Overview of Modern Semiconductor Device Technology

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Technology

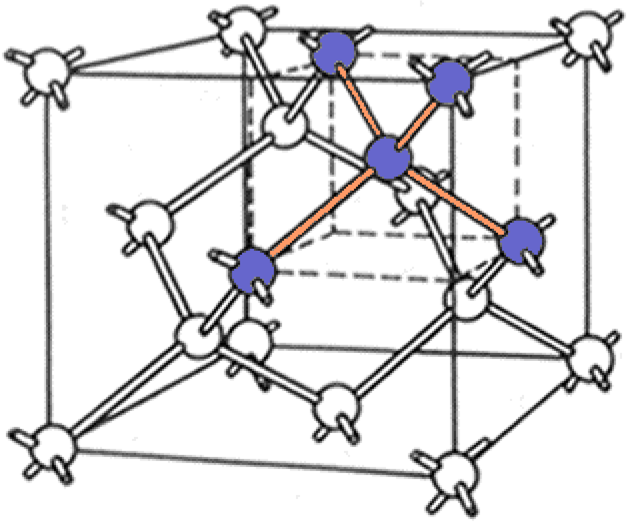
Integrated Circuits

Photonics

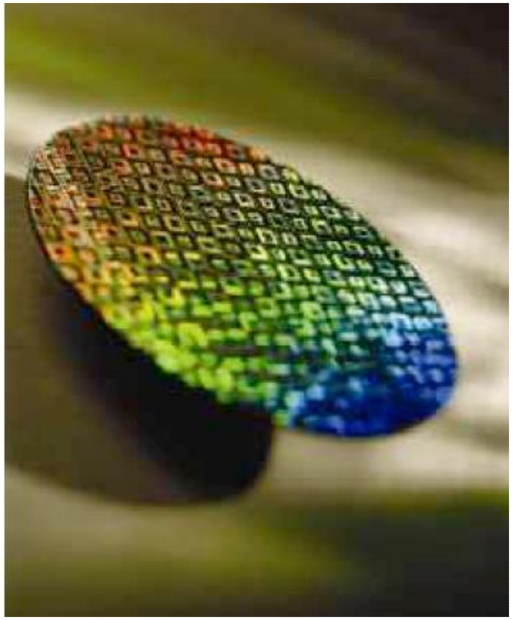
Communications Software

Wireless

Overall picture



- **Very rapid development**
- **Integrated circuits containing many many "components"**
- **Number of transistors on a chip (a measure of the power) roughly doubles every 18 months (Moores Law)**
- **Huge industry**
- **All based on physics and on the quantum theory of solids – one of the very few such industries**



Basic building blocks

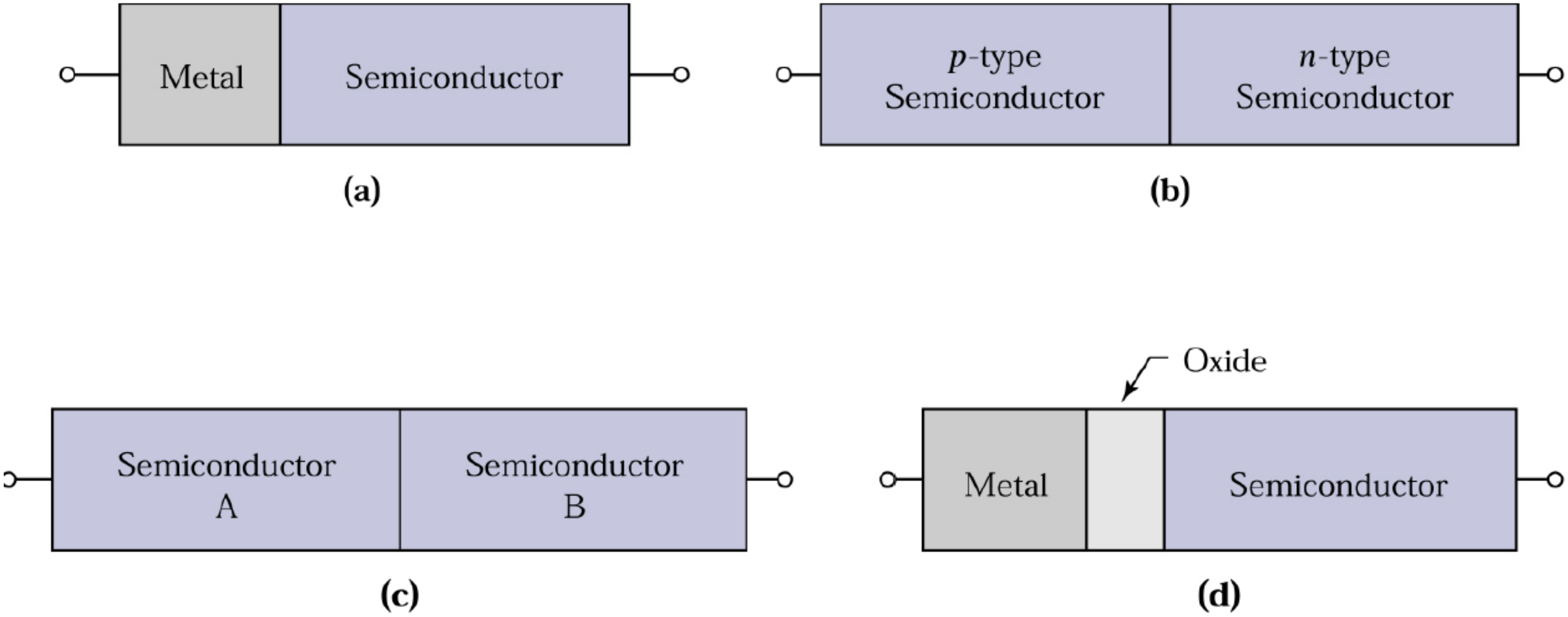
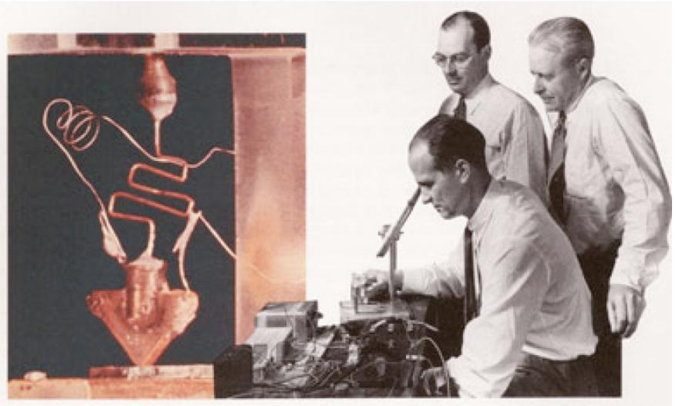
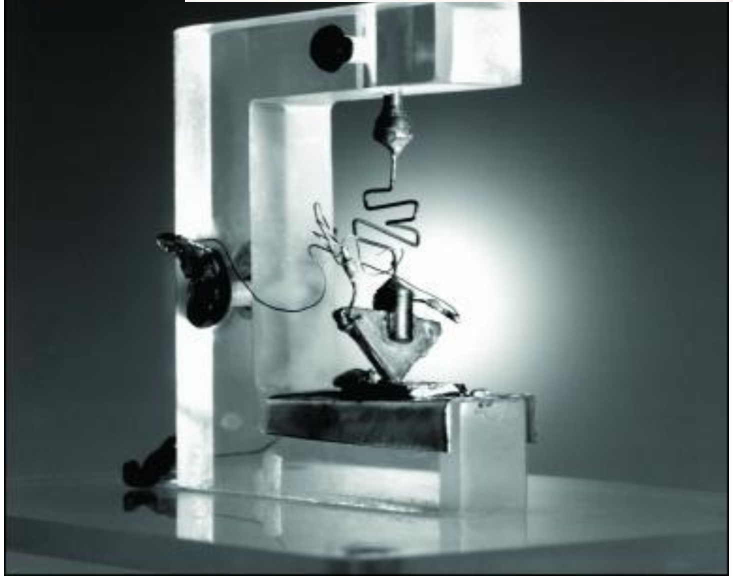


Figure 1.2. Basic device building blocks. (*a*) Metal-semiconductor interface; (*b*) *p-n* junction; (*c*) heterojunction interface; and (*d*) metal-oxide-semiconductor structure.

