Fundamentals of Solid State Physics

Introduction

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Goal of This Course

- Study the foundations of our world: solid materials
  - electronic, optical, magnetic, thermal, mechanical, ...
- Based on theories of physics
  - classical mechanics
  - electrodynamics
  - quantum mechanics
  - statistical mechanics
  - ...
- Emerging applications: semiconductors, lasers, ...

Goal of This Course

- Main Focus: Electrons

Department of Electronic Engineering

电子工程系

- Other topics: Photons, Phonons, Magnetics, ...

What is Unique?

- Programming (程序)
- Circuits (电路)
- Data and Algorithm (数据与算法)
- Signals and Systems (信号与系统)
- Probability (概率)
- Digital Logics (数字逻辑)
- Communications (通信)
- Media and Cognition (媒体与认知)
- Electromagnetism (电磁场)
- Solid State Physics (固体物理)

10 core courses in EE department

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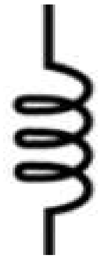
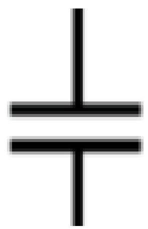
$$v = iR$$

$$v = L\frac{di}{dt}$$



$$i = C\frac{dv}{dt}$$



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$$\nabla \cdot \mathbf{D} = \rho_V$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

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maths,
engineering,
application,
design,
model,
perfect,
...

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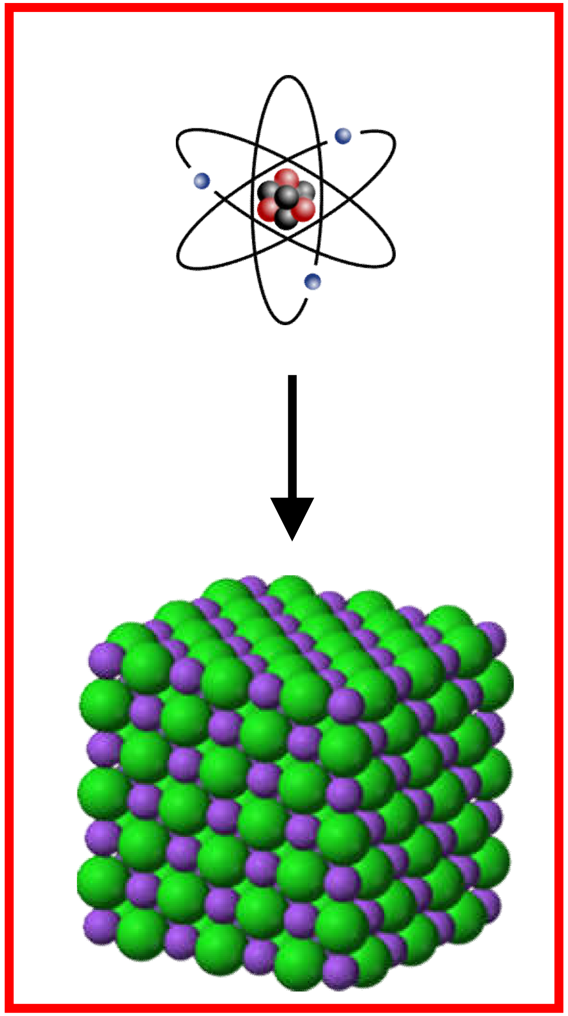

