Principles of Micro- and Nanofabrication for Electronic and Photonic Devices

Introduction

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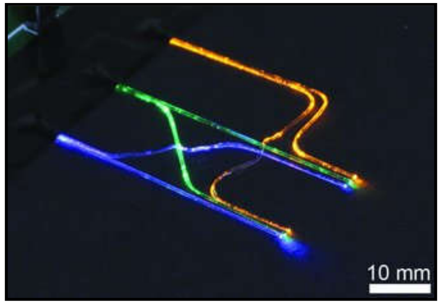
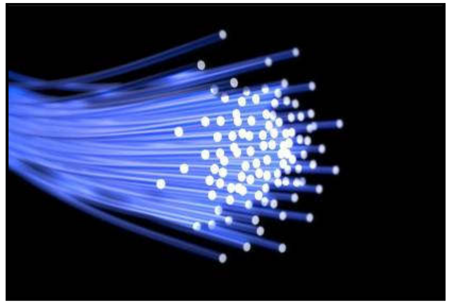
Optical and Electronic Devices

LEDs

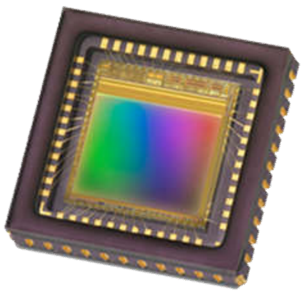
lasers



waveguides

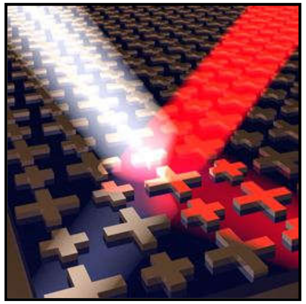


fibers

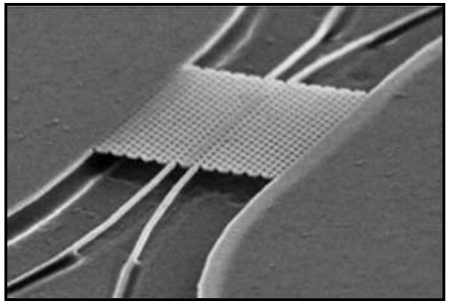


detectors

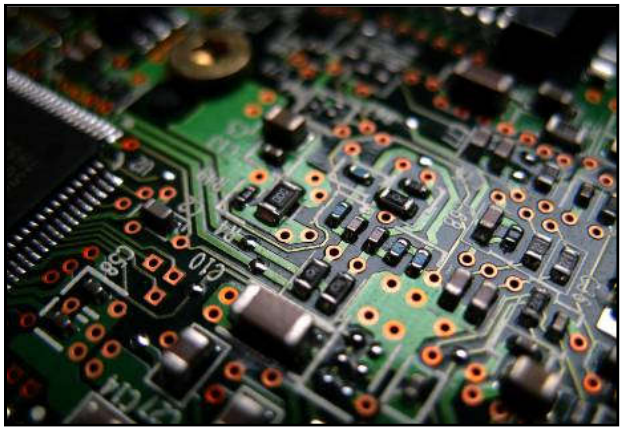
solar cells



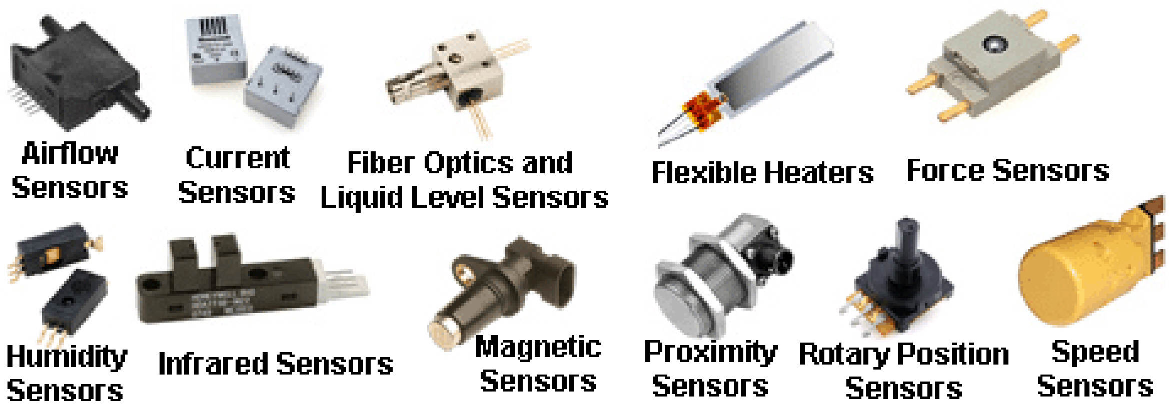
metamaterials



photonic crystals



integrated circuits



Goal of This Course

- Focus on the **fabrication and processing methods** to form electronic and optical devices at micro- and nano-scale
- Cover fundamental concepts to **grow, pattern, deposit, etch and integrate** various materials (silicon, III-V, etc) to form electronic and optical devices
- **Emerging fabrication technologies** such as nanofabrication and self-assembly will also be included

Nobel Prize in Physics

- 1956 Semiconductor transistors
- 1991 Liquid crystals
- 2000 Integrated circuits
- 2000 Semiconductor heterostructures
- 2009 CCD imaging sensors
- 2009 Optical fibers
- 2010 Graphene
- 2014 GaN based blue LEDs

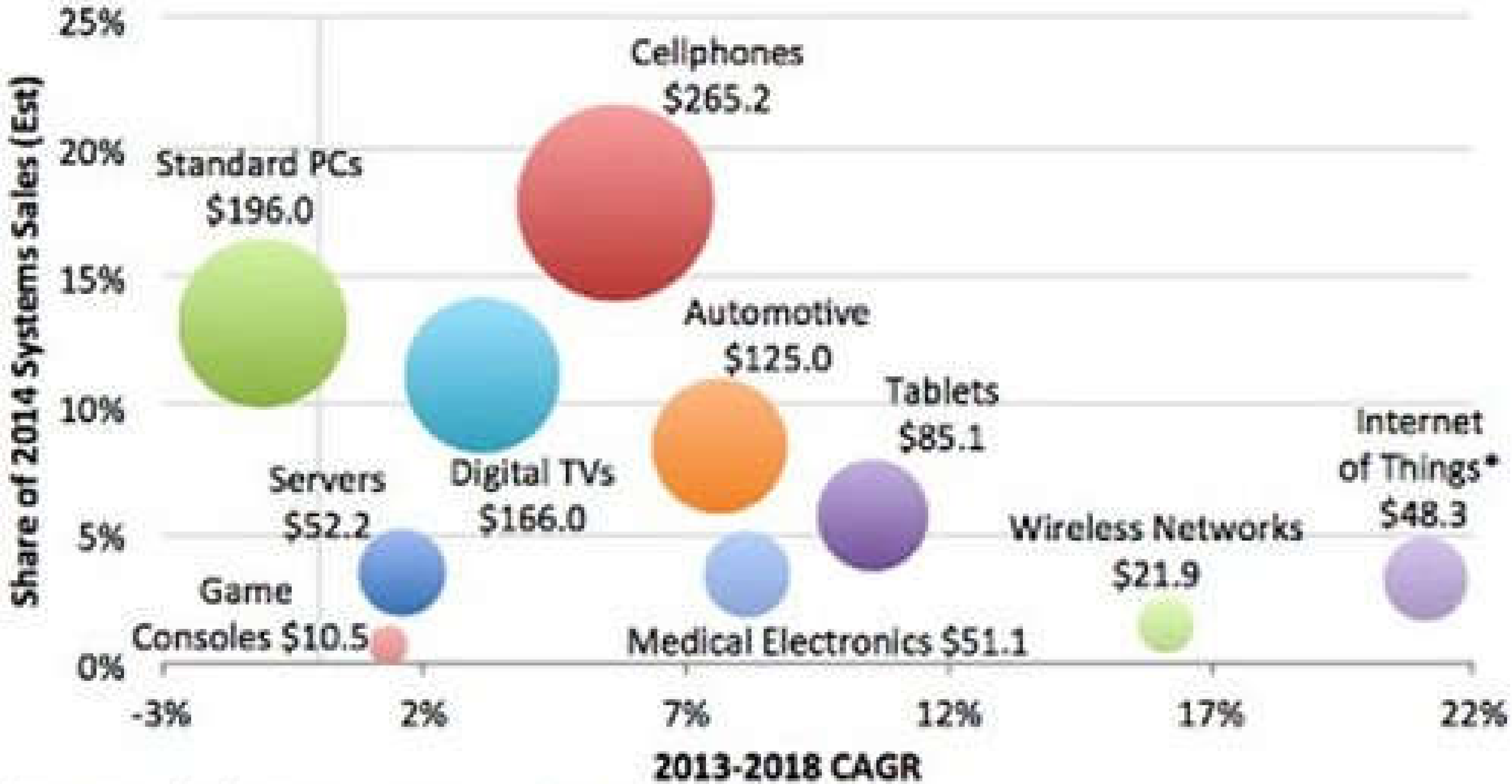
'Disruptive' Technologies

1956	Semiconductor transistors	← vacuum tubes
1991	Liquid crystals	← CRT displays
2000	Integrated circuits	
2000	Semiconductor heterostructures	
2009	CCD imaging sensors	← film cameras
2009	Optical fibers	← copper cables
2010	Graphene	
2014	GaN based blue LEDs	← incandescent light bulbs

Semiconductor Market

current ~ 500 billion $$$

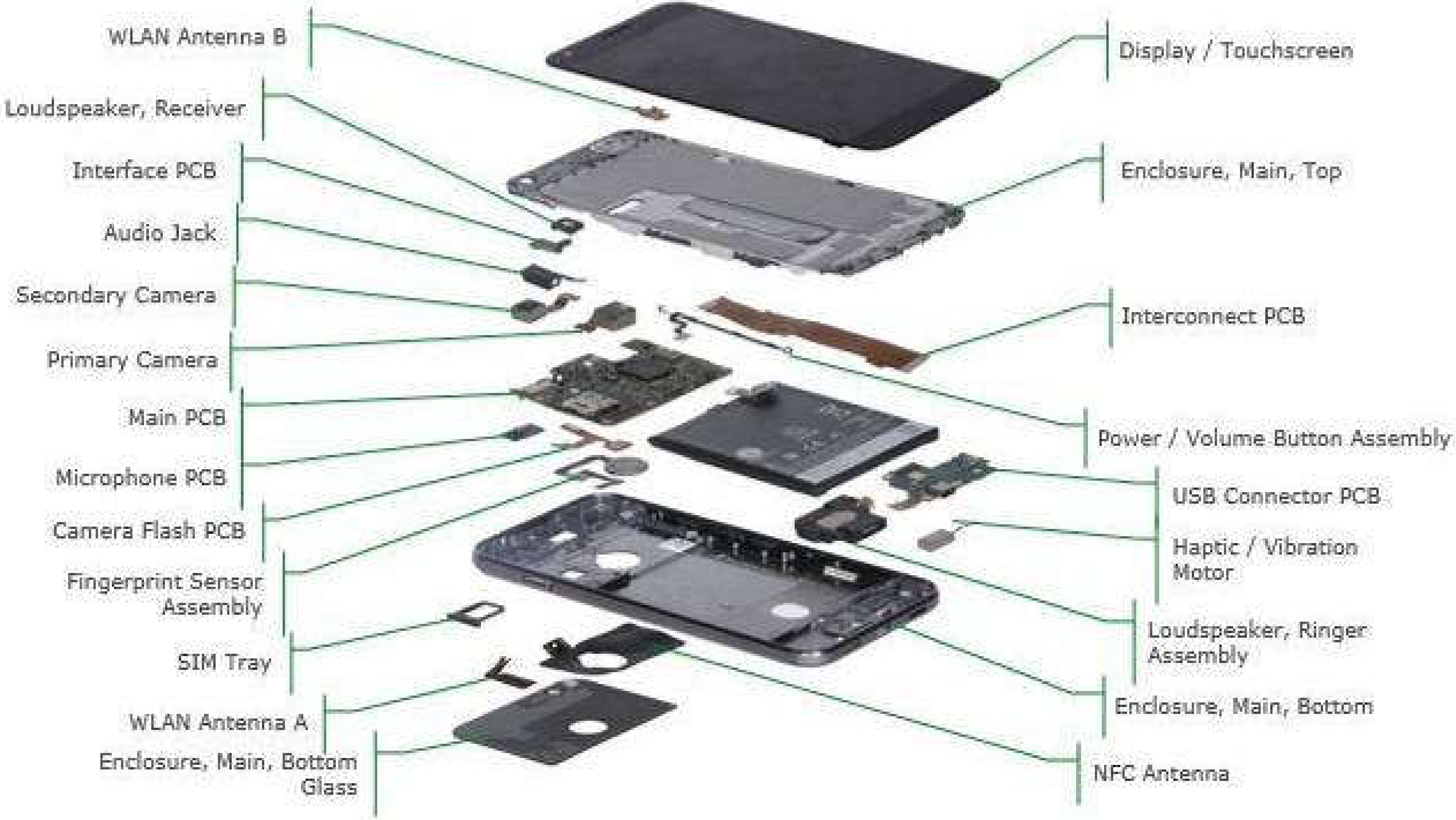
GDP of Thailand: 400 billion $$$



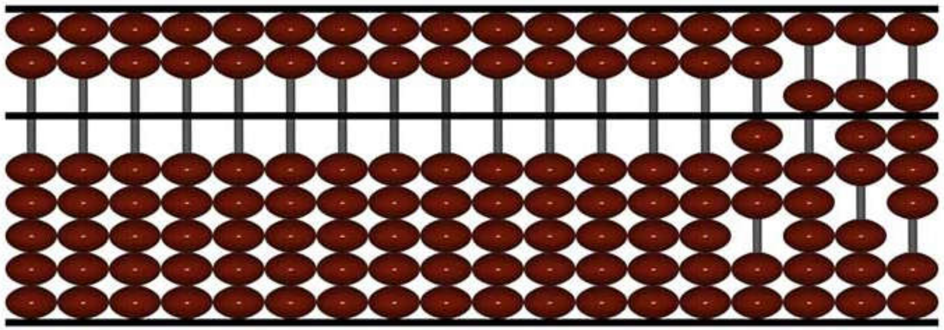
*Covers only the Internet connection portion of systems