The Start of the Modern Electronics Era

First transistor   Bardeen, Shockley and Brattain 1947





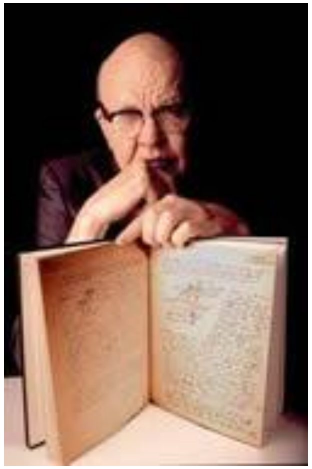
Bardeen, Shockley, and Brattain at Bell Labs - Brattain and Bardeen invented the bipolar transistor in 1947.

The first germanium bipolar transistor. Roughly 50 years later, electronics account for 10% (4 trillion dollars) of the world GDP.

Another Nobel Prize in Semiconductor

Left, H. Kroemer – Nobel Physics Laureate, 2000 (shared with J. Kilby and Z. Alferov)

Right: D. Harame of IBM – instrumental in commercialization of SiGe HBT

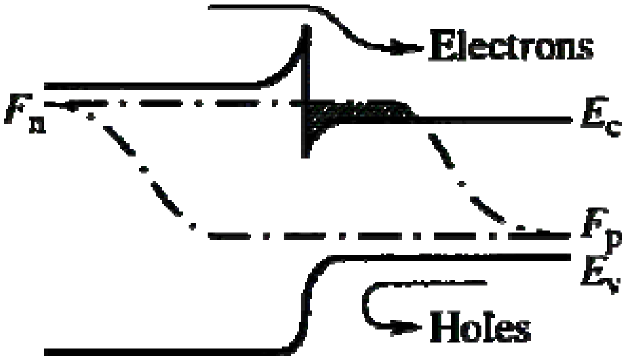


Jack Kilby, TI, inventor of Integrated circuits

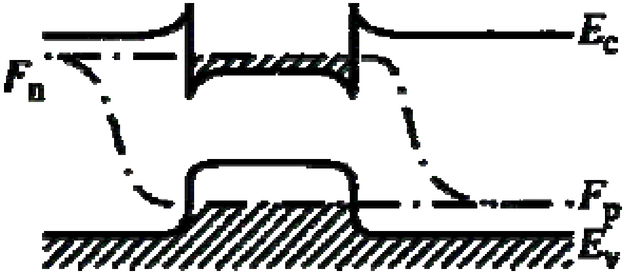
Heterojunction / Alferov version

- Double heterojunction laser - Foundation for room temperature laser

"Owing to potential barriers at the boundary of semiconductors with different bandgap widths... there is absolutely no indirect passage of electron and hole currents, and the emitters have zero recombination." – *Zhores Alferov, 1967*

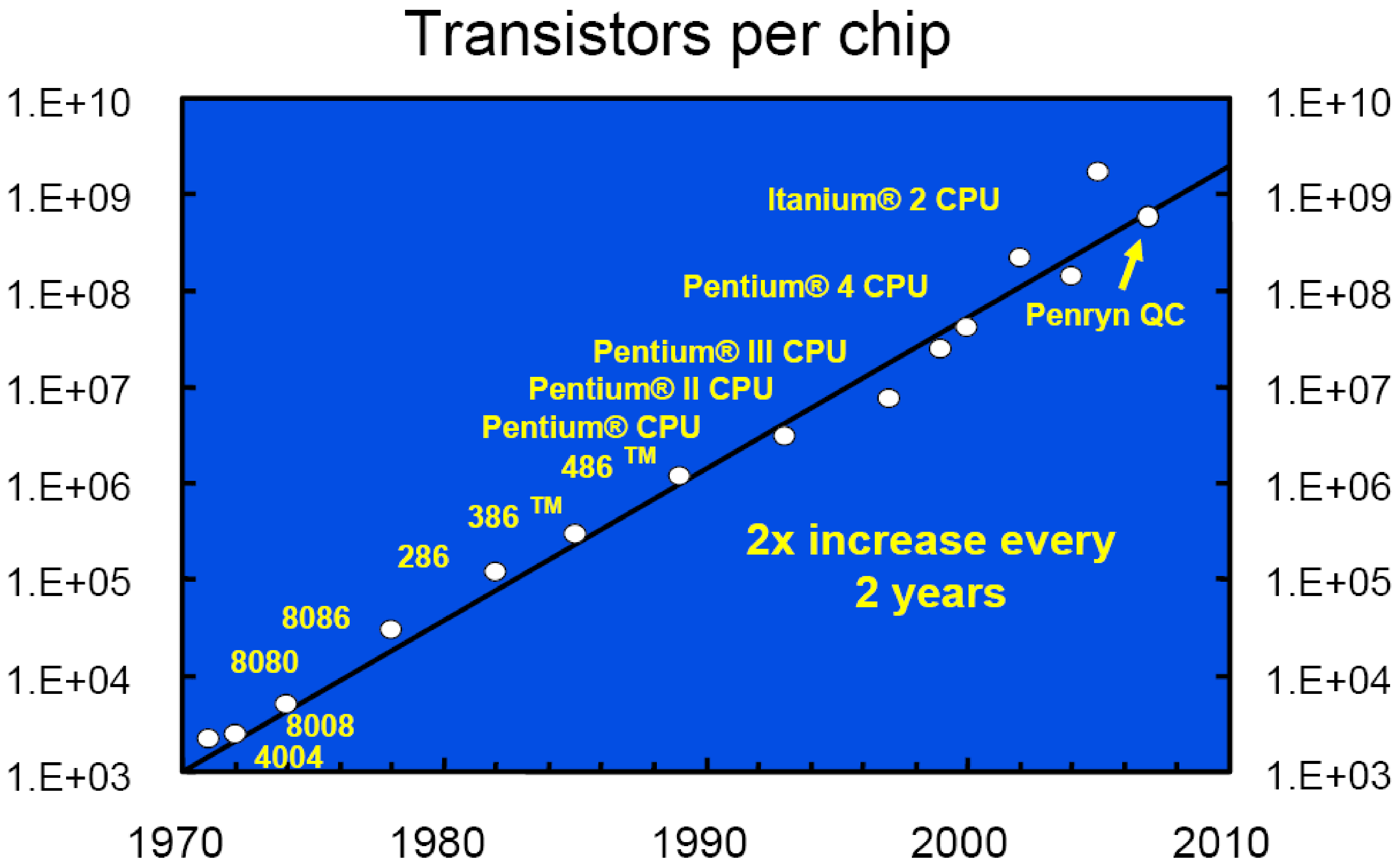


One-sided and super-injection



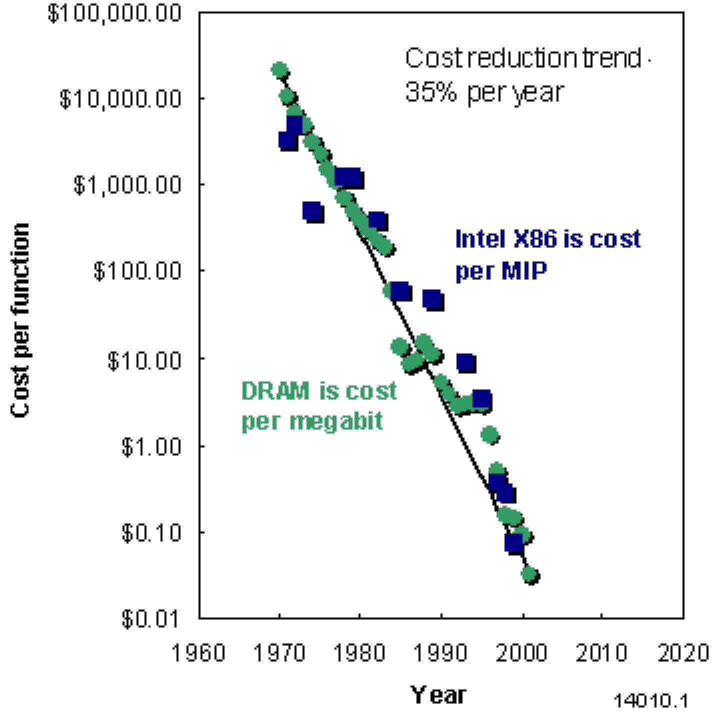
Electron and optical confinement

Microprocessor Perspective



Microprocessor complexity
versus time.

