

微纳光电子材料与器件工艺原理

Introduction

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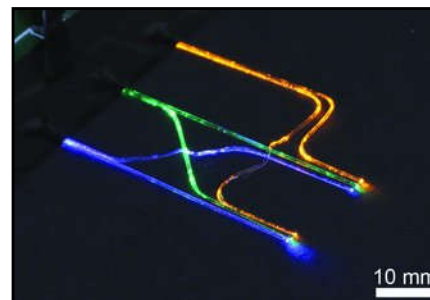
Optical and Electronic Devices



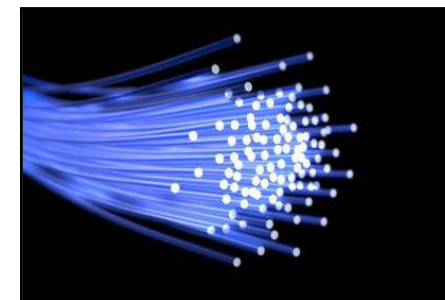
LEDs



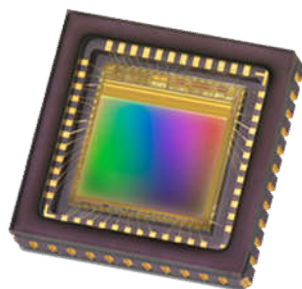
lasers



waveguides



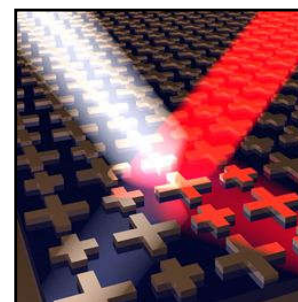
fibers



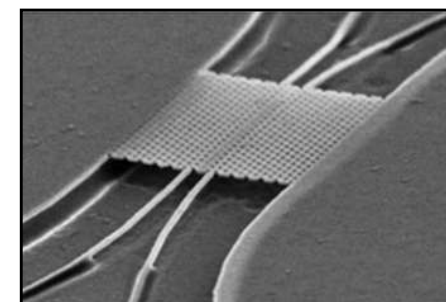
detectors



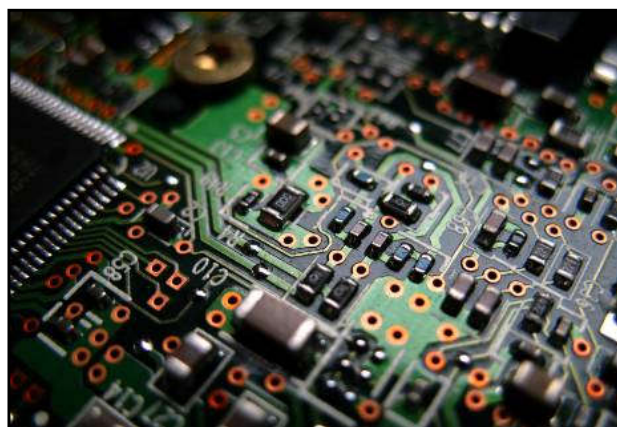
solar cells



metamaterials



photonic crystals



integrated circuits



**Airflow
Sensors**



**Current
Sensors**



**Fiber Optics and
Liquid Level Sensors**



Flexible Heaters



Force Sensors



**Humidity
Sensors**



Infrared Sensors



**Magnetic
Sensors**



**Proximity
Sensors**



**Rotary Position
Sensors**



**Speed
Sensors**

Course Information

- 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

Syllabus

- **Introduction (Week 1)**
- **Materials: Structures and Synthesis (Week 2)**
- **Cleanroom Environment (Week 3)**
- **Photolithography (Week 4, 5)**
- **Doping (Week 6)**
- **Materials Growth and Deposition (Week 7, 8, 9)**
- **Materials Etching (Week 10, 11)**
- **Integration and Packaging (Week 12)**
- **Emerging Technologies (Week 13, 14)**
- **Final Presentation (Week 15, 16)**

Syllabus

- **Introduction (Week 1)**
 - **Integration circuits, Moore's law**
 - **Advanced optical and electronic devices**
- **Materials: Structures and Synthesis (Week 2)**
- **Cleanroom Environment (Week 3)**
- **Photolithography (Week 4, 5)**
- **Doping (Week 6)**
- **Materials Growth and Deposition (Week 7, 8, 9)**
- **Materials Etching (Week 10, 11)**
- **Integration and Packaging (Week 12)**
- **Emerging Technologies (Week 13, 14)**
- **Final Presentation (Week 15, 16)**

Syllabus

- Introduction (Week 1)
- **Materials: Structures and Synthesis (Week 2)**
 - **Crystal structures**
 - **Semiconductor wafer preparation**
 - **Optical fiber drawing**
- Cleanroom Environment (Week 3)
- Photolithography (Week 4, 5)
- Doping (Week 6)
- Materials Growth and Deposition (Week 7, 8, 9)
- Materials Etching (Week 10, 11)
- Integration and Packaging (Week 12)
- Emerging Technologies (Week 13, 14)
- Final Presentation (Week 15, 16)

Syllabus

- Introduction (Week 1)
- Materials: Structures and Synthesis (Week 2)
- **Cleanroom Environment (Week 3)**
 - ▣ **Cleanroom, foundry**
 - ▣ **Contamination and cleaning**
 - ▣ **Lab safety**
- Photolithography (Week 4, 5)
- Doping (Week 6)
- Materials Growth and Deposition (Week 7, 8, 9)
- Materials Etching (Week 10, 11)
- Integration and Packaging (Week 12)
- Emerging Technologies (Week 13, 14)
- Final Presentation (Week 15, 16)

Syllabus

- Introduction (Week 1)
- Materials: Structures and Synthesis (Week 2)
- Cleanroom Environment (Week 3)
- **Photolithography (Week 4, 5)**
 - optical principles, emerging technologies
 - photoresist process
- Doping (Week 6)
- Materials Growth and Deposition (Week 7, 8, 9)
- Materials Etching (Week 10, 11)
- Integration and Packaging (Week 12)
- Emerging Technologies (Week 13, 14)
- Final Presentation (Week 15, 16)

Syllabus

- Introduction (Week 1)
- Materials: Structures and Synthesis (Week 2)
- Cleanroom Environment (Week 3)
- Photolithography (Week 4, 5)
- **Doping (Week 6)**
 - **p-type, n-type, pn junctions**
 - **diffusion doping, ion implantation, in situ doping**
- Materials Growth and Deposition (Week 7, 8, 9)
- Materials Etching (Week 10, 11)
- Integration and Packaging (Week 12)
- Emerging Technologies (Week 13, 14)
- Final Presentation (Week 15, 16)

Syllabus

- Introduction (Week 1)
- Materials: Structures and Synthesis (Week 2)
- Cleanroom Environment (Week 3)
- Photolithography (Week 4, 5)
- Doping (Week 6)
- **Materials Growth and Deposition (Week 7, 8, 9)**
 - **Epitaxy, thermal oxidation**
 - **dry process: PVD, CVD, ...**
 - **wet process: electrodeposition, spin coating, ...**
- Materials Etching (Week 10, 11)
- Integration and Packaging (Week 12)
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- Photolithography (Week 4, 5)
- Doping (Week 6)
- Materials Growth and Deposition (Week 7, 8, 9)
- **Materials Etching (Week 10, 11)**
 - **wet etch**
 - **dry etching**
 - **CMP, FIB, ...**
- Integration and Packaging (Week 12)
- Emerging Technologies (Week 13, 14)
- Final Presentation (Week 15, 16)

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- Photolithography (Week 4, 5)
- Doping (Week 6)
- Materials Growth and Deposition (Week 7, 8, 9)
- Materials Etching (Week 10, 11)
- **Integration and Packaging (Week 12)**
 - ▣ **wafer bonding, SOI, soldering, welding, transfer, ...**
- Emerging Technologies (Week 13, 14)
- Final Presentation (Week 15, 16)

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- Doping (Week 6)
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- Materials Etching (Week 10, 11)
- Integration and Packaging (Week 12)
- **Emerging Technologies (Week 13, 14)**
 - ▣ nanoimprint, 3D printing, self-assembly, epi release, transfer printing, flexible, ...
- Final Presentation (Week 15, 16)

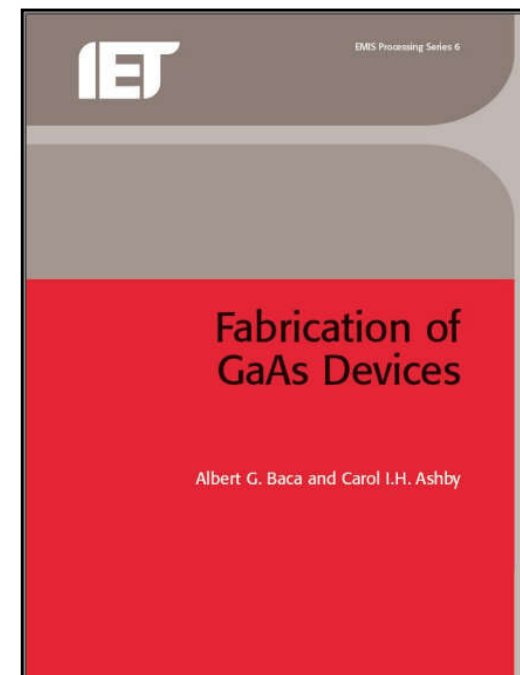
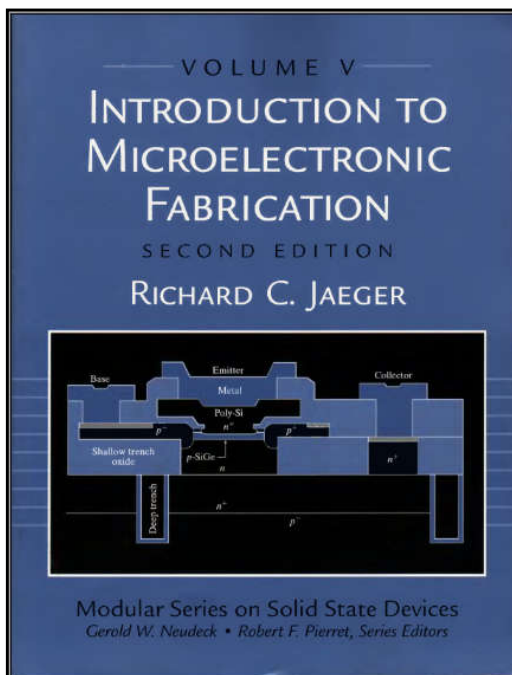
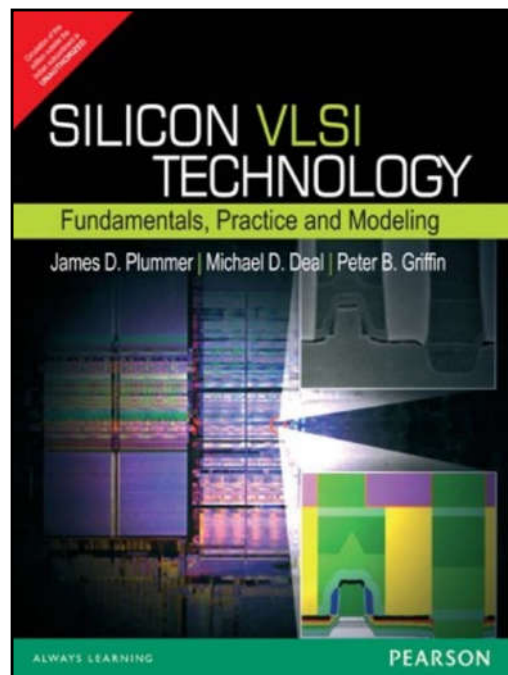
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- **Final Presentation (Week 15, 16)**