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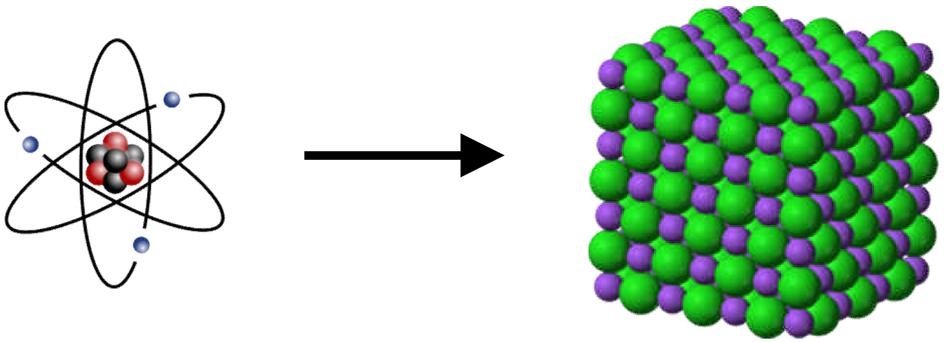
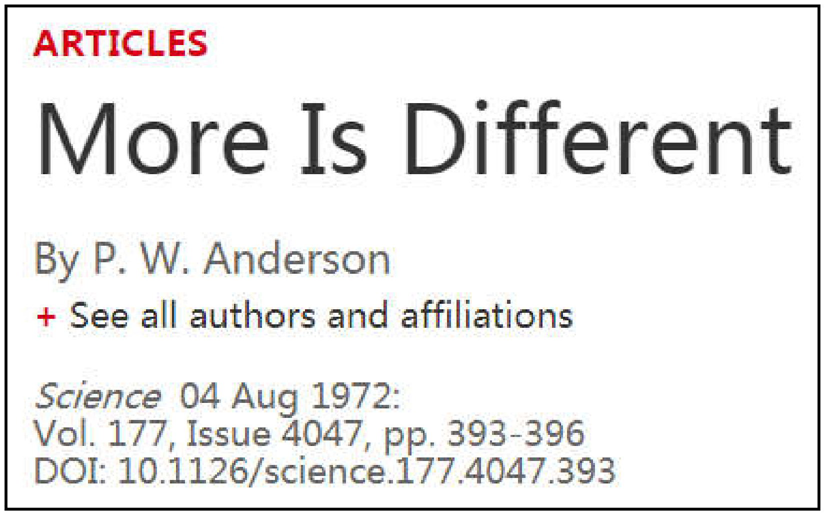
observation,
discovery,
understanding,
approximation,
modified theory,
imperfection,
...

Solid is very Complex

- **If we understand the basic physics of all the fundamental particles (electrons, photons, atoms, ...), can we understand everything?**

No!




ARTICLES

More Is Different

By P. W. Anderson

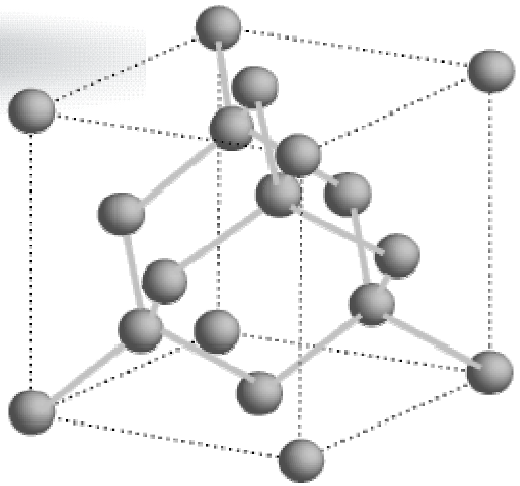
+ See all authors and affiliations

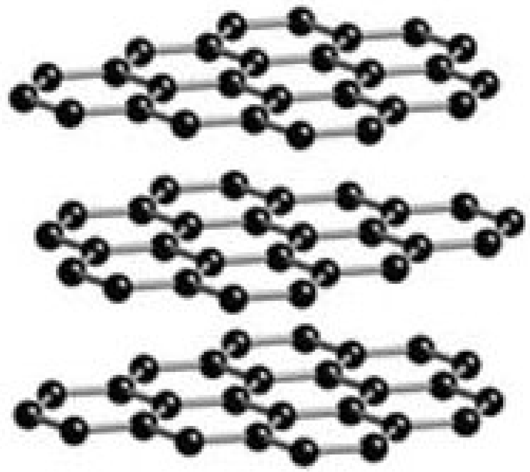
Science 04 Aug 1972:
Vol. 177, Issue 4047, pp. 393-396
DOI: 10.1126/science.177.4047.393

Philip W. Anderson
1923–2020

Example: Carbon

- Diamond 金刚石
  - hard
  - insulating
  - transparent
- Graphite 石墨
  - soft
  - conductive
  - black