Source: IC Insights

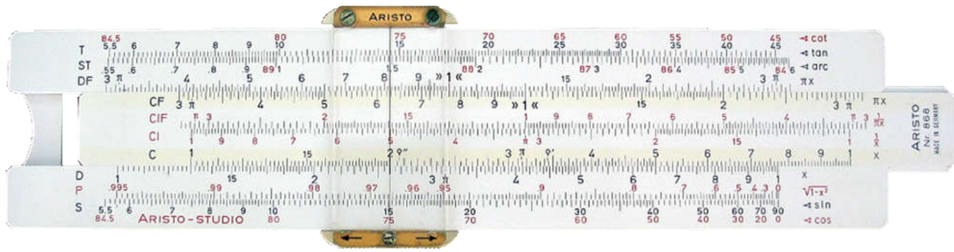
Devices in a Smartphone



Some 'Ancient' Computers

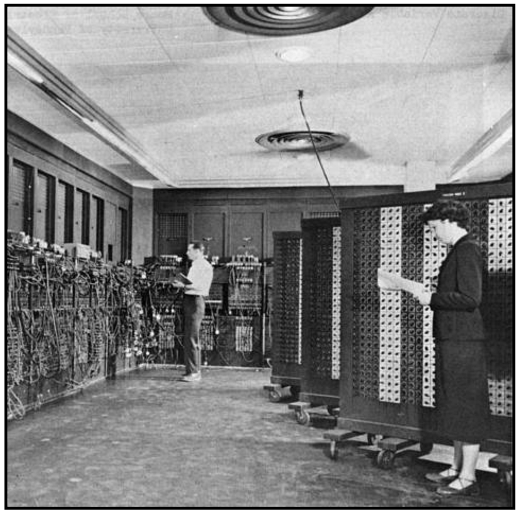


abacus



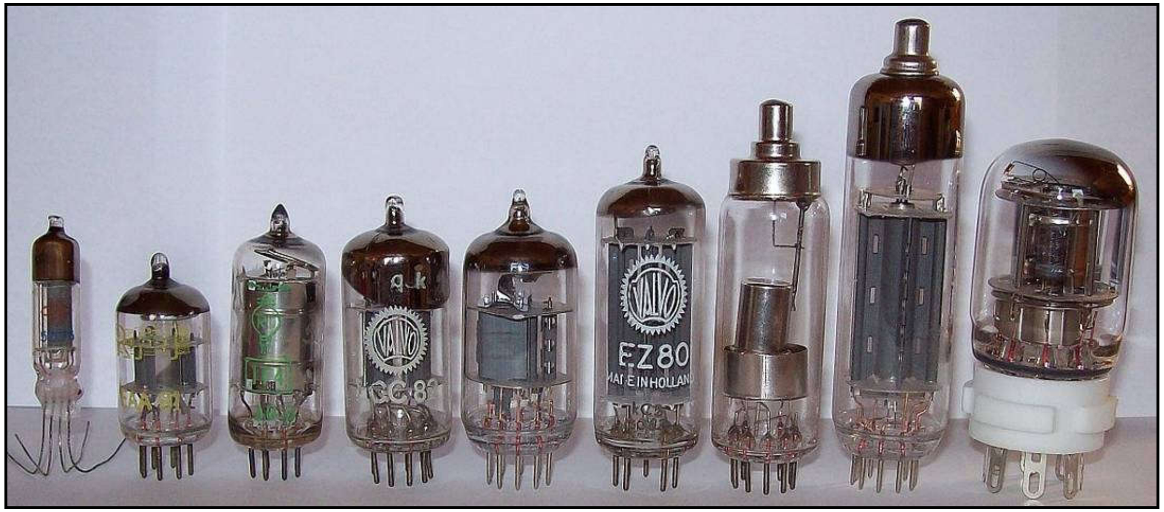
slide rule

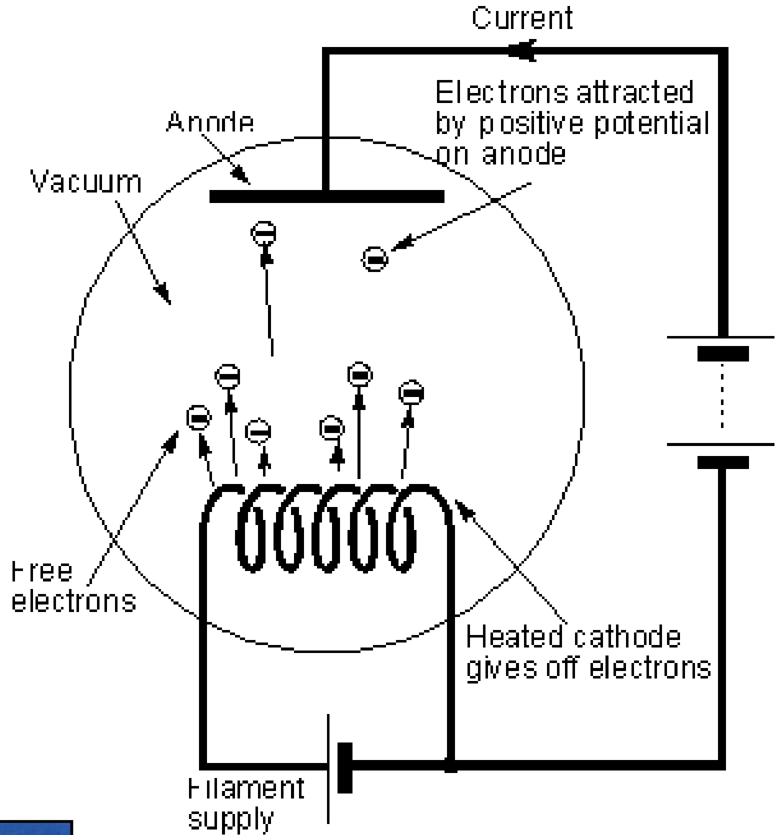
- First 'electronic' computer
  - ENIAC, 1943
  - 30 tons, 200 kW
  - 18000 vacuum tubes
  - 5000 times/sec
  - cost $480,000



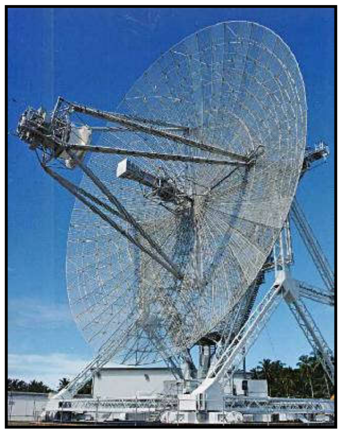
vacuum tube

Vacuum Tube





current flows only in one direction: *diode*



First Semiconductor Transistor

Germanium
Bipolar Transistor

The first point contact transistor
William Shockley, John Bardeen, and Walter Brattain
Bell Laboratories, Murray Hill, New Jersey (1947)

Bardeen Brattain

Shockley

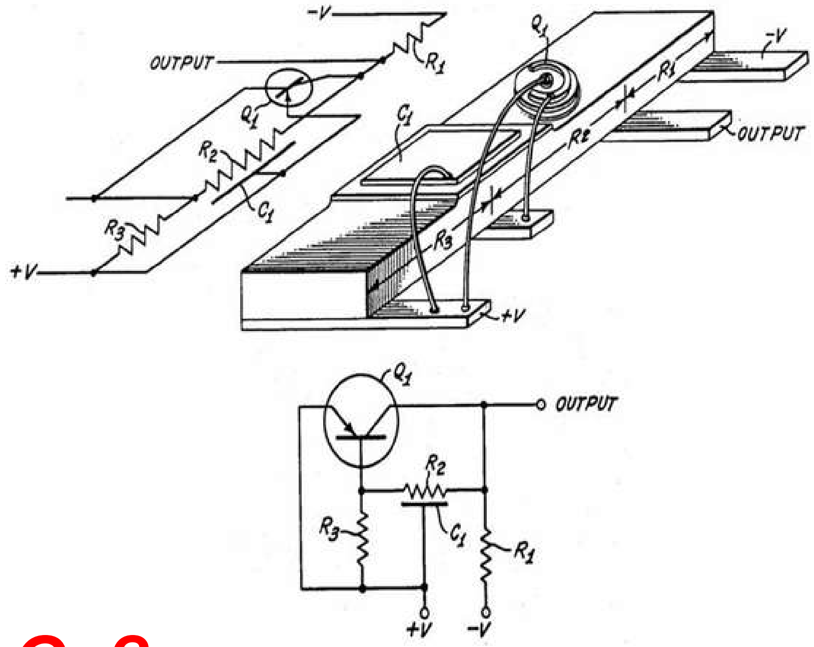
1956 Nobel Prize in Physics

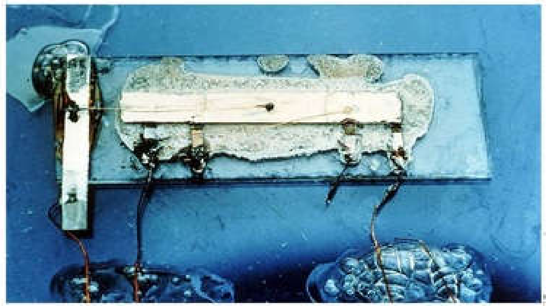
First Integrate Circuits

The First (2D) Integrated Circuit
Jack Kilby, Texas Instruments, 1958

- Transistor, Resistors and Capacitors on the same piece of semiconductor
- Interconnects between components not integrated
  → Low connectivity between components

Germanium



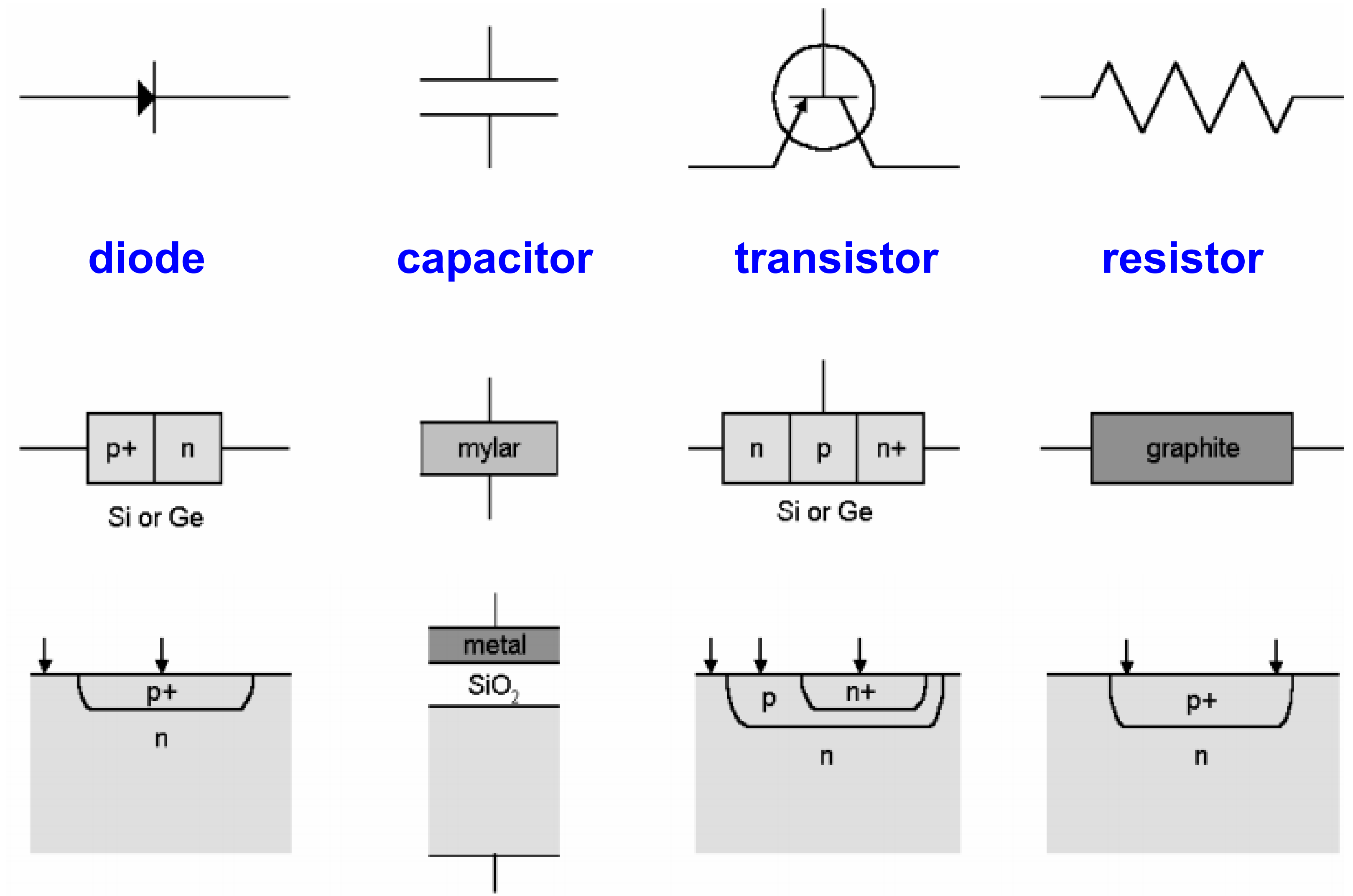


J. Kilby
1923–2005

Q: Why Ge?

2000 Nobel Prize in Physics

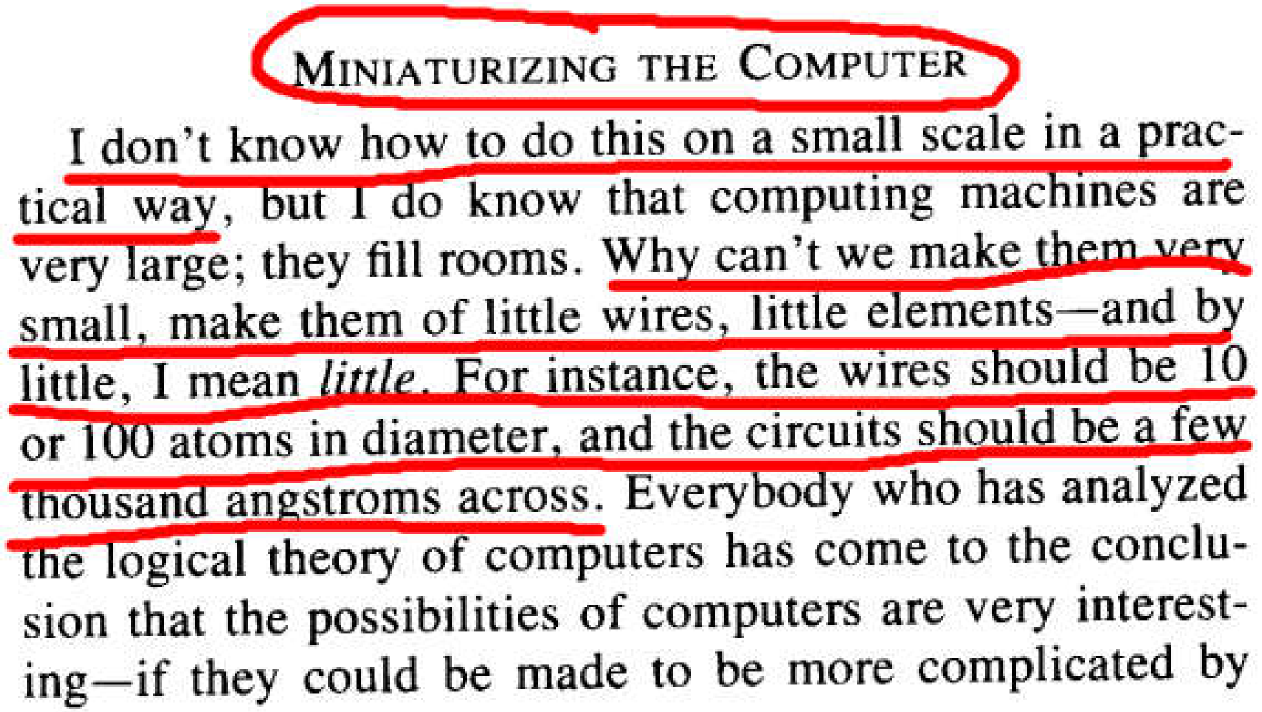
First Integrate Circuits



All devices can be made in the same semiconductor!

First Integrate Circuits

"There is plenty of room at the bottom", APS Meeting, 1959



MINIATURIZING THE COMPUTER

I don't know how to do this on a small scale in a practical way, but I do know that computing machines are very large; they fill rooms. Why can't we make them very small, make them of little wires, little elements—and by little, I mean *little*. For instance, the wires should be 10 or 100 atoms in diameter, and the circuits should be a few thousand angstroms across. Everybody who has analyzed the logical theory of computers has come to the conclusion that the possibilities of computers are very interesting—if they could be made to be more complicated by

R. Feynman

First Integrate Circuits

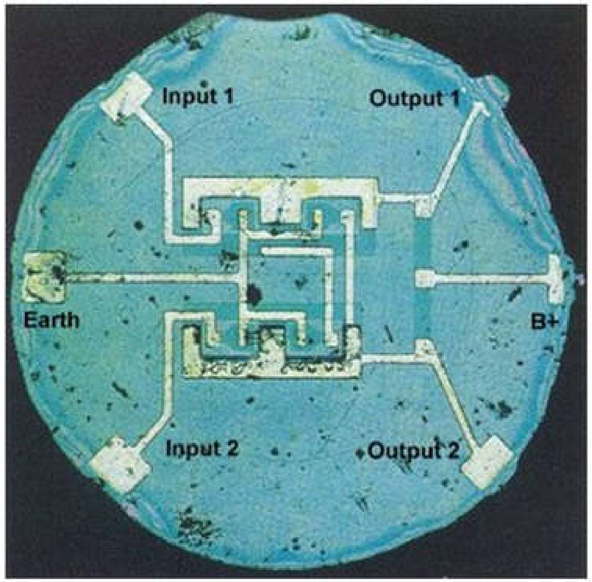
The First *Monolithic* (2D) Integrated Circuit
Robert Noyce, Fairchild Semiconductor, 1961

- Transistor, Resistors and Capacitors on the same piece of semiconductor
- Interconnects between components integrated

  → High connectivity between components

Silicon

4 transistors

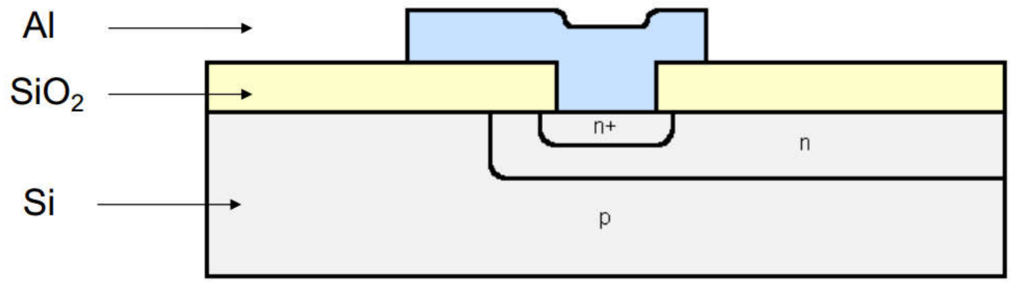


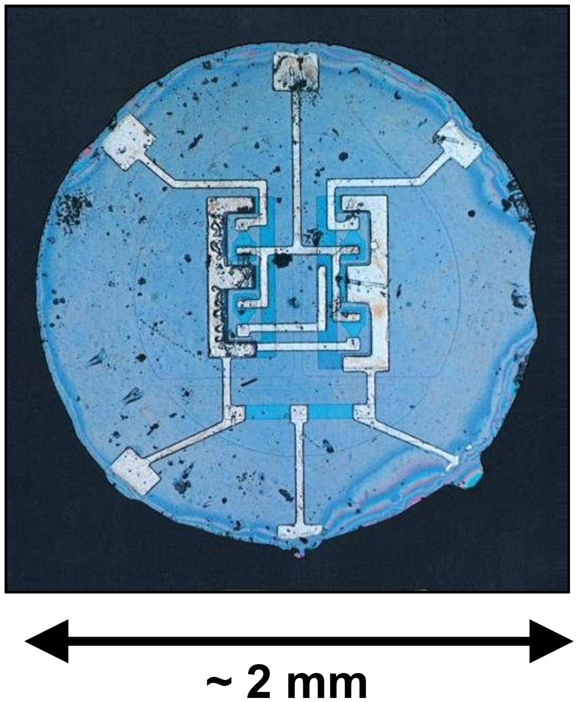
~ 2 mm

R. Noyce
1927–1990

First Integrate Circuits

- Thermal oxidation (SiO_2)
- Photolithography
- Etching
- Thermal diffusion (n-Si, p-Si)
- Metal deposition (Al)