References

- 清华网络学堂

<http://learn.tsinghua.edu.cn>



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**

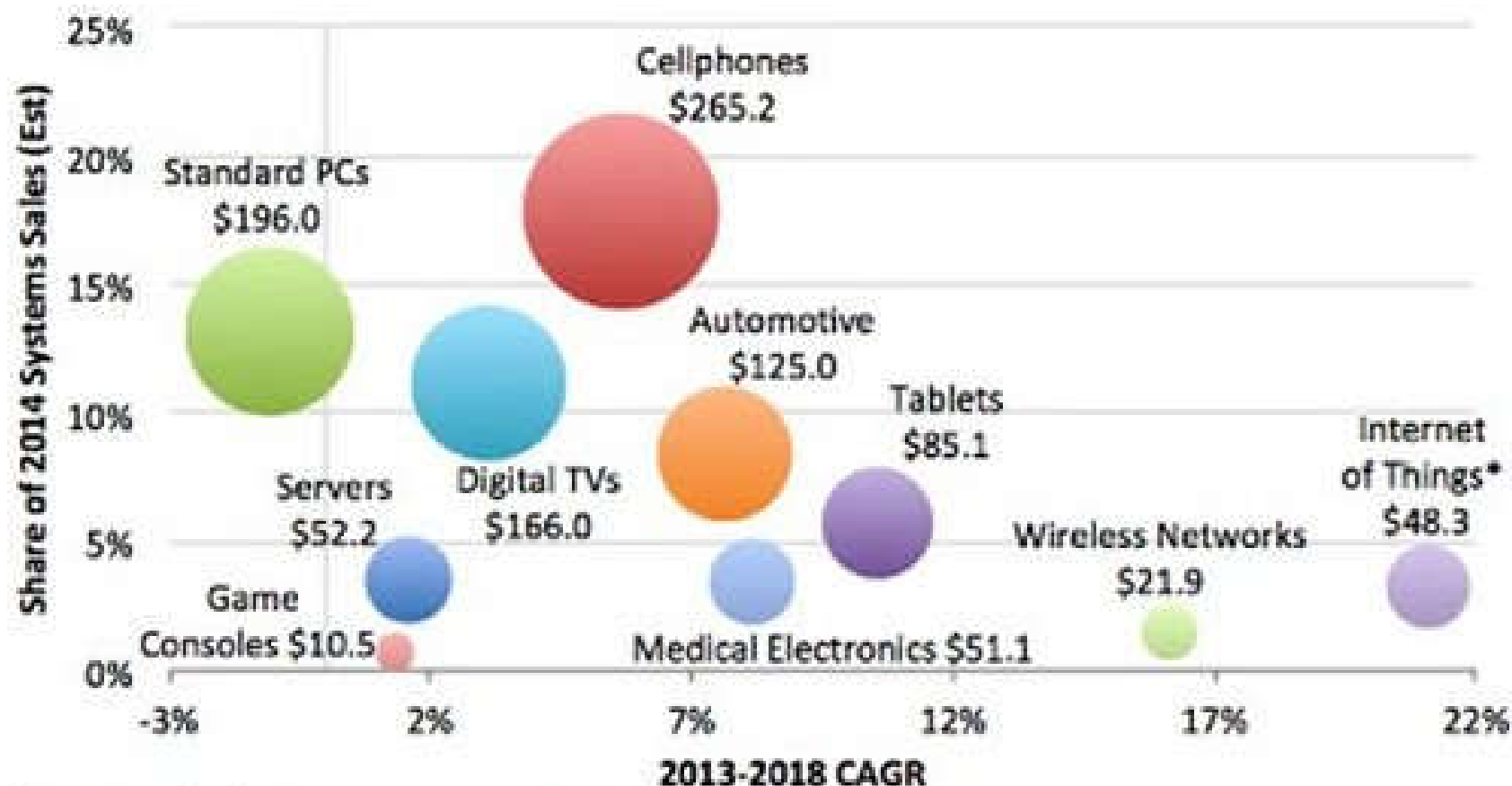
'Disruptive' Technologies

- 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 \$\$\$

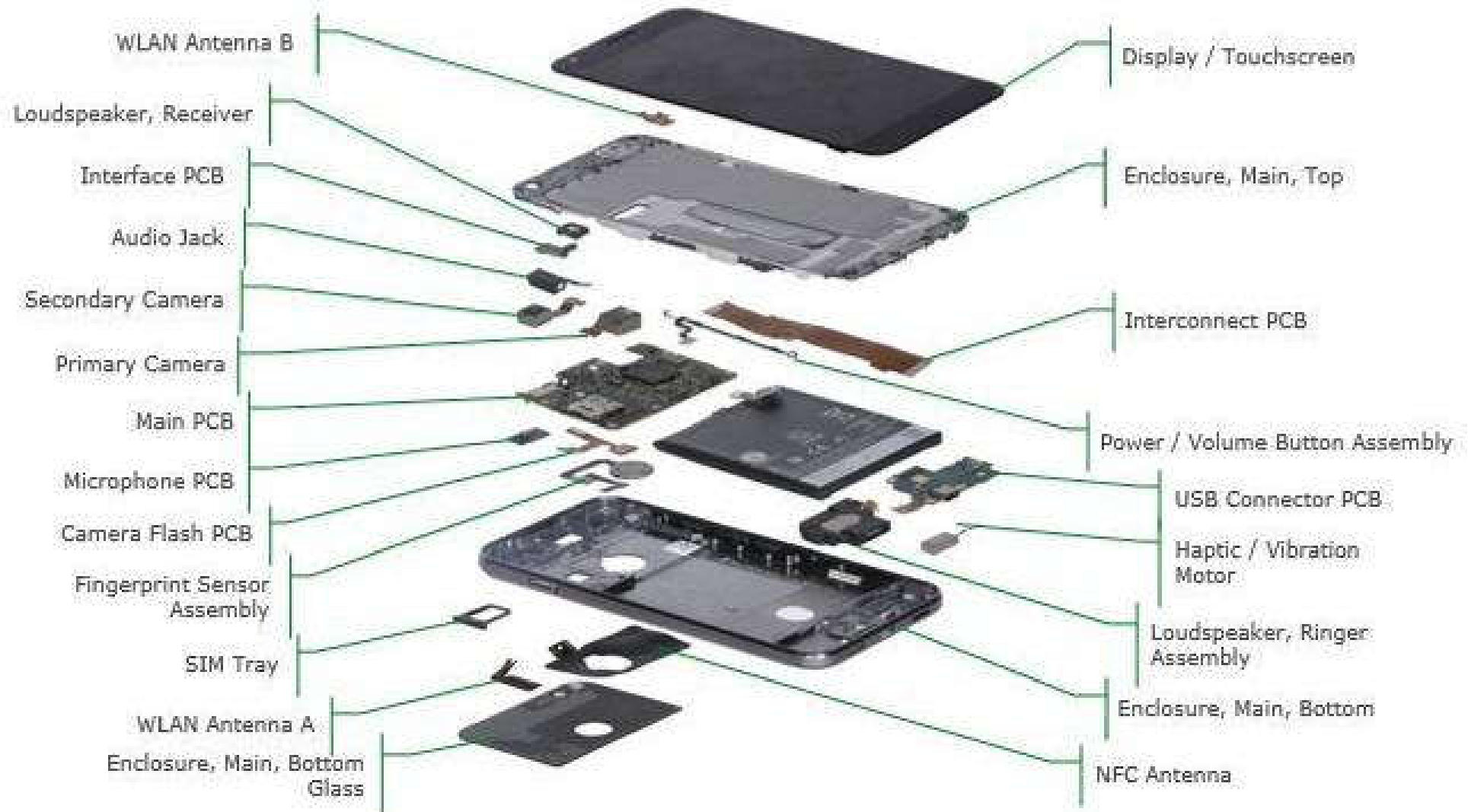
GDP of Thailand: 400 billion \$\$\$



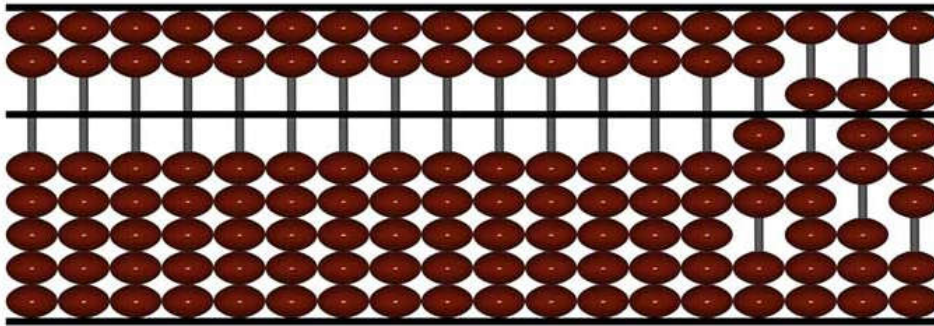
*Covers only the Internet connection portion of systems