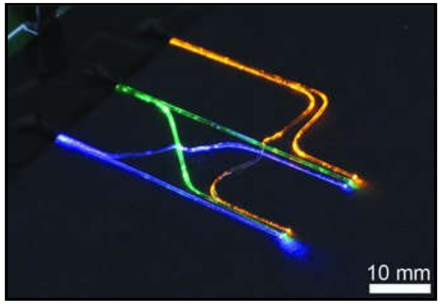




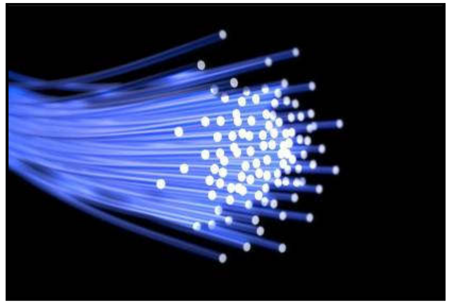
Optical and Electronic Devices

LEDs

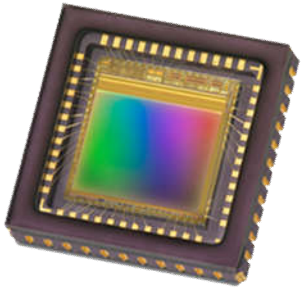
lasers



waveguides

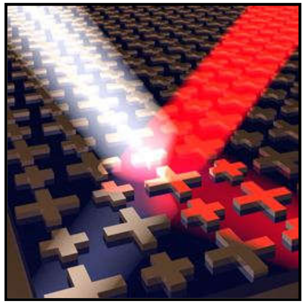


fibers

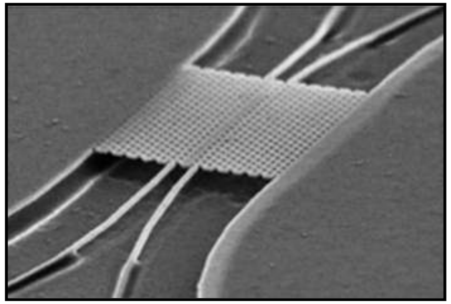


detectors

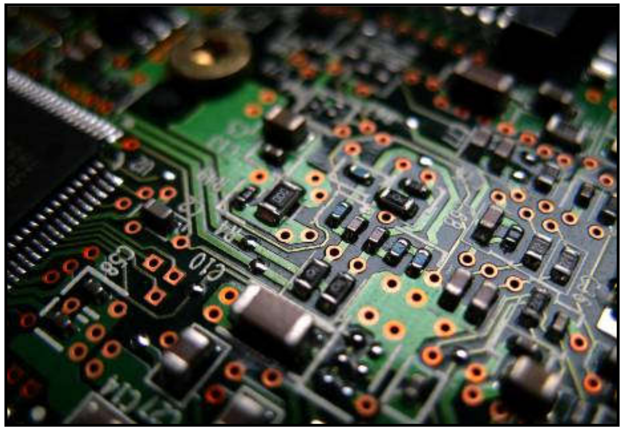
solar cells



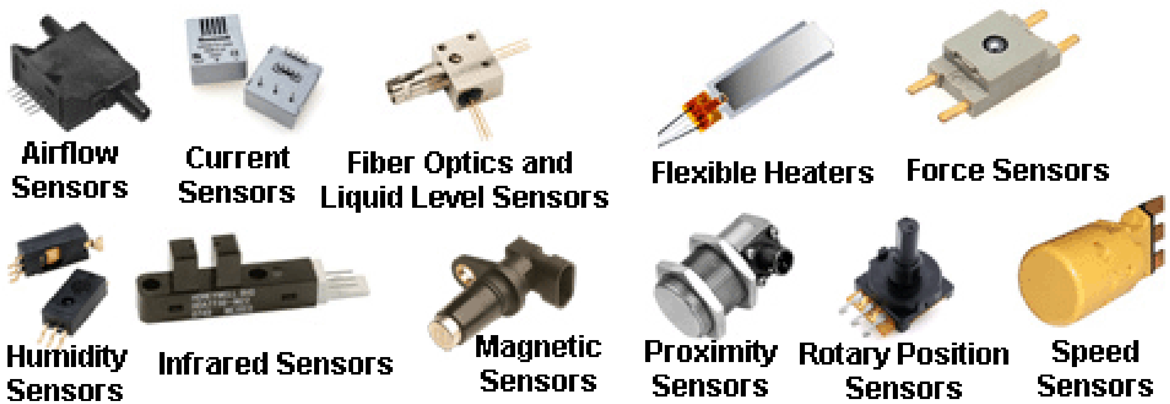
metamaterials



photonic crystals



integrated circuits



Nobel Prizes in Solid-State Physics

- Before 1950s
  - atoms, materials, radiation, quantum mechanics, ...
- 1956 Semiconductor transistors
- 1991 Liquid crystals
- 2000 Integrated circuits
- 2009 CCD imaging sensors
- 2009 Optical fibers
- 2014 GaN based blue LEDs