Microprocessor Cost Per MIPS (1997 to 2000)

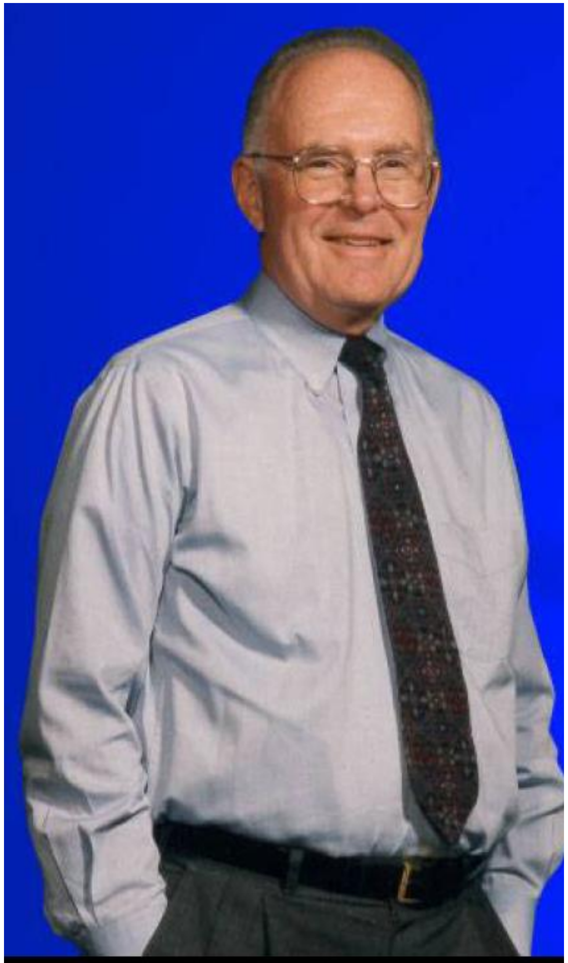


www.icknowledge.com/economics/dramcosts.html

- This figure illustrates the cost per Million Instructions Per Second (MIPS) for Intel Microprocessors from 1970 to 2000
- The costs have come down by six orders of magnitude in three decades!

Moore’s Law

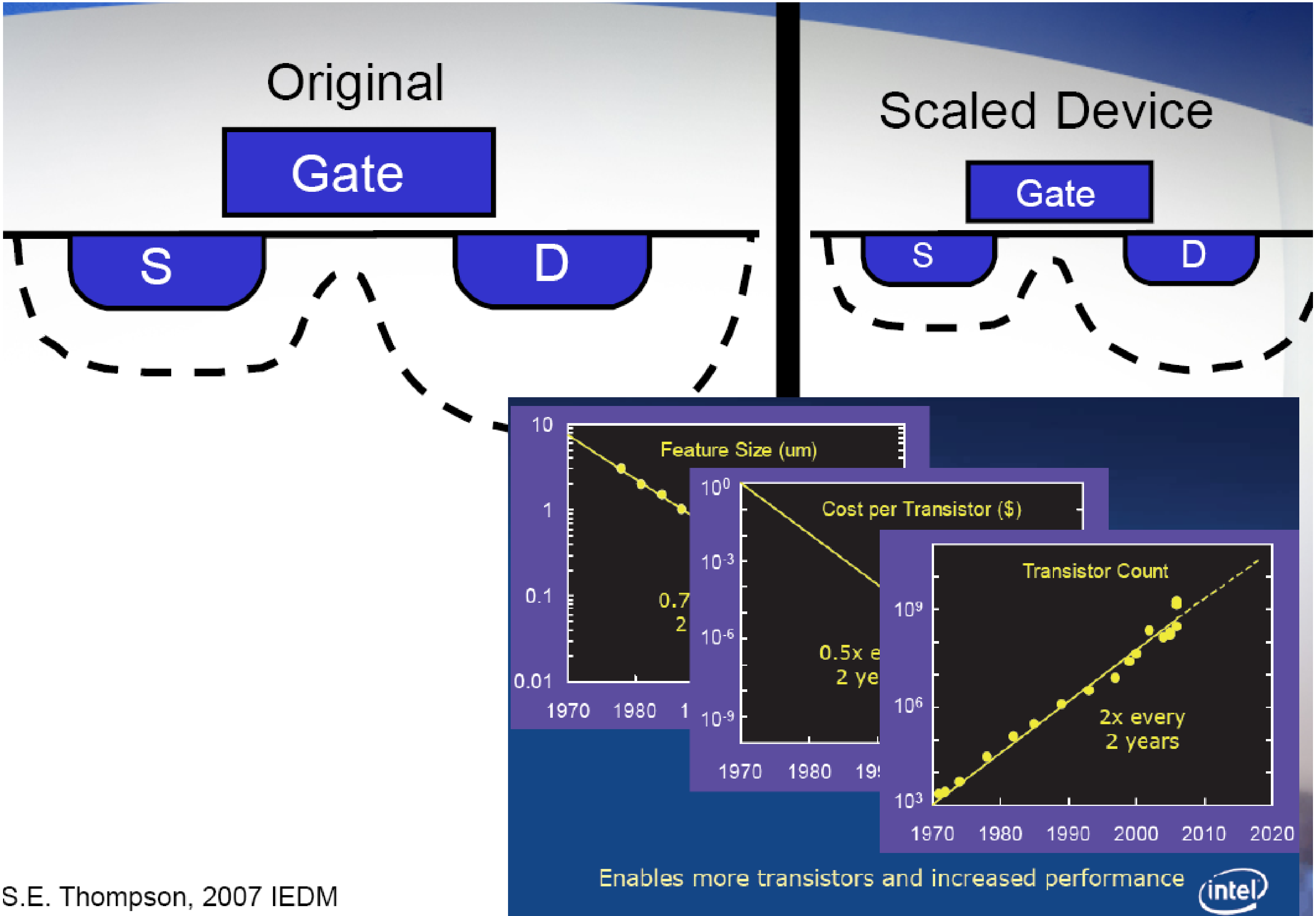
- **Moore’s Law: the trend that the demand for IC functions and the capacity of the semiconductor industry to meet that demand, will double every 1.5 to 2 years.**



According to Moore:
“Cheap way to do electronics”