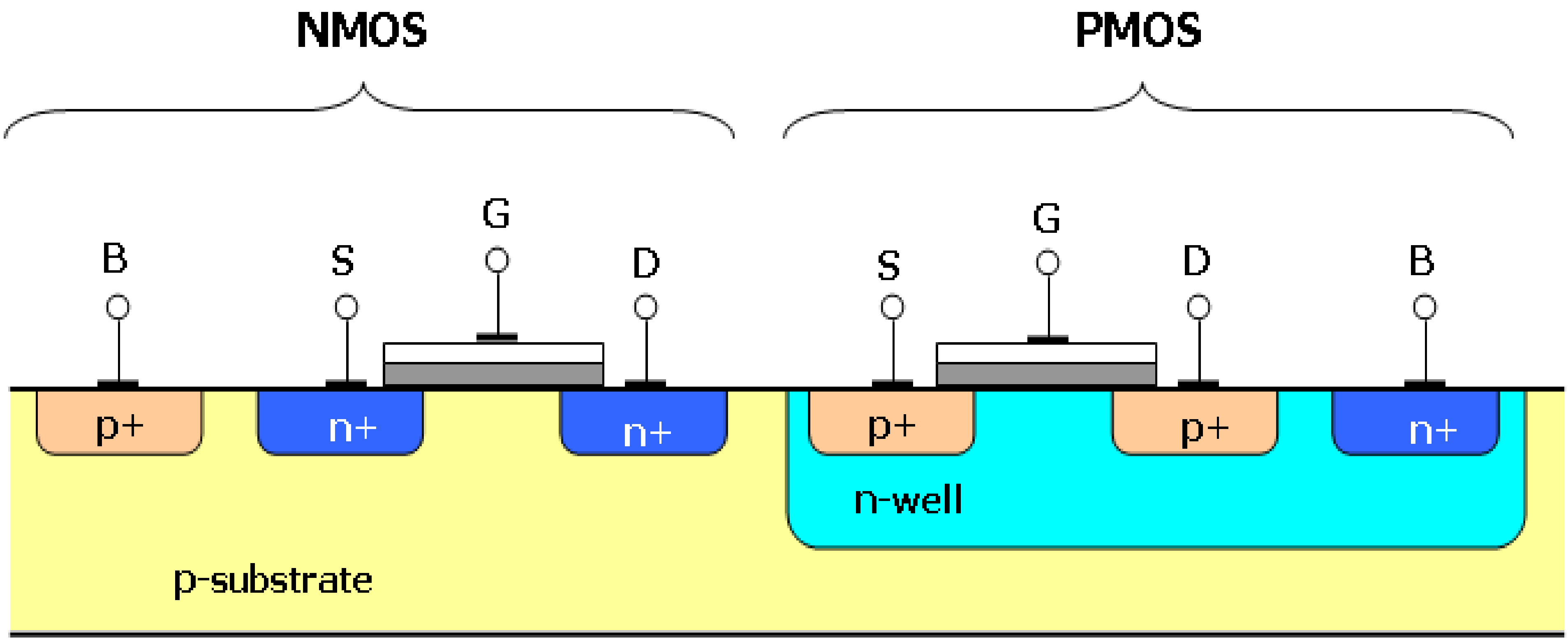




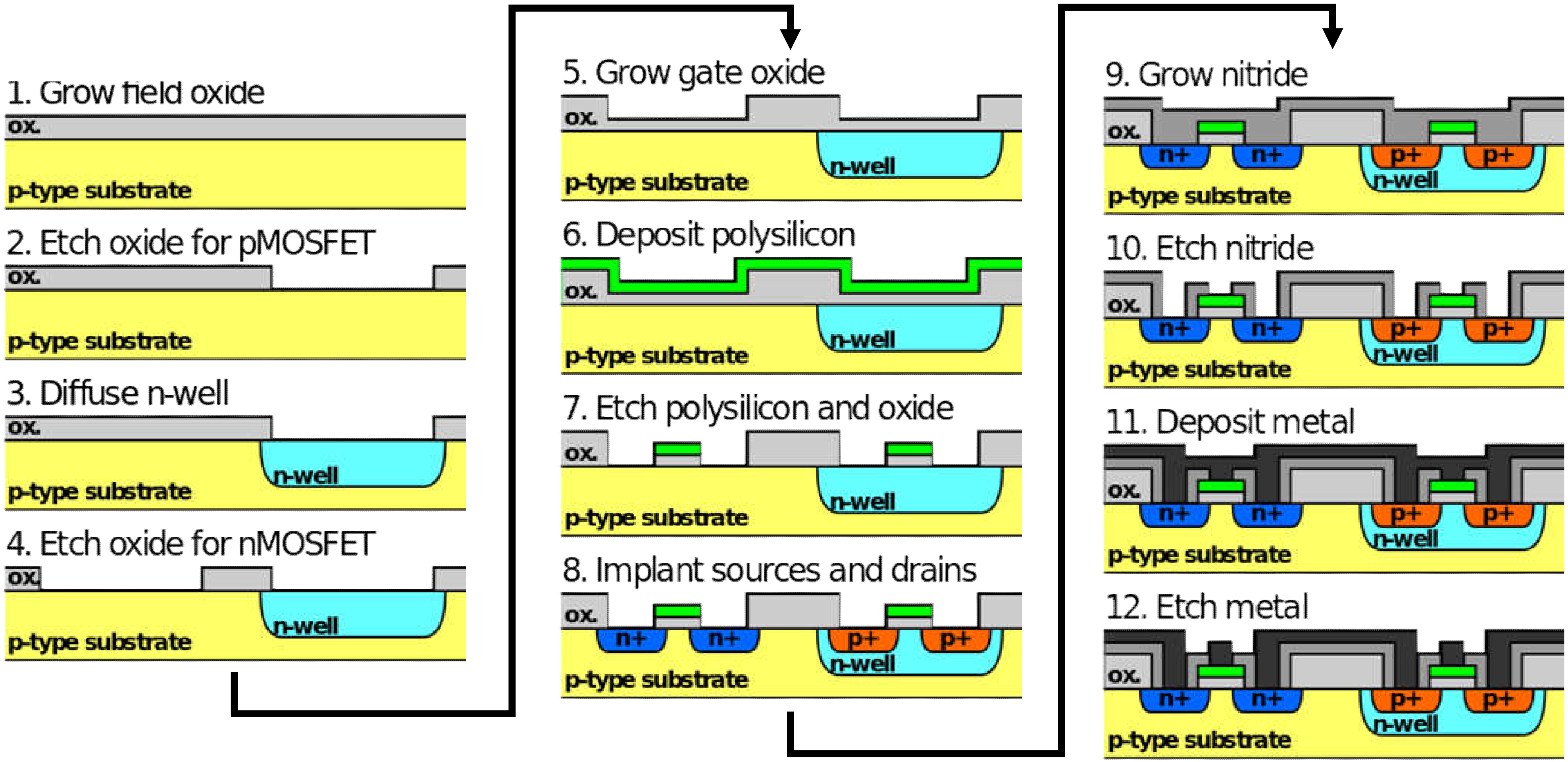
Very similar to today's process

CMOS

- **Complementary Metal-Oxide-Semiconductor**
  - **F. Wanlass, Fairchild, 1963**

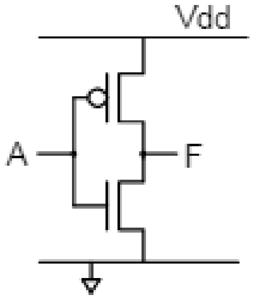


CMOS Process



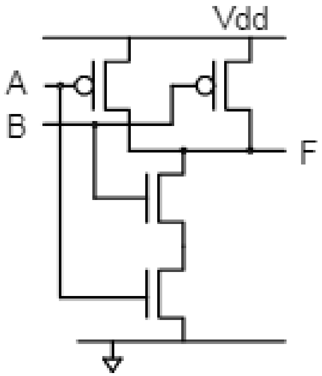
Video

CMOS Logic



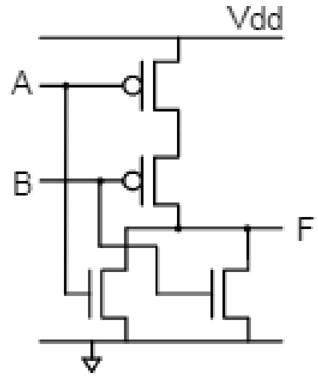
A	F
L	H
H	L

CMOS INVERTER



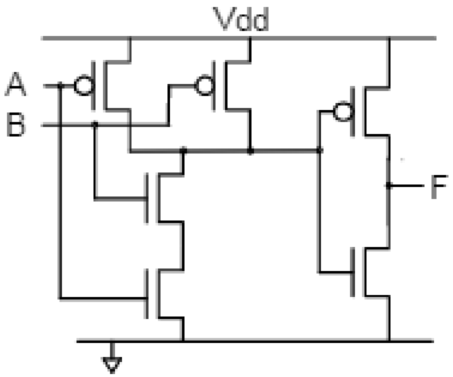
A	B	F
L	L	H
L	H	H
H	L	H
H	H	L

CMOS NAND



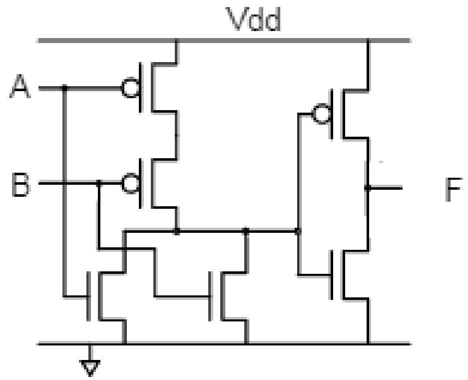
A	B	F
L	L	H
L	H	L
H	L	L
H	H	L

CMOS NOR



A	B	F
L	L	L
L	H	L
H	L	L
H	H	H

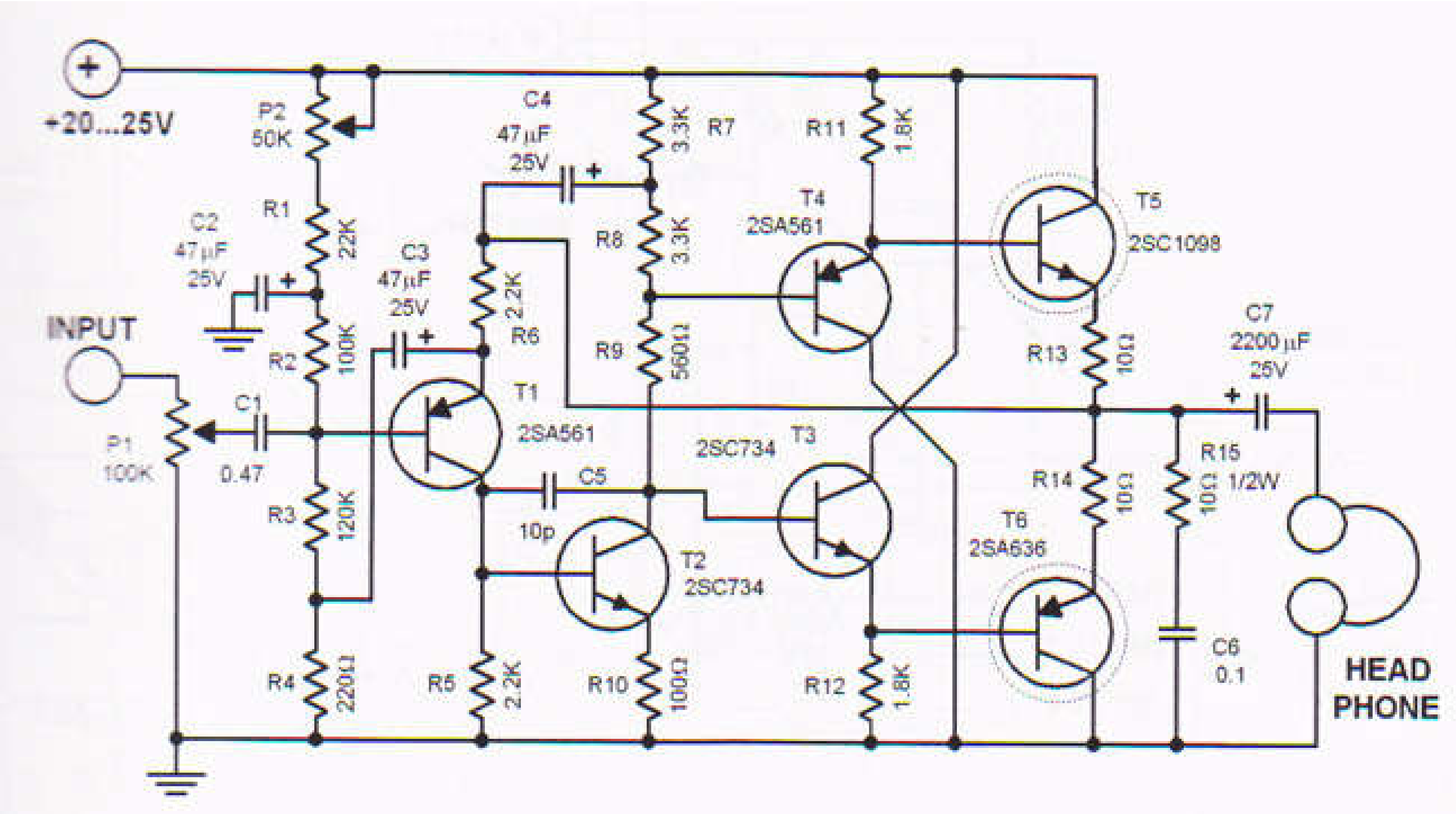
CMOS AND



A	B	F
L	L	L
L	H	H
H	L	H
H	H	H

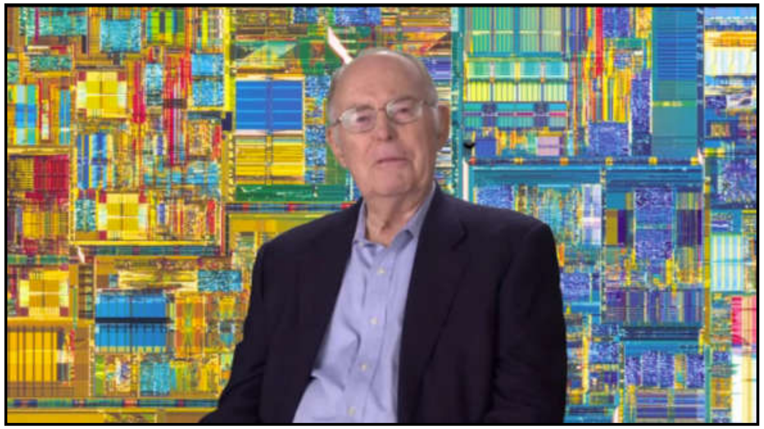
CMOS OR

CMOS Circuit



Integrate Circuits

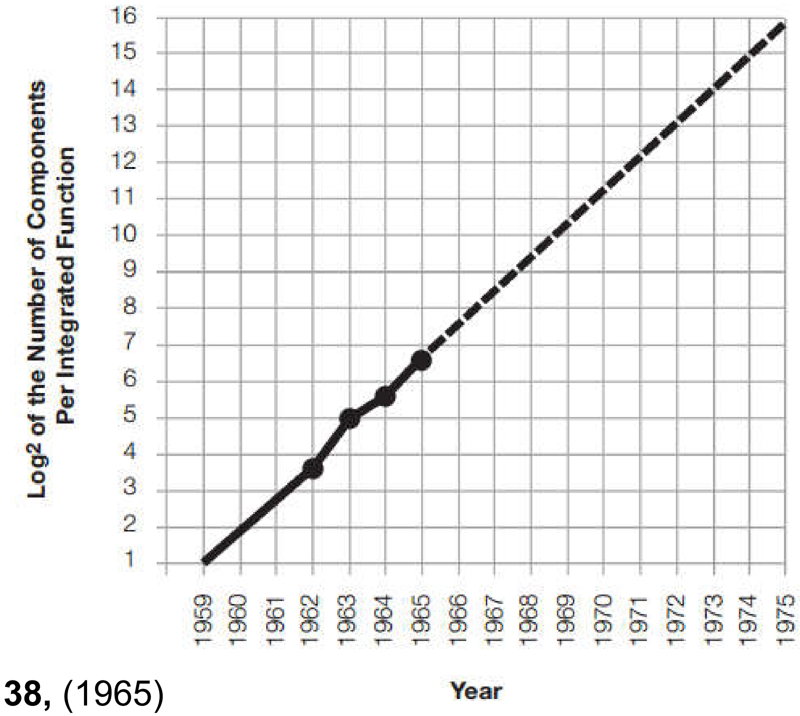
- **Moore's law, Fairchild, 1965**



G. Moore

The complexity for minimum component costs has increased at a rate of roughly a factor of two per year (see graph on next page). Certainly over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least 10 years. That means by 1975, the number of components per integrated circuit for minimum cost will be 65,000.

I believe that such a large circuit can be built on a single wafer.