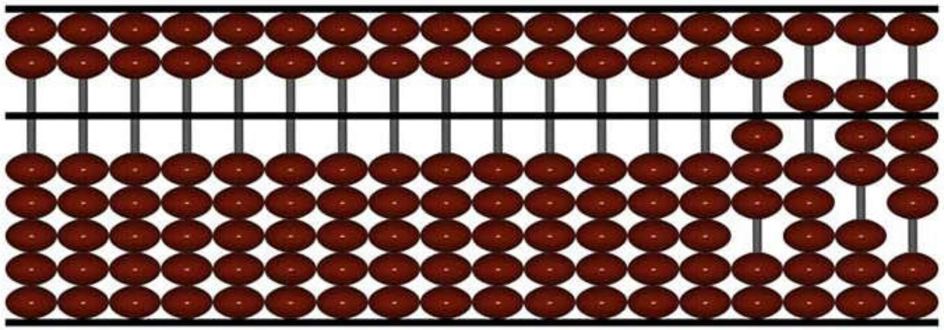
'Disruptive' Technologies 颠覆性技术

- Before 1950s
  - atoms, materials, radiation, quantum mechanics, ...
- 1956 Semiconductor transistors ← vacuum tubes
- 1991 Liquid crystals ← CRT displays
- 2000 Integrated circuits ← Computation
- 2009 CCD imaging sensors ← film cameras
- 2009 Optical fibers ← copper cables
- 2014 GaN based blue LEDs ← incandescent light bulbs

Devices in a Smartphone

	Nobel Prize
Transistors	1956
Liquid crystals	1991
Integrated circuits	2000
Semiconductor heterostructures	2000
CCD cameras	2009
GaN blue LEDs	2014
Li ion batteries	2019 (Chemistry)

Computation

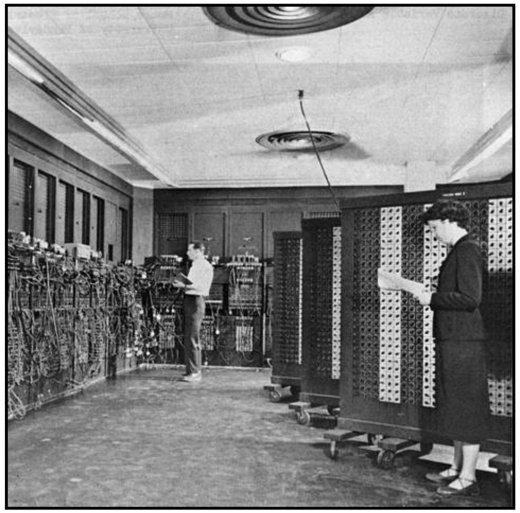


abacus

slide rule

- Ancient computers

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



vacuum tube

Transistors

Germanium
Bipolar Transistor

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

semiconductors

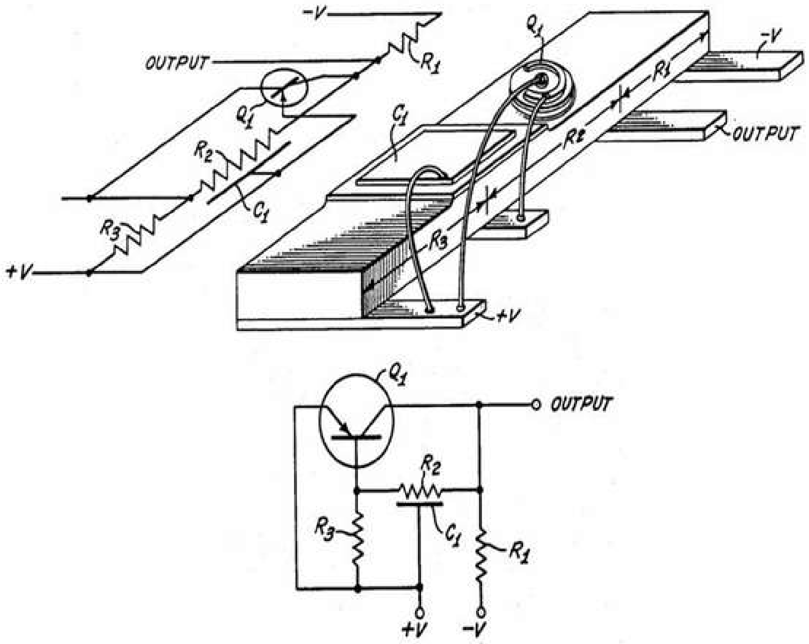
1956 Nobel Prize in Physics

First Integrated Circuits

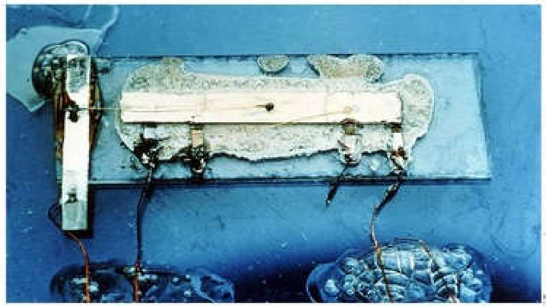
The First (2D) Integrated Circuit
Jack Kilby, Texas Instruments, 1958

