"Complementi di Fisica" *Lecture 1*

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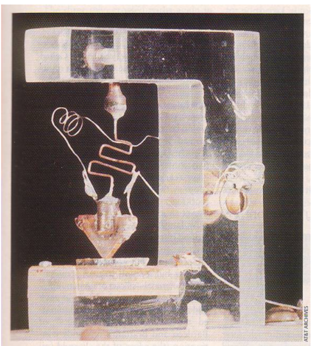
Lecture 1 - Outline

- **Introduction**
  - Chronology of a success story
  - Frontiers in physics and technology
    - amplifiers, electrons, waves
    - electron: particle or wave?
  - Interactions, units, orders of magnitude
  - Practical issues (textbooks, exams, …)

Introduction

Birth of an era

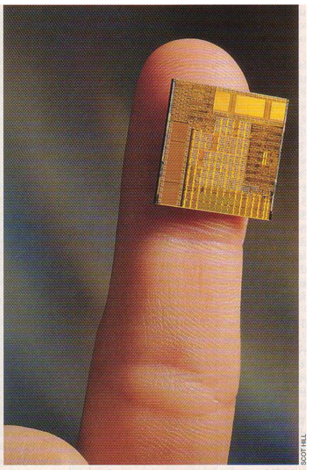


1947: the first solid-state amplifier
Shockley, Bardeen and Brittain
(Bell Labs, solid-state physics group)

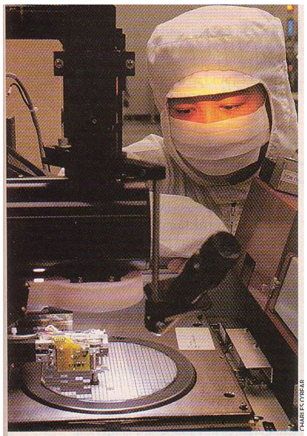
INVENTORS Shockley (*seated*), Bardeen (*left*) and Brattain (*right*) were the first to demonstrate a solid-state amplifier (*opposite page*).

from: Scientific American, The Solid State Century, Special Issue, 1998

Recent past



INTEGRATED CIRCUIT, or die, for Motorola's Power PC 620 microprocessor has nearly seven million transistors. It was designed mainly for use in computer workstations and file servers.



CLEAN ROOMS, where wafers are made, are designed to keep human handling and airborne particles to a minimum. A single speck of dust can damage a tiny transistor.

from: Scientific American, The Solid State Century, Special Issue, 1998

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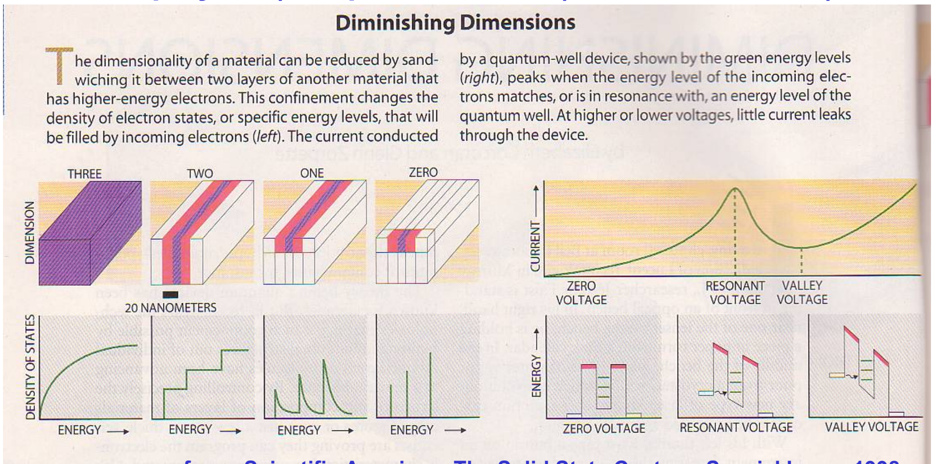
Future ?

