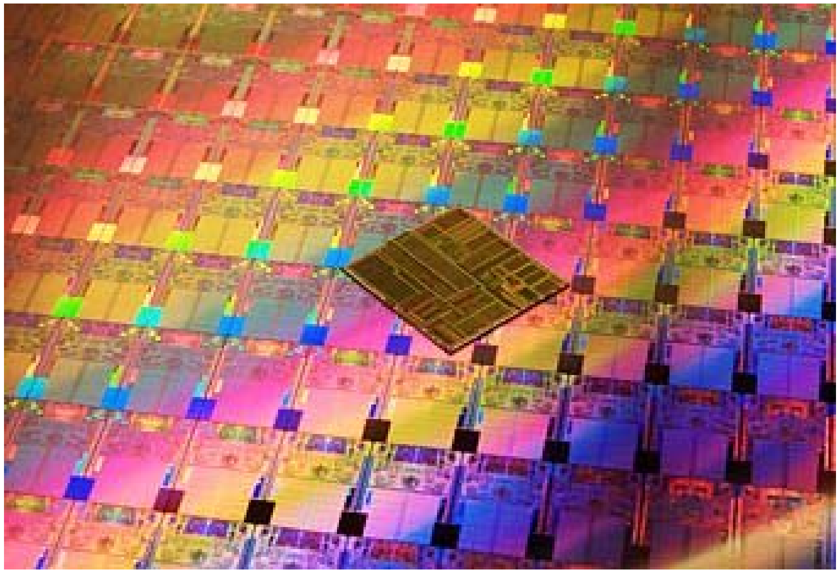
ECE 3080: Semiconductor Devices

for Computer Engineering and Telecommunication Systems

"The significant problems we face cannot be solved by the same level of thinking that created them." – Albert Einstein

Dr. Alan Doolittle

School of Electrical and Computer Engineering
Georgia Institute of Technology



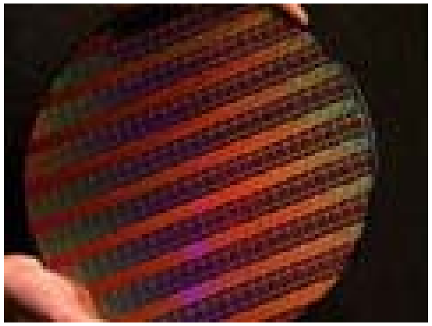
Intel, 45-nm CMOS "Dual Core" process technology Compared to older Pentium processor

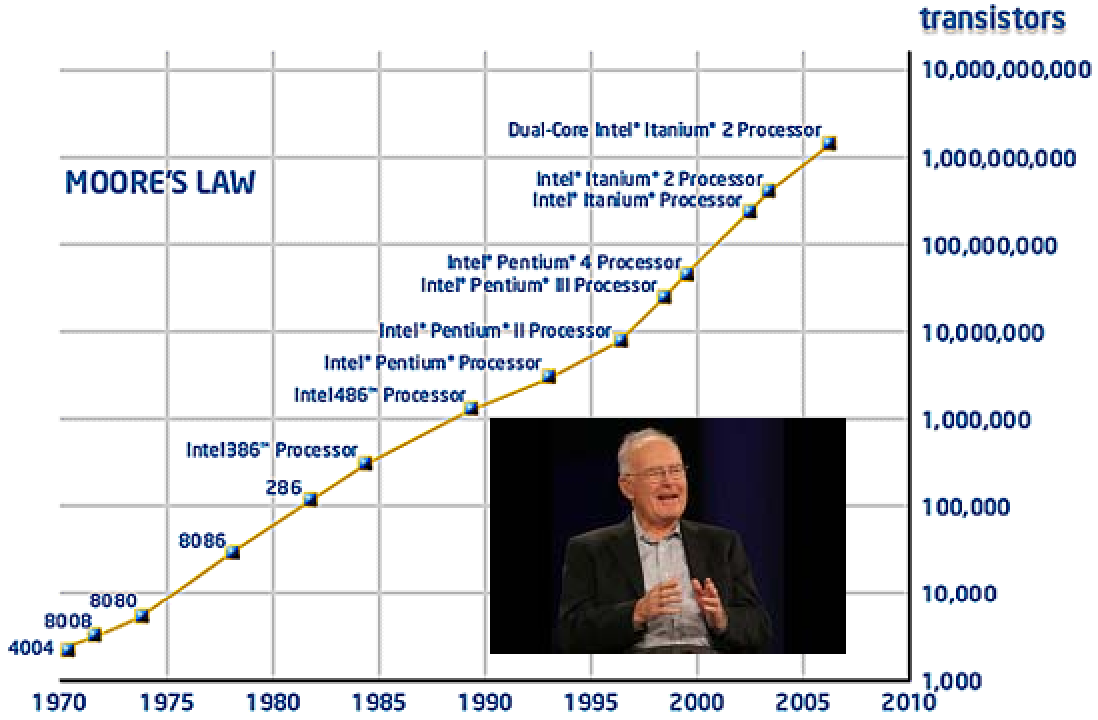
Note: several images in this lecture were obtained from the Intel web pages

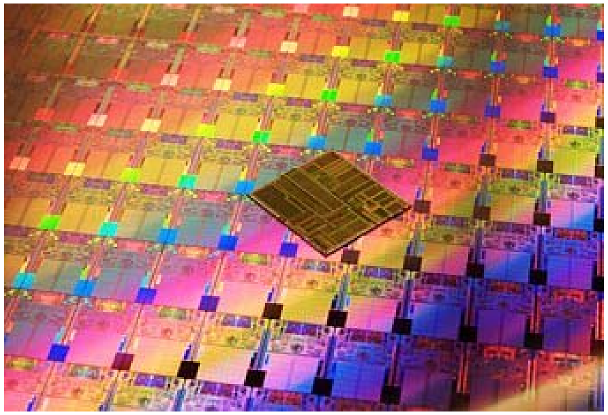
Why do we need to know about Nano-electronic “materials” details? – A Case study of the evolution of the Transistor

Moore’s Law: The Growth of the Semiconductor Industry

Moore’s law (Gordon Moore, co-founder of Intel, 1965):
Empirical rule which predicts that the number of components per chip doubles every 18-24 months
Moore’s Law turned out to be valid for more than 30 years (and still is!)







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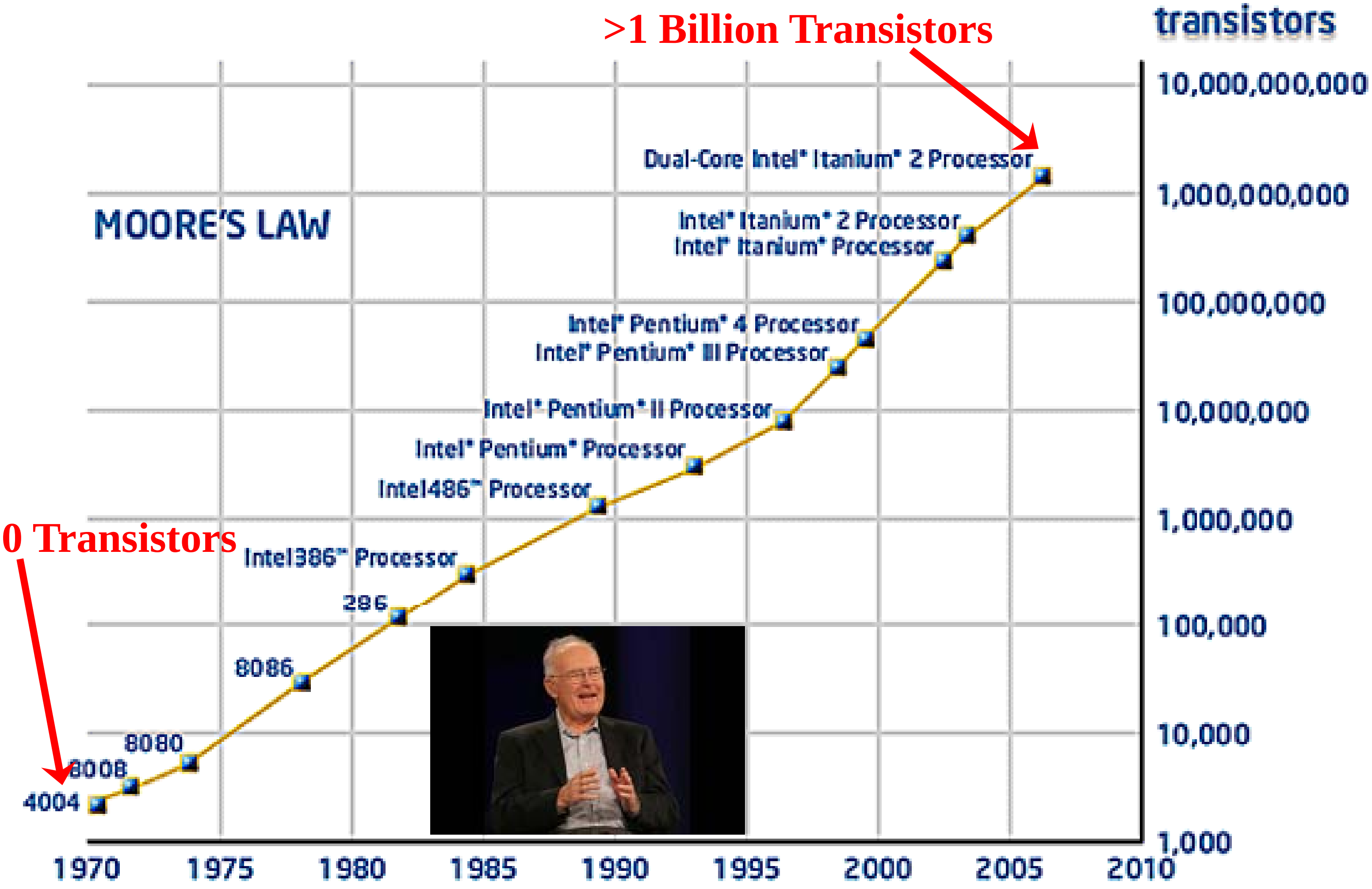
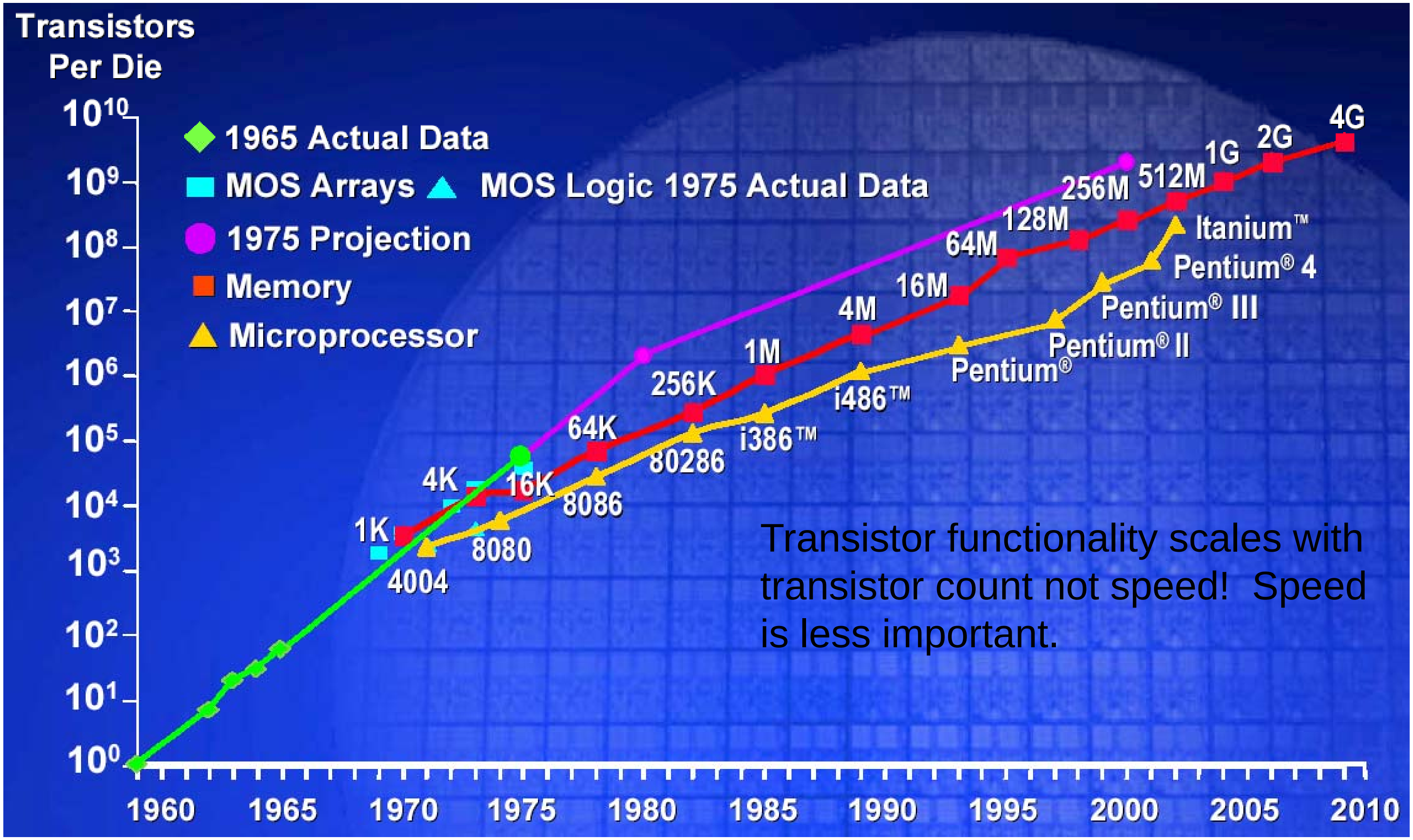
Moore's Law: The Growth of the Semiconductor Industry