- 2X increase in density every 1 year (1965)
- Updated to every 2 years in 1975

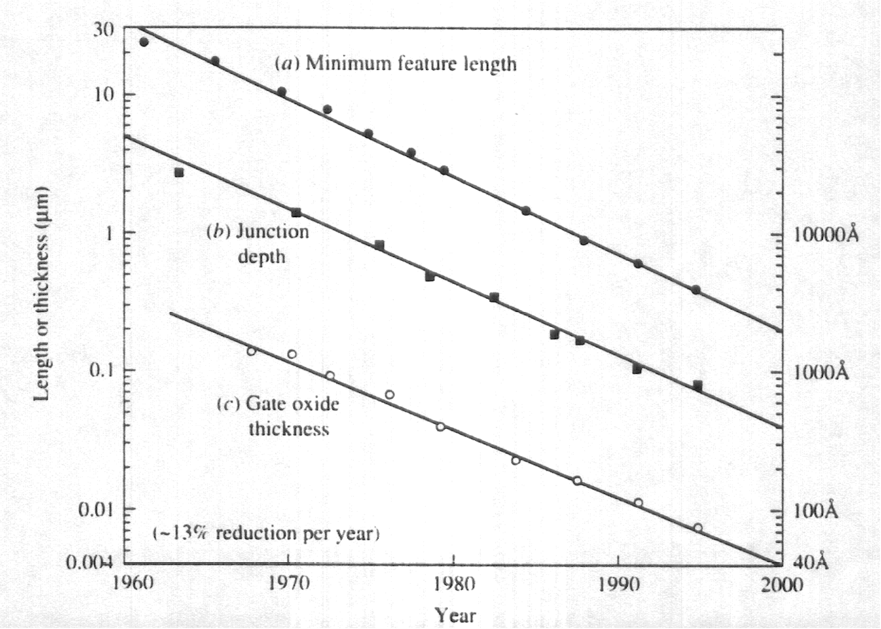
Device Feature Size Scaling



Enables more transistors and increased performance

S.E. Thompson, 2007 IEDM

Scaling of Critical Geometries



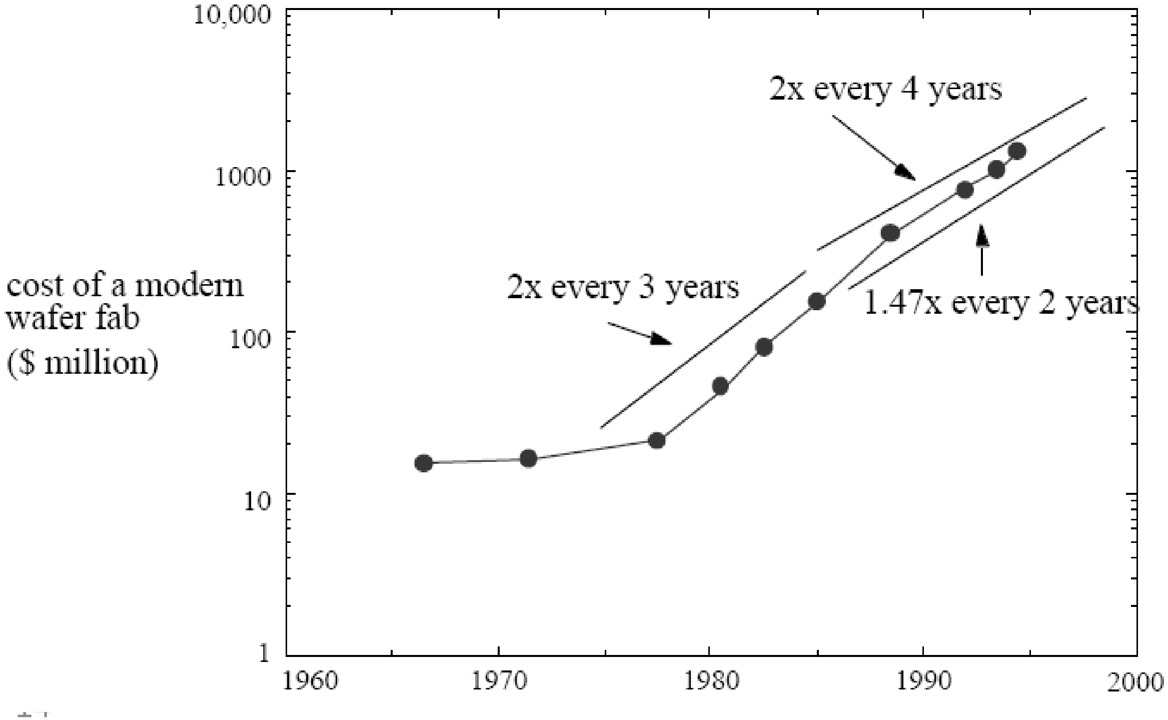
Decrease of feature size, junction depth and gate oxide thickness

Scaling is NOT enough!

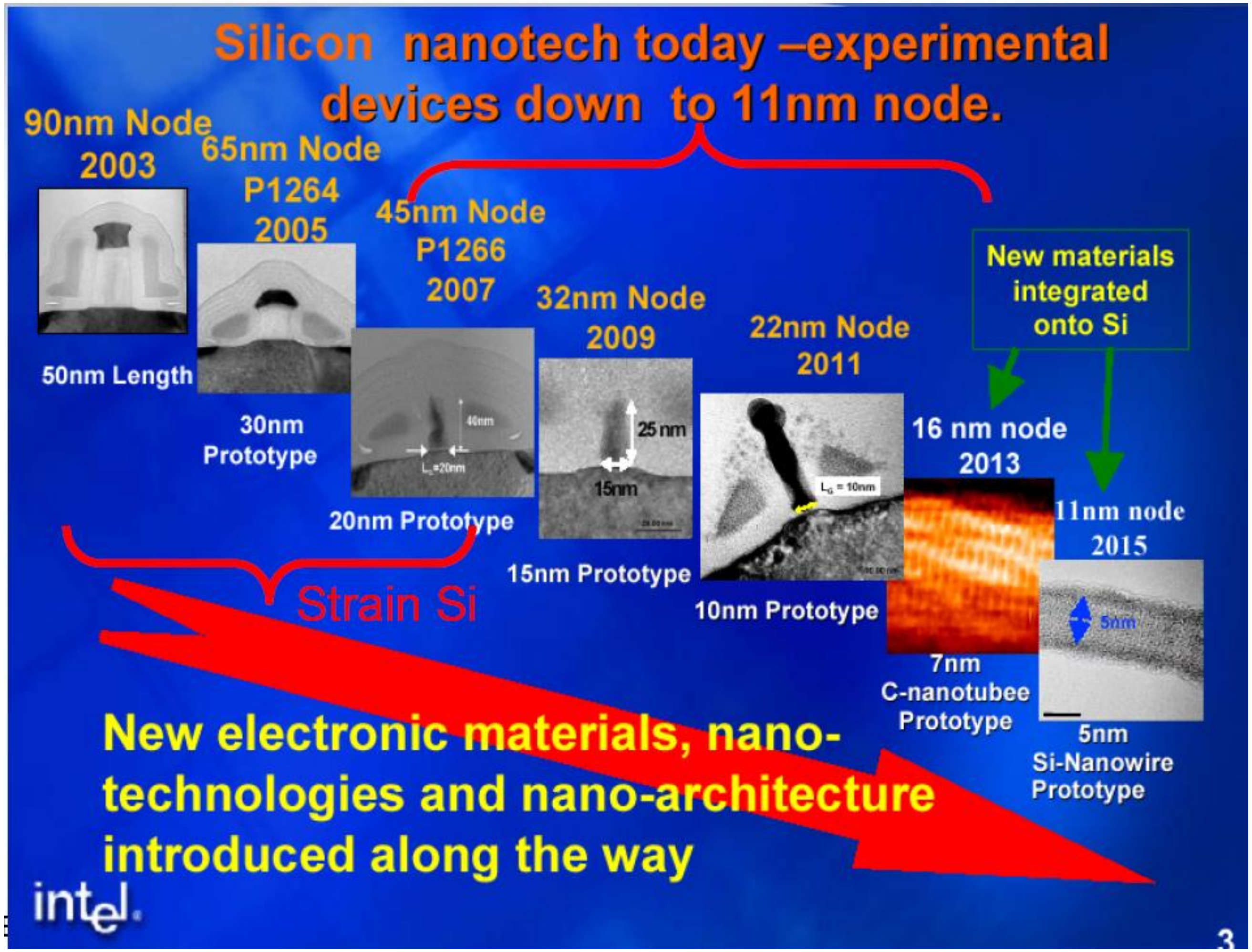
- In the past years (below 90nm technologies), scaling is not enough
- New material changes have been introduced to cope with new problems
  - Strain Si
  - Strain SiGe
  - High K
  - Metal gate

Moore's 2^{nd} Law

- We need to understand how the devices function to ensure proper performance, reliability and economic implications.
- For many generations, scaling was relatively straightforward. Today, it also involves new materials and increased complexity, greatly increasing cost.