- From quantum wells (already here, in everybody's CD player…) to quantum dots ("artificial atoms")



Diminishing Dimensions

The dimensionality of a material can be reduced by sandwiching it between two layers of another material that has higher-energy electrons. This confinement changes the density of electron states, or specific energy levels, that will be filled by incoming electrons (*left*). The current conducted by a quantum-well device, shown by the green energy levels (*right*), peaks when the energy level of the incoming electrons matches, or is in resonance with, an energy level of the quantum well. At higher or lower voltages, little current leaks through the device.

from: Scientific American, The Solid State Century, Special Issue, 1998

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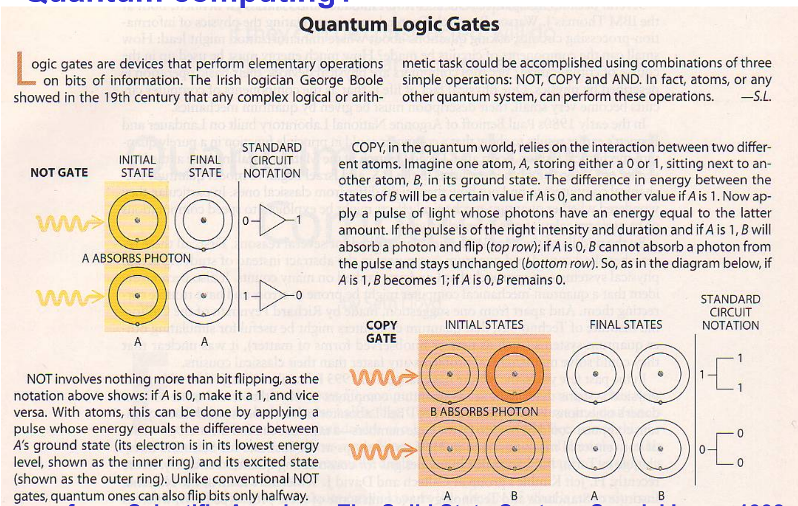
Future ?

- **Quantum computing?**



from: Scientific American, The Solid State Century, Special Issue, 1998

Chronology of a success story

Year	event	notes
1947	bipolar transistor	Shockley-Brittain-Bardeen - Bell Labs
1956	Nobel Prize	
1954	bipolar transistor, grown junction technique	Texas Instruments
main difficulties: high purity material and doping technique; surface passivation		
1957-1958	diffusion doping technique	
1961	oxidation of Silicon surface	Germanium abandoned
next advance: integration of several devices		
1959	patent of original idea	Jack Kilby - Texas Instruments
1961	patent of planar technology and microchip integrated circuit	Robert Noyce, co-founder of Fairchild and Intel
		Jean Horni - Fairchild
1961	use of planar technology for discrete transistors	
bipolar transistors -> MOS transistors		
1960	first reliable MOS transistor	
1962	first MOS IC marketed	
mid-1960's	mastering of all aspects of IC technology	
1965-2000: unique progress !!!		
	device dimensions: factor 10000	
	integration scale: factor 1000000	

What do we learn from this?

- Discoveries & inventions almost never just "happen"
  - The Bell Telephone Laboratories solid-state physics research team had been working on related ideas for almost a decade before realizing the first solid-state amplifier
  - A really interesting story! See for instance: http://www.pbs.org/transistor/index.html, http://www.pbs.org/transistor/science/index.html, …
- Progress in fabrication of practical devices needs both:
  - Breakthroughs in technology, for example in this case:
    - Material purity control
    - Surface passivation
    - Doping by diffusion
    - Etc…
  - Understanding the underlying physical processes

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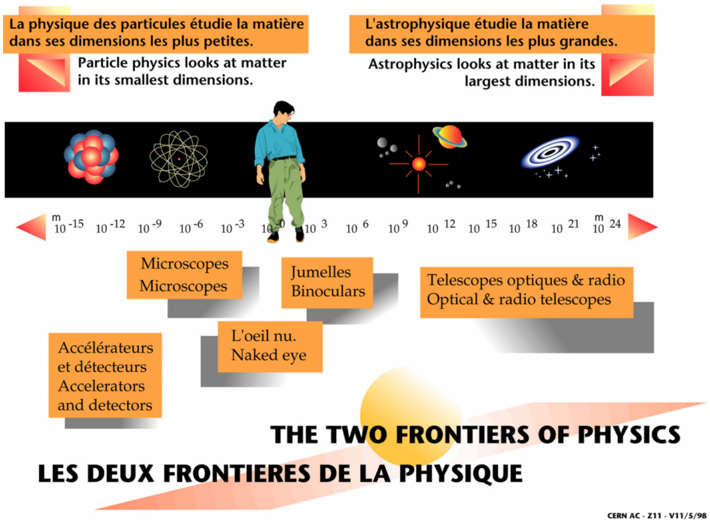
Physics and Technology

Frontiers in Physics



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Frontiers in Physics

- **Very large:** mainly gravitation
- **Very small:** elementary particles and their interactions (electromagnetic, weak, strong)
- **Very complex:** qualitative changes of system behaviour when many objects interact (i.e. atoms in solids)