>1 Billion Transistors

2000 Transistors

Why do we need to know about Nano-electronic "materials" details? – A Case study of the evolution of the Transistor



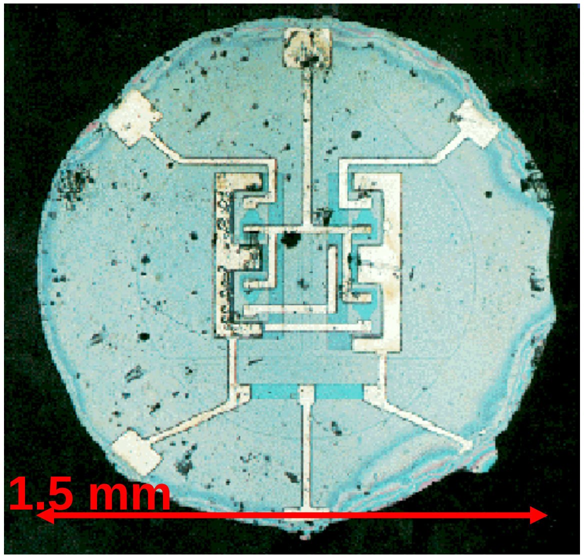
Transistor functionality scales with transistor count not speed! Speed is less important.

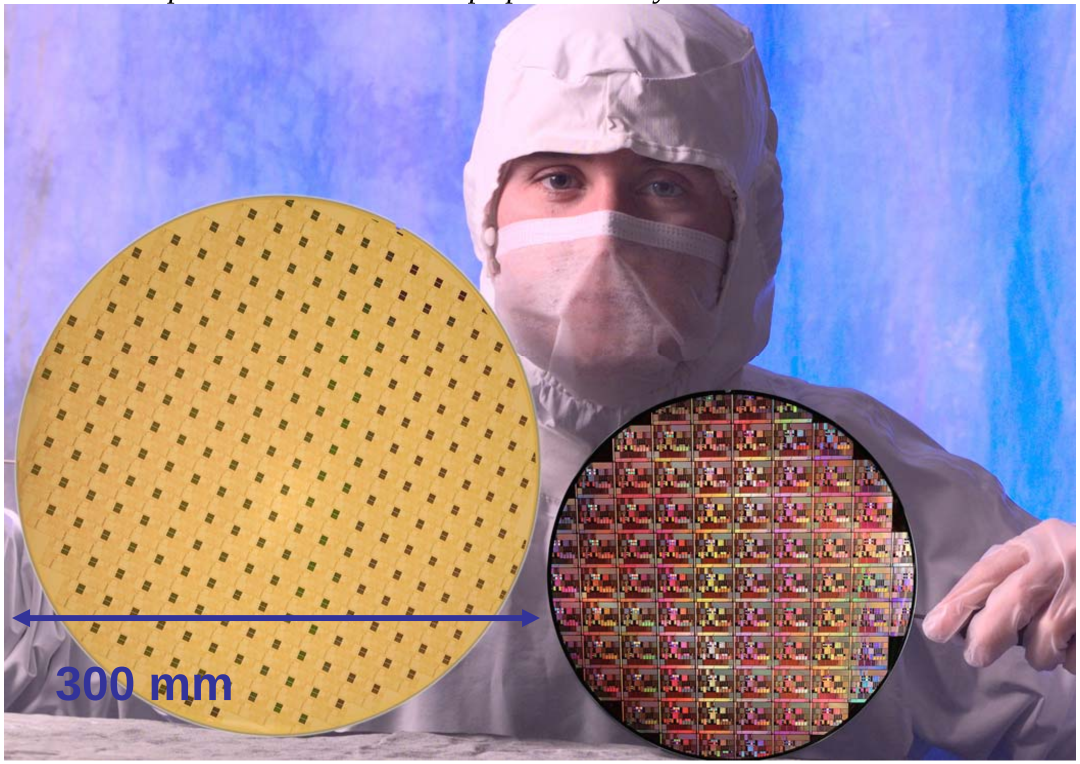
from G. Moore, ISSCC 2003

Why do we need to know about Nano-electronic "materials" details? – A Case study of the evolution of the Transistor

How did we go from 4 Transistors/wafer to Billions/wafer?

IBM 200 mm and 300 mm wafer
http://www-3.ibm.com/chips/photolibrary

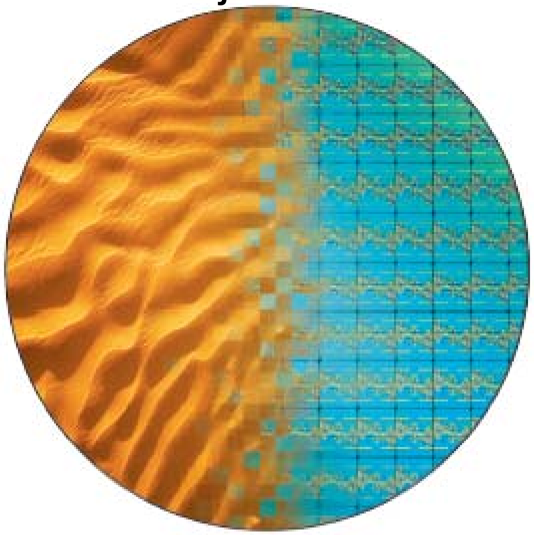


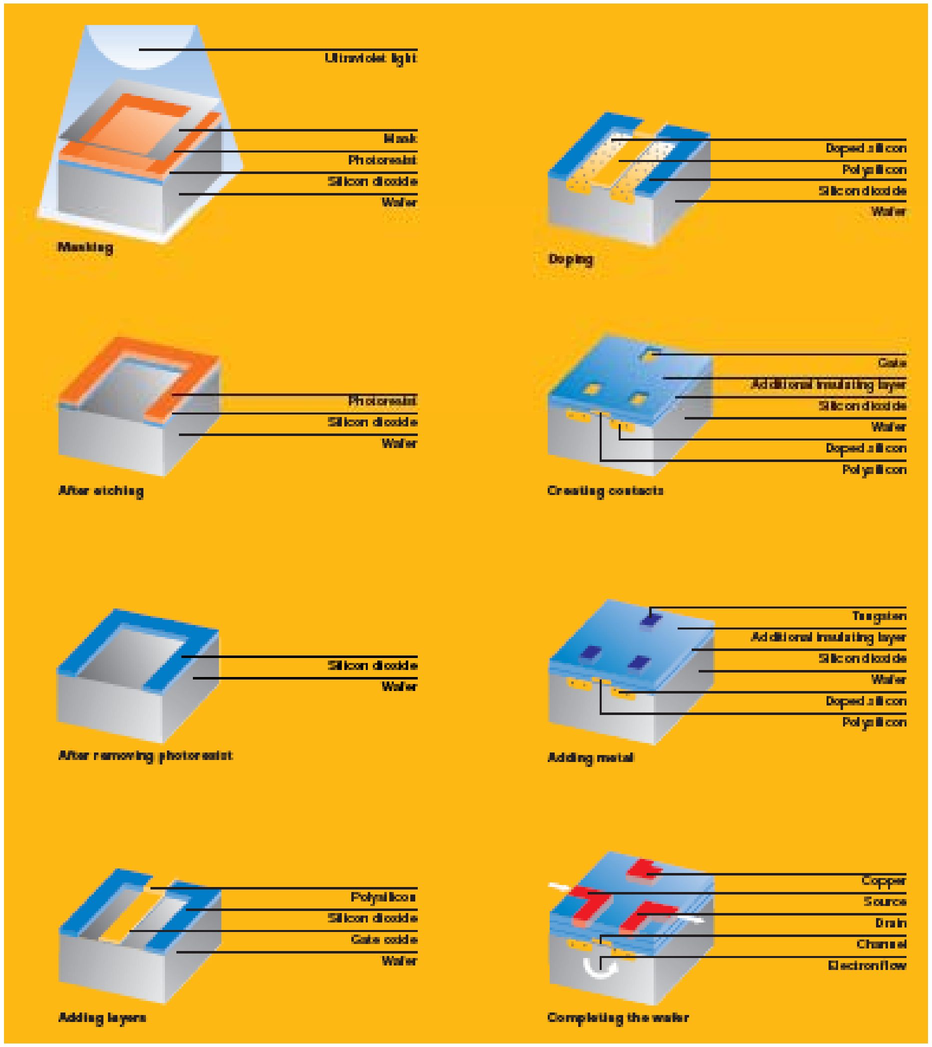


First Planar IC
1961, Fairchild
http://smithsonianchips.si.edu/

Why do we need to know about Nano-electronic "materials" details? – A Case study of the evolution of the Transistor

Sand to Silicon – Major Historical Hurdles.



