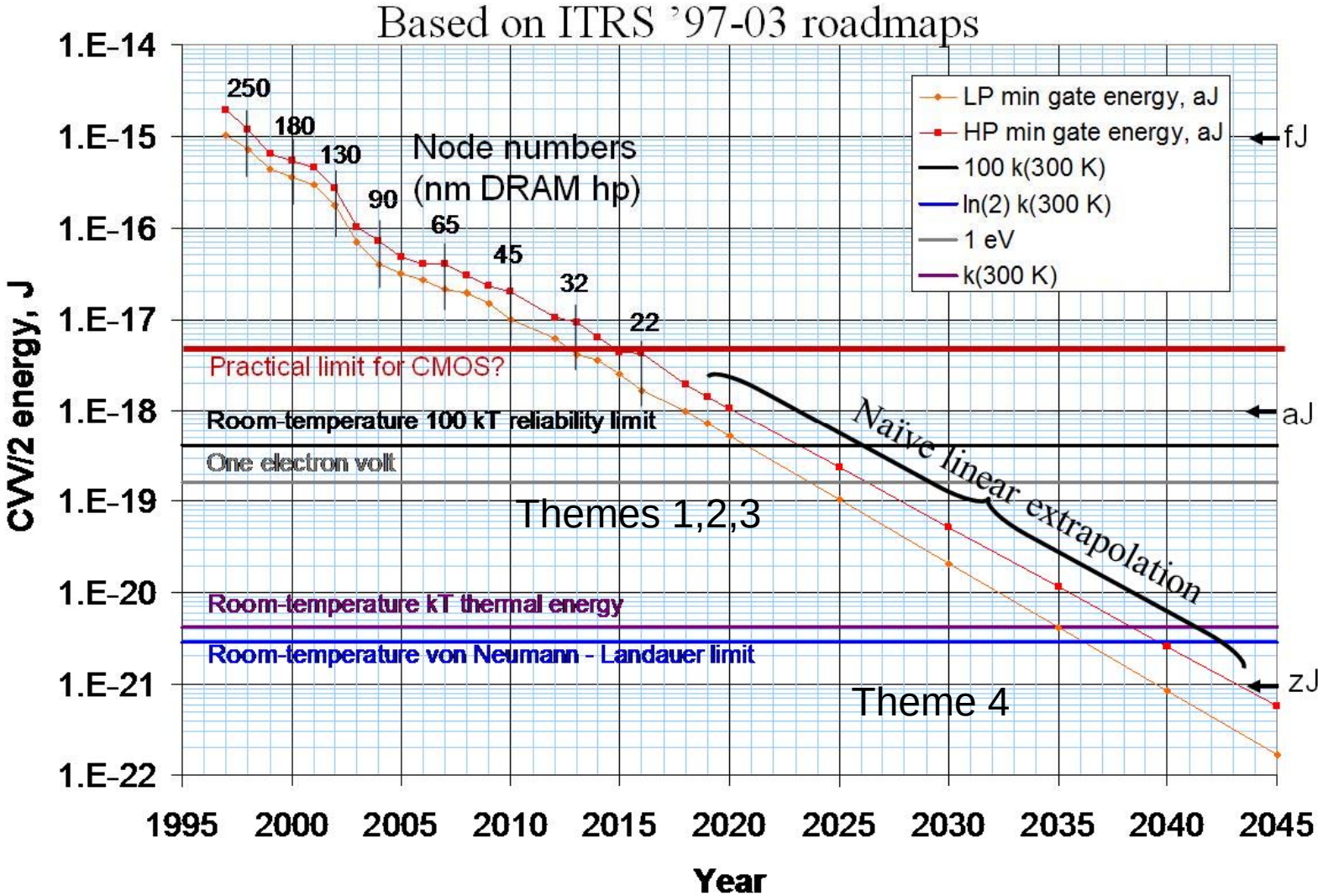
**Logical Reversibility of Computation**

**John von Neumann**

**Rolf Landauer**

**Charles Bennett**

# Trend of Min. Transistor Switching Energy




M. Frank, "Introduction to Reversible Computing"

Judy L. Hoyt

Ming C. Wu

Irfan Siddiqi

Jeff H. Lang

Tsu-Jae King Liu

Eli Yablonovitch

Dimitri A. Antoniadis

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# It's Time to Reinvent the Transistor!

**Thomas N. Theis* and Paul M. Solomon**

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