New Device Options on Intel’s Roadmap



Silicon nanotech today –experimental devices down to 11nm node.

90nm Node
2003

50nm Length

65nm Node
P1264
2005

30nm
Prototype

45nm Node
P1266
2007

20nm Prototype

32nm Node
2009

15nm Prototype

22nm Node
2011

10nm Prototype

New materials
integrated
onto Si

16 nm node
2013

7nm
C-nanotubee
Prototype

11nm node
2015

5nm
Si-Nanowire
Prototype

Strain Si

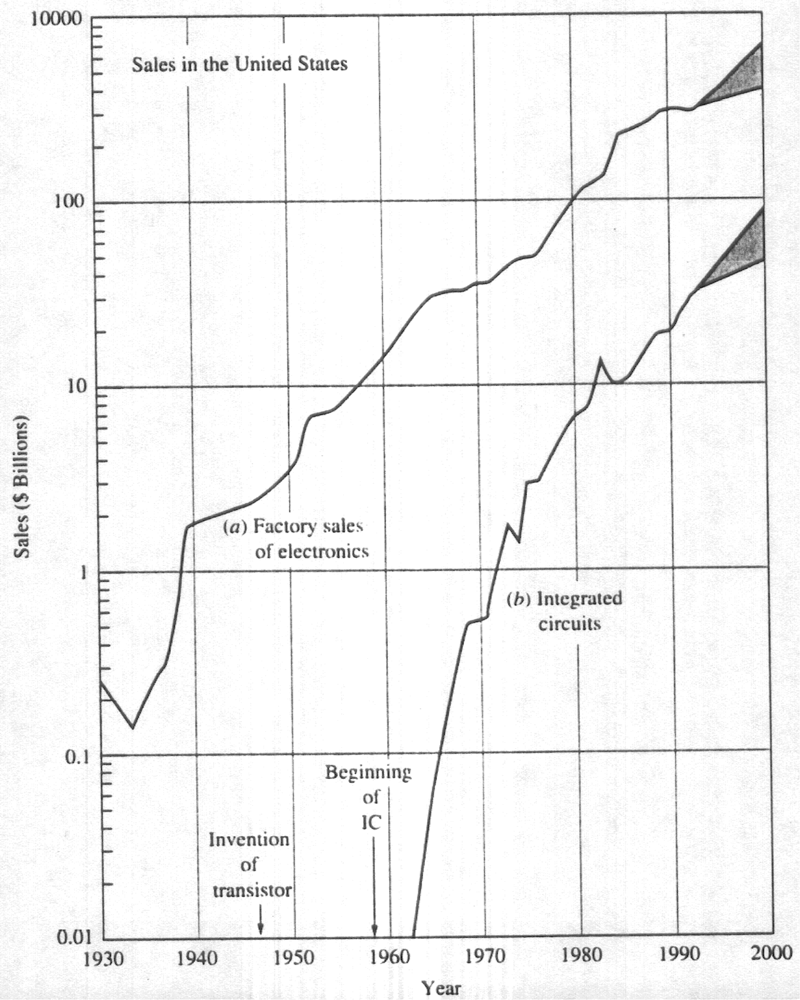
New electronic materials, nano-technologies and nano-architecture introduced along the way

intel

3

Growth of Semiconductor Industry

- Faster than any other industry!
- One of the few physics based technologically important industry

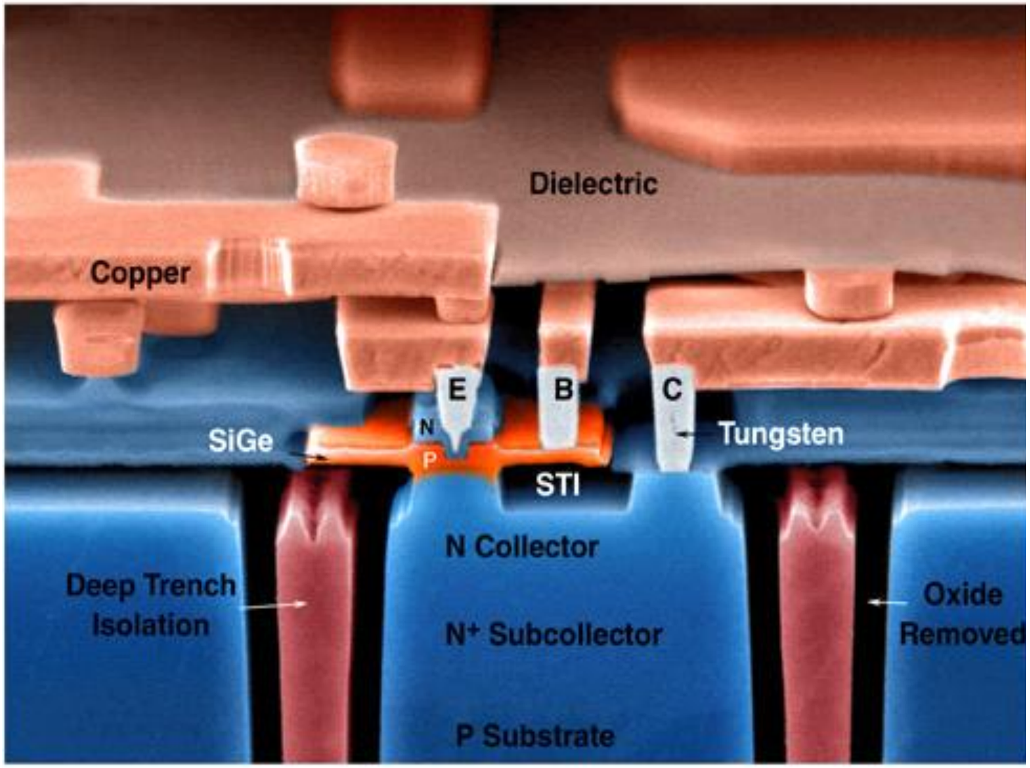


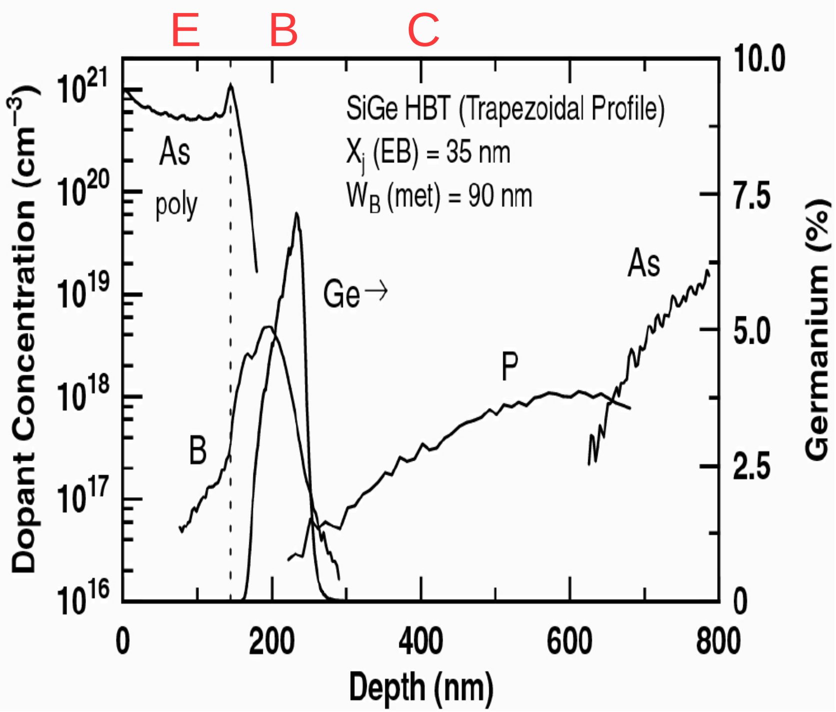
Technology Transitions

- The first transistor was a bipolar transistor, as were the first ICs
- Initial MOS only had incremental advantages over bipolar until CMOS
- High speed bipolar was initially developed for digital, but CMOS quickly took over
- However, bipolar / BiCMOS technology has found new applications, mainly communication
- III-V technology is largely optoelectronics--a complement to CMOS
- Is there anything beyond CMOS?