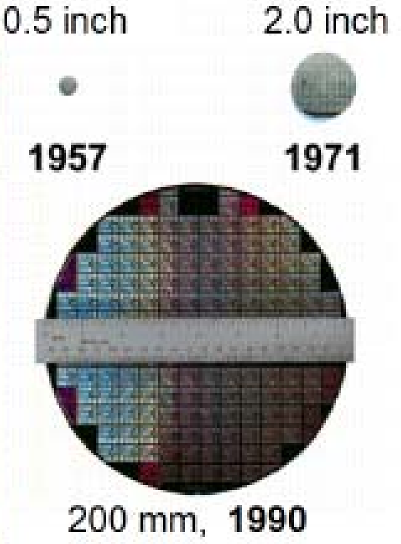


Play parts of movie on Silicon Fabrication

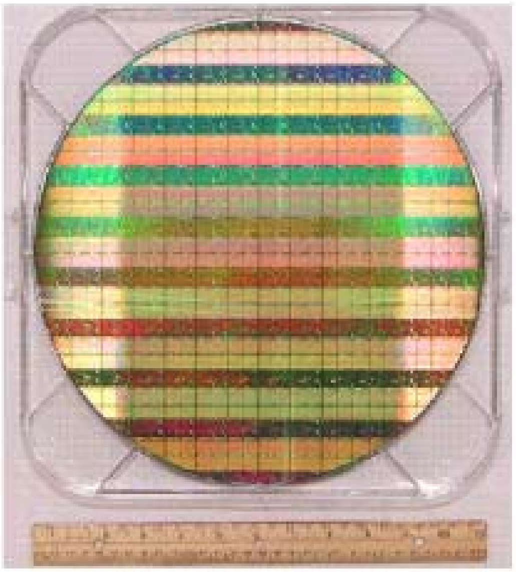
Why do we need to know about Nano-electronic “materials” details? – A Case study of the evolution of the Transistor

Some Facts About Silicon (Si):

- Si is a Group IV element, and crystallizes in the diamond structure
- Perfect Si crystals can be grown very large (12 inches by 8 feet!)
- Si can be made extremely pure (< .000001 ppm impurities!)
- Si is very abundant and non-toxic (70% of the earth’s crust are silicates!)
- Si oxidizes trivially to form one of nature’s most perfect insulators (SiO_2)
- Si is a great conductor of heat (better than many metals!)



200 mm, **1990**



300 mm, **2005**

Slide after Dr. John Cressler

Why do we need to know about Nano-electronic "materials" details? – A Case study of the evolution of the Transistor

Common Statement: First Transistor was invented by Shockley, Brattain and Bardeen on December 23, 1947 at 5 PM – Wrong!

The first patent for the field-effect transistor principle was filed in Canada by Austrian-Hungarian physicist Julius Edgar Lilienfeld on October 22, 1925

The level of understanding you gained about transistors in ECE 3040 is 60 years old!!!!

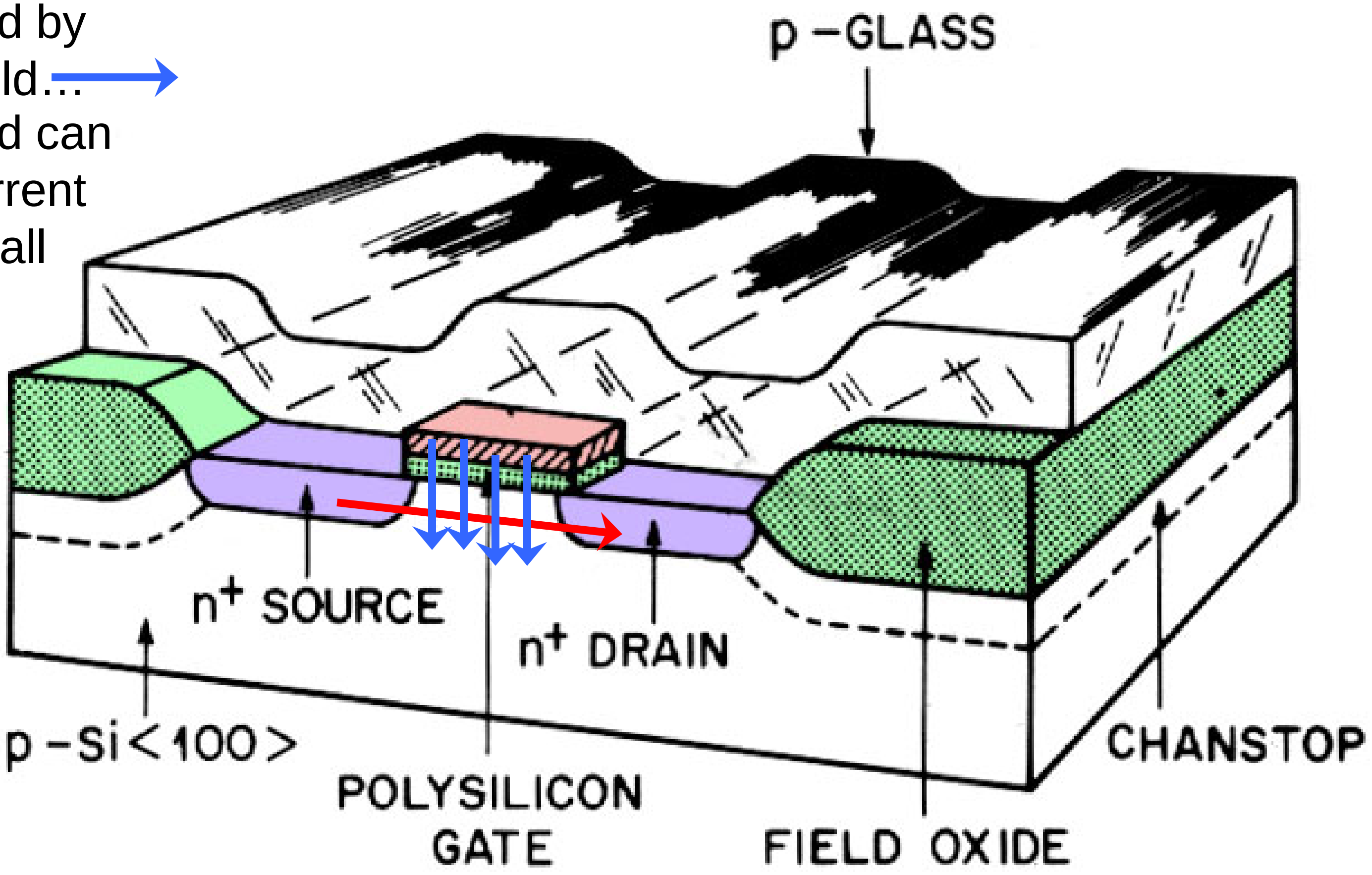
Ga Tech Graduates make the future happen and thus need to understand the state of the art in order to advance it.

The Basic Device in CMOS Technology is the MOSFET

Direction of Desired Current flow… →

…is controlled by an electric field… →

…but this field can also drive current through a small gate. Modern transistors have more power loss in the gate circuit than the source - drain! New approaches are needed.



Why do we need to know about Nano-electronic “materials” details? – A Case study of the evolution of the Transistor

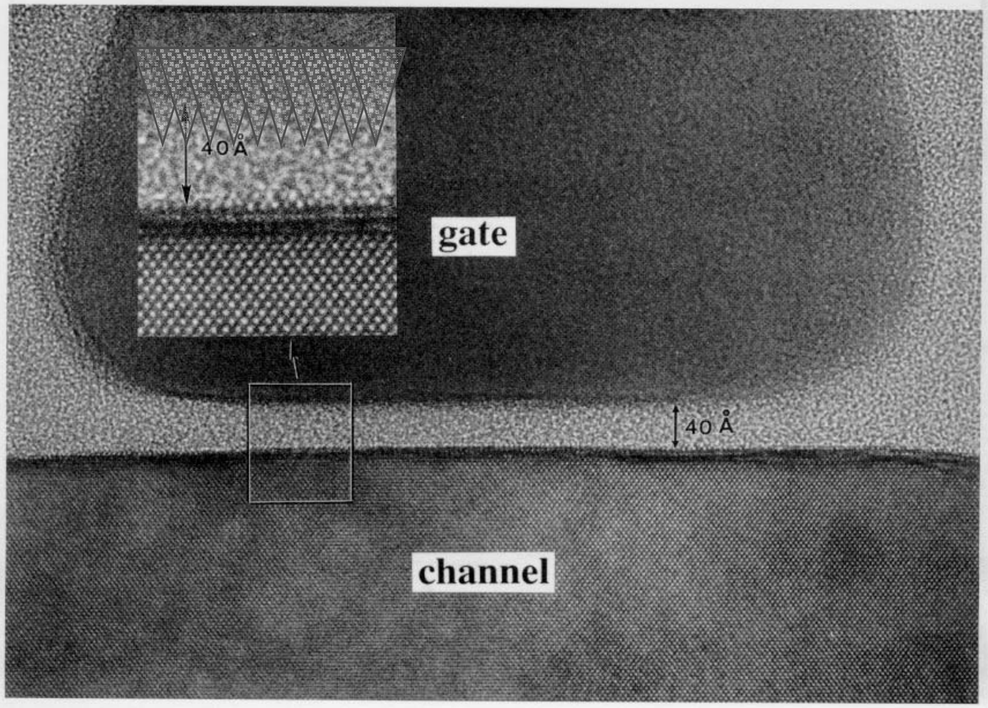
Early MOSFET: SiO_2 Gate Oxide, Aluminum (Al) Source/Drain/Gate metals

Problem: As sizes shrank, devices became unreliable due to metallic spiking through the gate oxide.

Solution: Replace Metal Gate with a heavily doped poly-silicon.

This change carried us for decades with challenges in fabrication (lithography) being the primary barriers that were overcome …until…

Cross section of a MOSFET. This high resolution transmission electron micrograph of a silicon Metal-Oxide-Semiconductor Field Effect Transistor shows the silicon channel and metal gate separated by a thin (40Å, 4nm) silicon-dioxide insulator. The inset shows a magnified view of the three regions, in which individual rows of atoms in the crystalline silicon can be distinguished. (Photograph courtesy of AT&T Bell Laboratories.)