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

→ Low connectivity between components



Germanium

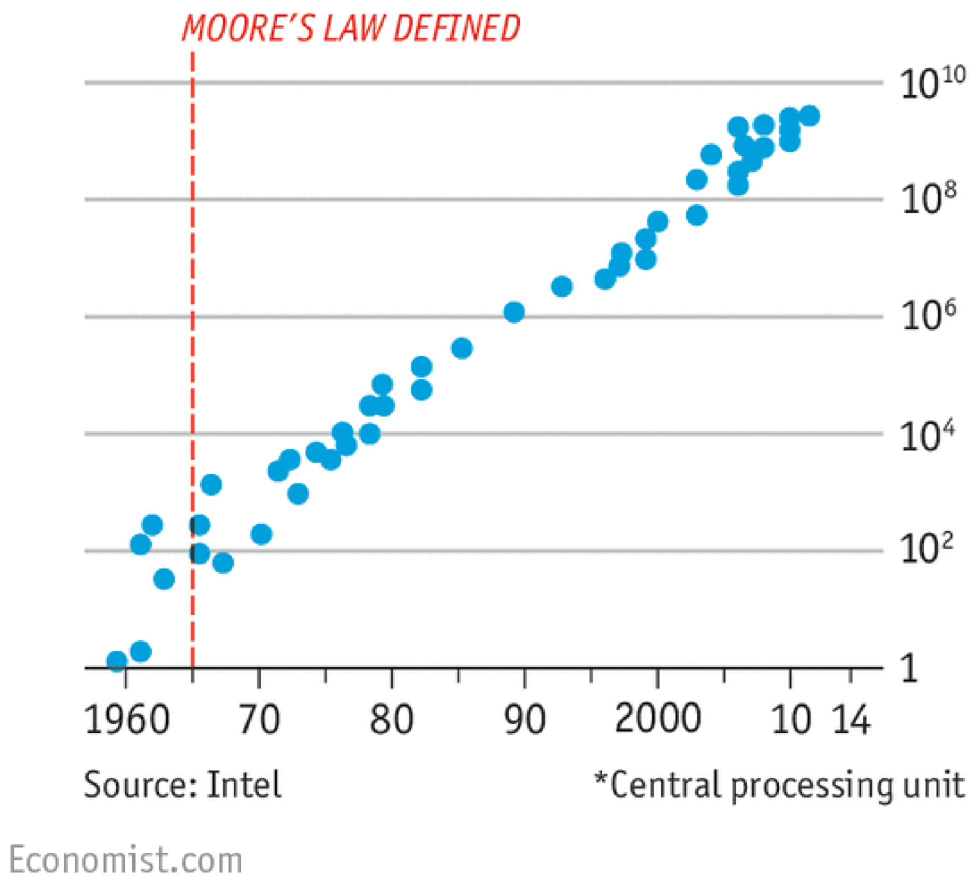


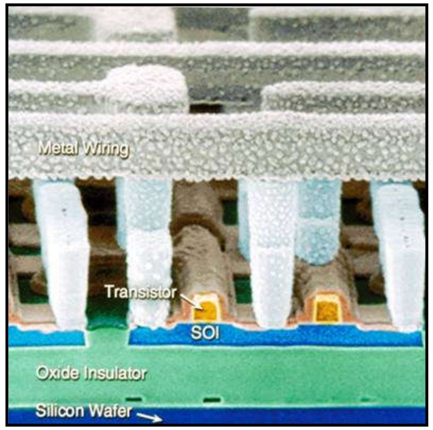
J. Kilby

2000 Nobel Prize in Physics

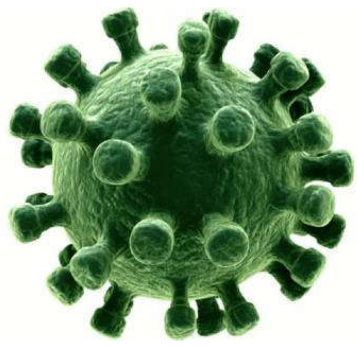
Modern Integrated Circuits

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

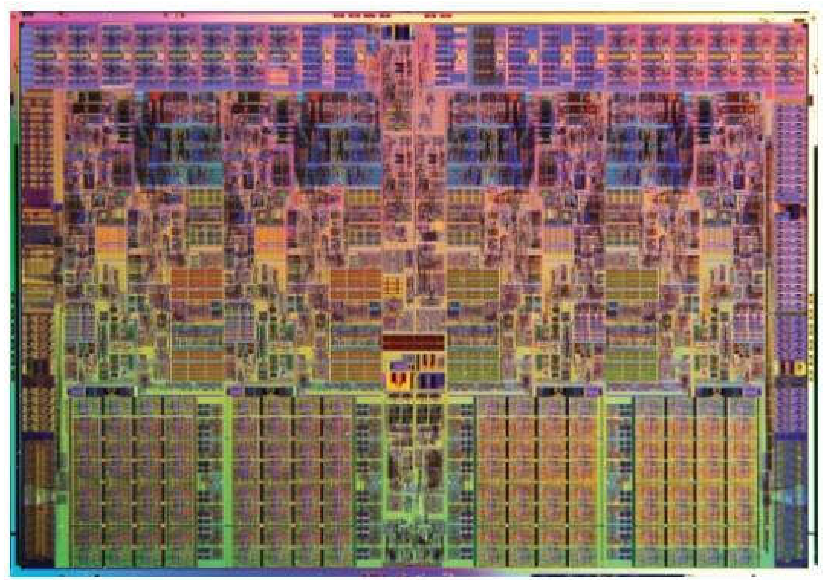




< 100 nm



coronavirus



Modern Electronics is a real Nanotechnology

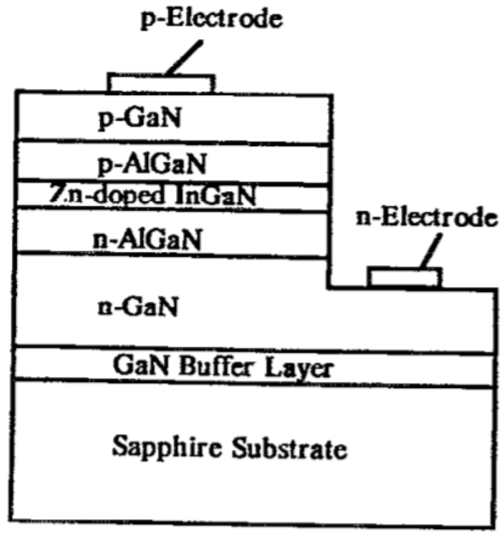
Intel i7 CPU, ~ 10^9 transistors

Lighting

Incandescent bulb

Fluorescent lamp

GaN blue LEDs



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

I. Akasaki

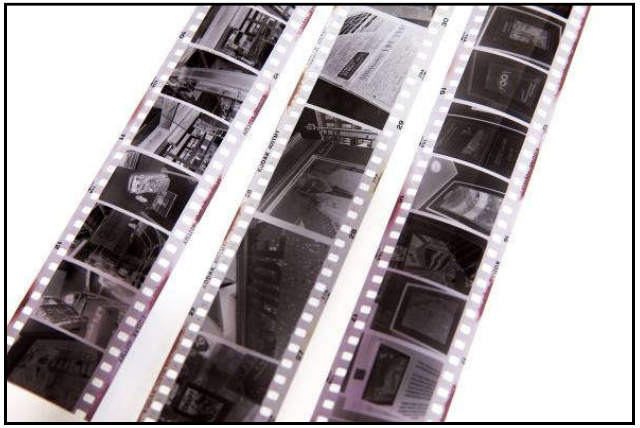
H. Amano