G. E. Moore, *Electronics Mag.* **38,** (1965)

Integrate Circuits

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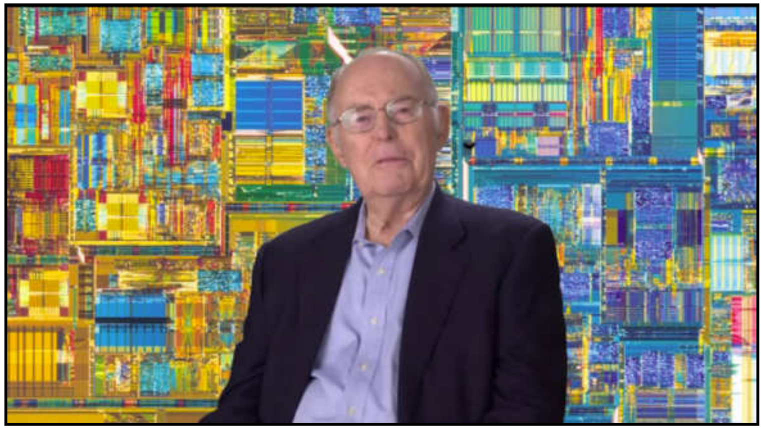

G. Moore

G. E. Moore, *Electronics Mag.* **38,** (1965)

Integrate Circuits

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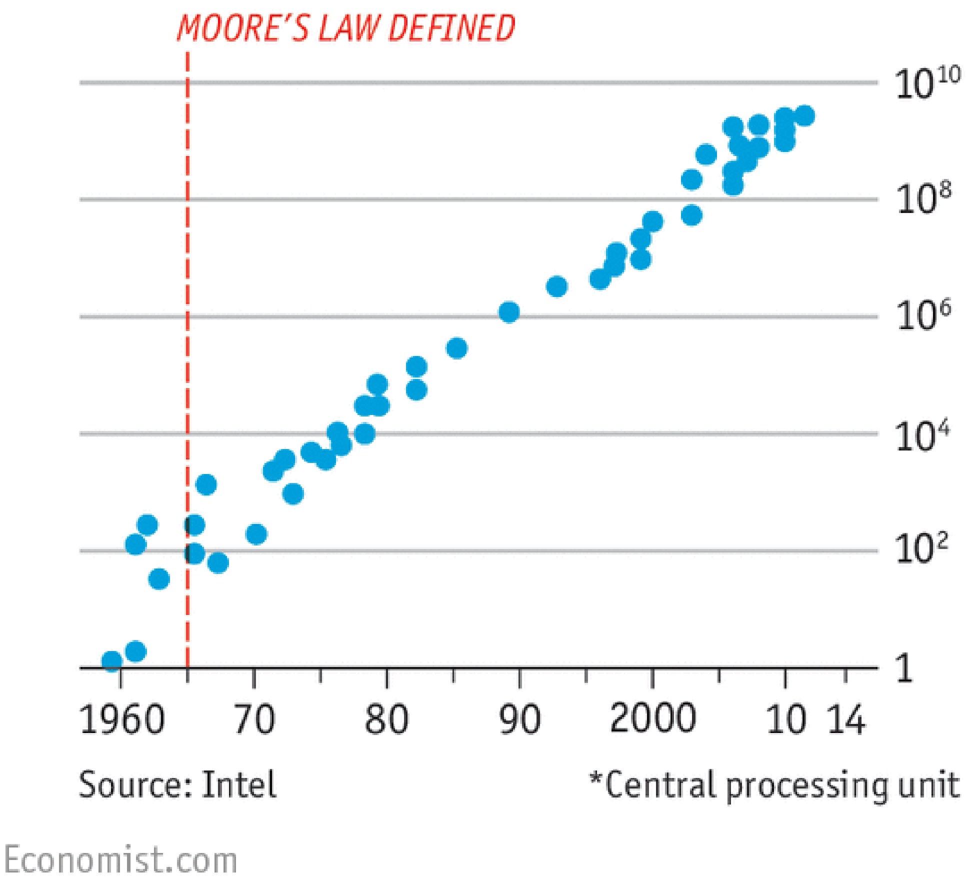
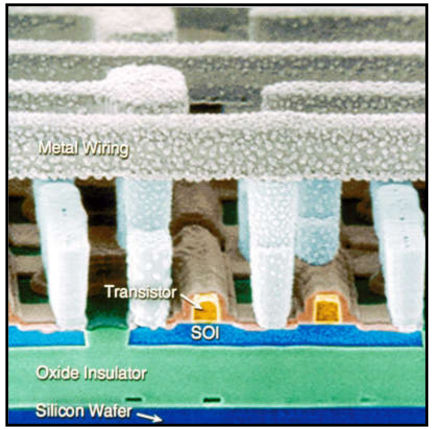
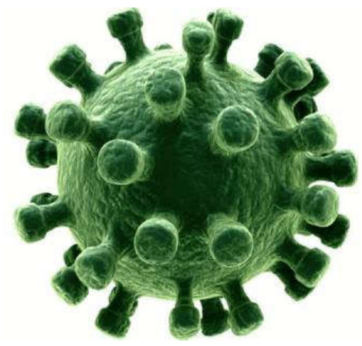
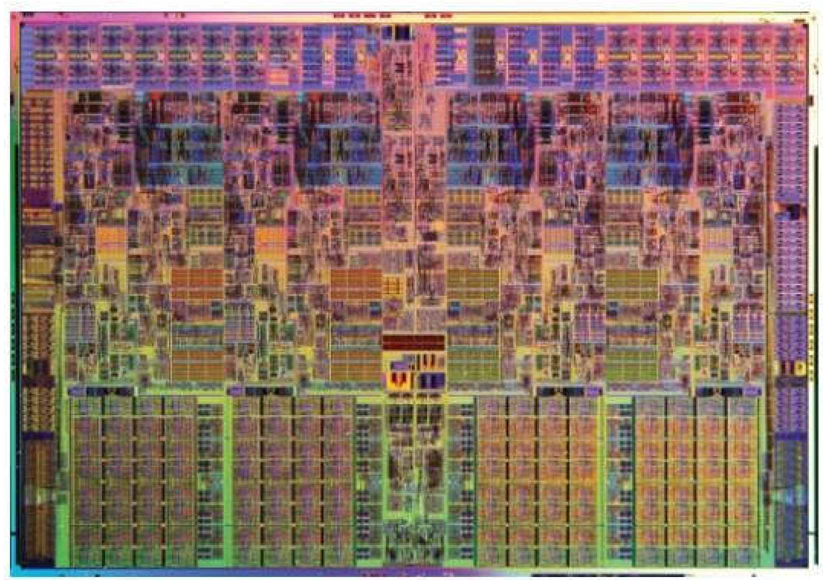




< 100 nm



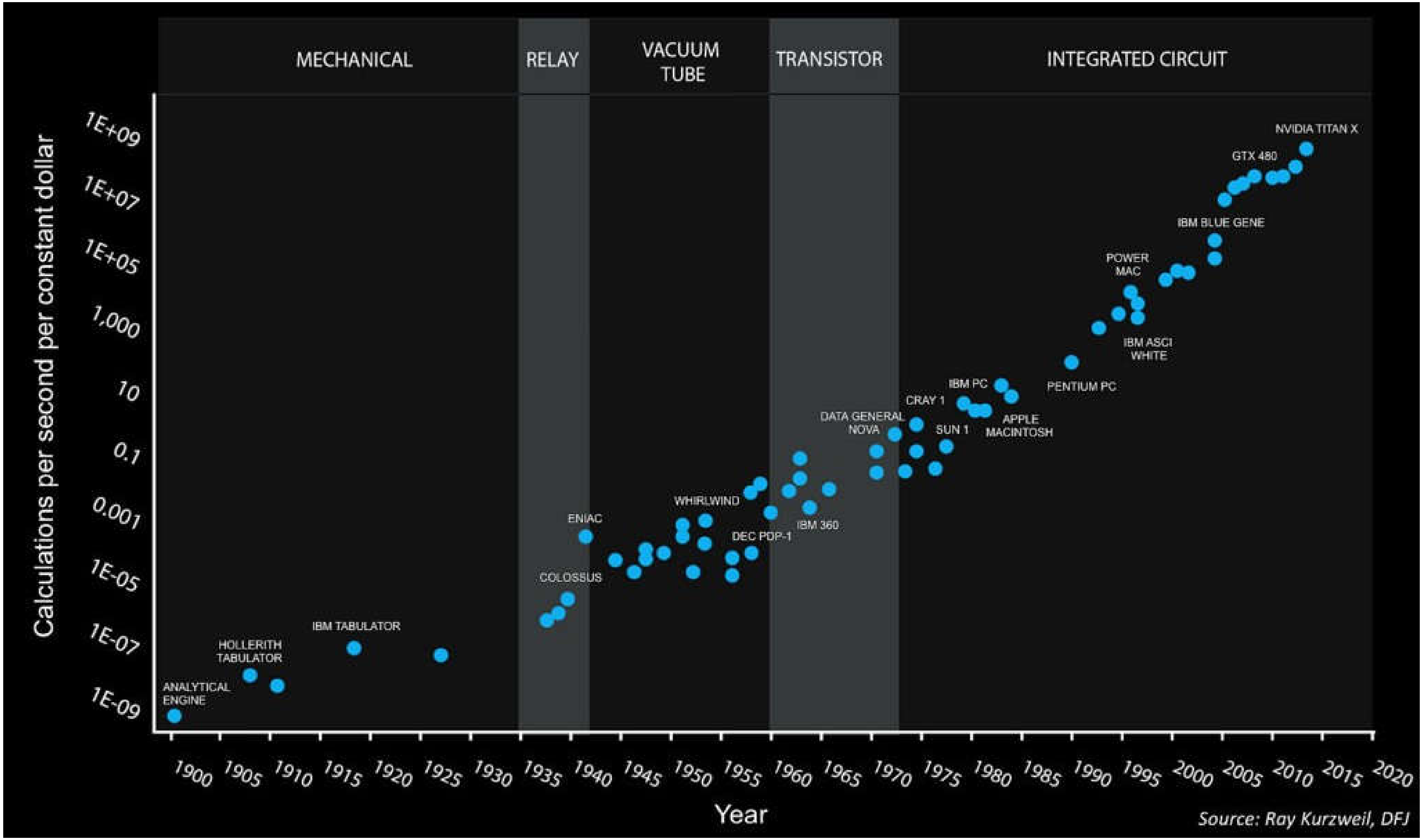
virus



Modern Electronics is a real Nanotechnology

Intel i7 CPU, ~ 10^9 transistors

120 Years of Moore's Law



Integrate Circuits

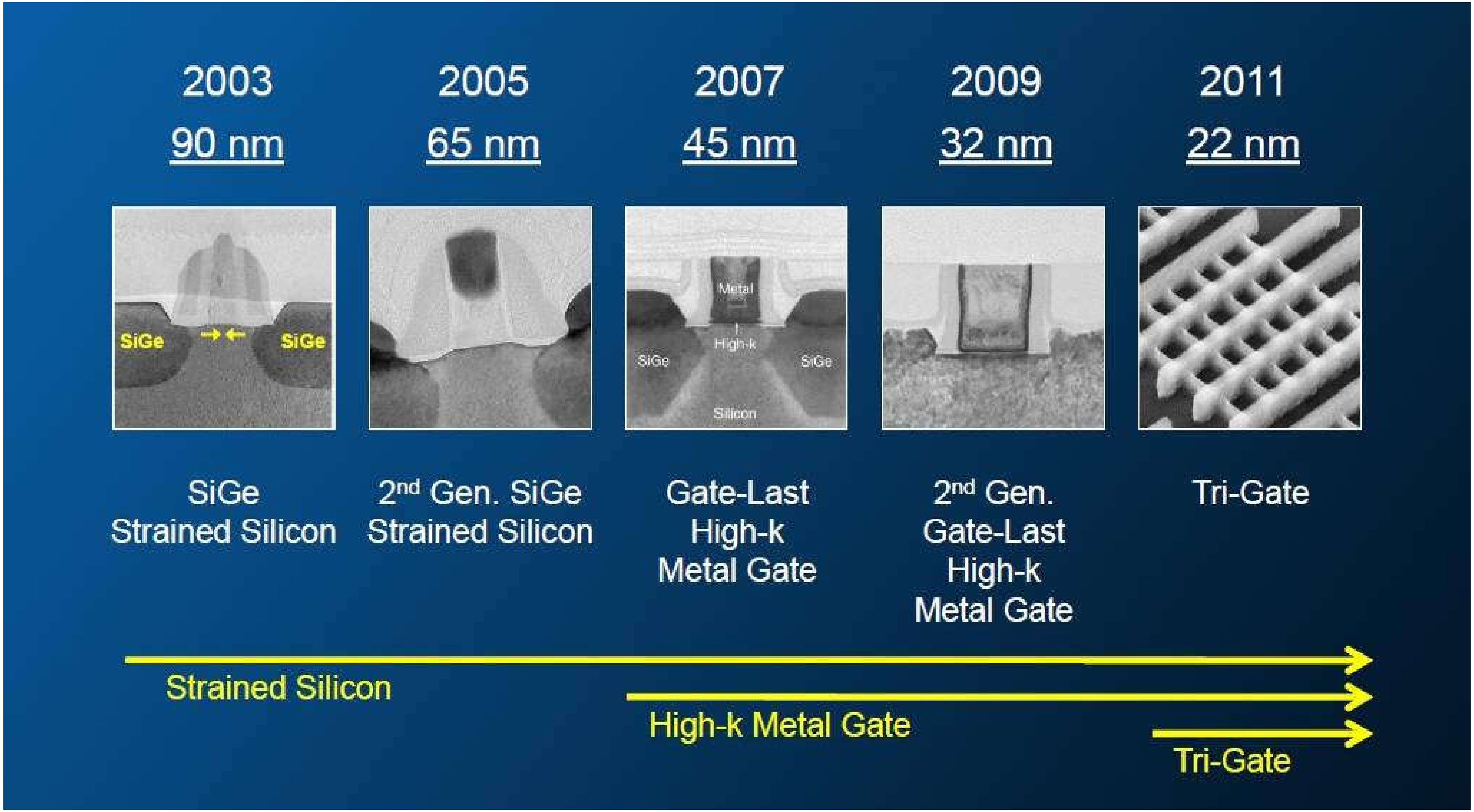
1980s

¥2549.00

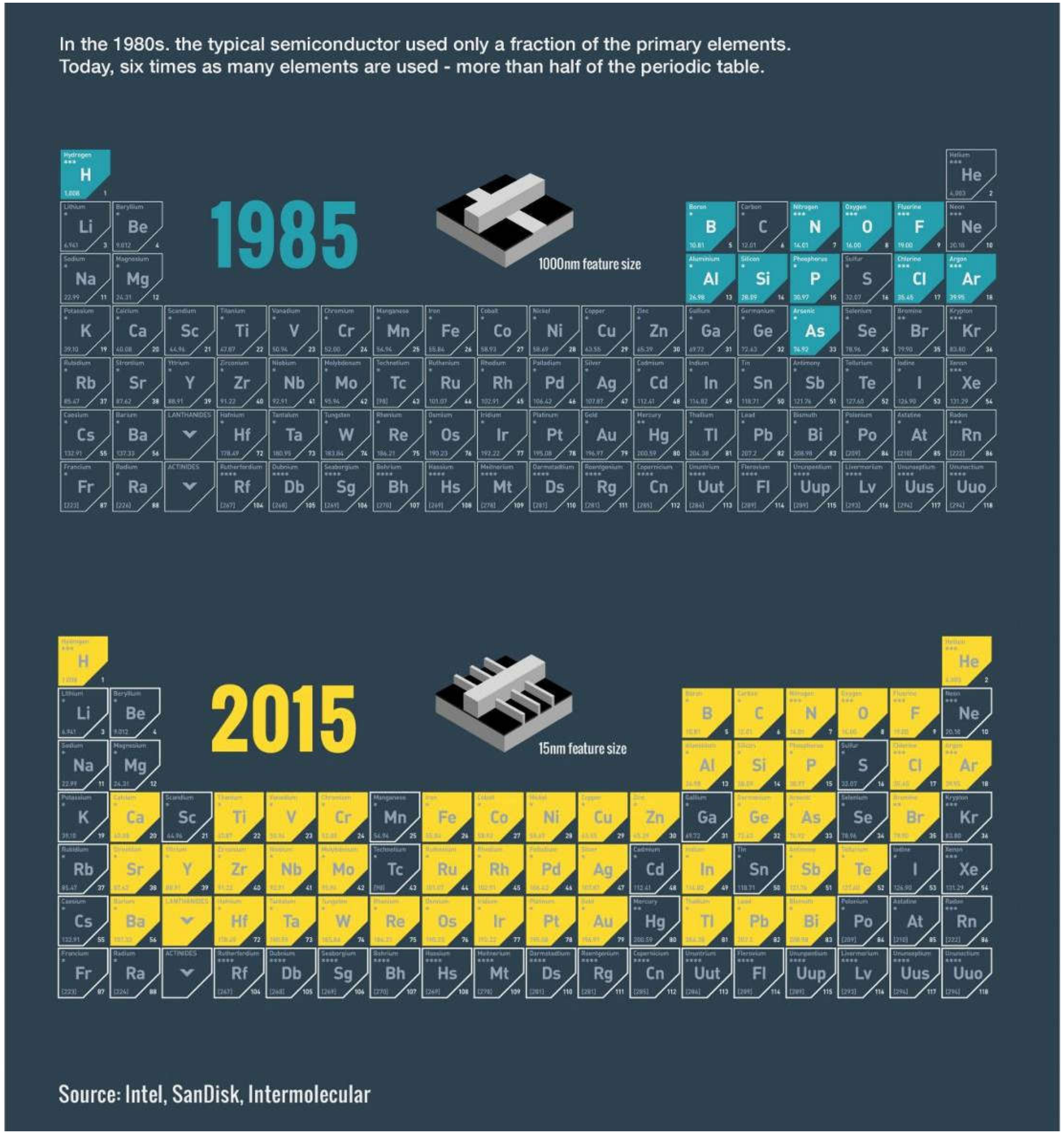
英特尔（Intel）酷睿四核I7-7700k 盒装 CPU处理器 采用Kabylake架构，LGA 1151