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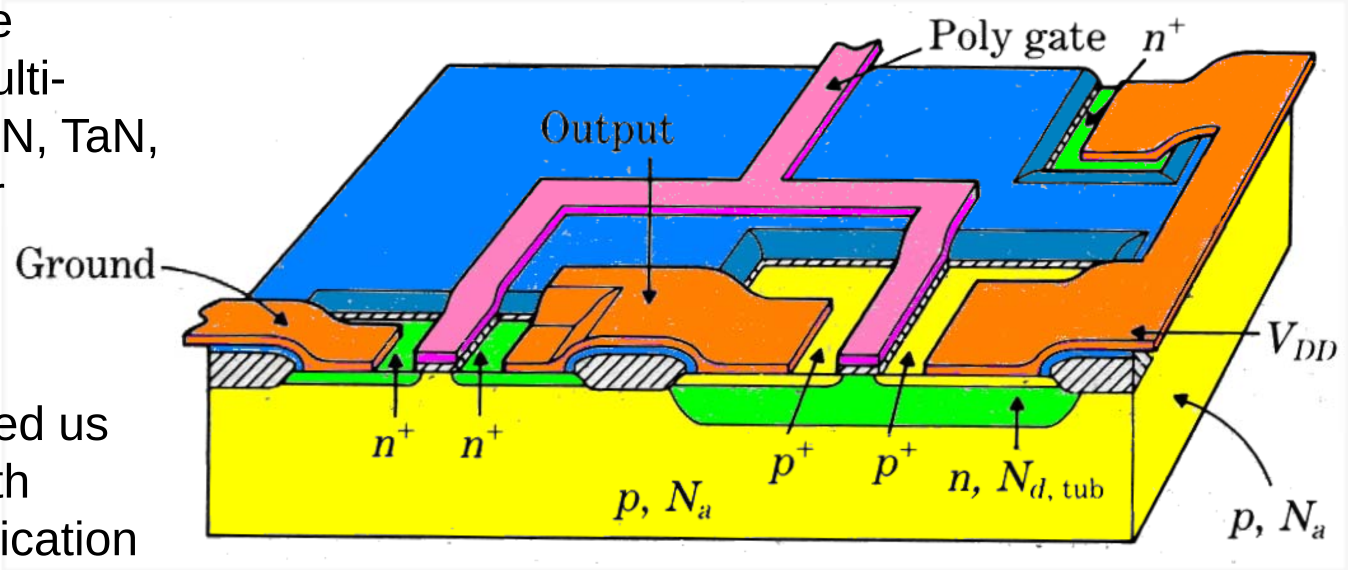
Semi-Modern MOSFET (late 1990's vintage): SiO_2 Gate Oxide, Polysilicon gate metals, metal source/drain contacts and Aluminum metal interconnects

Problem: As interconnect sizes shrank, Aluminum lines became too resistive leading to slow RC time constants

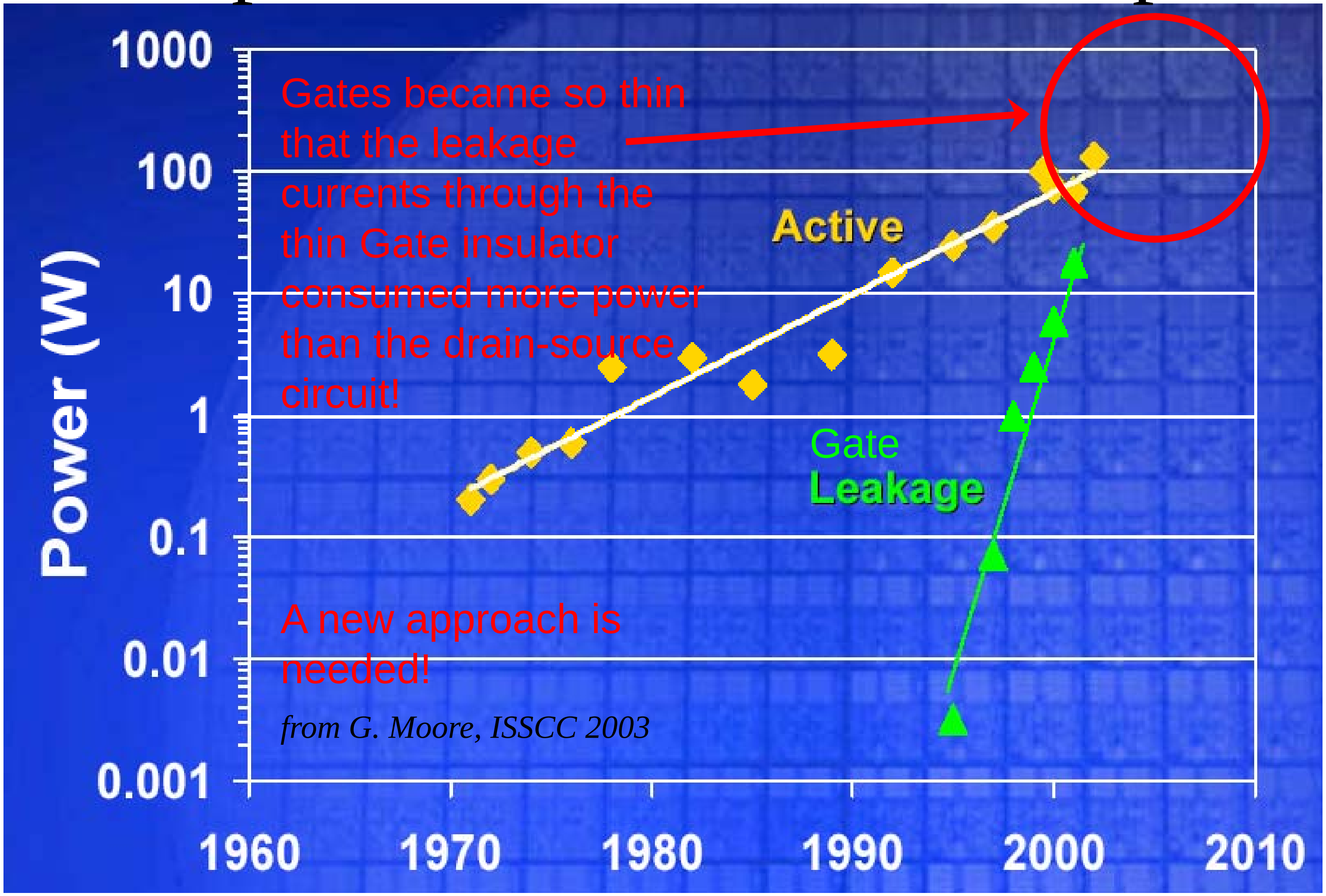
Solution: Replace Aluminum with multi-metal contacts (TiN, TaN, etc…) and copper interconnects.



This change carried us for ~ 1 decade with challenges in fabrication (lithography) being the primary barriers that were overcome …until…

Why do we need to know about Nano-electronic “materials” details? – A Case study of the evolution of the Transistor

Microprocessor Power Consumption

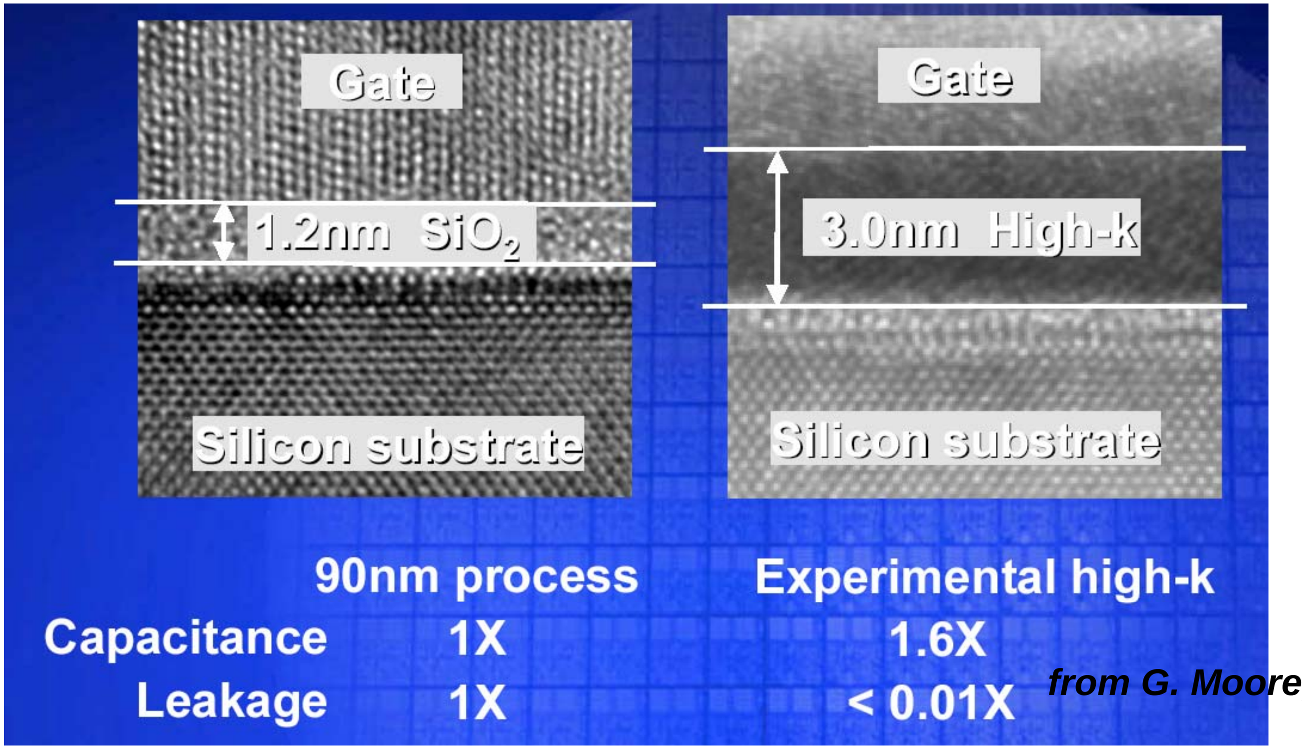


Gates became so thin that the leakage currents through the thin Gate insulator consumed more power than the drain-source circuit!