Source: IC Insights

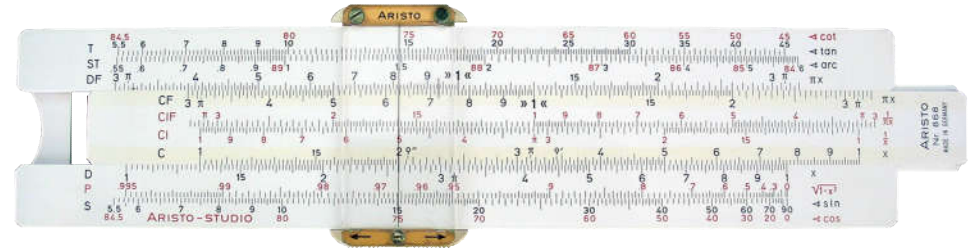
Devices in a Smartphone



Some 'Ancient' Computers



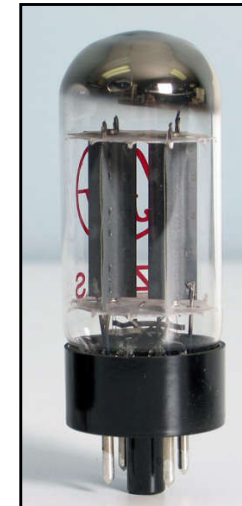
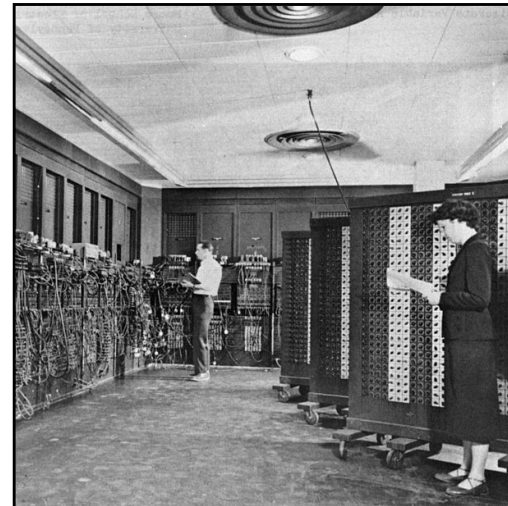
abacus



slide rule

■ First 'electronic' computer

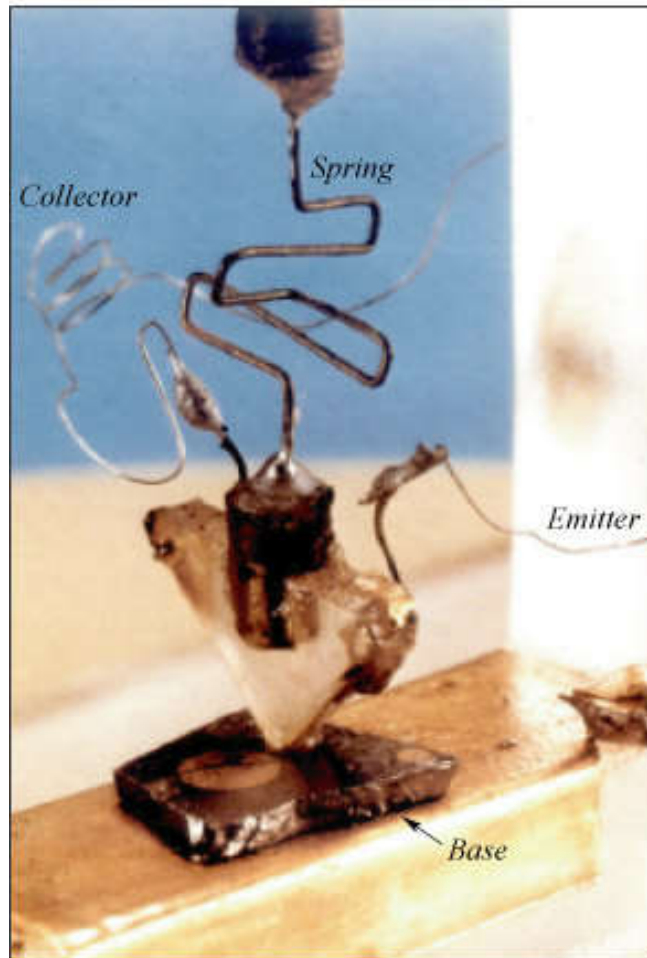
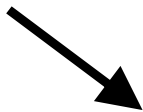
- ❑ ENIAC, 1943
- ❑ 30 tons, 200 kW
- ❑ 18000 vacuum tubes
- ❑ 5000 times/sec
- ❑ cost \$480,000



vacuum tube

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)



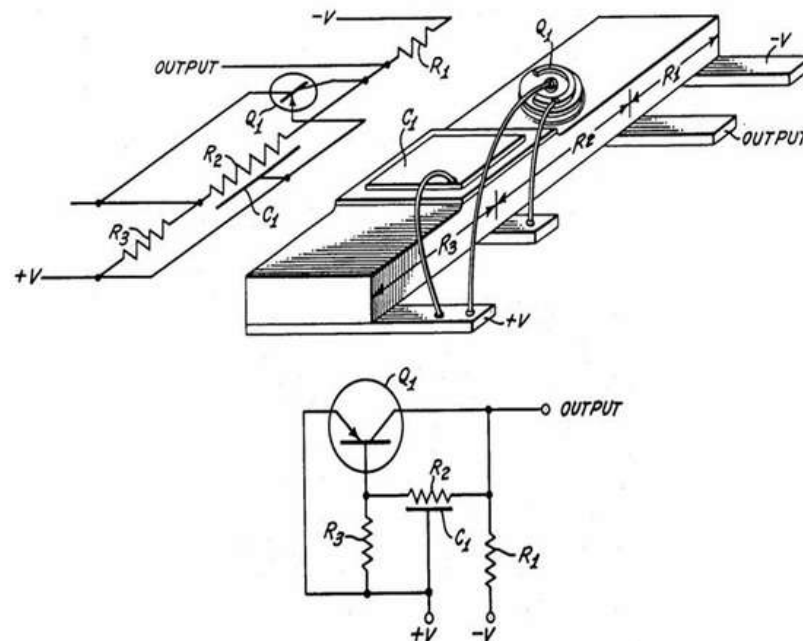
1956 Nobel Prize in Physics

First Integrate Circuits

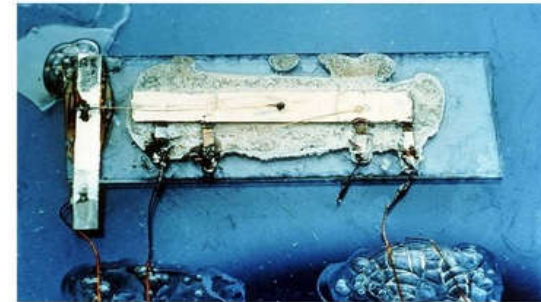
The First (2D) Integrated Circuit

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



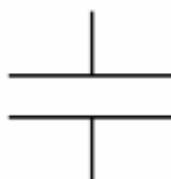
J. Kilby
1923–2005

2000 Nobel Prize in Physics

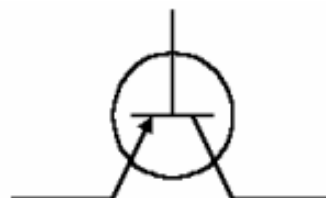
First Integrate Circuits



diode



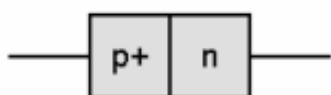
capacitor



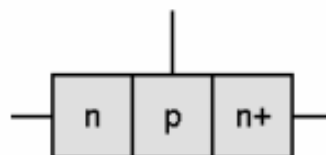
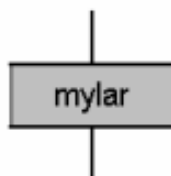
transistor



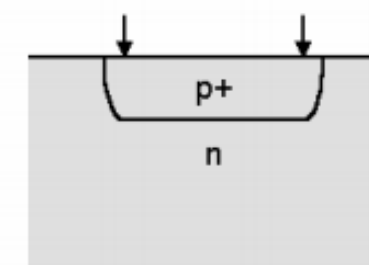
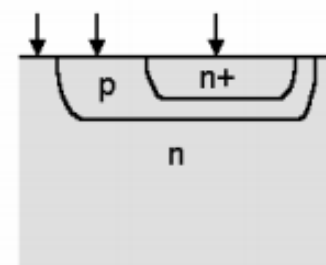
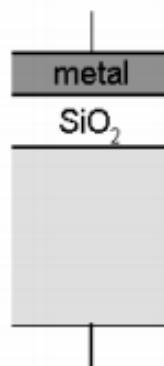
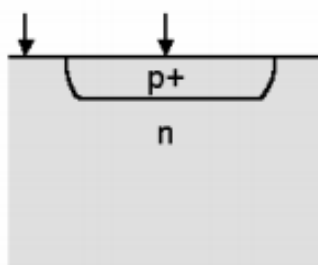
resistor



Si or Ge



Si or Ge



All devices can be made in the same semiconductor!