2017, price > gold

Transistor Evolution



Materials in IC



Modern IC foundry

Video 1

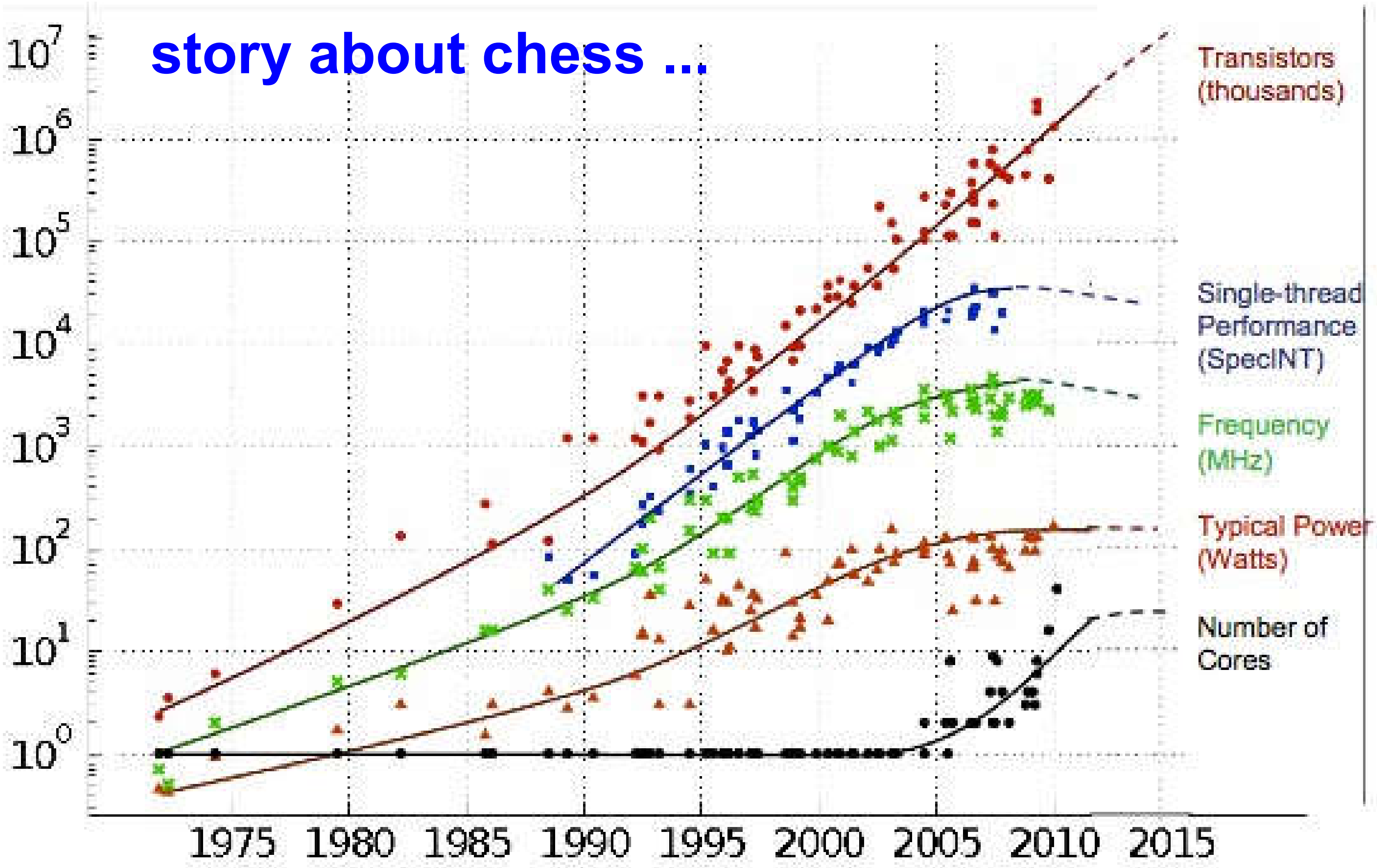
Video 2 Intel

Global Foundries

Samsung

Cost > 10 billion $$$

All Good Things Come to an End

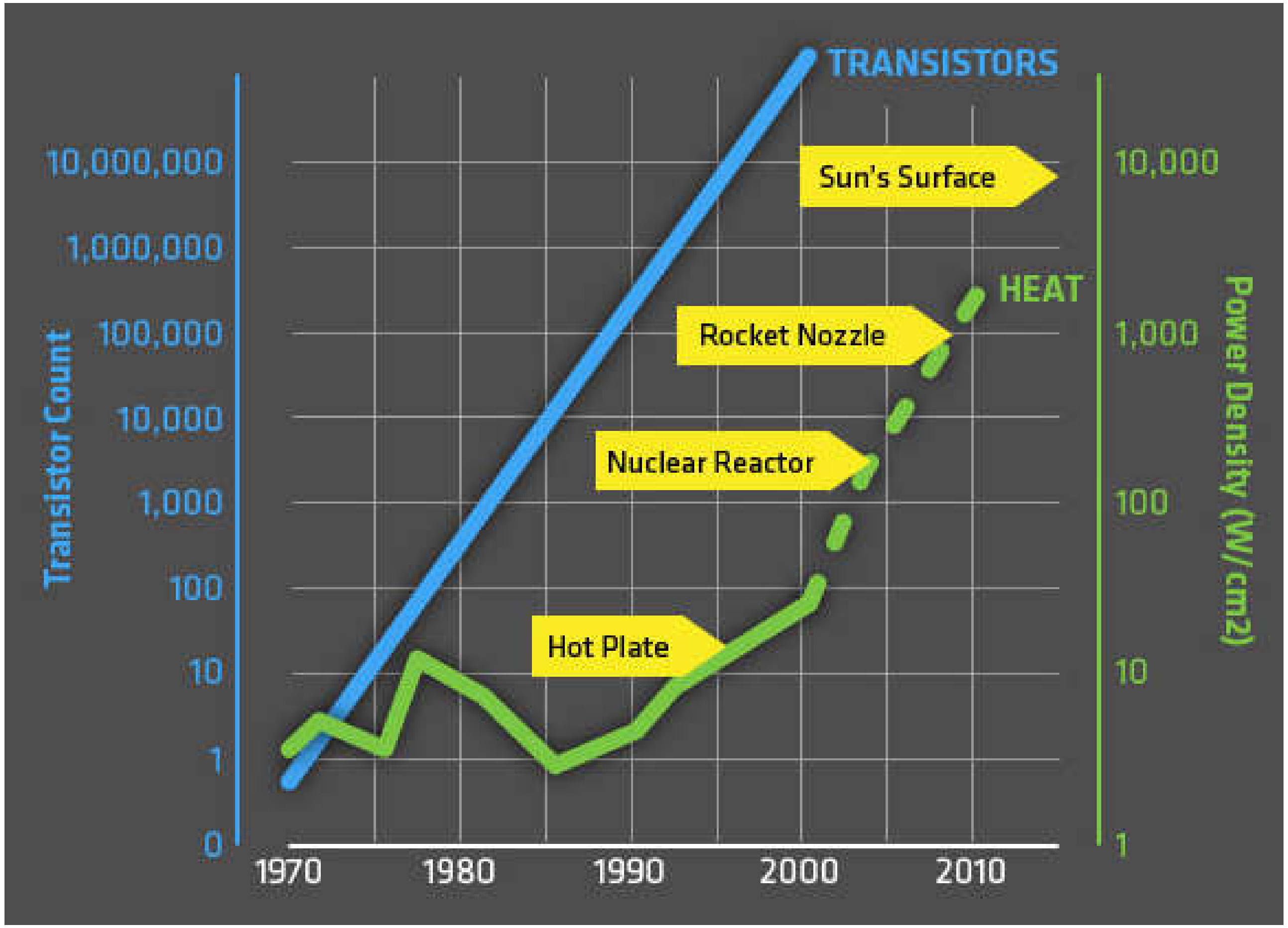


Original data collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond and C. Batten
Dotted line extrapolations by C. Moore

Power Consumptions

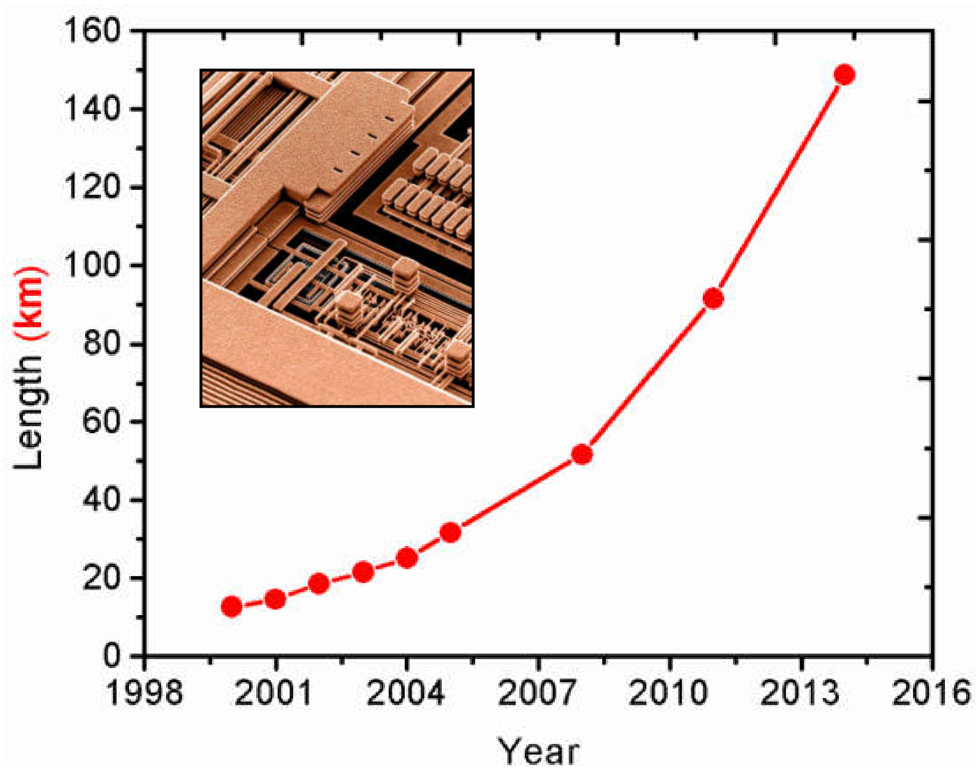
Shannon-von Neumann-Landauer (SNL) limit:

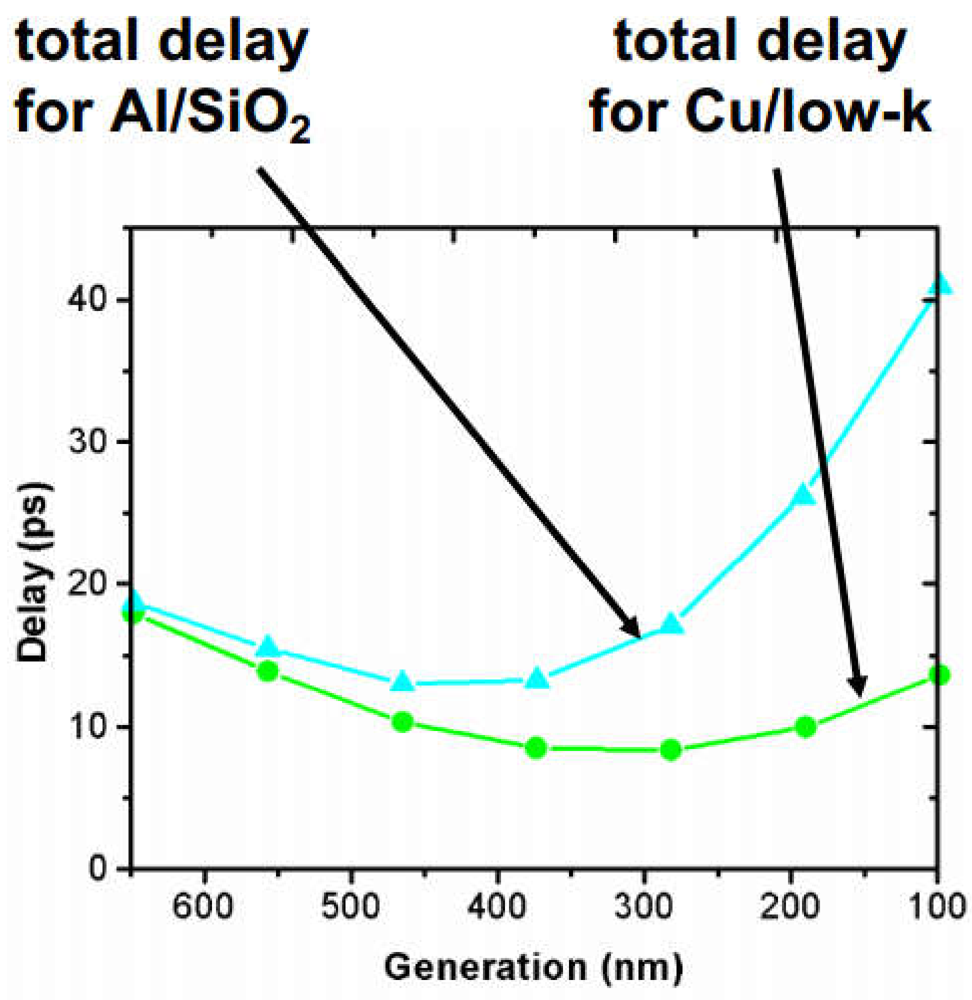
minimum energy per bit ~ $k_B T * \ln(2)$



IC Delays

$$t \sim RC$$



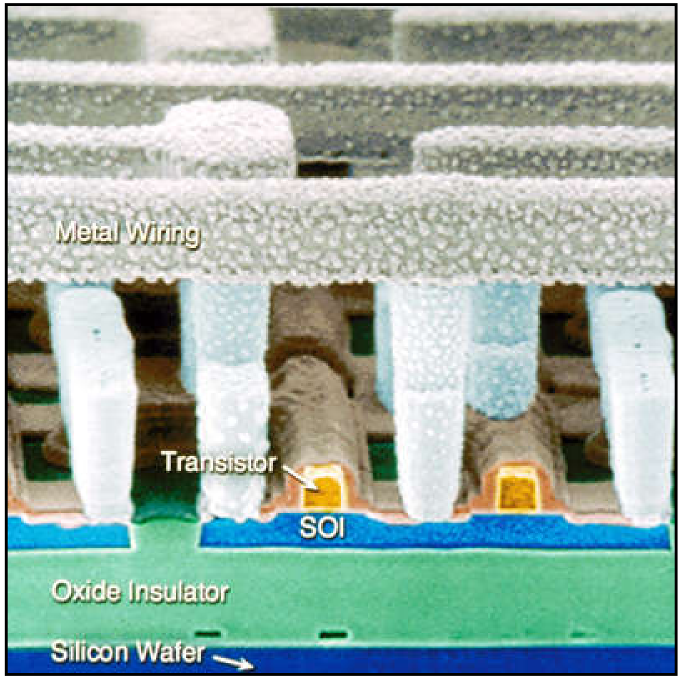


more conductive electrodes, lower *k* dielectrics

Doping in Nano Devices

atomic density of Si **= 5 * 10^{22} /cm^3**

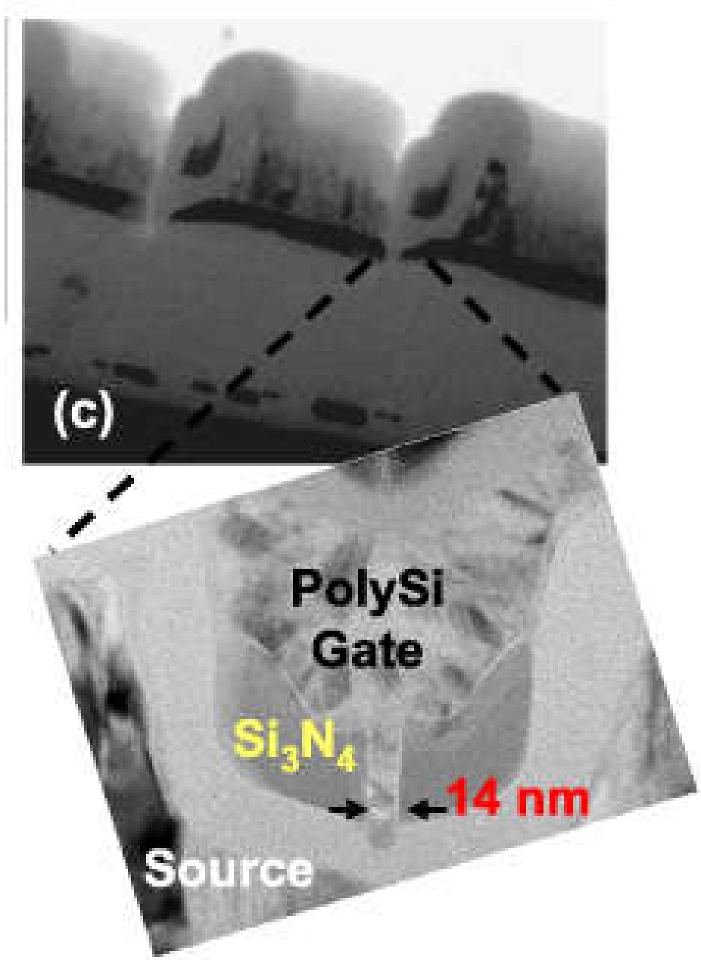
if the transistor size is
10 nm * 10 nm * 10 nm,
and doping concentration is
1 * 10^{18} /cm^3



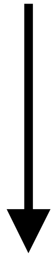
↓

There is only 1 dopant atom in the transistor!