A new approach is needed!

from G. Moore, ISSCC 2003

Why do we need to know about Nano-electronic "materials" details? – A Case study of the evolution of the Transistor



	90nm process	Experimental high-k
Capacitance	1X	1.6X
Leakage	1X	< 0.01X

from G. Moore, ISSCC 2003

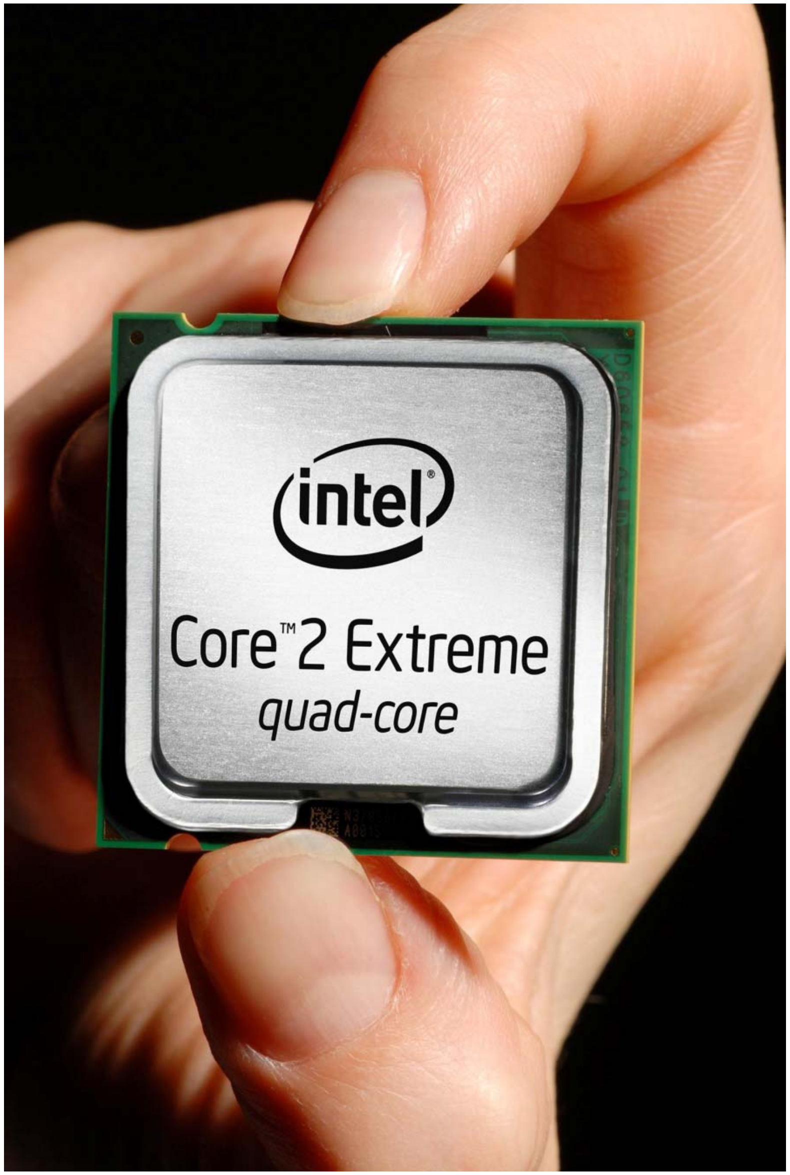
$$D_{insulator} = k_{insulator} E$$

$$D_{insulator} = k_{insulator} \left(\frac{V_{Gate}}{t_{Gate}} \right)$$

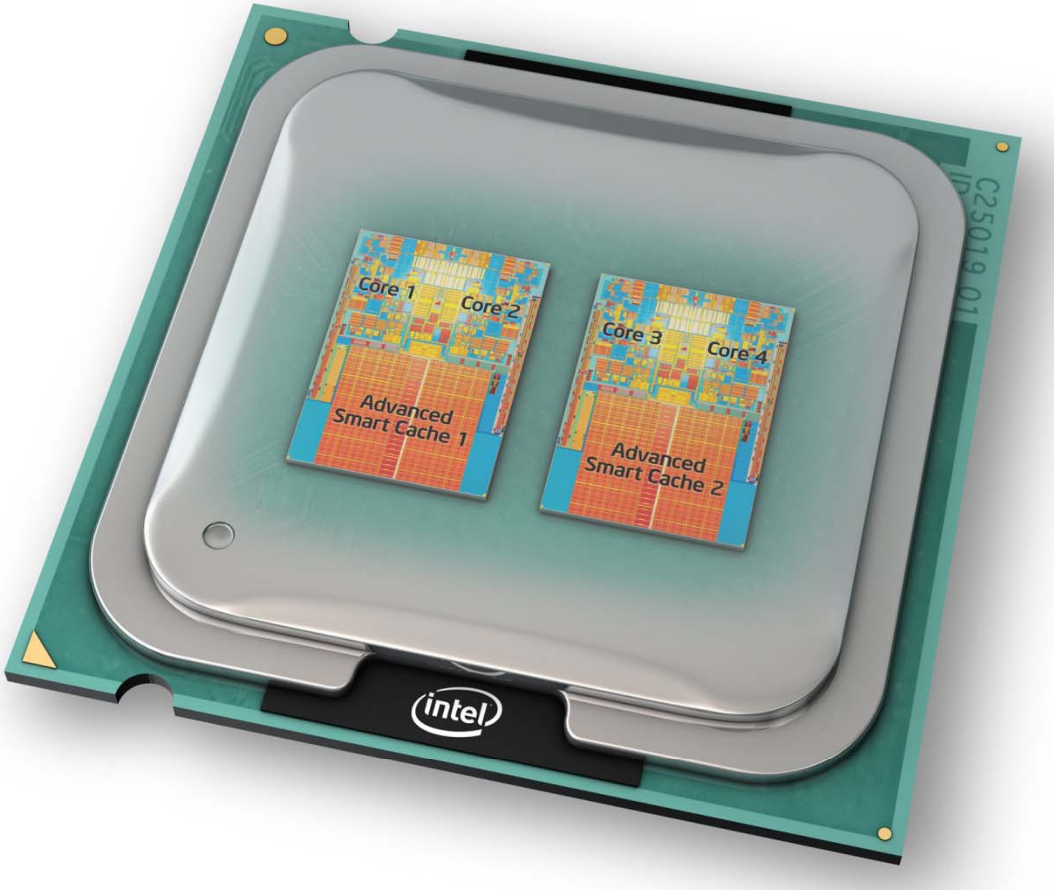
$$I_{Gate\ Leakage} \propto e^{t_{Gate}}$$

Gate leakage current can be dramatically lowered by increasing Gate insulator thickness but to do so without changing the channel conductivity, you have to increase the dielectric constant of the insulator. NEW GATE INSULATORS FOR THE FIRST TIME IN 60 YEARS!!!!