First Integrate Circuits

"There is plenty 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



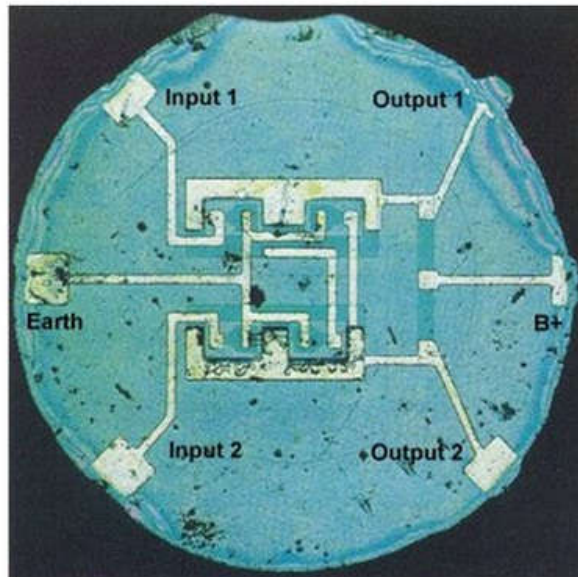
R. Feynman

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

4 transistors



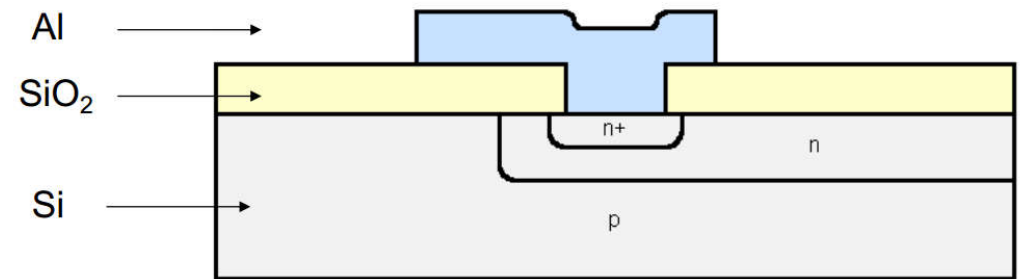
Silicon



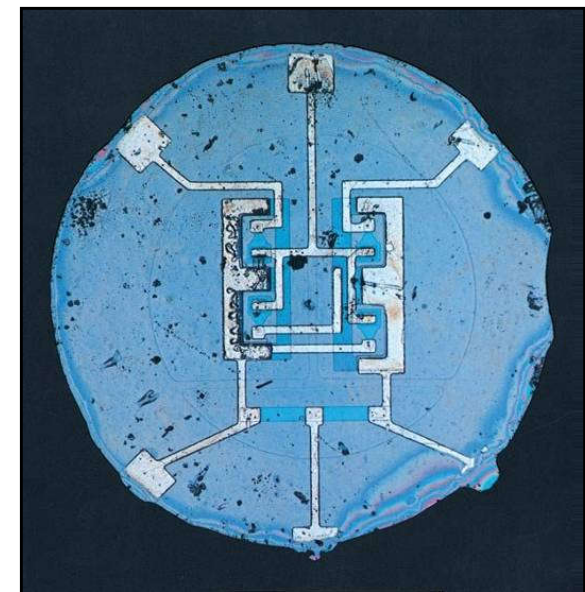
R. Noyce
1927–1990

First Integrate Circuits

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



Explained on board

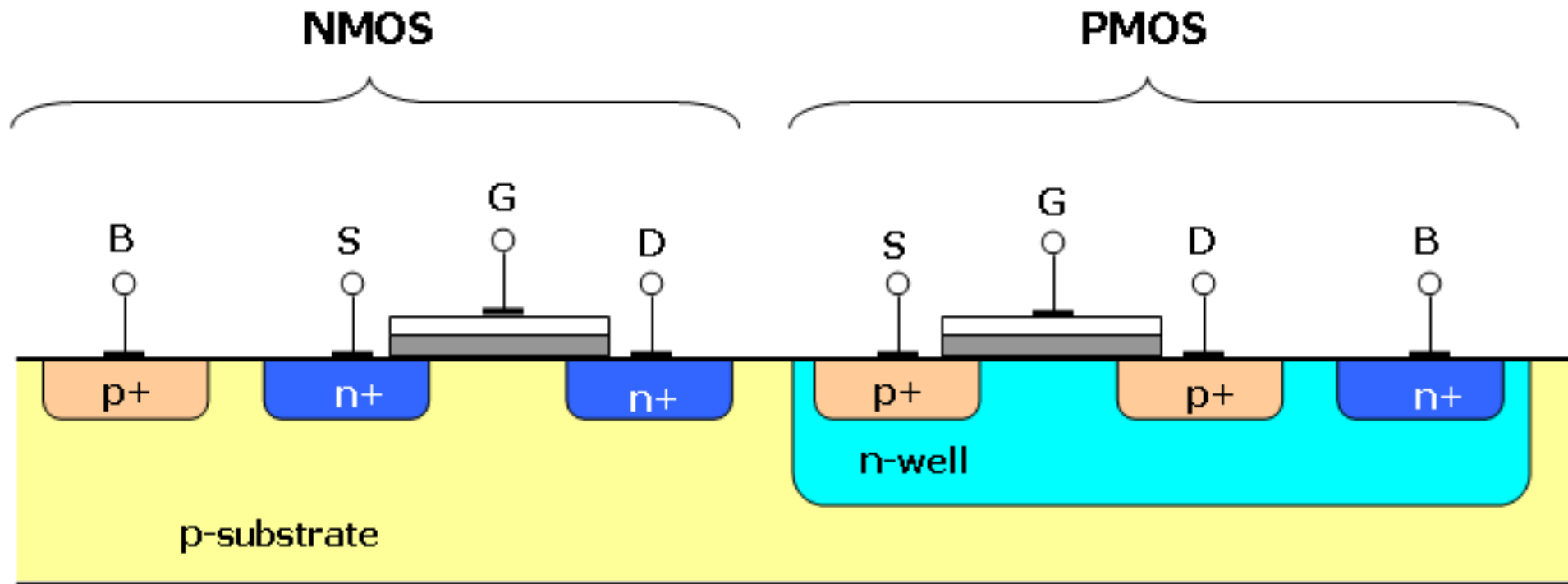


~ 2 mm

Very similar to today's process

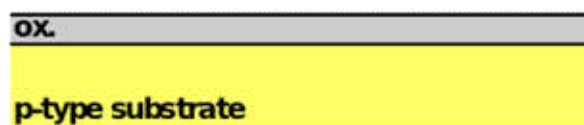
CMOS

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

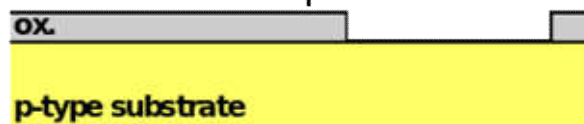


CMOS Process

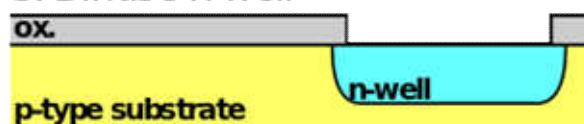
1. Grow field oxide



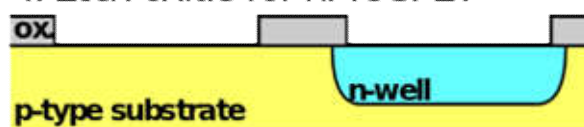
2. Etch oxide for pMOSFET



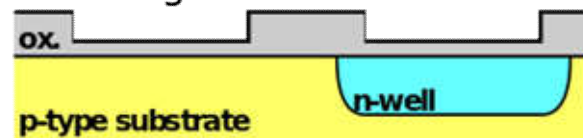
3. Diffuse n-well



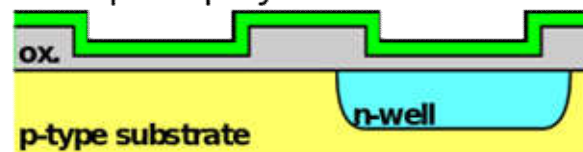
4. Etch oxide for nMOSFET



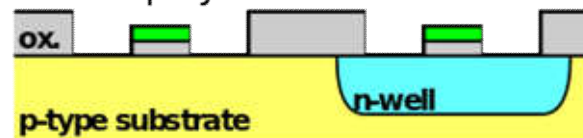
5. Grow gate oxide



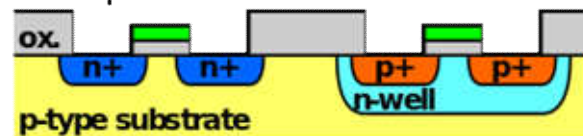
6. Deposit polysilicon



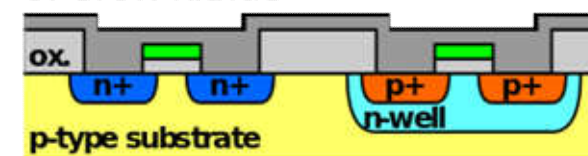
7. Etch polysilicon and oxide



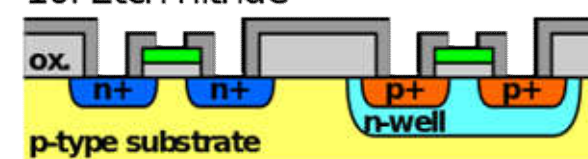
8. Implant sources and drains



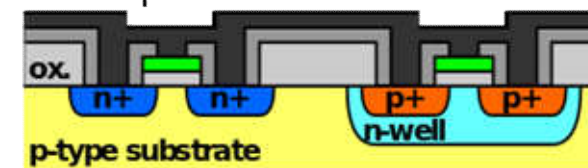
9. Grow nitride



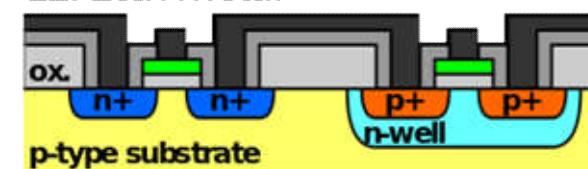
10. Etch nitride



11. Deposit metal

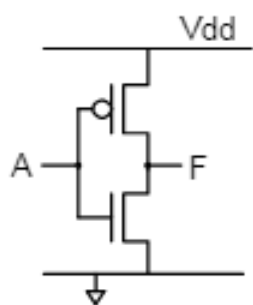


12. Etch metal



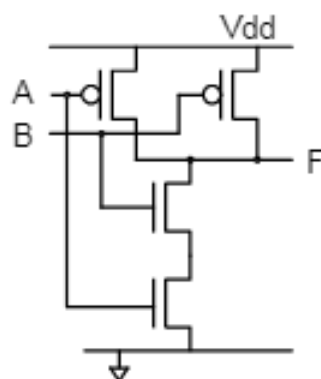
[Video](#)