Atomic level bandgap engeering in Si - SiGe transistor

- Electronic picture of nano scale SiGe HBTs

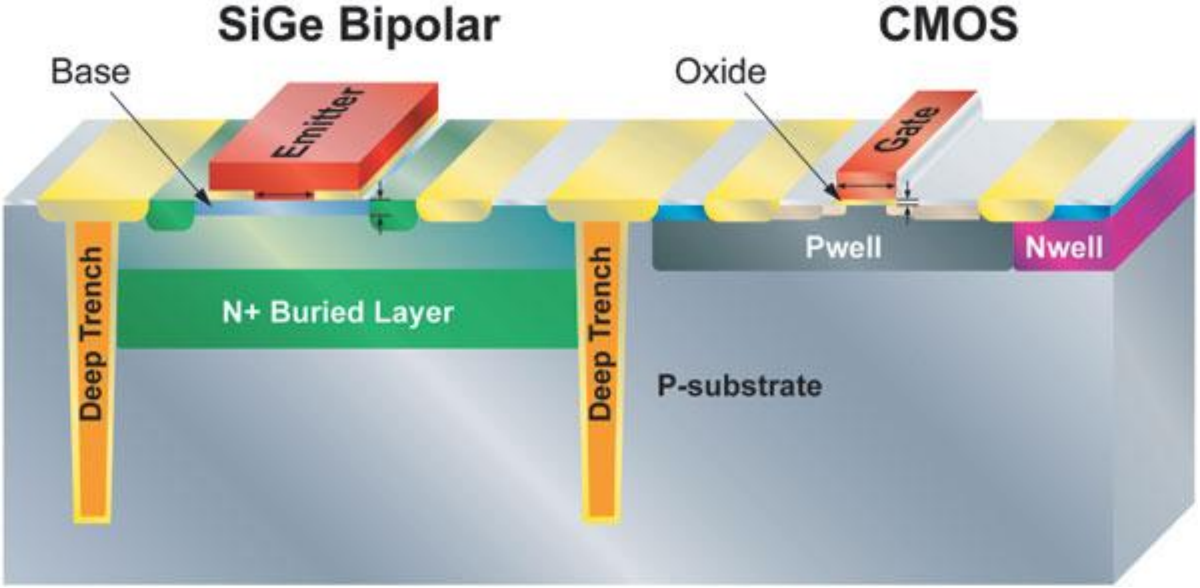




In commercial mainstream application for wireless, wireline, mixed-signal

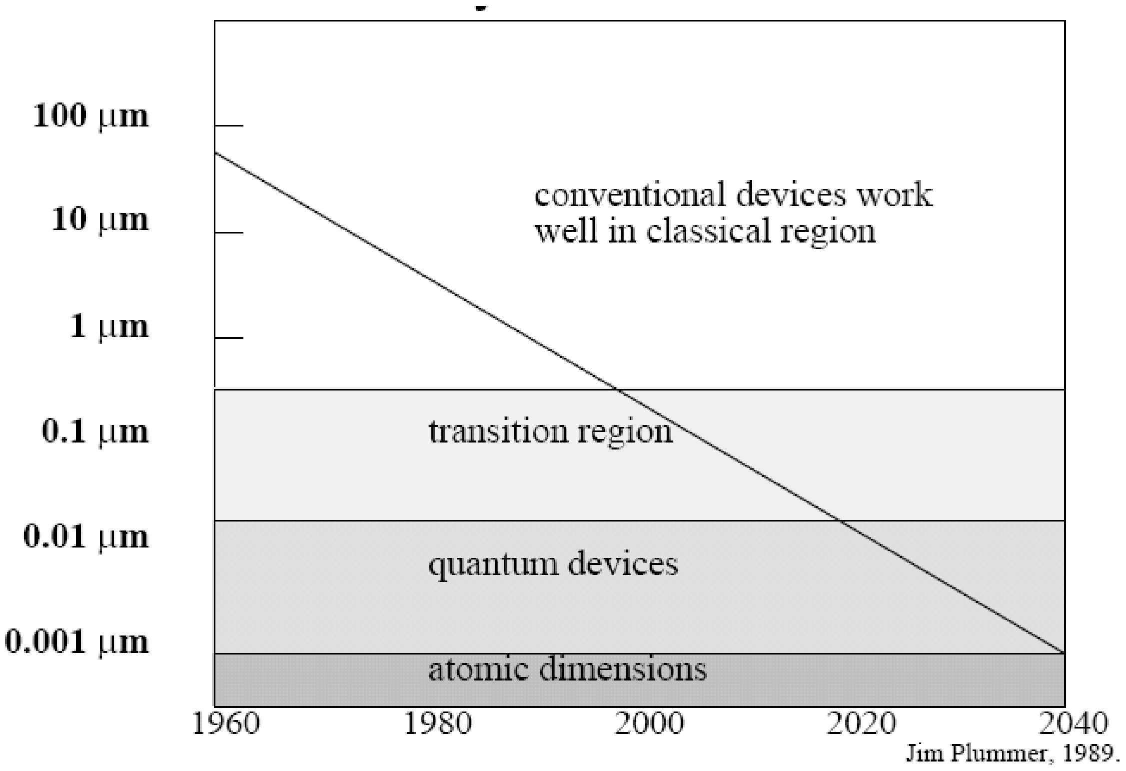
BiCMOS technologies

- Bipolar + CMOS on the same chip
- Often used in Mixed-signal and RF applications



Technology transition beyond CMOS?

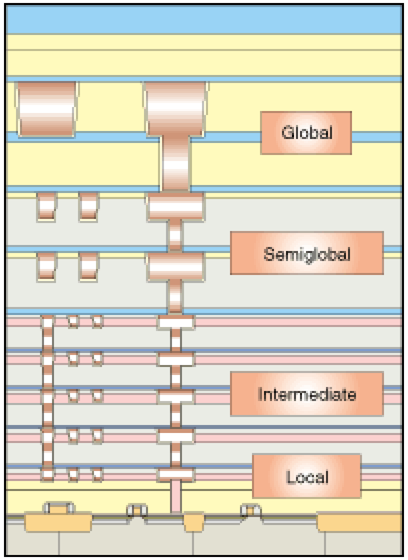
- Devices are getting very small. Will they reach quantum or even atomic dimensions?
- What principles will they operate on?
- Still charge or is spin or something else possible?