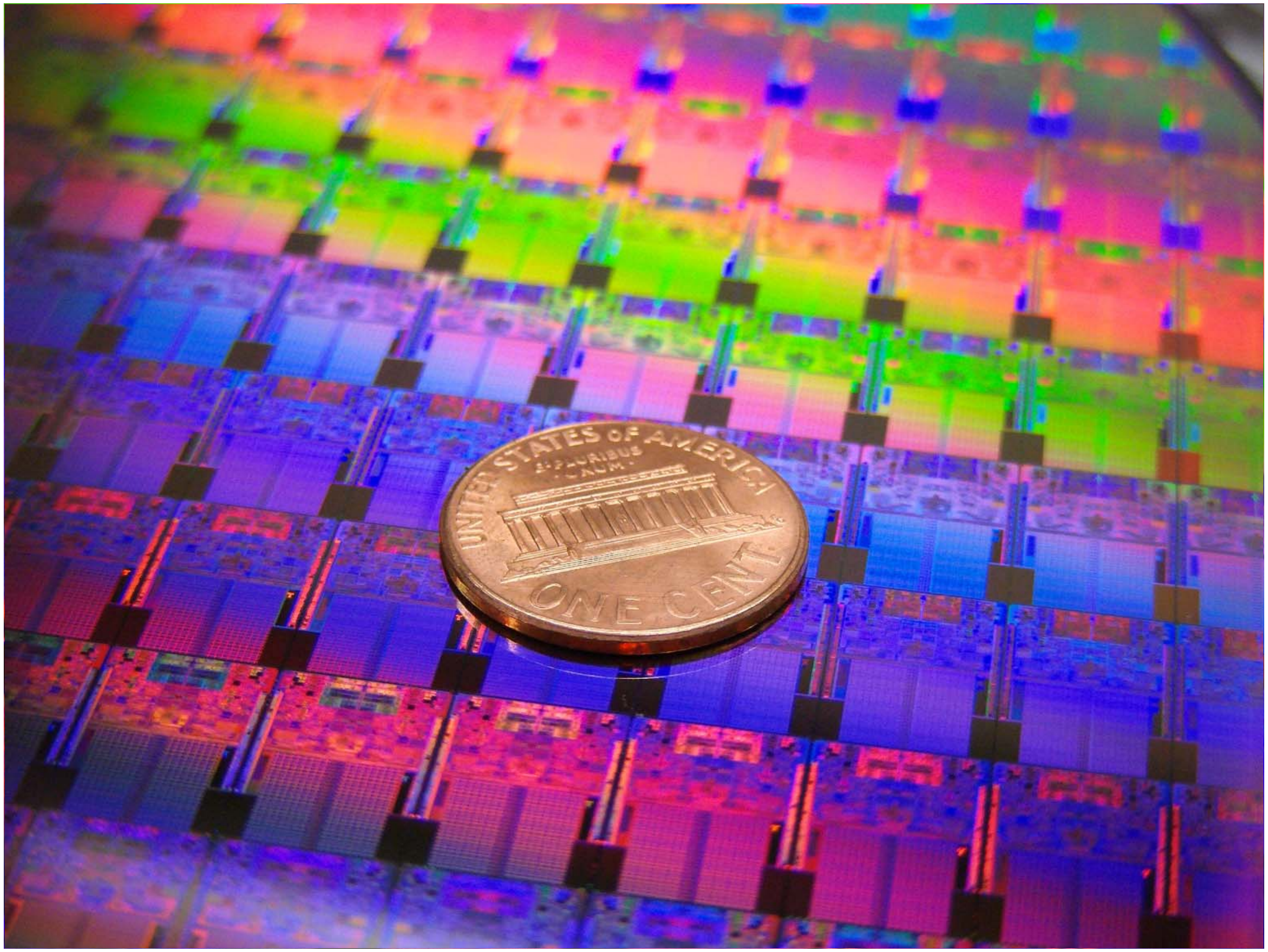
2008 Vintage Intel Microprocessor



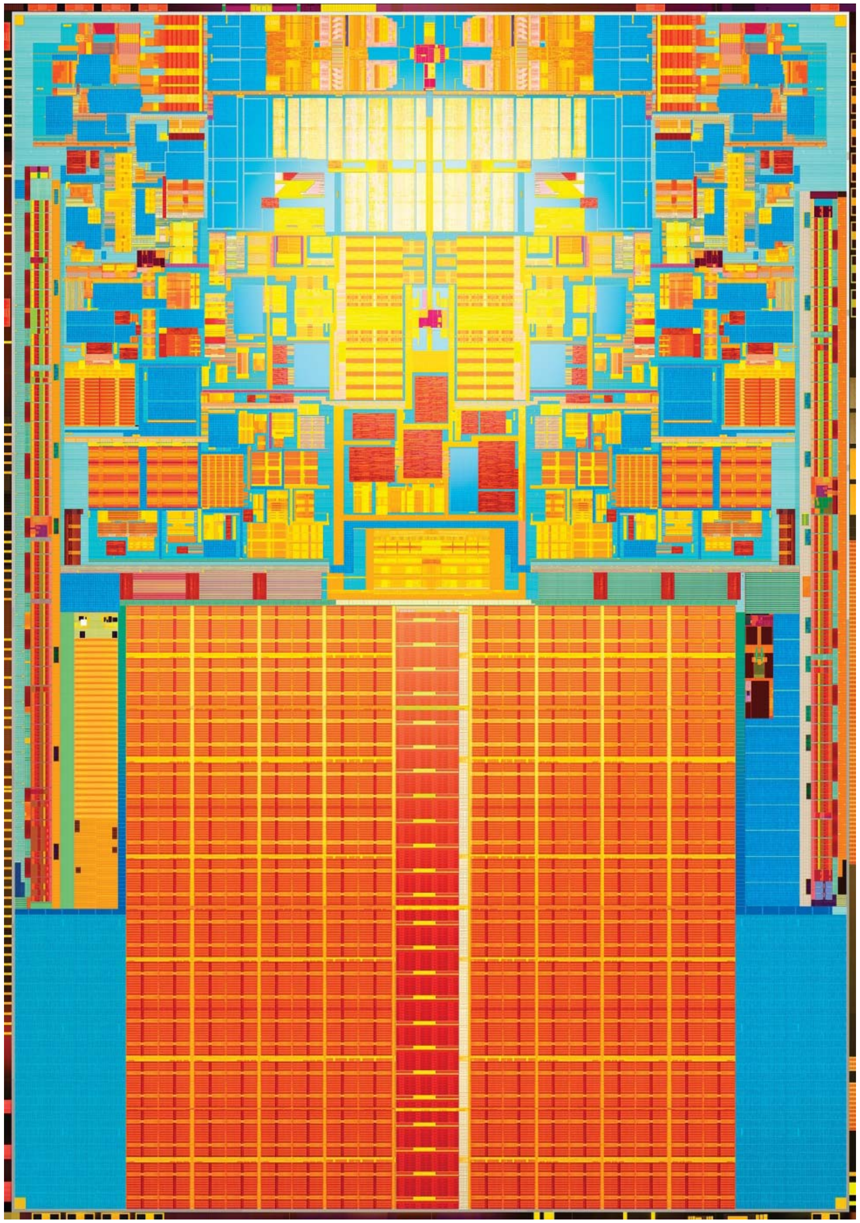
2008 Vintage Intel Microprocessor



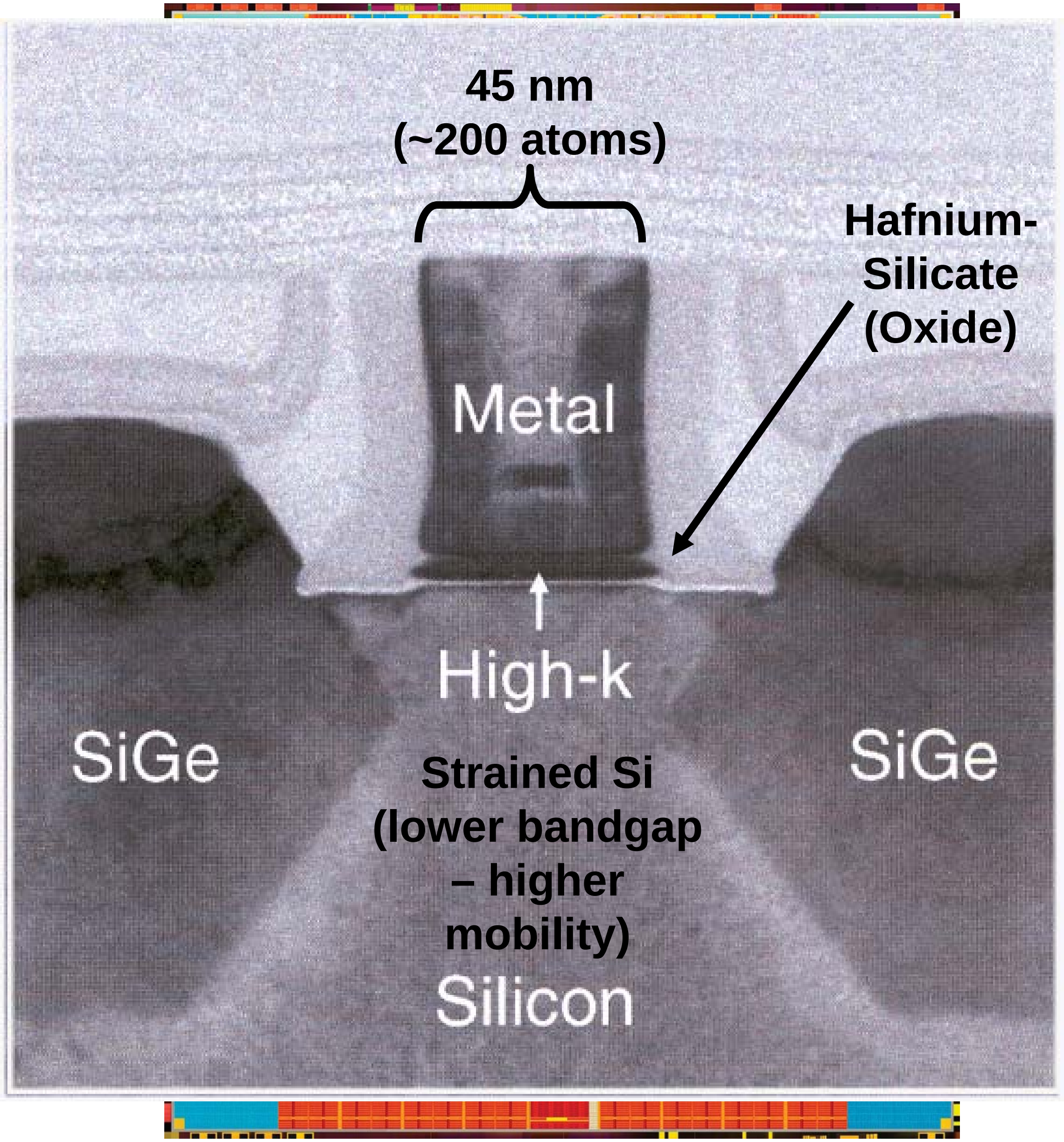
2008 Vintage Intel Microprocessor



2008 Vintage Intel Microprocessor

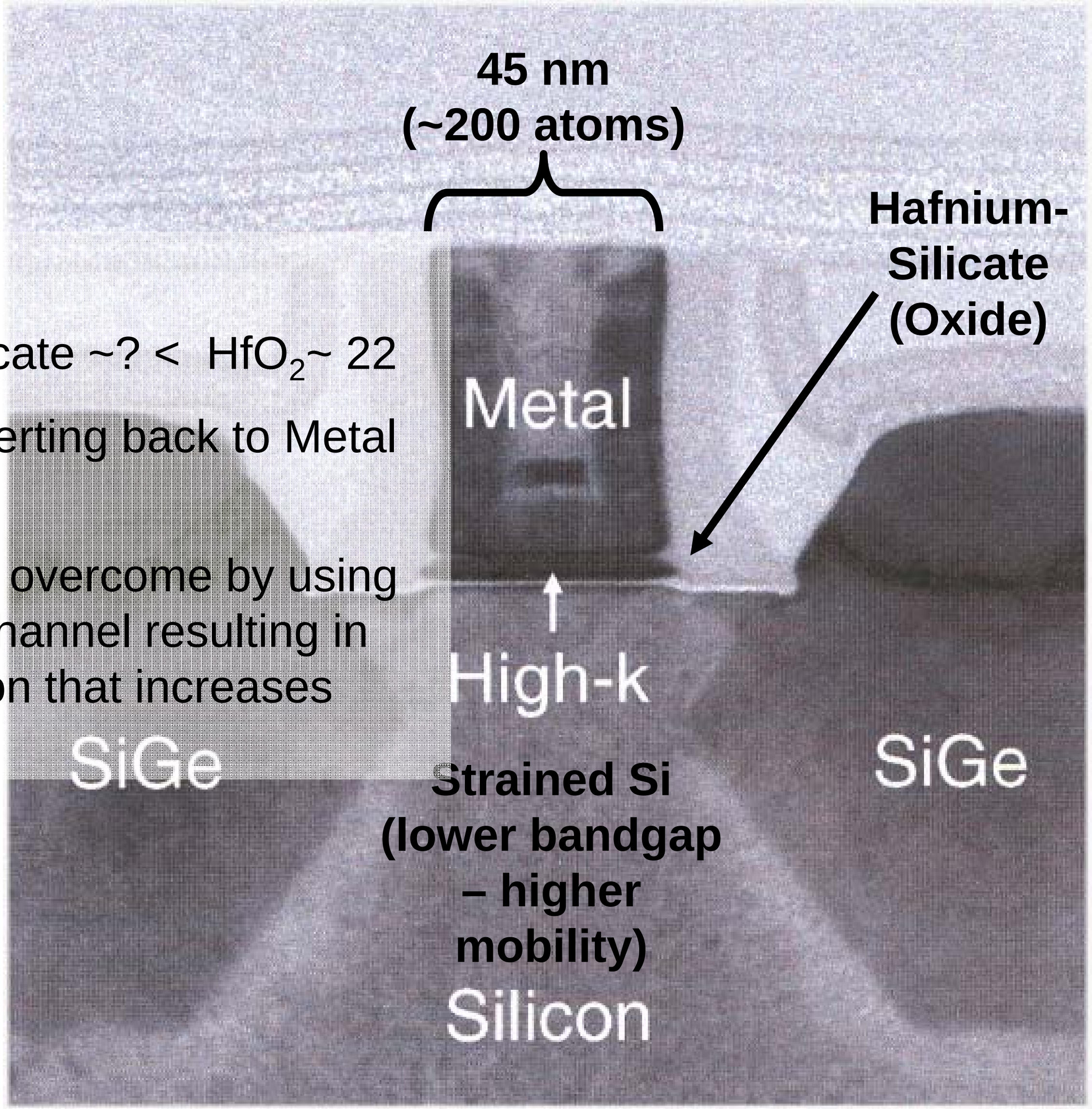


2008 Vintage Intel Microprocessor

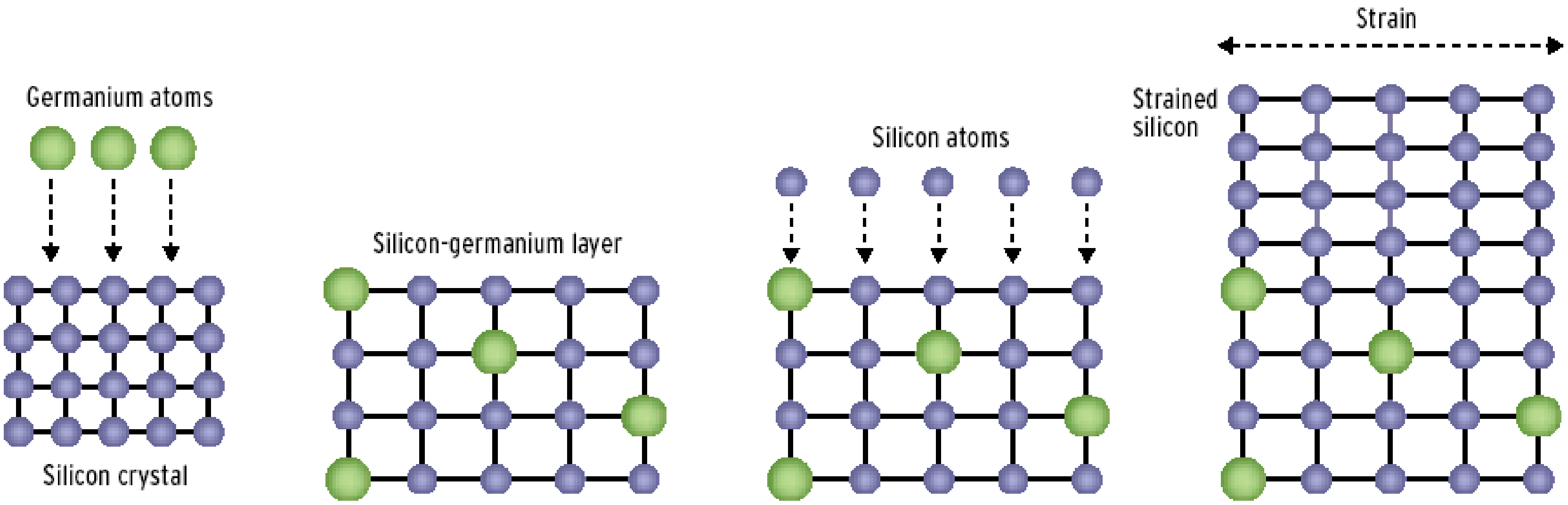


2008 Vintage Intel Microprocessor

- High K Gate Dielectric:
    - K of SiO_2~3.9< Hafnium Silicate ~? < HfO_2~ 22
- Deviation from SiO_2 required reverting back to Metal Gates (no Poly-silicon)
- Limited Speed of Silicon partially overcome by using SiGe to “mechanically strain” Si channel resulting in Energy Band structure modification that increases electron/hole mobility.