CMOS Logic



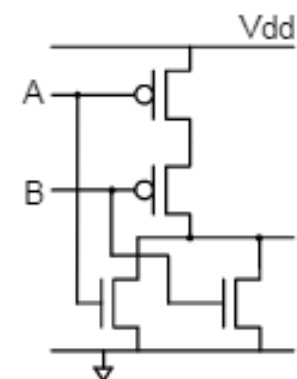
A	F
L	H
H	L

CMOS INVERTER



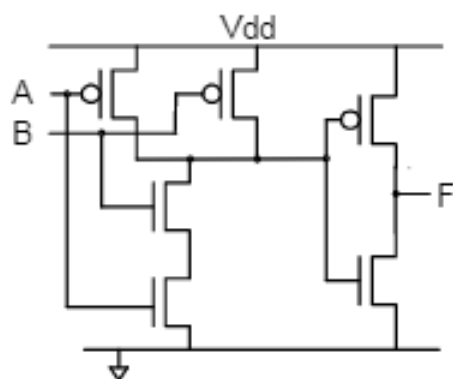
A	B	F
L	L	H
L	H	H
H	L	H
H	H	L

CMOS NAND



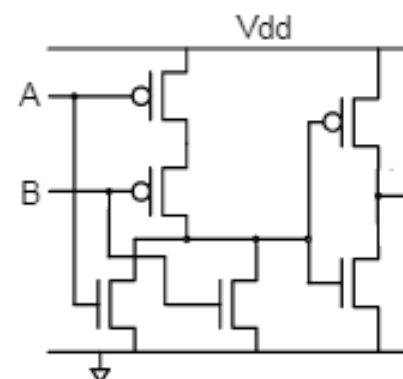
A	B	F
L	L	H
L	H	L
H	L	L
H	H	L

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

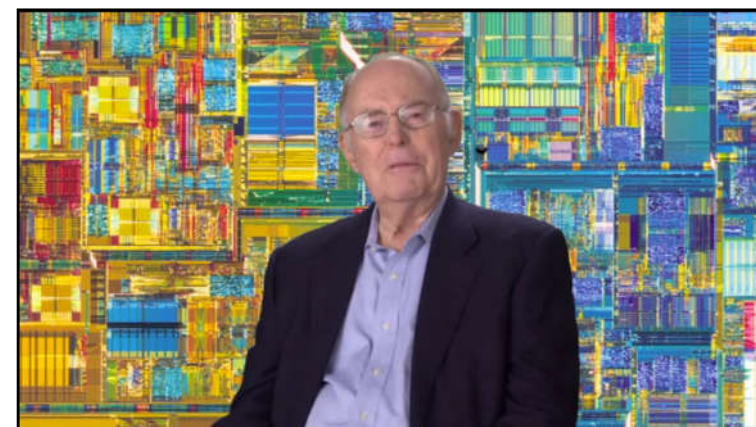
CMOS OR

Integrate Circuits

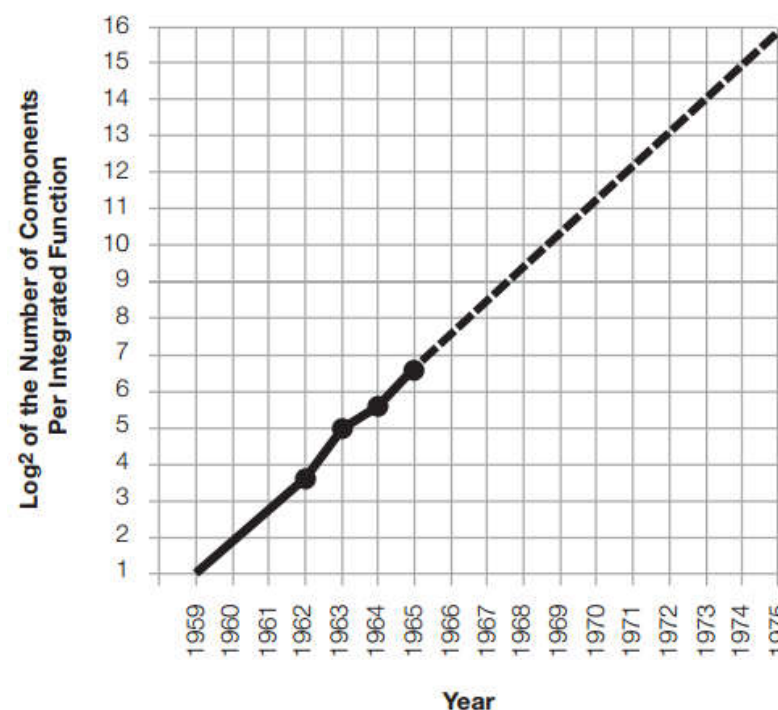
- Moore's law, Fairchild, 1965

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. Moore



Integrate Circuits

- Moore's law, Fairchild, 1965

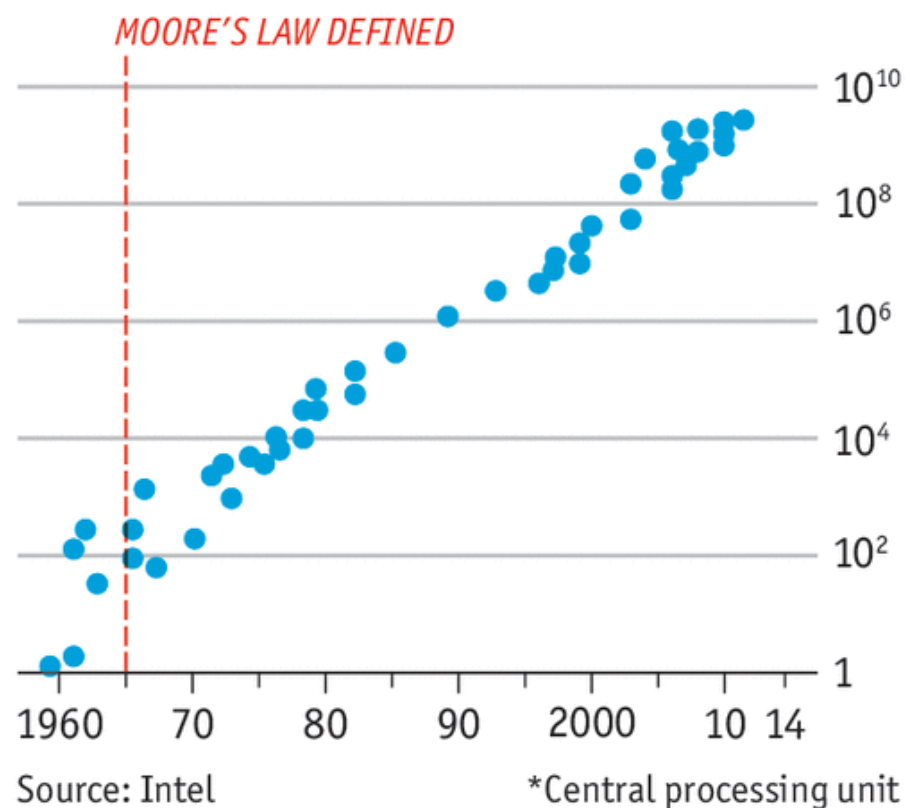


G. Moore



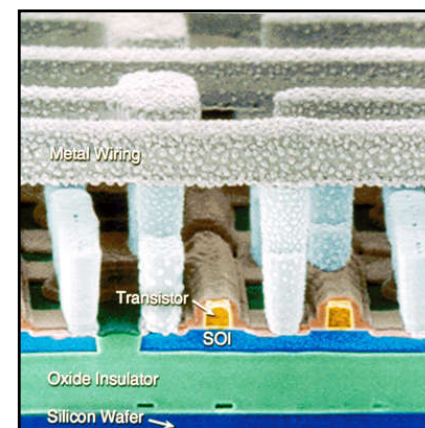
Integrate Circuits

■ Moore's law, Fairchild, 1965

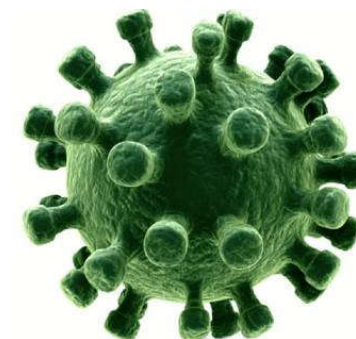


Economist.com

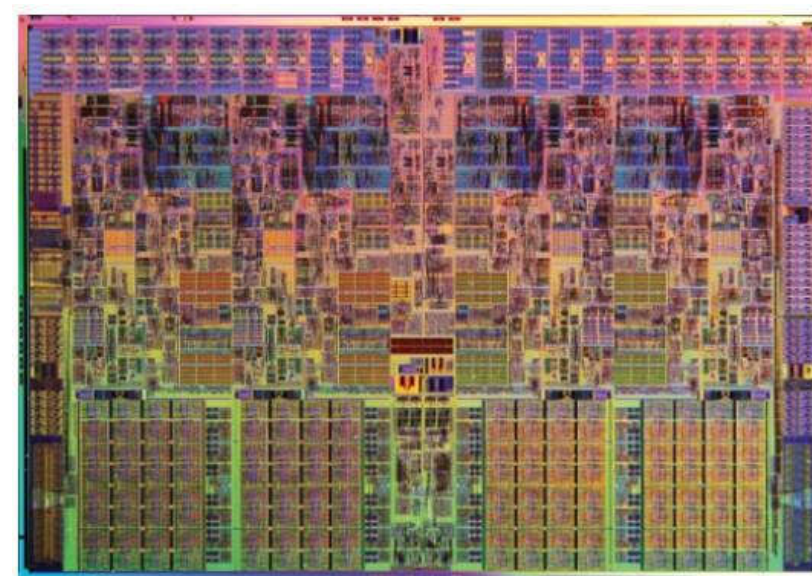
***Modern Electronics is a
real Nanotechnology***



< 100 nm



virus



Intel i7 CPU, ~ 10^9 transistors

Integrate Circuits

**the 10-Megabyte
Computer System**



**Only
\$5995
COMPLETE**

New From IMSAI

- 10-Megabyte Hard Disk
- 5 1/4" Dual-Density Floppy Disk Back-up
- 8-Bit Microprocessor (Optional 16-bit Microprocessor)
- Memory-Mapped Video Display Board
- Disk Controller
- Standard 64K RAM (Optional 256K RAM)
- 10-Slot S-100 Motherboard
- 28-Amp Power Supply
- 12" Monitor
- Standard Intelligent 82-Key ASCII Keyboard (Optional Intelligent 88-Key ASCII Extended Keyboard)
- 100-Column Dot-Matrix Printer
- CP/M[®] Operating System

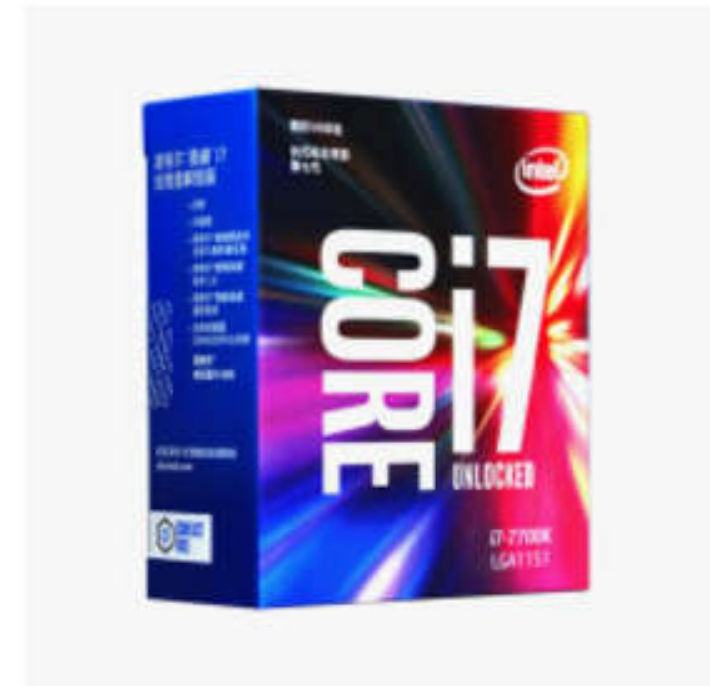
*You Read It Right —
All for \$5995!*

IMSAI ... Thinking ahead for the 80's

415/635-7615 Computer Division of The Farnsworth Corporation
910 81st Avenue, Bldg. 14 • Oakland, CA 94621

CP/M is a trademark of Digital Research. Intel is a trademark of The Farnsworth Corporation.