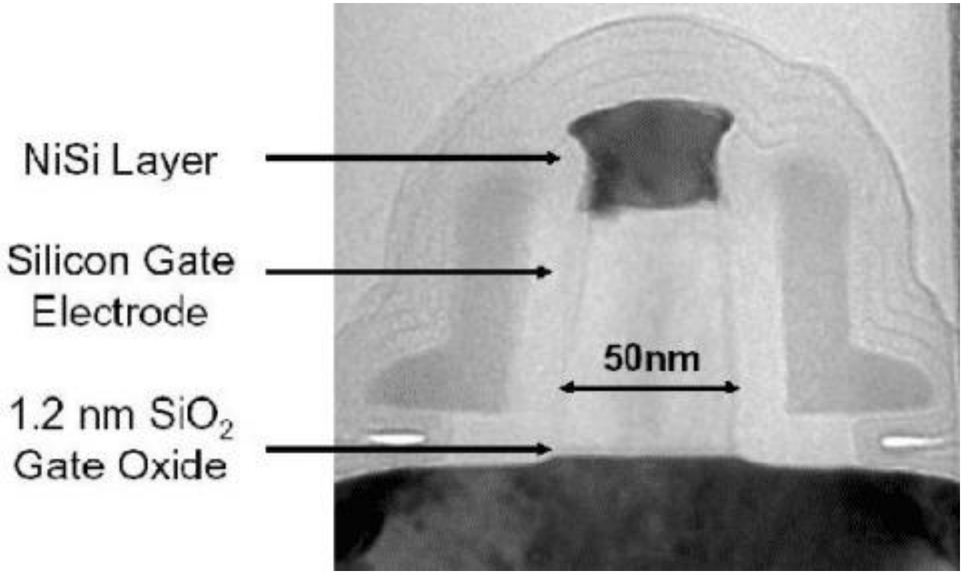


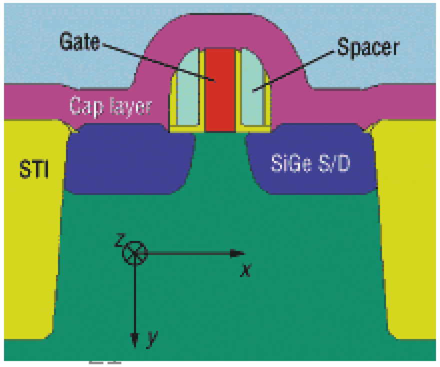
Jim Plummer, 1989.

State-of-the-art CMOS

- Intel Core 2 Duo processor - 291 million transistors built using 65nm CMOS technology





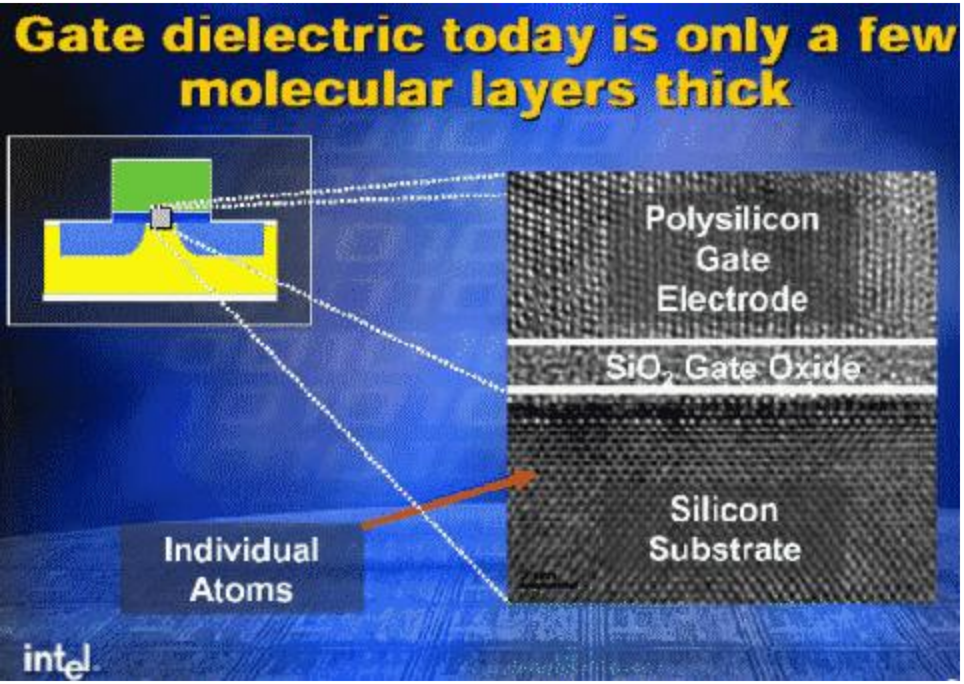


Silicon-Germanium

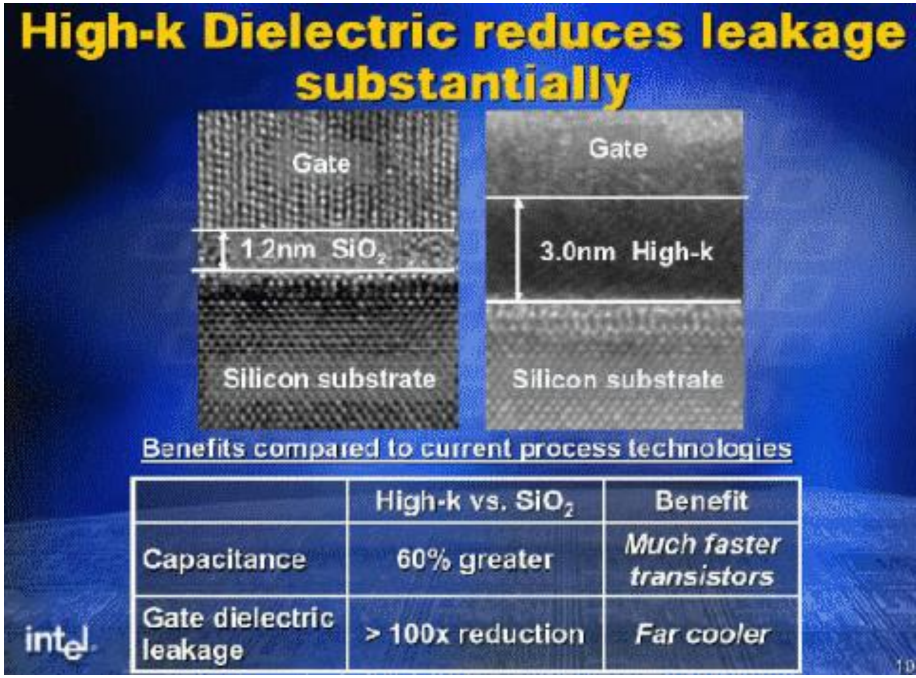
- Bandgap engineering
  - Base for bipolar transistor
  - Substrate for making strained Silicon channel
  - Source/drain for lowering contact resistance and producing channel stress to improve mobility

New developments and challenges

- Gate oxide – high K
- Metal gate
- New channel material strain silicon
- And many others ….



Gate dielectric today is only a few molecular layers thick



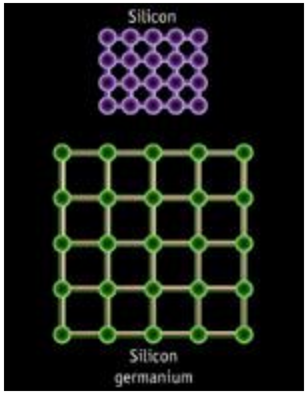
High-k Dielectric reduces leakage substantially

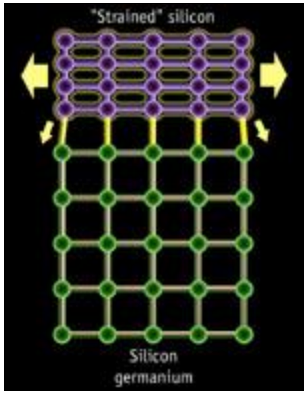
Benefits compared to current process technologies