↓

- **Ambitious project: full picture of the Universe and of its history**
  - Elementary particles and their interactions (QM&relativity)
  - Astrophysics and Cosmology: all ingredients play a role!
- **Many mysteries still remain; some examples:**
  - Origin of mass, pattern of masses, symmetries, …
  - Matter-antimatter asymmetry, “dark matter”, “dark energy”, …

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Frontiers in Technology

- Examples of frontiers from information technologies:
  - What limits the bit density for semiconductor memories?
  - What limits the bit density in a typical hard disk?
  - What limits the bit density for optical storage?
  - Where does electronic noise come from, and how does it limit data rates?
  - What is a quantum computer?
  - Why does computation require energy?
  - …
- Not surprisingly, in several cases technology is close to limits set by the underlying physical phenomena
  - Example: GPS (atomic clocks on the satellites; general relativity corrections at the receiver end)
- For a discussion of information technologies & physical limits:
  - *N.Gershenfeld, the Physics of Information Technology, Cambridge University Press, 2002*

Technology and Physics: links

- A basic understanding of the physics involved in technology is often needed.
  - In this course we will explore the microscopic behaviour of matter (with emphasis on electrons in semiconductor crystals) mainly from the point of view of electrical conduction
- For instance, starting from technology:
  - What is an amplifier? Etc…
- We will address basic questions, such as:
  - What is an electron?
  - What is a wave?
  - Is the electron a particle or a wave?
  - How can I understand the behaviour of an electron in a crystal and exploit it practically?

What is an amplifier?

- Two centuries of industrial revolution
  - large effort in “power control” (power = work per unit time)
  - Progress in power control: getting better “amplifiers”
- What is an amplifier?
  - It is NOT just “a device to make something bigger” !
  - An amplifier is a device through which a large amount of power is controlled by a small amount of power
- Examples:
  - Levers, transformers, hydraulic jacks *ARE NOT* amplifiers: power transfer ratio at most = 1
  - A simple electrical switch on the wall *IS* an amplifier (…)
- The transistor is now the most ubiquitous amplifier
  - it can easily achieve power gains of 1000. To understand its operation (and also other modern devices) we need to learn about *electrons moving in crystals* and more

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What is an electron?

- “Elementary particle”
  - Rest mass ≅ 10^{-30} kg ≅ 500000 eV/c^2 ≅ 9 $\times 10^{-14}$ joules ($E=m_0c^2$)
  - Electric charge ≅ -1.6×10^{-19} coulombs
- Particle: operational definition ?
  - For *macroscopic* objects, we are used to think in terms of “sharp boundaries”, observable for instance by optical experiments or scattering experiments
  - For *microscopic* objects like electrons, criteria are:
    - “Discreteness” or “countability” in energy flow
    - Each count is associated with a “quantum” of energy (≅ 500000 eV ≅ 9 $\times 10^{-14}$ joules for the electron)
- This definition will give us surprises!
  - For instance, when we apply it to less obvious energy flows such as light or sound waves in solids…

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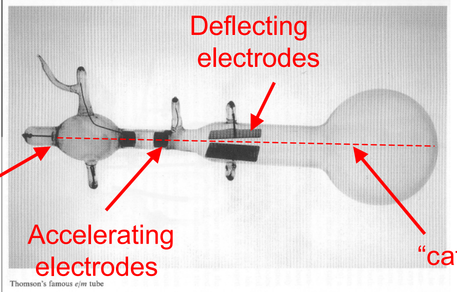
Electron as a particle

- **Discovered by J.J.Thomson (1897) as a particle**
  - Research on discharges in gases, on "cathode rays" emitted by the negative electrode, and on X-rays
  - "cathode rays" interpreted as "corpuscles" (later called electrons) after careful study of the association of charge with deflected trajectory
  - e/m ratio measured by deflection in electric and magnetic fields;
  - also evidence that the electron is part of the atom, since m/e ~ 10^{-11} kg/C << 10^{-8} kg/C (hydrogen, electrolysis)



From:
E.A.Davis, I.J.Falcomer, **J.J.Thomson and the Discovery of the Electron,** *Taylor&Francis, 1997*

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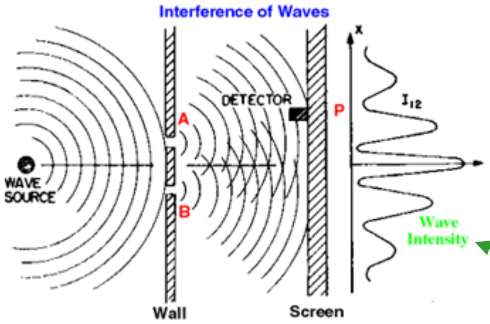
What is a wave?