1980s



¥2549.00

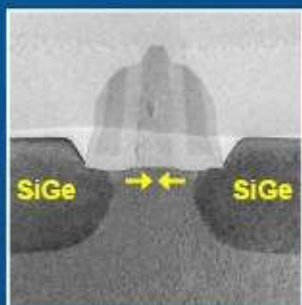
英特尔 (Intel) 酷睿四核 i7-7700k 盒装

CPU处理器 采用KabyLake架构, LGA 1151

2017, price > gold

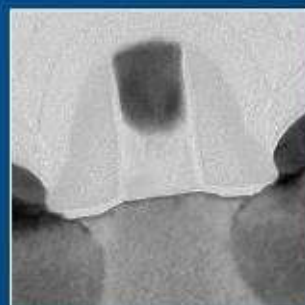
Transistor Evolution

2003
90 nm



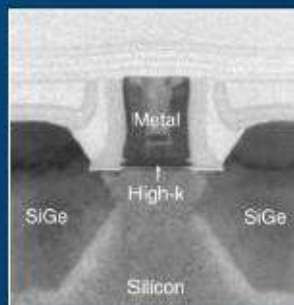
SiGe
Strained Silicon

2005
65 nm



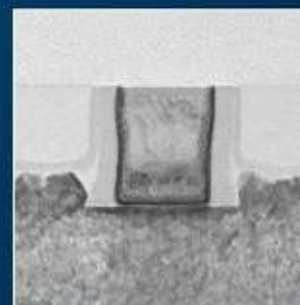
2nd Gen. SiGe
Strained Silicon

2007
45 nm



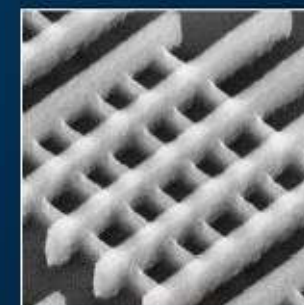
Gate-Last
High-k
Metal Gate

2009
32 nm



2nd Gen.
Gate-Last
High-k
Metal Gate

2011
22 nm



Tri-Gate

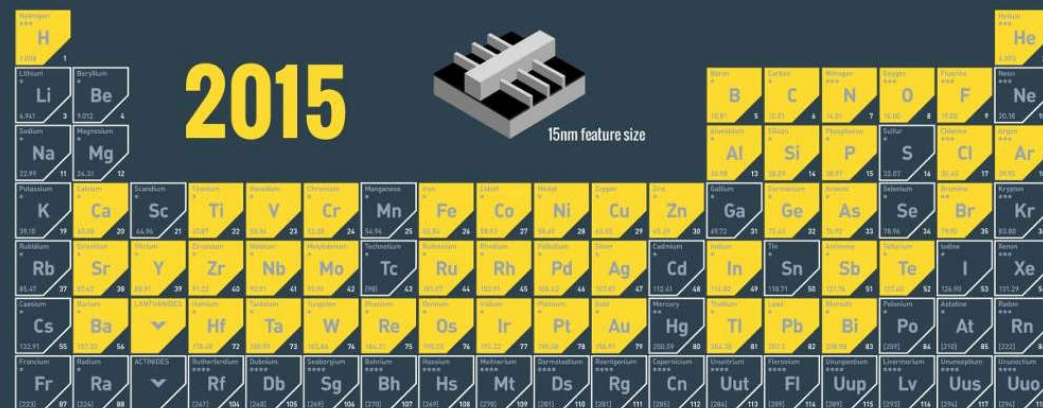
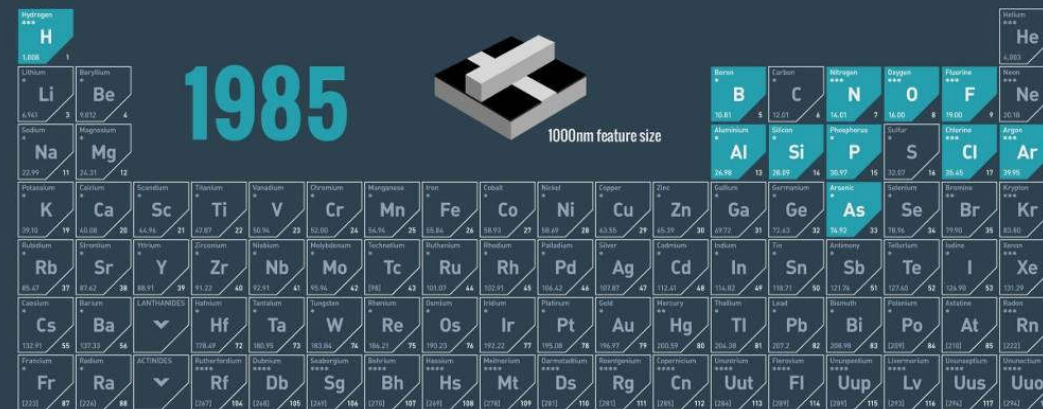
Strained Silicon

High-k Metal Gate

Tri-Gate

Materials in IC

In the 1980s, the typical semiconductor used only a fraction of the primary elements.
Today, six times as many elements are used - more than half of the periodic table.



Source: Intel, SanDisk, Intermolecular

Modern IC foundry

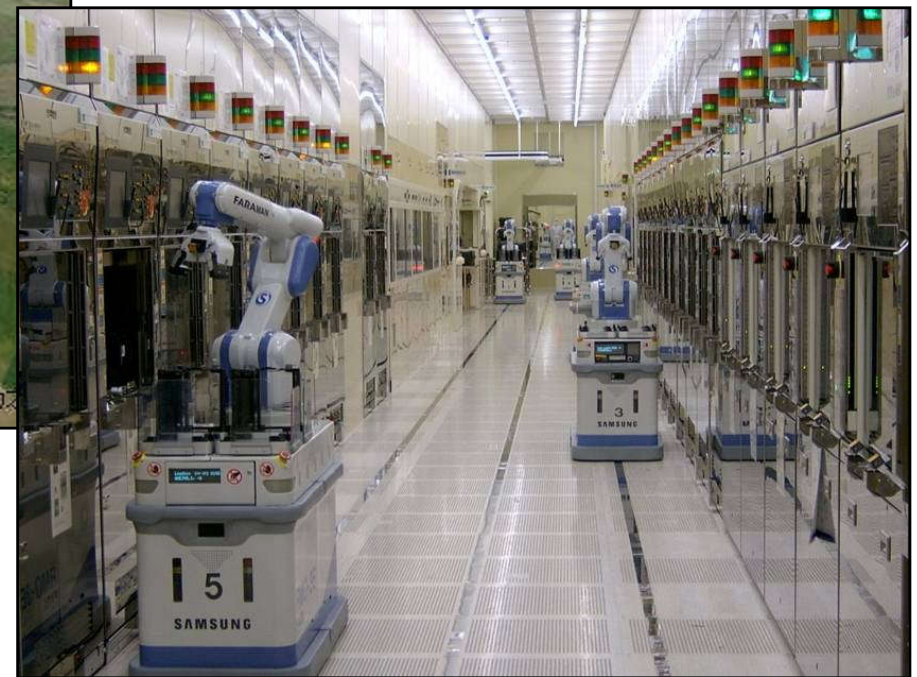
[Video 1](#)