Grain Sizes in Nano Transistors

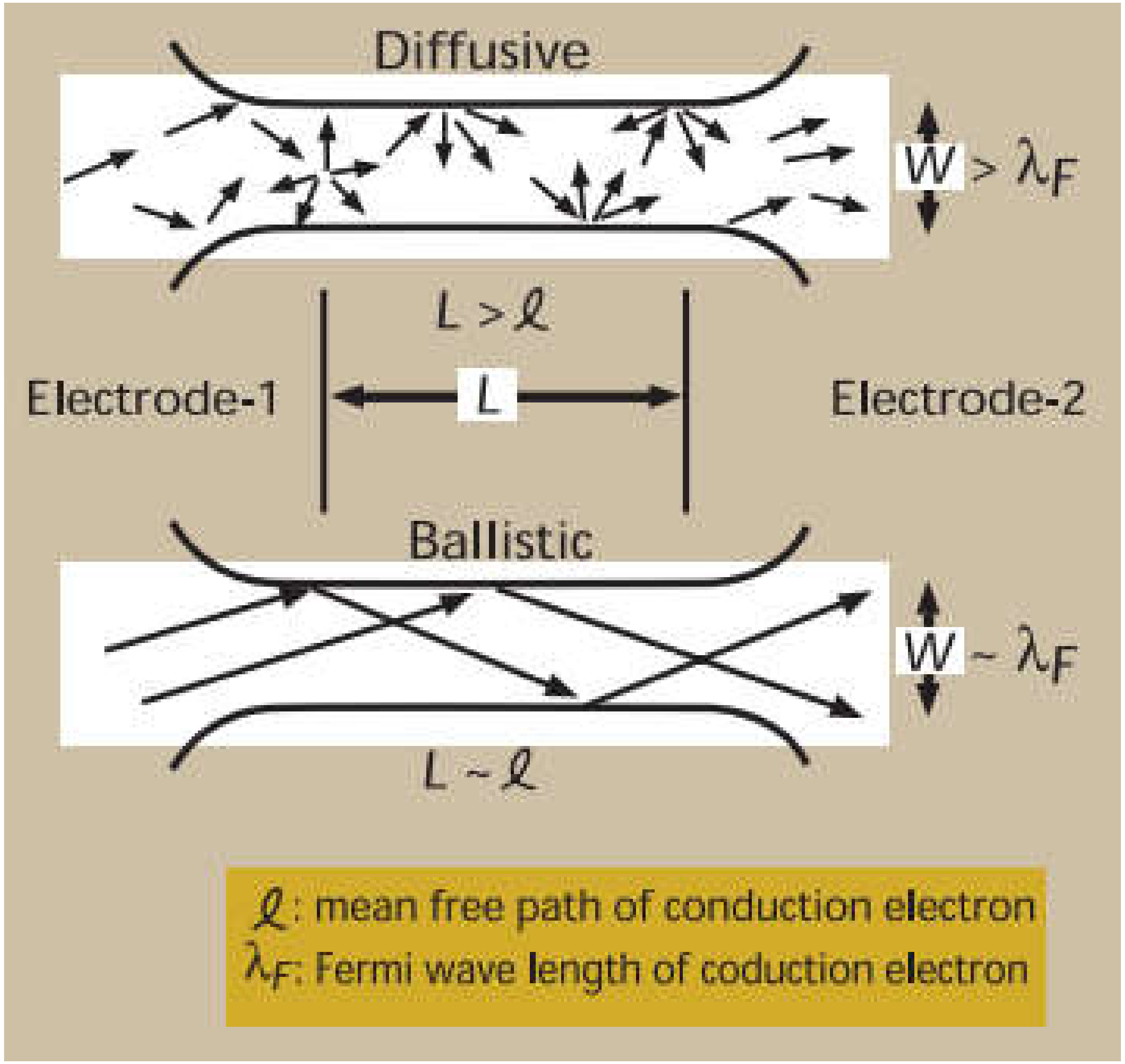


grain size ~ a few nm



grain boundary, roughness, increased electron scattering, ...

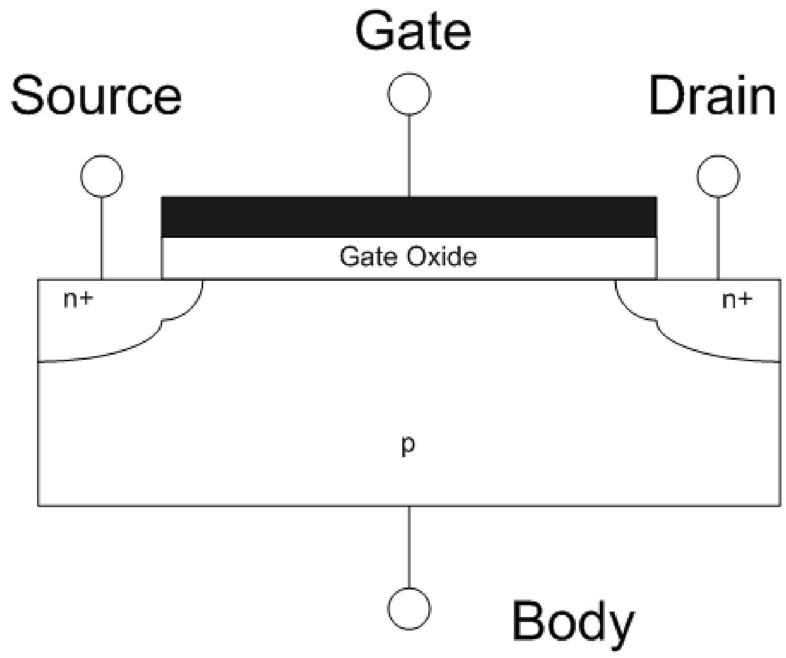
Carrier Transport



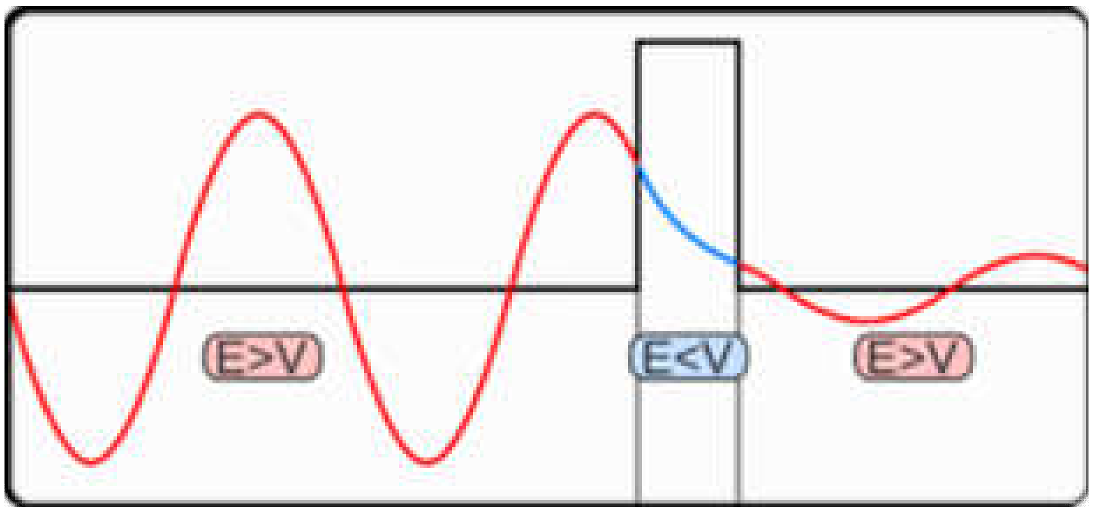
Carrier Transport

$$I_{D,Sat} = \frac{W}{L}\mu C\frac{(V_G - V_{th})^2}{2}$$

$$C = \frac{\kappa\varepsilon_0 A}{t}$$

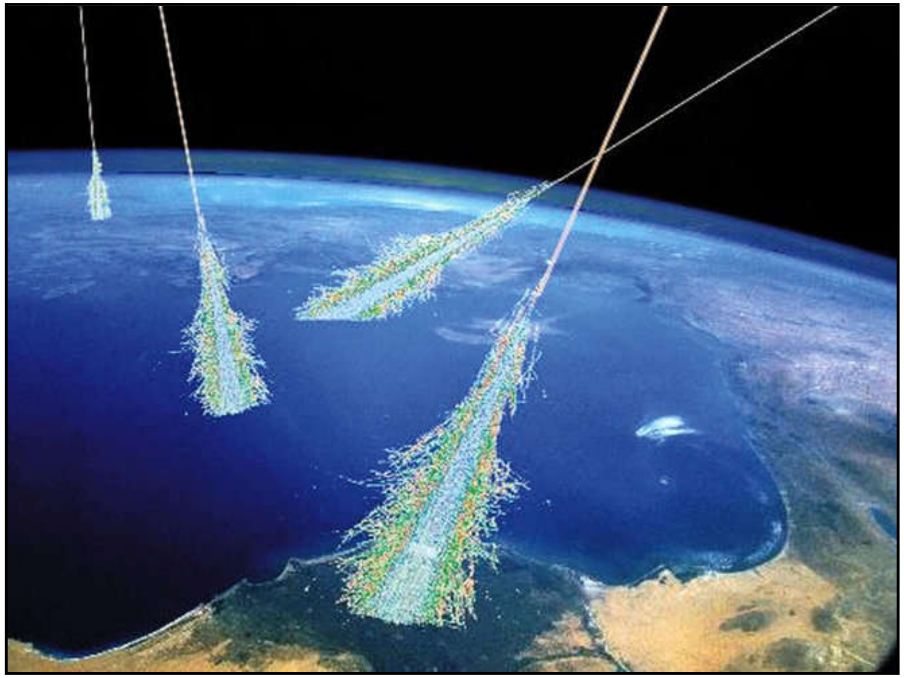


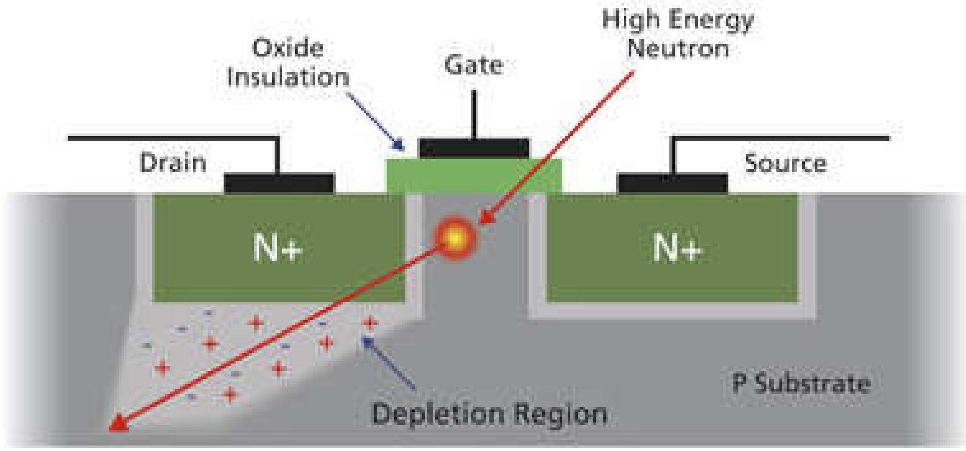
large C requires small t



quantum tunneling

Danger from Outer Space





smaller devices are more susceptible to cosmic rays

All Good Things Come to an End

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FEATURE NEWS

THE SEMICONDUCTOR INDUSTRY WILL SOON ABANDON ITS PURSUIT OF MOORE'S LAW.

NOW THINGS COULD GET A LOT MORE INTERESTING.

City. The Semiconductor Industry Association (SIA) in Washington DC, which represents all the major US firms, has already said that it will cease its participation in the road-mapping effort once the report is out, and will instead pursue its own research and development agenda.

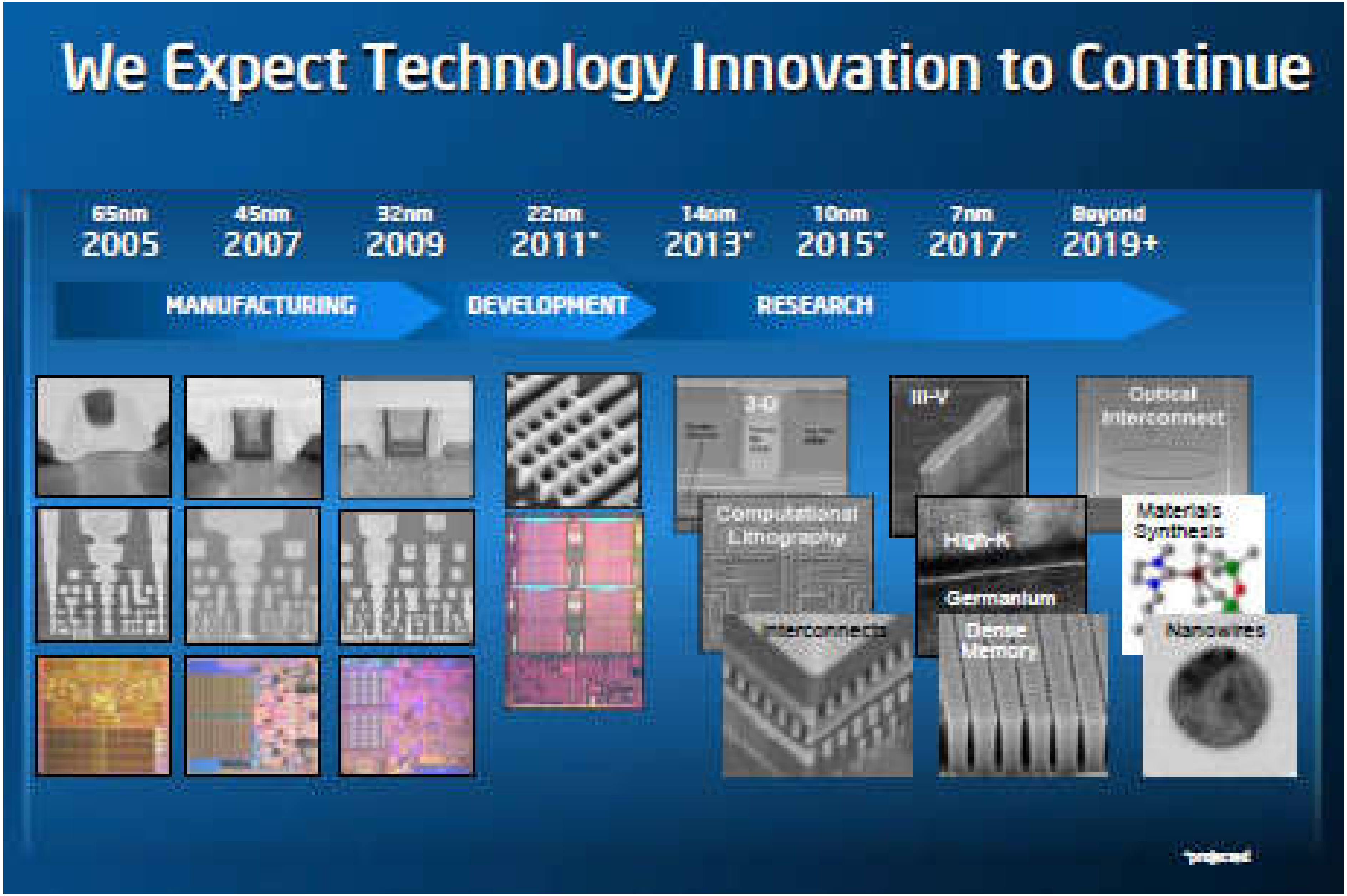
Everyone agrees that the twilight of Moore's law will not mean the end of progress. "Think about what happened to airplanes," says Reed. "A Boeing 787 doesn't go any faster than a 707 did in the 1950s — but they are very different airplanes", with innovations ranging from fully electronic controls to a carbon-fibre fuselage. That's what will happen with computers, he says: "Innovation will absolutely continue — but it will be more nuanced and complicated."