Strained Silicon MOSFET



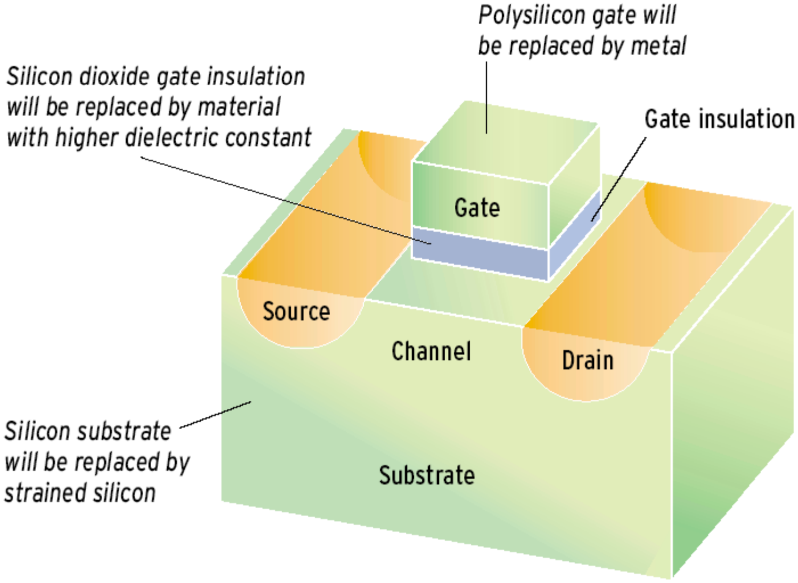
from IEEE Spectrum, 10/2002

- Silicon in channel region is strained in two dimensions by placing a Si-Ge layer underneath (or more recently adjacent to) the device layer
- Strained Si results in changes in the energy band structure of conduction and valence band, reducing lattice scattering
- Benefit: increased carrier mobility, increased drive current (drain current)

Slide after Dr. Oliver Brandt

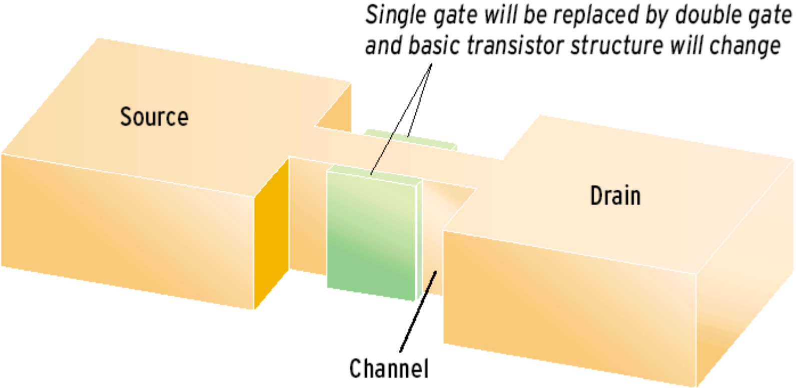
What is in the future? Double-Gate Transistors

- Change of basic transistor structure by introducing a double gate (or more general enclose the channel area by the gate)
- Benefit: better channel control resulting in better device characteristics
- Challenge: double-gate transistors require completely **new device structures** with **new fabrication challenges**


Polysilicon gate will be replaced by metal

Silicon dioxide gate insulation will be replaced by material with higher dielectric constant

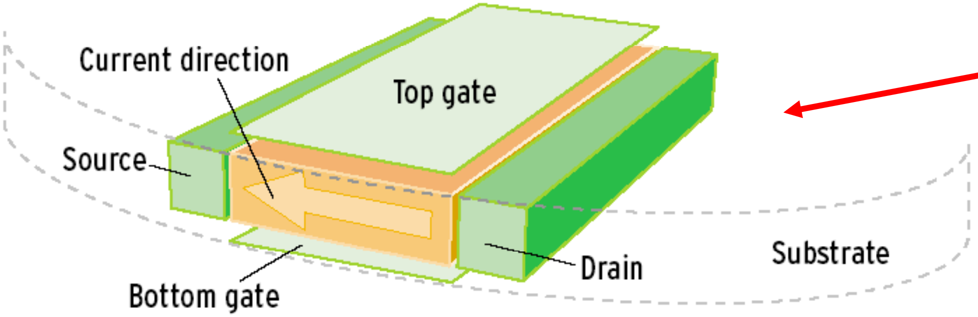
Silicon substrate will be replaced by strained silicon


Single gate will be replaced by double gate and basic transistor structure will change

from IEEE Spectrum, 10/2002

Slide after Dr. Oliver Brandt

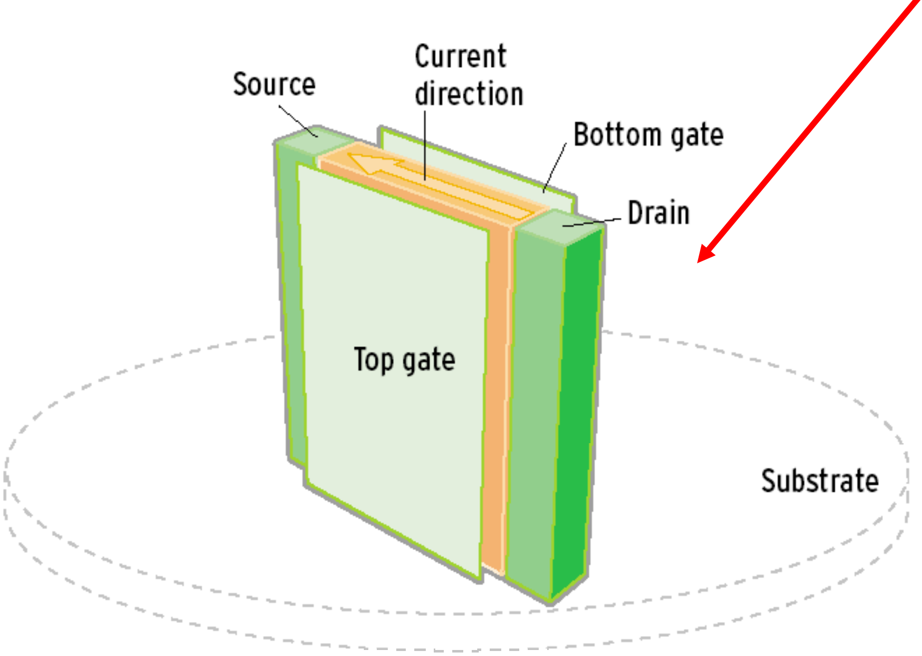
Double-Gate Transistor Designs

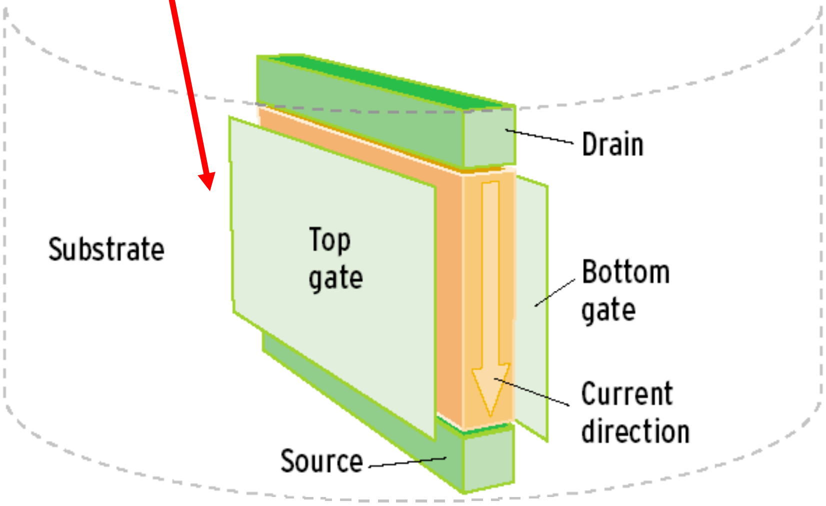


Channel in chip plane

Channel perpendicular to chip plane with current flow in chip plane (FinFET)

Channel perpendicular to chip plane with current flow perpendicular to chip plane