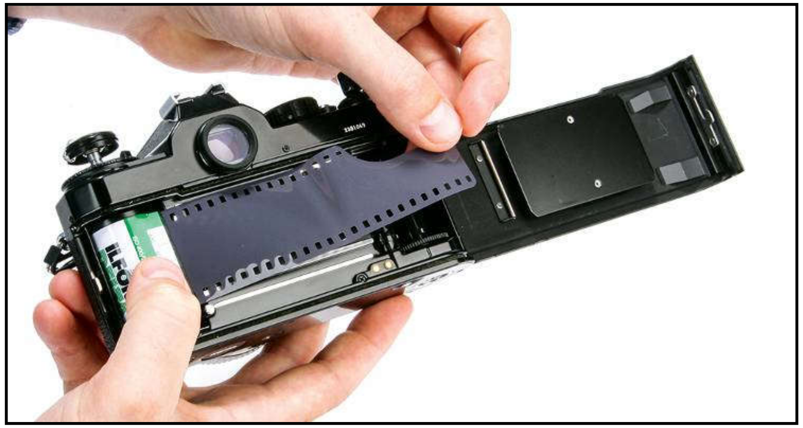
S. Nakamura

2014 Nobel Prize in Physics

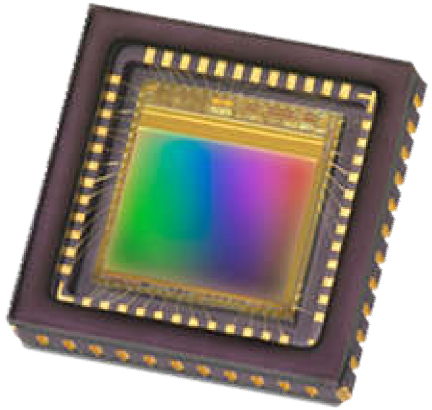
Imaging

CCD and CMOS cameras





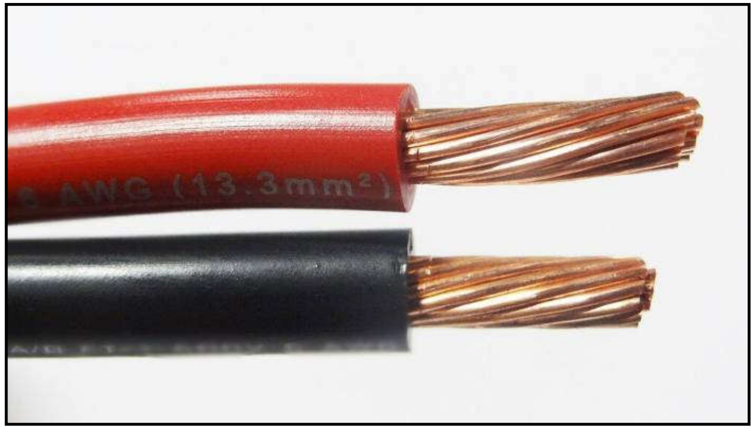
films



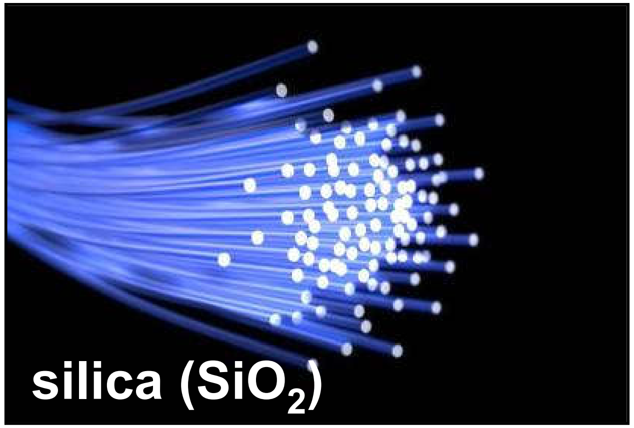
W. Boyle and G. Smith

2009 Nobel Prize in Physics

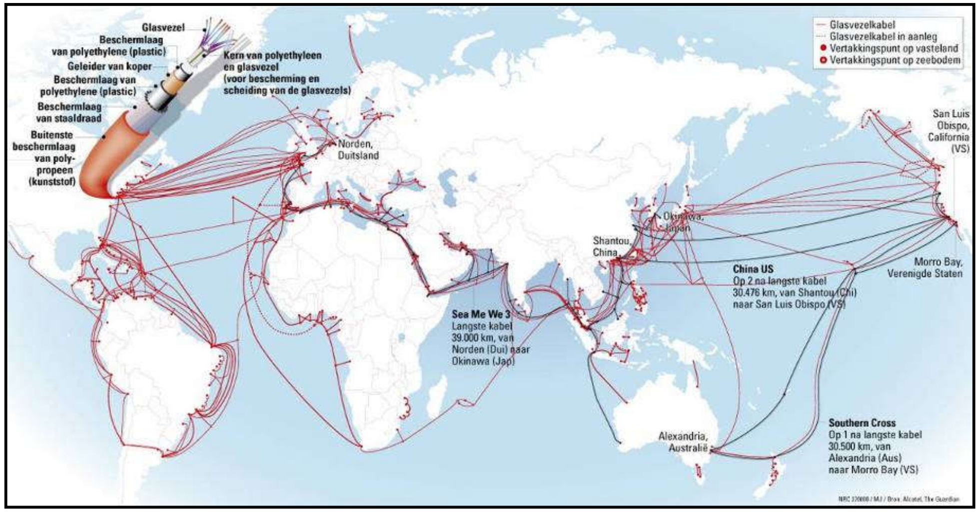
Communication



copper cables



optical fibers

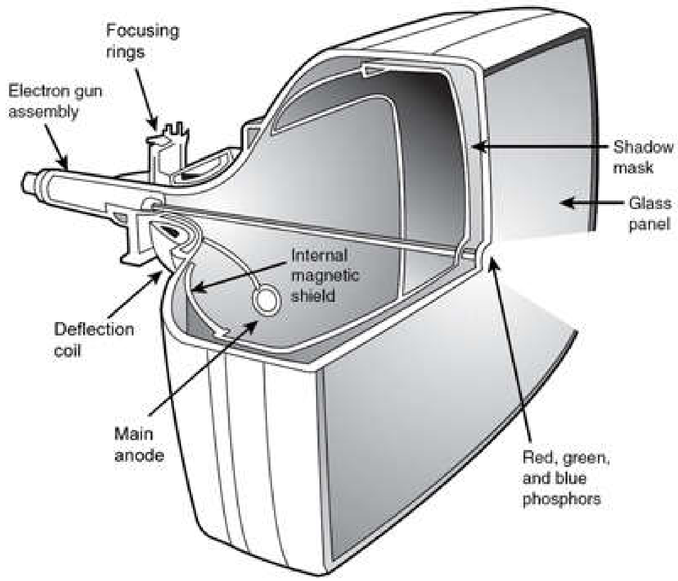


K. Kao (高锟)

2009 Nobel Prize in Physics

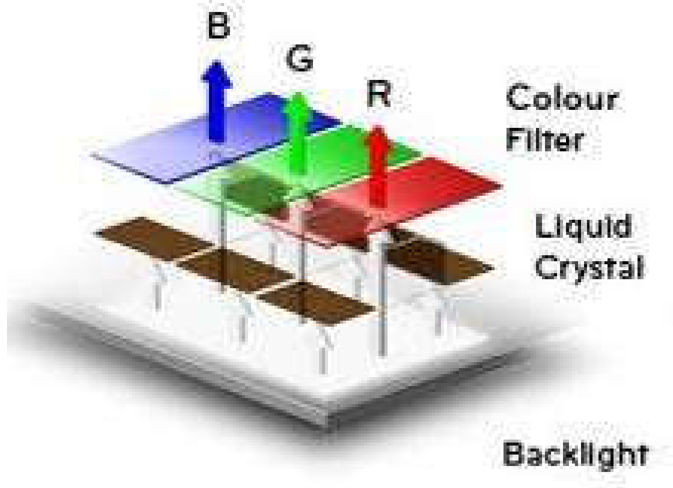
K. C. Kao, G. A. Hockham, *Proc. IEE* **113,** 1151 (1966)

Displays



CRT

liquid crystal display (LCD)



flat panel

de Gennes

1991 Nobel Prize in Physics

Syllabus

- Introduction (Week 1)
- Materials and Crystal Structures (Week 2–3)
- Electronic Properties (Week 4–12)
- Thermal Properties (Week 13)
- Optical Properties (Week 14)
- Magnetic Properties (Week 15)

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- **Introduction (Week 1)**
  - **Overview, history, applications**
  - **Preliminary knowledge**
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  - Crystal structures, lattices
  - Reciprocal space, Brillouin zones
  - Materials Characterization: Wave diffraction, the Bragg law
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  - Free electrons (the Drude and Sommerfeld models)
  - Electrons in a periodic potential (Bloch's Theorem)
  - The near-free electron model, the tight-binding model
  - Electronic band diagram, band gaps, effective mass
  - Metals, insulators, semiconductors
  - Devices: junctions, diodes, transistors
- Thermal Properties (Week 13)
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- Magnetic Properties (Week 15)

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  - Crystal vibration, phonon band
  - Thermal conductivity and capacity
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  - Origin of Dielectric constant (ε) and Refractive index (n)
  - Optical absorption, reflection, refraction, emission
- Magnetic Properties (Week 15)

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  - Origin of Magnetics
  - Diamagnetism, Paramagnetism, Ferromagnetism
  - Superconductivity

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