- **A "thing" is a wave if…**
  - The associated *energy flow* propagates in a peculiar way, characterized by *Young's two-slit experiment (diffraction)*;
  - for instance, light souce (Na-vapour lamp) in air: the thermal field due to air heating does not show diffraction, while the optical (electromagnetic) field does!



Electric field from point source i

$$\vec{E}_i(\vec{r},t) = \vec{E}_0(\vec{r})e^{j(\omega t - \vec{k}\bullet\vec{r})}$$

Superposition from slits A and B

$$\vec{E} = \vec{E}_A + \vec{E}_B$$

Intensity (~ energy)

$$\langle I(\vec{r})\rangle_t = \vec{E}(\vec{r},t)\vec{E}^*(\vec{r},t)$$

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Can an electron be also a wave?

- Why not?
  - To be decided by a *two-slit diffraction experiment*
  - *Yes*, if a diffraction pattern is observed when both slits are open (and *it is indeed observed* !)
- The main logical problem:
  - Fundamental indivisibility of fundamental particles
  - If one electron at a time is sent through the apparatus, the observed diffraction requires that ONE electron goes simultaneously through TWO slits! How can this be?
  - This is what happens, because if we close one slit the interference pattern disappears!
- More on this later…
  - This is just one example of the intriguing behaviour of matter at microscopic level

Units, interactions and orders of magnitude

International System (SI), fundamental units

quantity	unit		description
length	meter	m	length of path traveled by light in vacuum during a time interval of 1/299 792 458 of a second
mass	kilogram	kg	equal to the mass of the international prototype of the kilogram
time	second	s	duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom
current	ampere	A	that constant current which, if maintained in two straight parallel conductors of infinite length, negligible circular cross section, and placed 1 meter apart in vacuum, would produce a force equal to 2 x 10e7 newtons per meter of length
temperature	kelvin	K	the fraction 1/273.16 of the thermodynamic temperature of the triple point of water
quantity	mole	mol	amount of substance of a system which contains as many elementary units as there are atoms in 0.012 kg of carbon 12 (i.e. Avogardro's number N = 6.022…x10e23)
intensity	candela	cd	luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540x10e12 hertz and has a radiant intensity of 1/683 watts/steradian

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International System (SI), some other units

quantity	unit		description	
force	newton	N	(m kg s^-2) that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/s^2	
energy	joule	J	(m^2 kg s^-2) the work done when the point of application of a force is displaced a distance of 1 meter in the direction of the force	
power	watt	W	(m^2 kg s^-3) power corresponding to the production of energy at a rate of 1 joule per second	
potential	volt	V	(m^2 kg s^-3 A^-1) difference of electric potential between two points of a conductor carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt	*
resistance	ohm	Ω	(m^2 kg s^-3 A^-2) electric resistance between two points of a conductor, when a constant differenceof potential of 1 volt, applied between these two points, produces a current of 1 ampere	*
conductance	siemens	S	conductance = 1 / resistance	
capacitance	farad	F	(m^-2 kg^-1 s^4 A^2) capacitance of a capacitor with a differerence of potential of 1 volt between its plates when charged with a charge of 1 coulomb	*

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International System (SI), some other units

quantity	unit		description
inductance	henry	H	(m^-2 kg^-1 s^4 A^2) inductance of a closed circuit in which an electromotive force of 1 volt is produced when the electric current in the circuit varies uniformly at a rate of 1 ampere per second
magnetic flux	weber	Wb	(m^2 kg s^-2 A^-1) magnetic flux which, linking a circuit of 1 tun, produces in it an electromotive force of 1 volt as it is reduced to zero at a uniform rate in 1 second
magnetic flux density	tesla	T	(kg s^-2 A^-1) magnetic flux density given by a magnetic flux of 1 weber per square meter

* recently the definitions of volt, ohm, and farad have been replaced with more fundamental ones, based on Josephson junction, quantum Hall effect, and Single-Electron Tunneling devices

In discussing semiconductor physics and devices, we will be using mixed units, in particular for
- Energy (electronvolts instead of joules)
- Length (centimeters instead of meters)

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Some constants and conversion factors