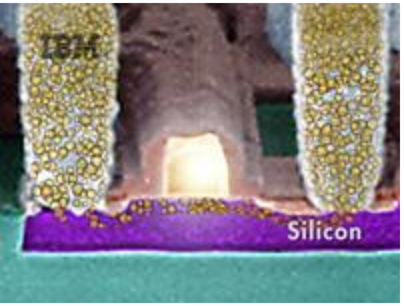
	High-k vs. SiO_2	Benefit
Capacitance	60% greater	*Much faster transistors*
Gate dielectric leakage	> 100x reduction	*Far cooler*

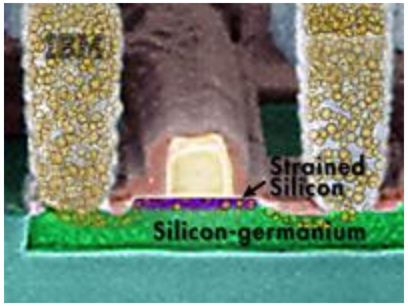
Strained silicon CMOS

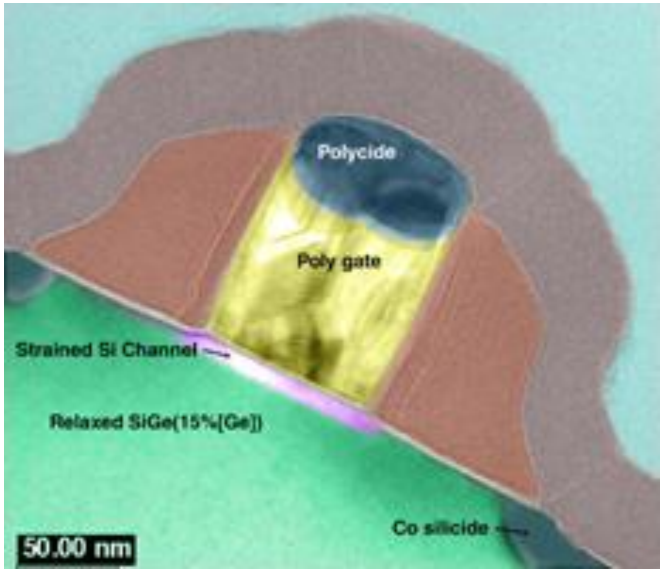
- Strained silicon -> faster transistor
- Demo movie



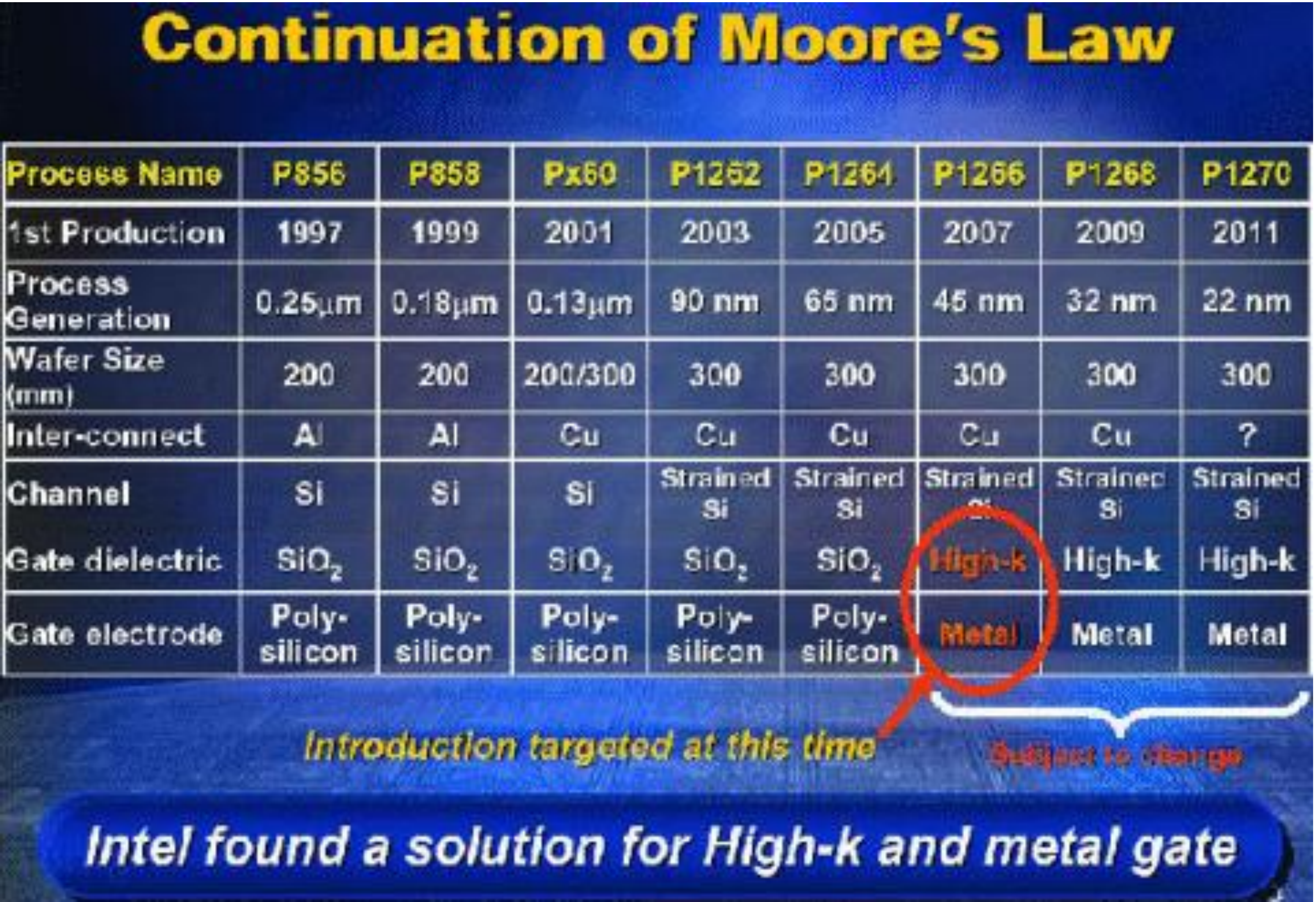








Continuing with Moore’s law



Continuation of Moore’s Law

Process Name	P856	P858	Px60	P1262	P1264	P1266	P1268	P1270
1st Production	1997	1999	2001	2003	2005	2007	2009	2011
Process Generation	0.25µm	0.18µm	0.13µm	90 nm	65 nm	45 nm	32 nm	22 nm
Wafer Size (mm)	200	200	200/300	300	300	300	300	300
Inter-connect	Al	Al	Cu	Cu	Cu	Cu	Cu	?
Channel	Si	Si	Si	Strained Si	Strained Si	Strained Si	Strained Si	Strained Si
Gate dielectric	SiO_2	SiO_2	SiO_2	SiO_2	SiO_2	High-k	High-k	High-k
Gate electrode	Poly-silicon	Poly-silicon	Poly-silicon	Poly-silicon	Poly-silicon	Metal	Metal	Metal

Introduction targeted at this time

Subject to change

Intel found a solution for High-k and metal gate

Why Si?

- **SiO2 is a Magical Material**
  - SiO2 passivates the surface of Si
  - SiO2 is an excellent insulator
  - SiO2 is an excellent barrier against impurity diffusion
  - SiO2 has very high etch selectivity to Si
- Si is easily purified and can be grown defect free single crystal
- Si has reasonably good electronic properties which produce a variety of devices with excellent performance
- Si and SiO2 are tolerant to a variety of harsh environments used in fabrication and is highly manufacturable
- Si has excellent mechanical properties which facilitate handling and manufacturing
- Si is readily available and very plentiful in nature

Applications and Physics

- **The principal applications of any sufficiently new and innovative technology have been—and will continue to be applications created by that technology.”** (Herb Kroemer, 2000 Nobel Laureate in Physics)
- When talking about semiconductors, if you cannot draw band diagrams, you do not know what you are talking about … (Herb Kroemer, 2000 Nobel Laureate in Physics)