LAYING DOWN THE LAW

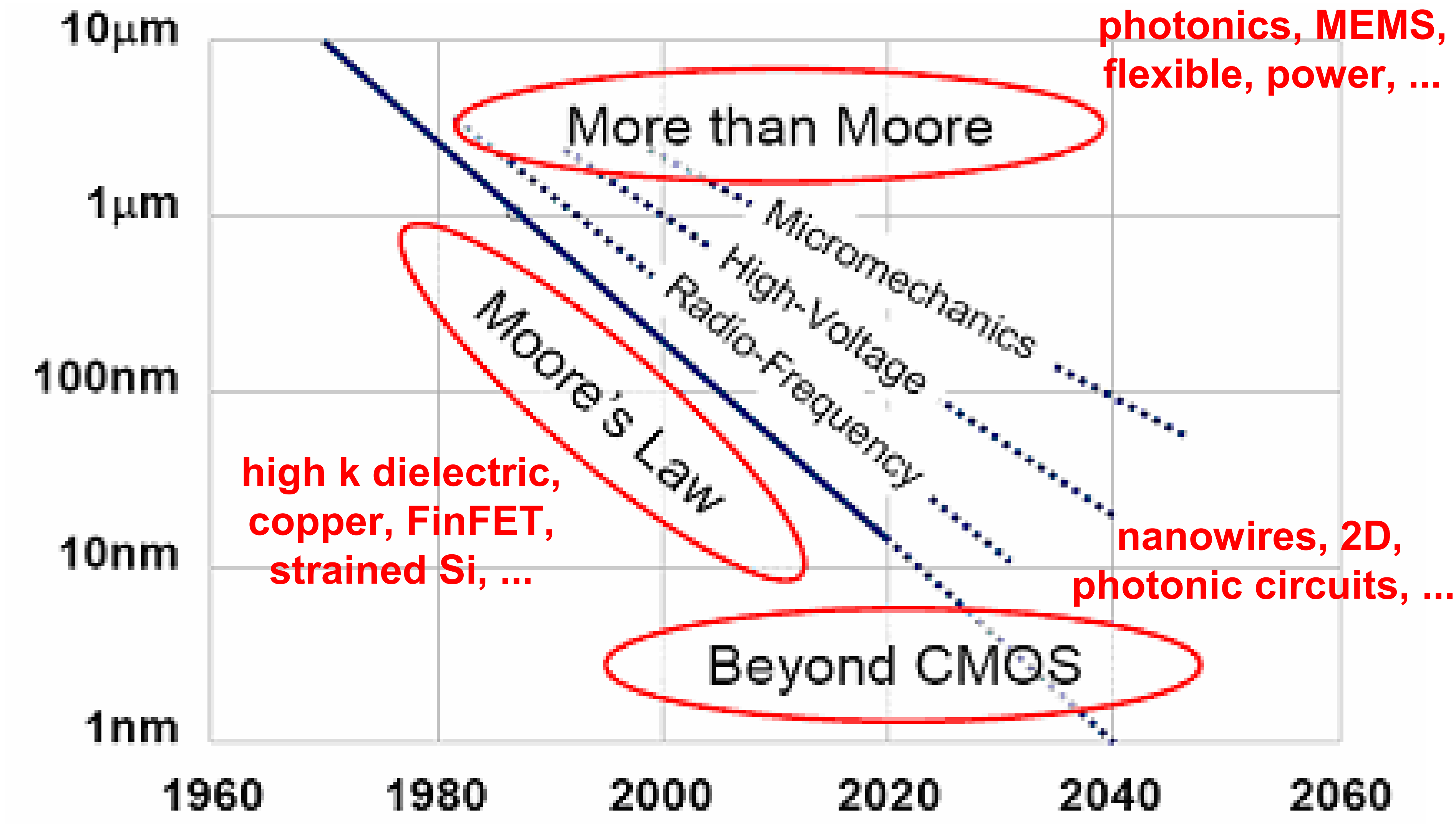
The 1965 essay[1] that would make Gordon Moore famous started with a meditation on what could be done with the still-new technology of integrated circuits. Moore, who was then research director of Fairchild

M. M. Waldrop, *Nature* **530,** 144 (2016)

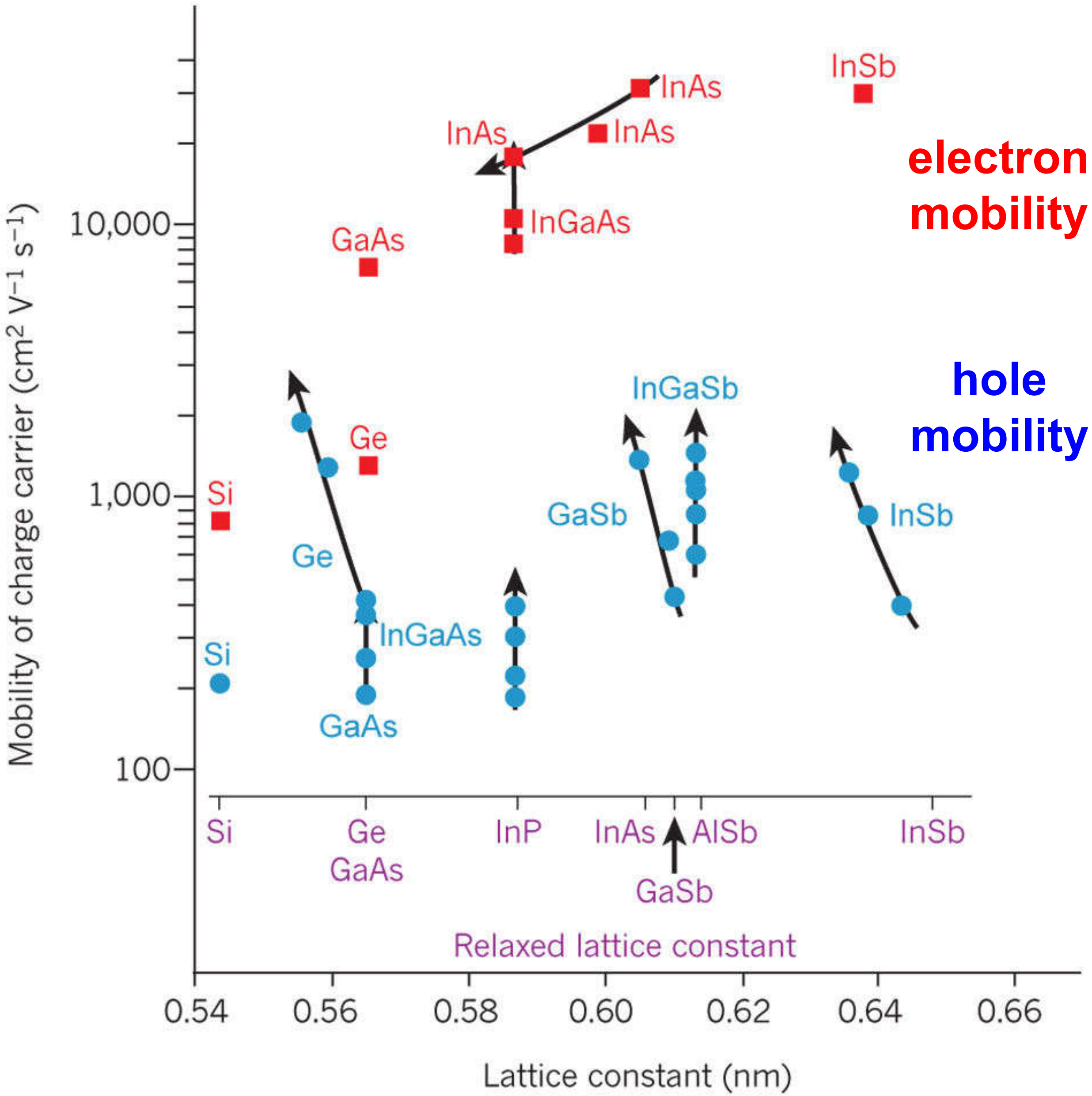
New Opportunities



New Opportunities



High Electron Mobility Transistor (HEMT)

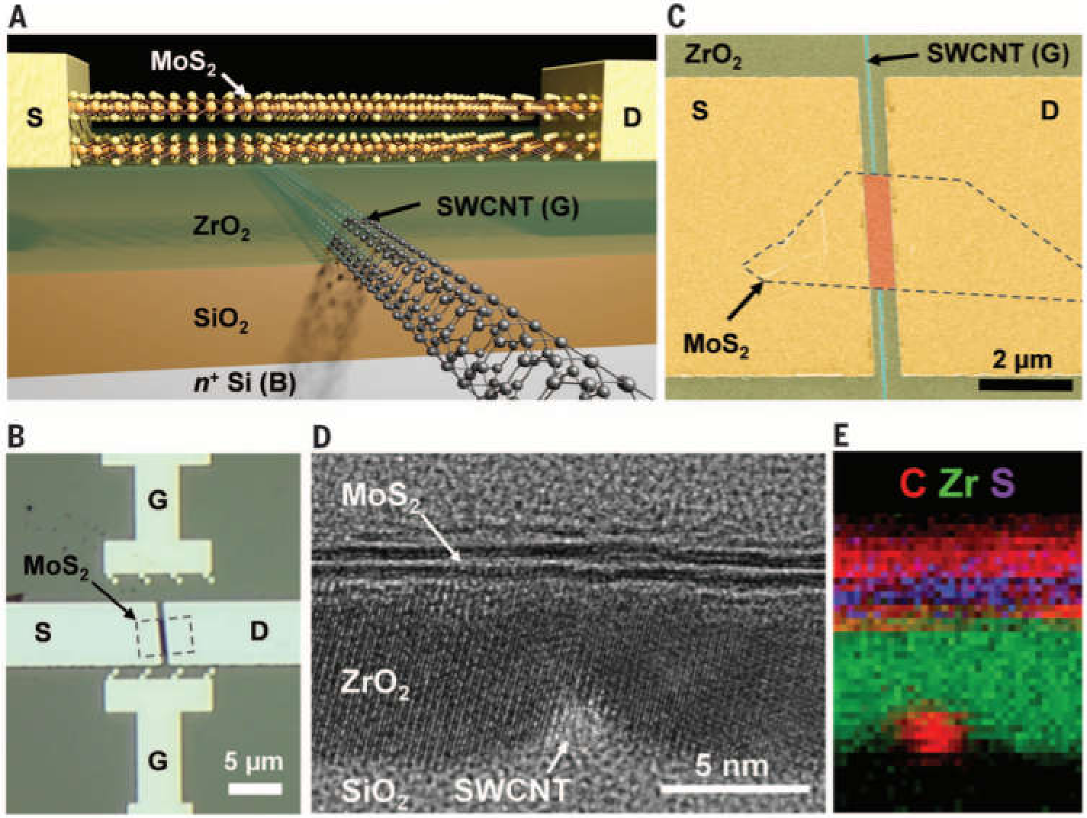


Nano-Transistors

DEVICE TECHNOLOGY

MoS_2 transistors with 1-nanometer gate lengths

Sujay B. Desai,[1,2,3] Surabhi R. Madhvapathy,[1,2] Angada B. Sachid,[1,2]
Juan Pablo Llinas,[1,2] Qingxiao Wang,[4] Geun Ho Ahn,[1,2] Gregory Pitner,[5] Moon J. Kim,[4]
Jeffrey Bokor,[1,2] Chenming Hu,[1] H.-S. Philip Wong,[5] Ali Javey[1,2,3]*

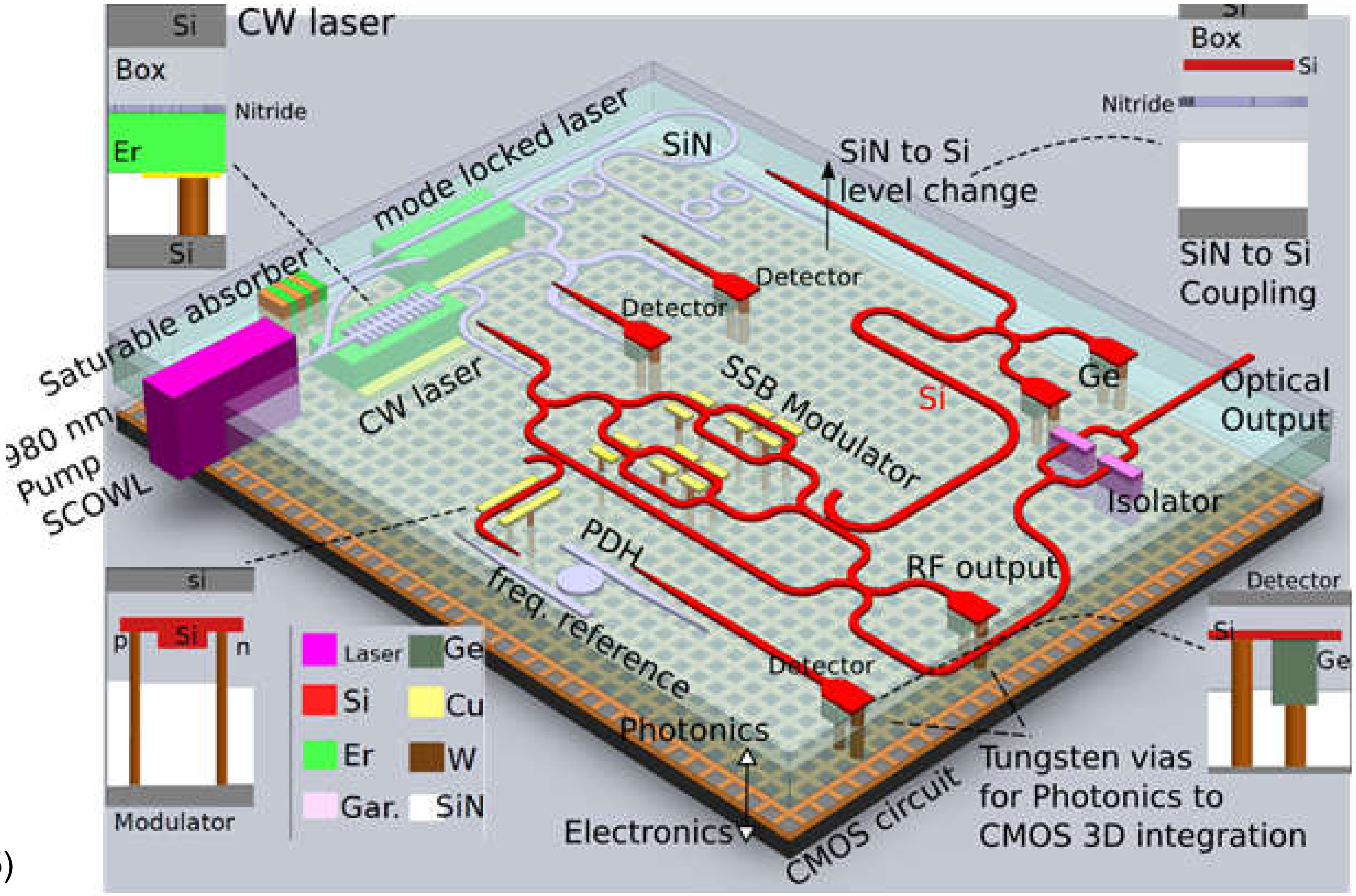


S. Desai, *et al.*, *Science* **354,** 99 (2016)

Photonic Integrated Circuits

Single-chip microprocessor that communicates directly using light

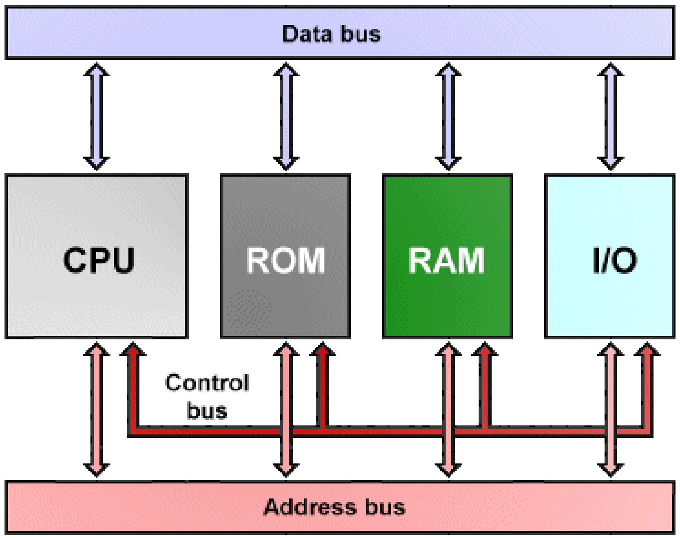
Chen Sun[1,2*], Mark T. Wade[3*], Yunsup Lee[1*], Jason S. Orcutt[2†*], Luca Alloatti[2], Michael S. Georgas[2], Andrew S. Waterman[1], Jeffrey M. Shainline[3†], Rimas R. Avizienis[1], Sen Lin[1], Benjamin R. Moss[2], Rajesh Kumar[3], Fabio Pavanello[3], Amir H. Atabaki[2], Henry M. Cook[1], Albert J. Ou[1], Jonathan C. Leu[2], Yu-Hsin Chen[2], Krste Asanović[1], Rajeev J. Ram[2], Miloš A. Popović[3] & Vladimir M. Stojanović[1]

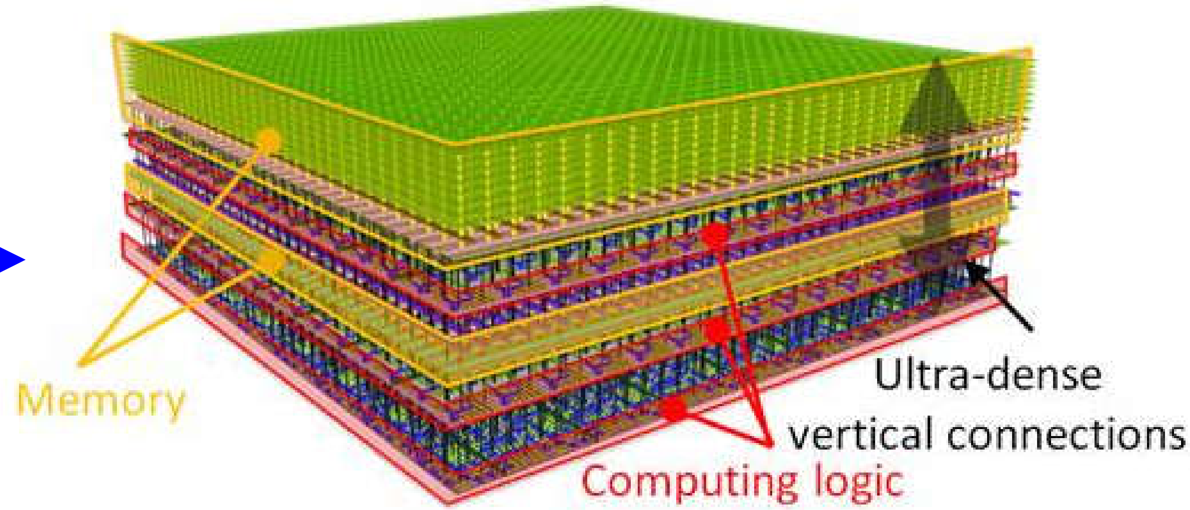


C. Sun, *et al.*, *Nature* **528,** 534 (2015)

3D IC

- **Logic + Memory + Sensing + ...**



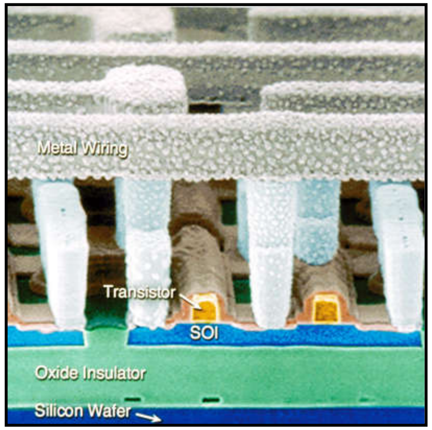


conventional

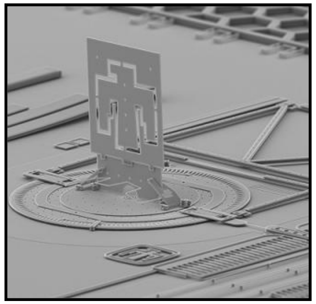
3D IC

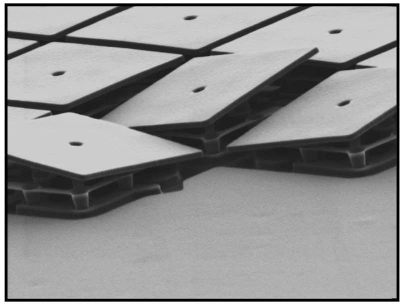
M. M. Shulaker, *et al.*, *Nature* **547**, 74 (2017)