[Video 2](#) Intel



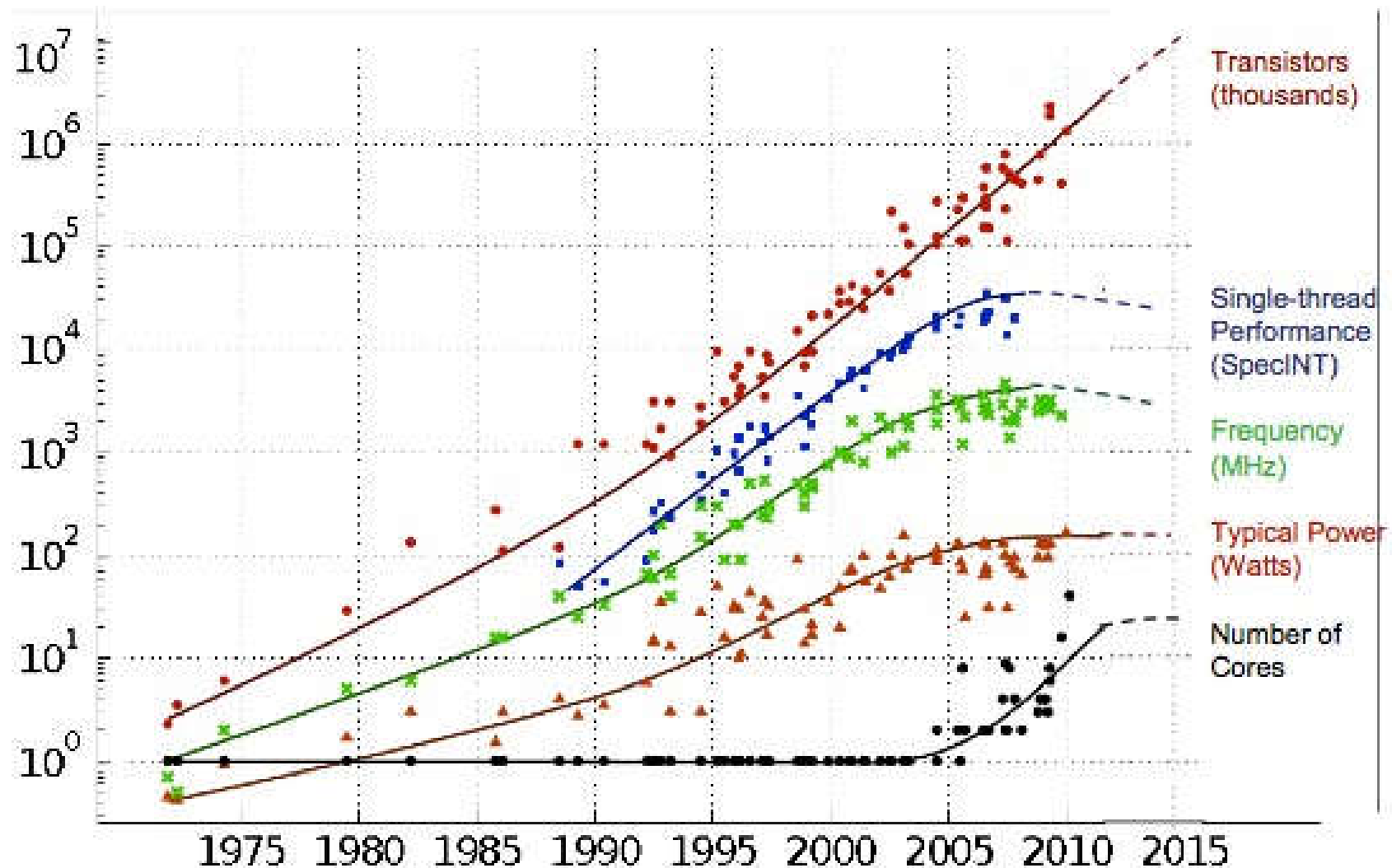
Global Foundries

Cost > 10 billion \$\$\$



Samsung

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

All Good Things Come to an End

144 | NATURE | VOL 530 | 11 FEBRUARY 2016
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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.

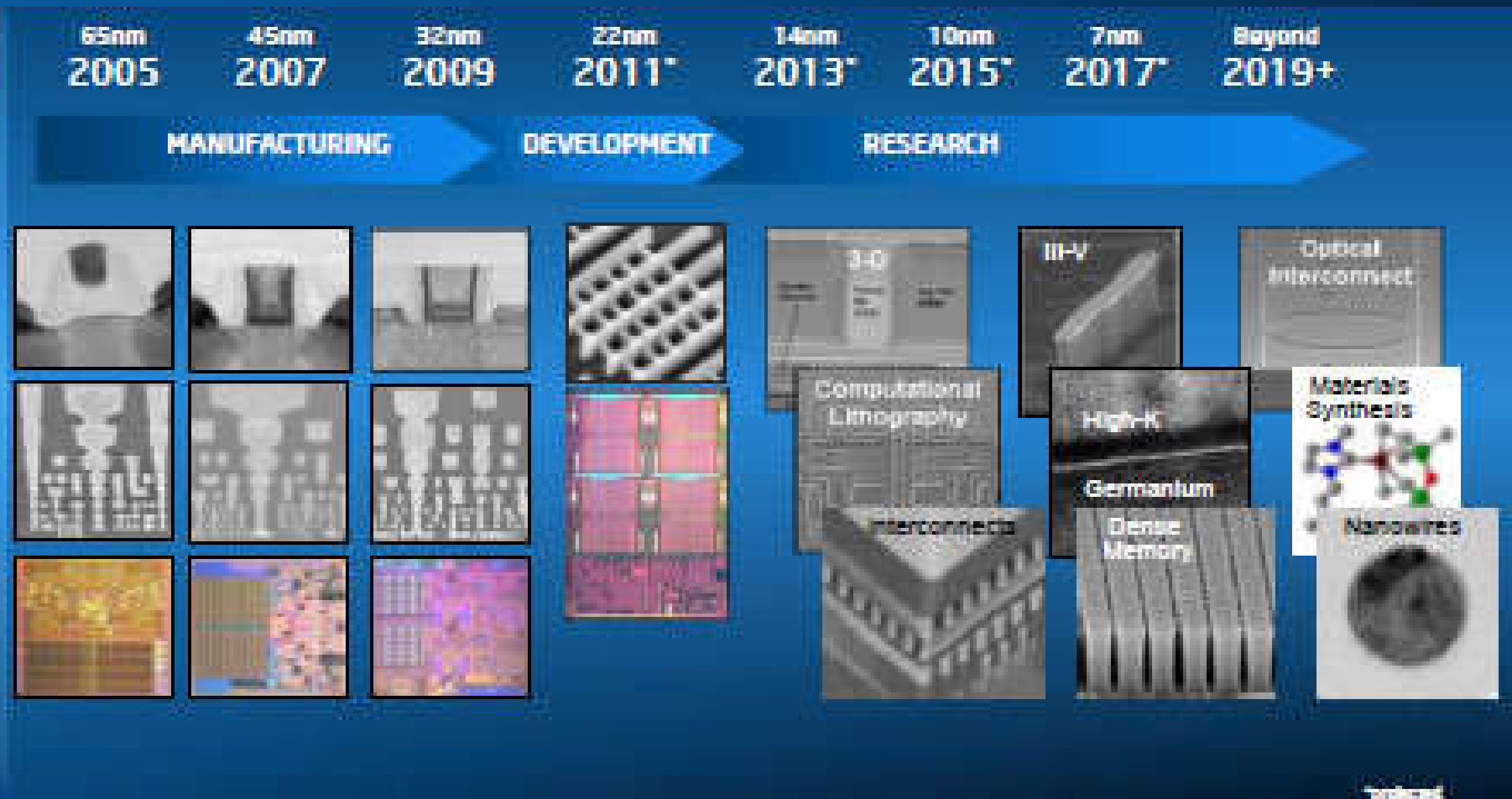
Everyone agrees that the twilight of Moore's law will not mean the end of progress. "Think about what happened to airplanes," says Reed. "A Boeing 787 doesn't go any faster than a 707 did in the 1950s — but they are very different airplanes", with innovations ranging from fully electronic controls to 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 essay¹ 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

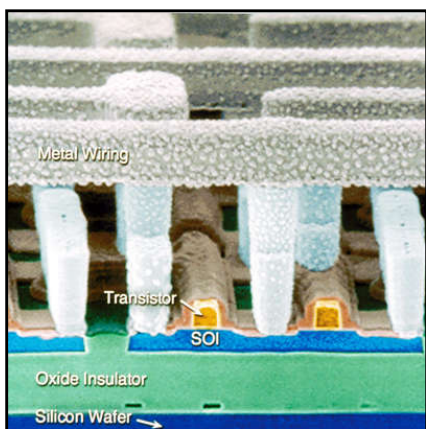
M. M. Waldrop, *Nature* **530**, 144 (2016)

New Opportunities

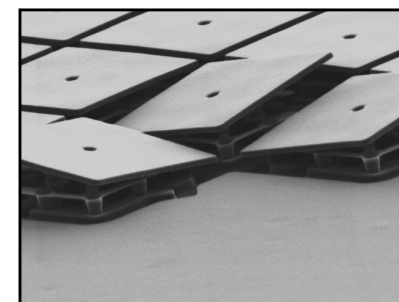
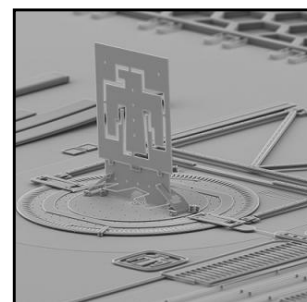
We Expect Technology Innovation to Continue



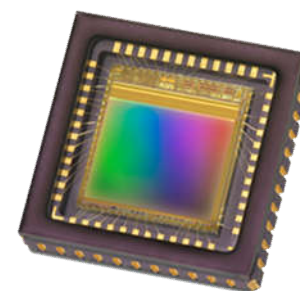
New Devices and Applications



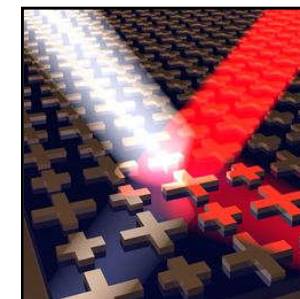
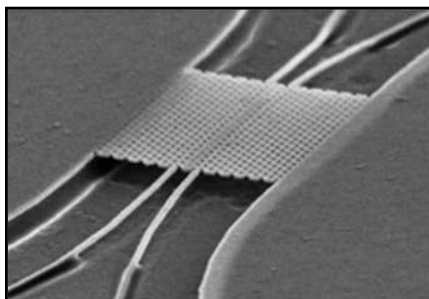
Microelectronics



Microelectromechanical Systems (MEMS)