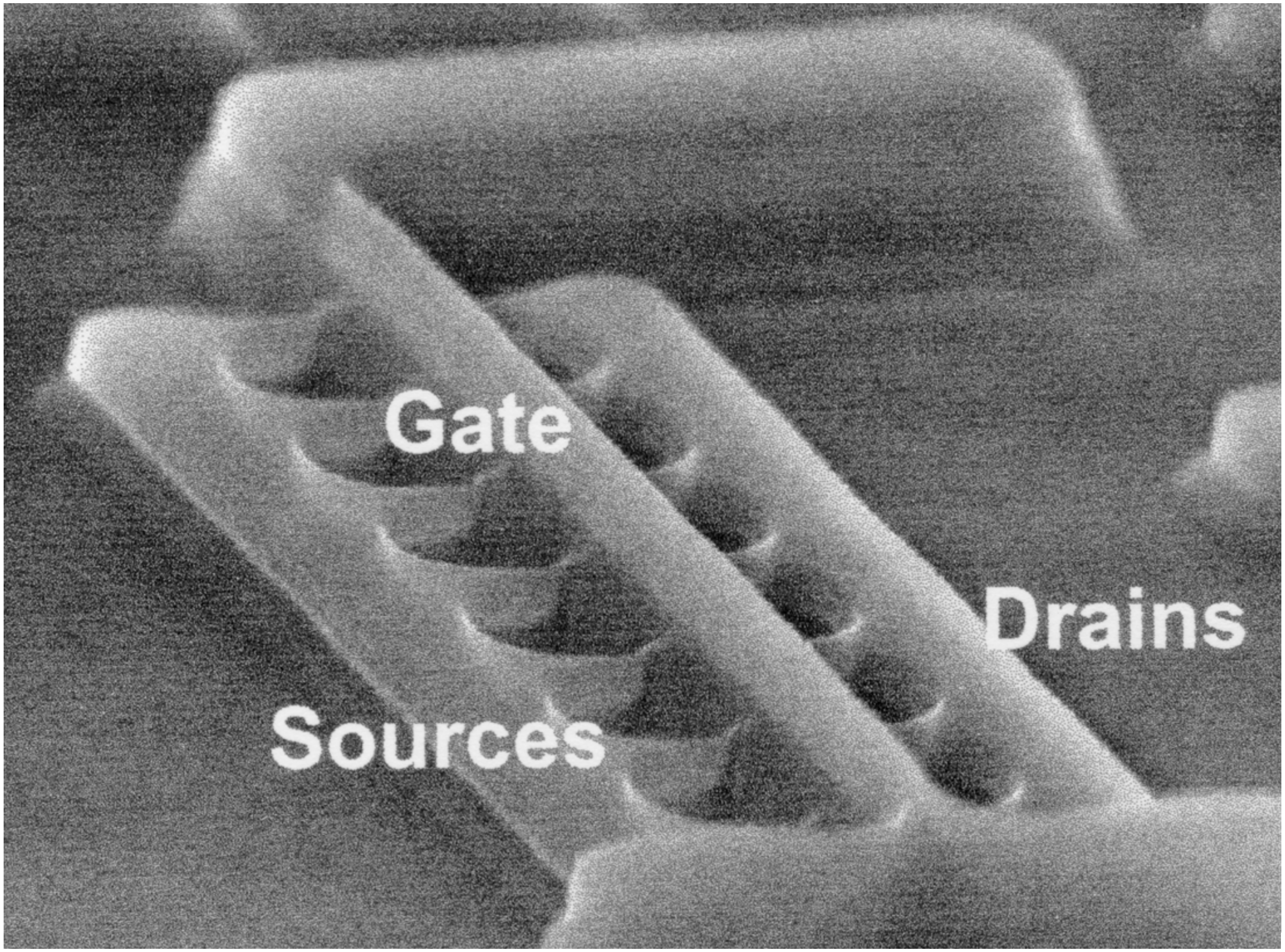




from IEEE Spectrum, 10/2002

Slide after Dr. Oliver Brandt

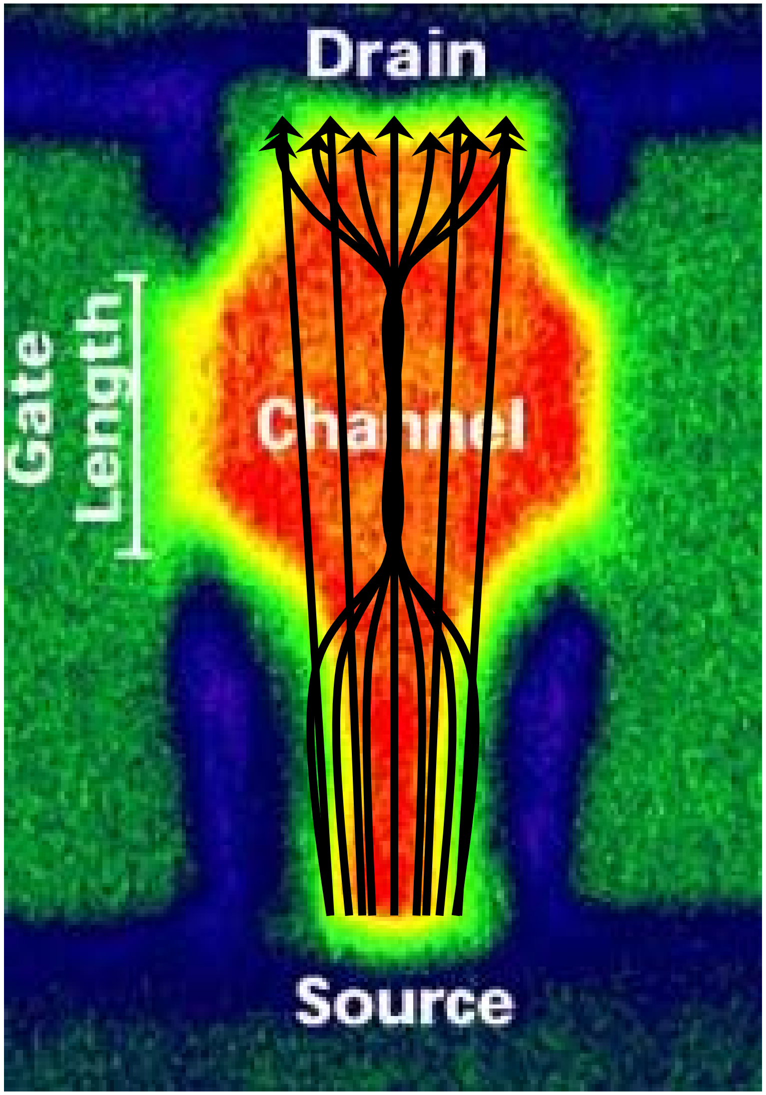
FinFET Double-Gate Transistor



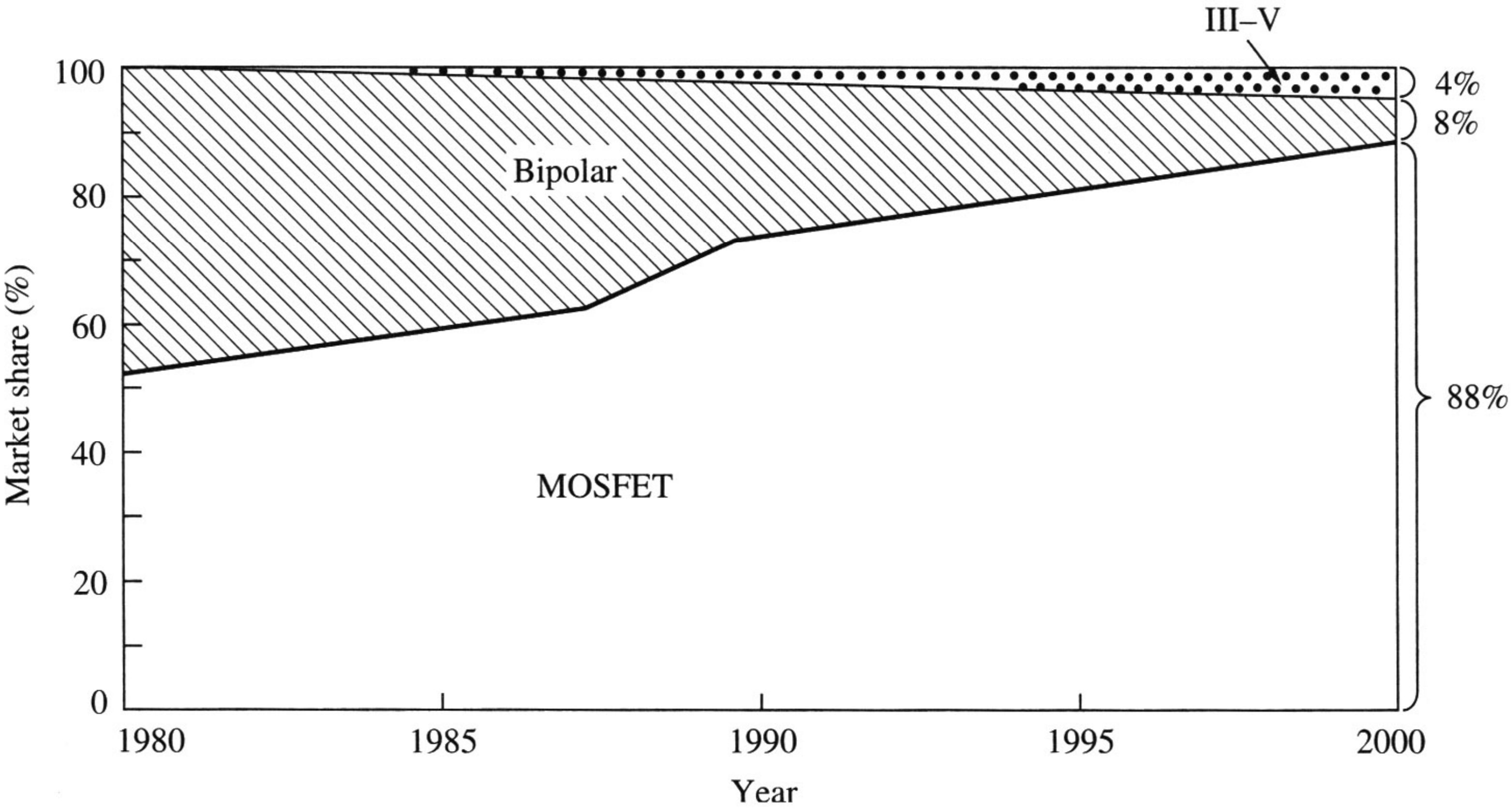
from http://www.intel.com/pressroom

Slide after Dr. Oliver Brandt

Vertical multi-gate structures take us back to JFET like structures but now with the advantage of insulators. – Life is circular

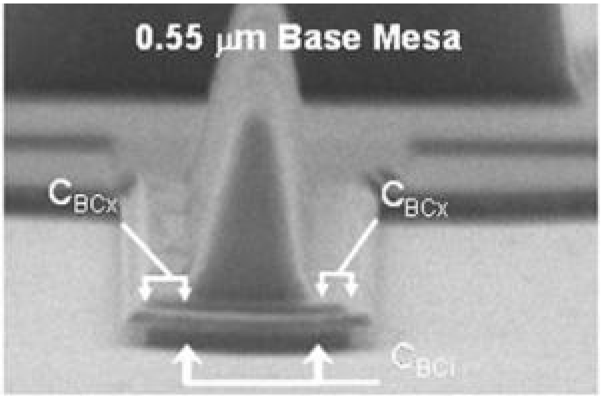


And what about Bipolar and III-V?



Future for Compound Semiconductors is strong!!!

- InP HEMT (transistors) operate above 1THz – Northrop Grumman Inc.
- InP Double Heterostructure Bipolar Transistors (DHBT) operate to as high as 865 GHz! - Milton Feng et al.
- InP Double Heterostructure Bipolar Transistors (DHBT) circuits operate to as high as 310 GHz! - HRL Inc.
- Demonstration of InP Optical Transistors and Lasers that can directly integrate into fiber optic systems at 100's of GHz. – Milton Feng et al.
- SiGe HBTs operate to 300 GHz (500 GHz at cryogenic temperatures) – IBM / Dr. John Cressler et al.
- InSb based devices offer even more promise for low power high speed (transistor mobility of ~30,000 compared to ~100 in Si MOSFET).
- GaN based devices offer 100x improvement in power density!
- SiC based devices offer Megawatts switching capability.
- Will likely see a surge in "Hybrid Si - ??? Technologies"



Consider LED as a Case Study of why we must know the materials technologies on the “Nano Scale”

Movie Complements of Dr. Christian Kisielowski
from Lawrence Berkeley DOE Labs.