More than Moore

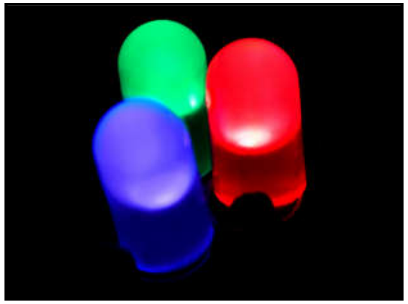


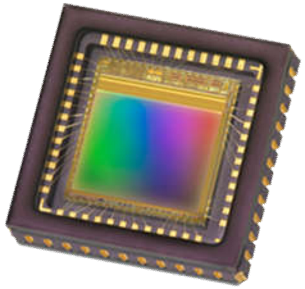
Microelectronics



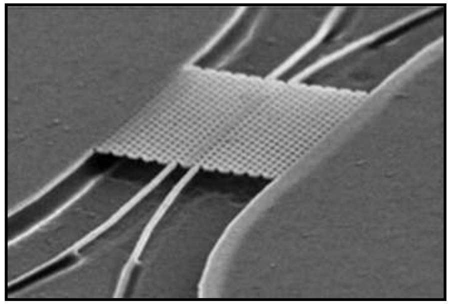


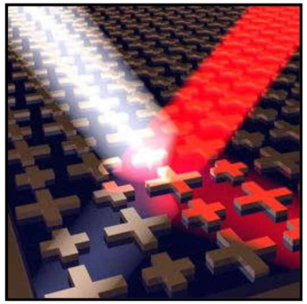
Microelectromechanical Systems (MEMS)





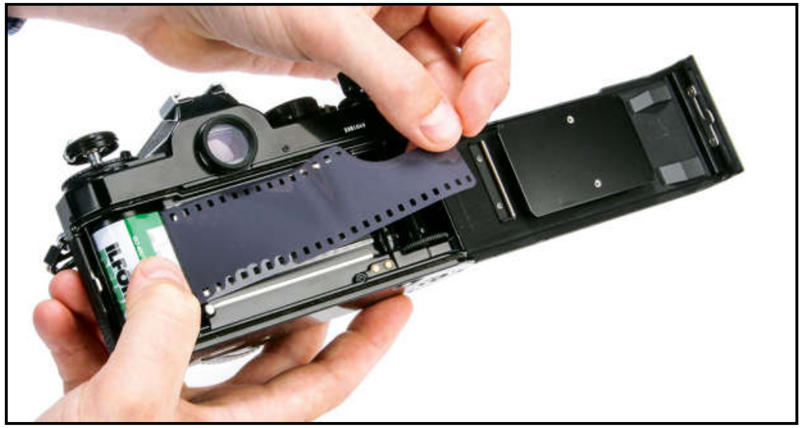
Optoelectronics



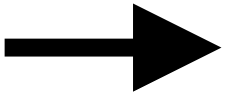


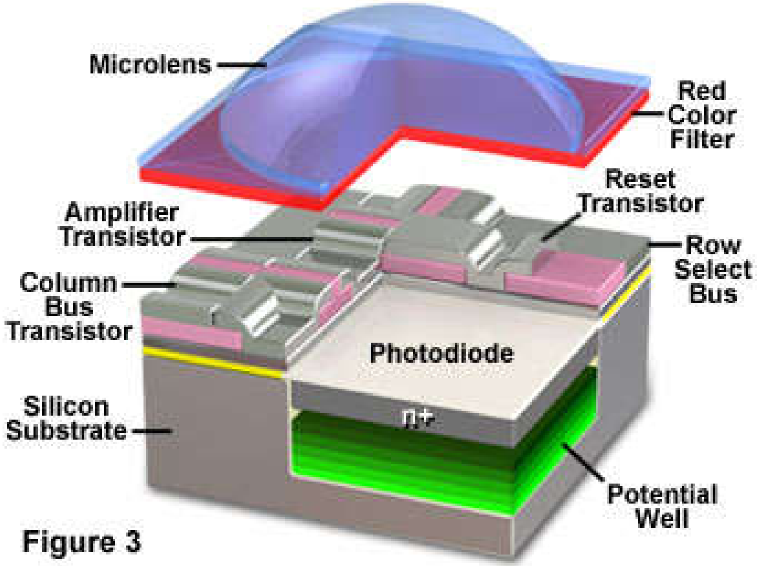
Micro and Nano Photonics

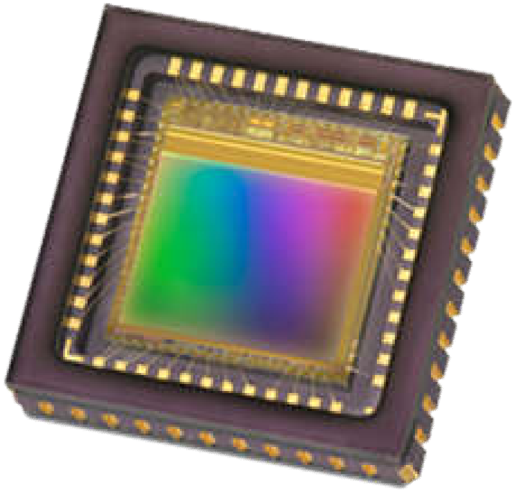
Image Sensors



films

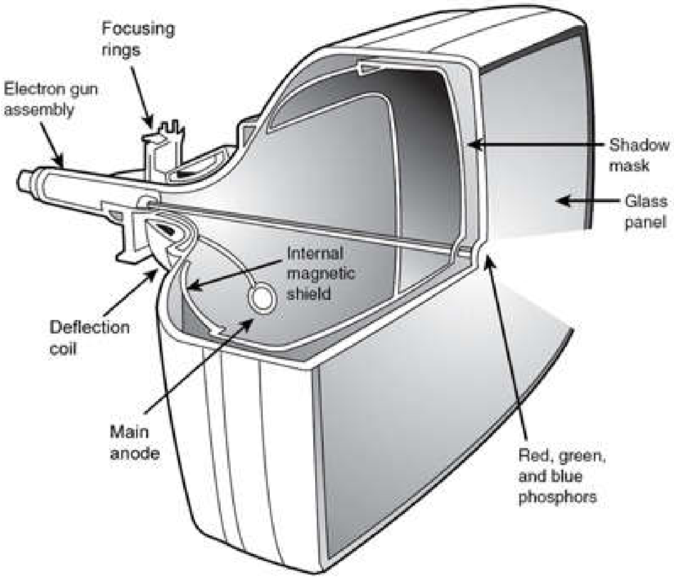


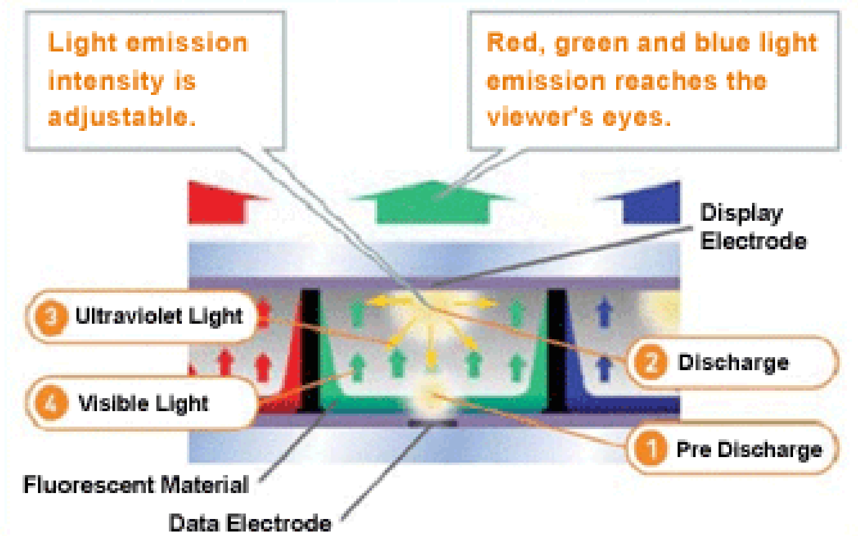




CMOS sensors

Displays



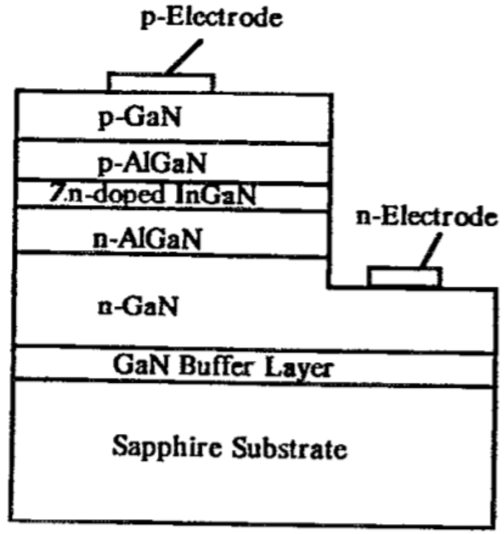


CRT

Flat panel

Light Sources

Incandescent bulb

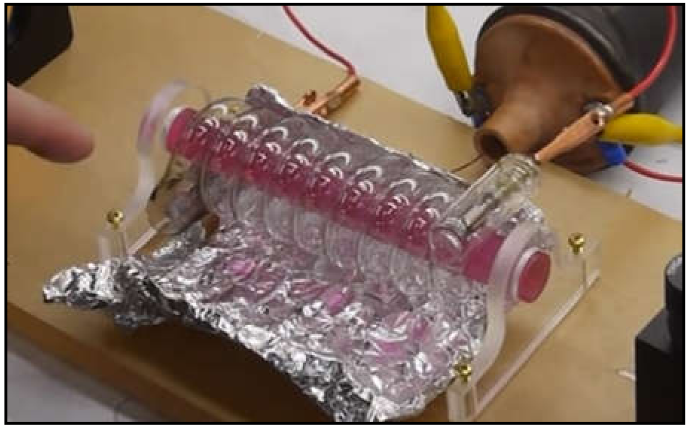


S. Nakamura, *et al.*, *Appl. Phys. Lett.* **64,** 1687 (1994)

Fluorescent lamp

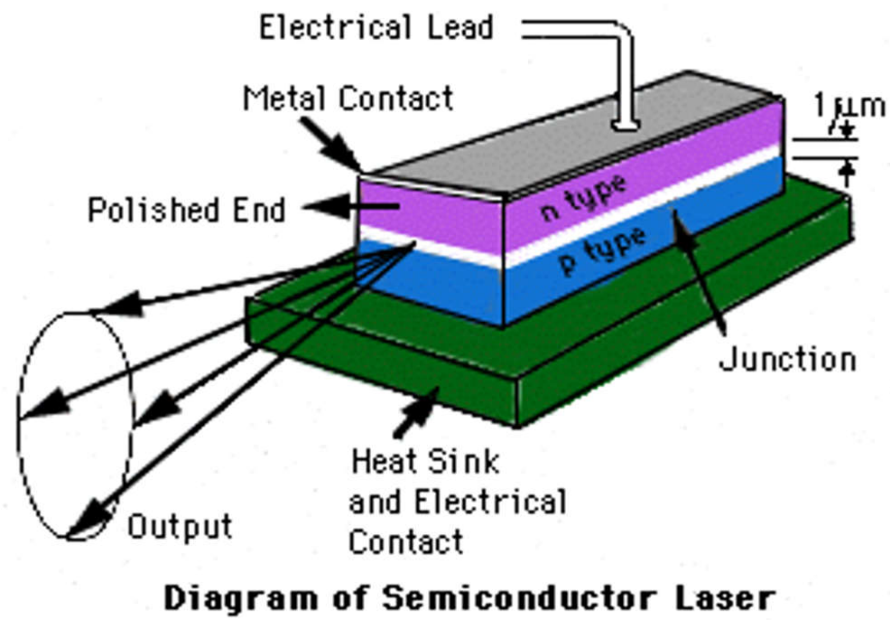
LEDs

Light Sources



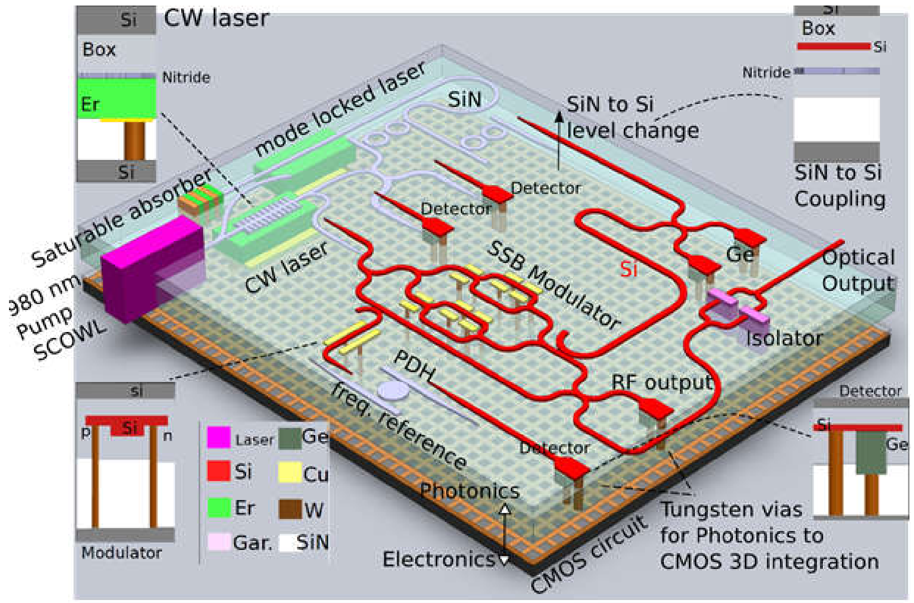
ruby laser

gas laser



semiconductor laser

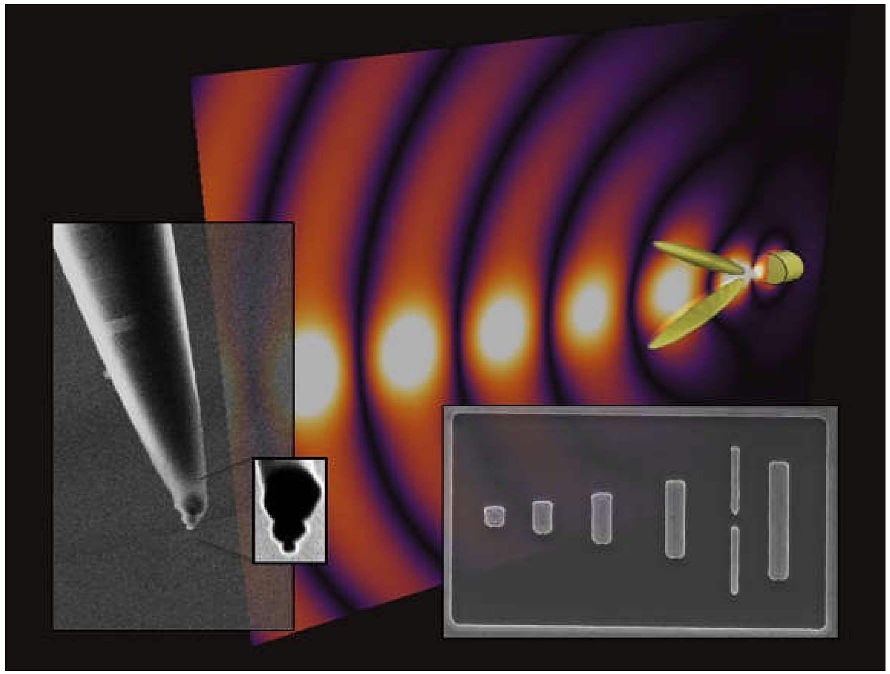
Integrated Photonic Circuits



Conventional optics **Integrated photonics**

Integrated Photonic Circuits

Microwave Antenna



Optical Antenna