Some General Constants

Avogadro's number	$N_A = 6.02 \times 10^{23}$ molecules/mole
Boltzmann constant	$k_B = 1.38 \times 10^{-23}$ J/K $= 8.63 \times 10^{-5}$ eV/K
Coulomb constant	$1/4\pi\varepsilon_O = 8.99 \times 10^{9}$ N-m²/C²
Gravitational constant	$G = 6.67 \times 10^{-11}$ N-m²/kg²
Permittivity of free space	$\varepsilon_O = 8.85 \times 10^{-12}$ C²/N-m²
Planck constant	$h = 6.63 \times 10^{-34}$ J-sec $= 4.14 \times 10^{-15}$ eV-sec
Speed of light	$c = 3.00 \times 10^{8}$ m/sec
Universal gas constant	$R = 8.31$ J/mole-K

More constants and more significant digits: see appendices in textbooks and:

L.Anderson, ed., A Physicist's Desk Reference, AIP, New York

$1\ \text{eV} = 1.6022 \times 10^{-19}\ \text{J}$

$1\ \text{fermi} = 10^{-15}\ \text{m}$

$1\ \text{inch} = 2.54\ \text{cm}$

$kT \cong 1/40$ eV at room temperature (293K)

$1\ \text{gauss} = 10^{-4}\ \text{T}$

1 atomic mass unit $u = 1.661 \times 10^{-27}$ kg

energy equivalent of 1 $u(= uc^2) = 931.5$ MeV

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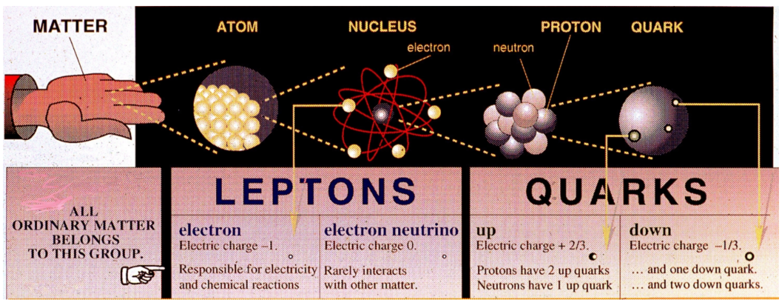
Other numbers we will often use…

Atomic and Semiconductor Data

Electronic charge	1.6×10^{-19} C
Mass of the electron	9.11×10^{-31} kg
Mass of the proton	1.67×10^{-27} kg
Mass of the neutron	1.67×10^{-27} kg
Bohr radius	5.3×10^{-11}m
Ionization energy of hydrogen	13.6 eV
Effective mass of electrons in silicon	$0.31 \times 9.11 \times 10^{-31}$ kg
Effective mass of holes in silicon	$0.38 \times 9.11 \times 10^{-31}$ kg
Energy gap (E_g) in silicon	1.1 eV
Effective mass of electrons in germanium	$0.12 \times 9.11 \times 10^{-31}$ kg
Effective mass of holes in germanium	$0.23 \times 9.11 \times 10^{-31}$ kg
Energy gap (E_g) in germanium	0.67 eV

Orders of magnitude

system	atom	nucleus	neutrons and protons
components	nucleus and electrons	neutrons and protons	quarks
typical length	1Å = 10^{-10}m	10 fm = 10^{-14}m	1 fm = 10^{-15}m
typical energy	1 eV ÷ 1keV	1 MeV = 10^{6} eV	1 GeV = 10^{9} eV
interaction	electromagnetic	strong	strong



Practical issues

Course outline and textbooks

- ½ Quantum Mechanics: an introduction
  - *J.R.Taylor, C.D.Zafiratos, M.A.Dubson*, Modern Physics for Scientists and Engineers (2nd ed.)
  - *P.A.Tipler, G.Mosca*, Corso di fisica - 3 - Fisica moderna, (quarta ed.) Zanichelli, 2009, Bologna.
  - Further reading from:
    - *D.J.Griffiths*, Introduction to Quantum Mechanics, *Prentice-Hall*
    - *Other texts: see* moodle *site*

Course outline and textbooks

- ½ The physics of semiconductor devices: an introduction
  - *D.A.Neamen,* Semiconductor Physics and devices, *McGraw-Hill, 3rd ed., 2003*: Chapters 1, (2-3), 4-6
  - Also material from other texts… see *moodle* site:

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Documentation and exams

- The documentation for this course will be made available at:
  http://moodle.units.it/moodle
- The following ingredients will be taken into account for the final grading:
  - Homework during the course (assignments)
  - Final exam:
    - Discussion of homework ~ 1/3
    - One subject chosen by you ~ 1/3
    - One subject chosen by me ~ 1/3

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