Optoelectronics



Micro and Nano Photonics

Image Sensors



films

Anatomy of the Active Pixel Sensor Photodiode

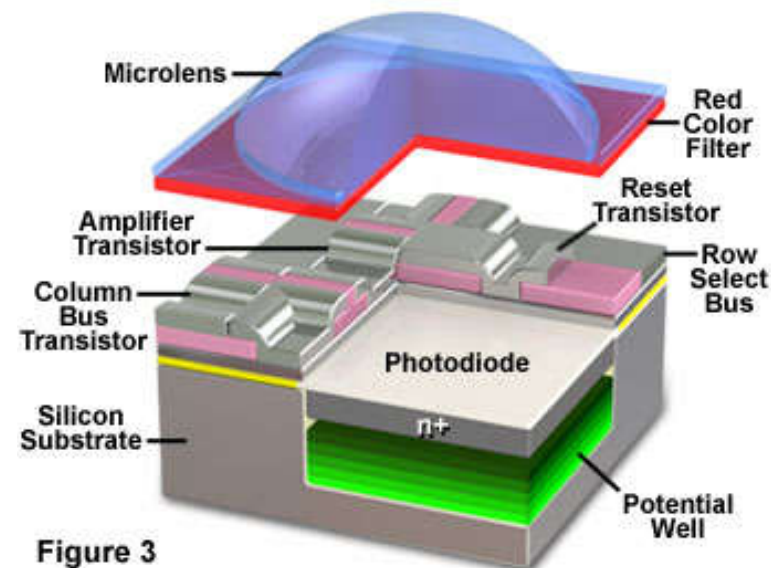
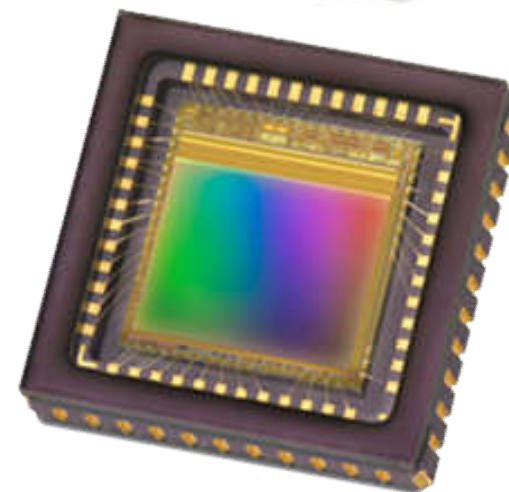
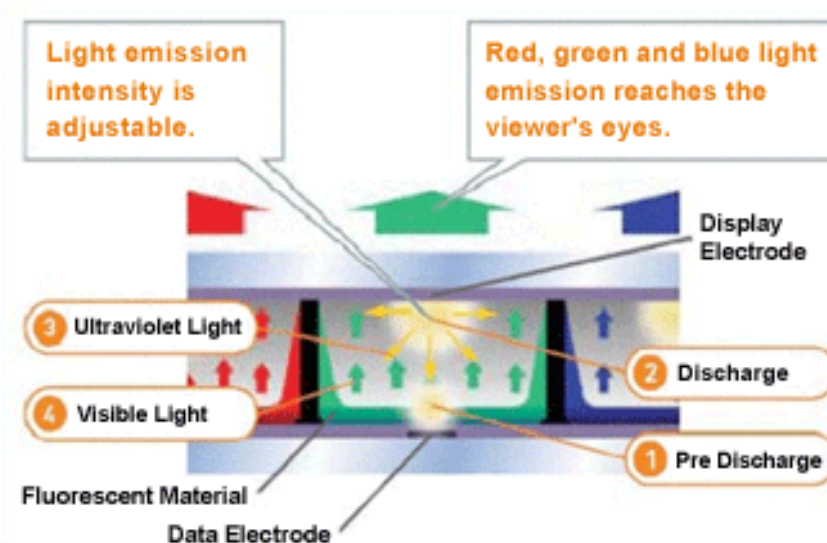
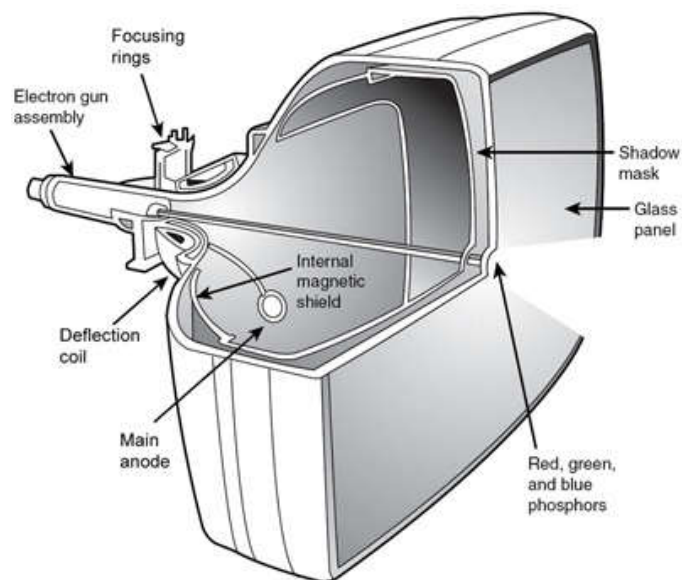


Figure 3



CMOS sensors

Displays



CRT

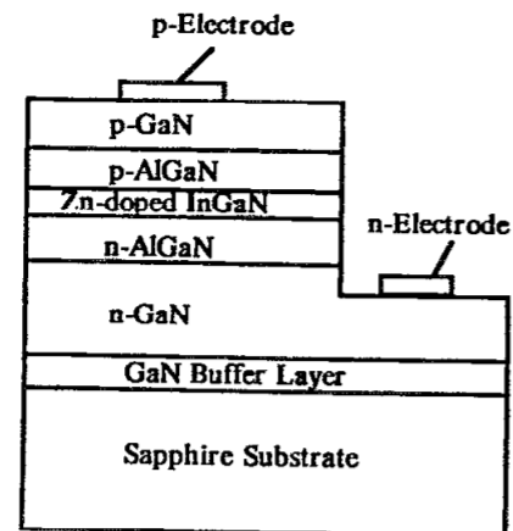


Flat panel

Light Sources



Incandescent bulb



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



Fluorescent lamp



LEDs

Gallium Nitride (GaN) LED

- GaN LED on sapphire

- 日本, Nichia
- 2014 Nobel Prize in Physics



I. Akasaki



H. Amano



S. Nakamura

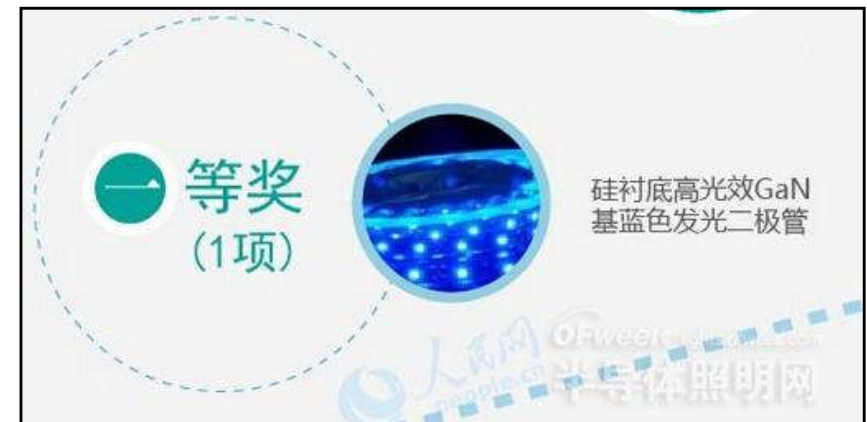
- GaN LED on silicon carbide (SiC)

- USA, Cree



- GaN LED on silicon

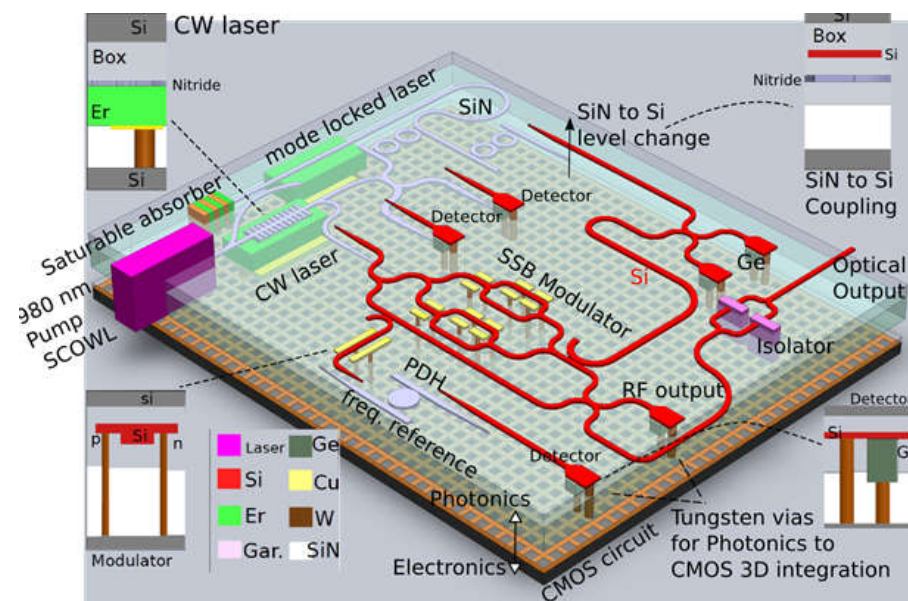
- 中国, 南昌大学
- 2015年中国技术发明一等奖



Integrated Photonic Circuits



Conventional optics

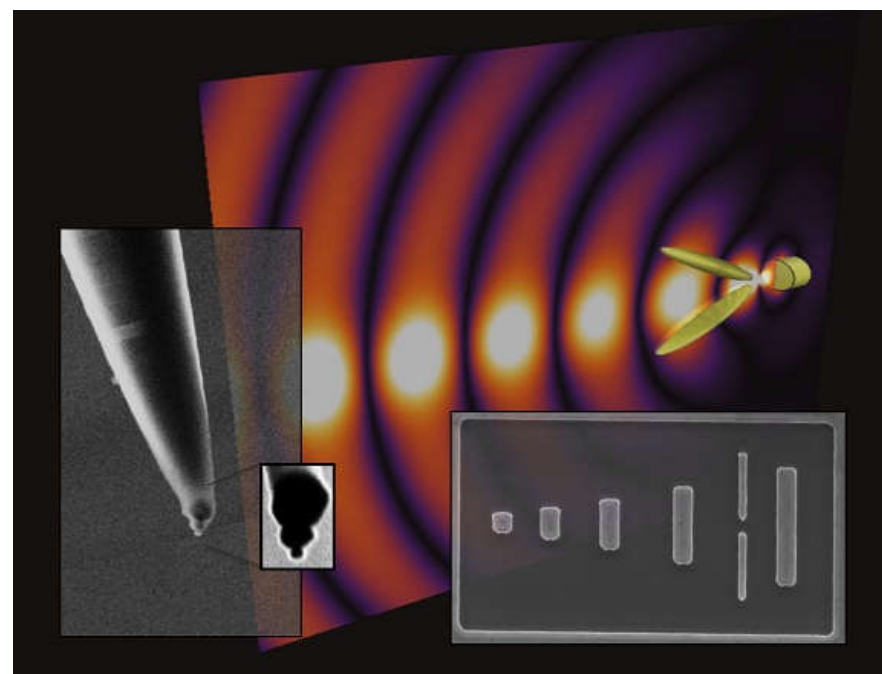
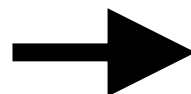


Integrated photonics

Integrated Photonic Circuits



Microwave Antenna



Optical Antenna

Thank you for your attention