“Complementi di Fisica”
Lecture 1

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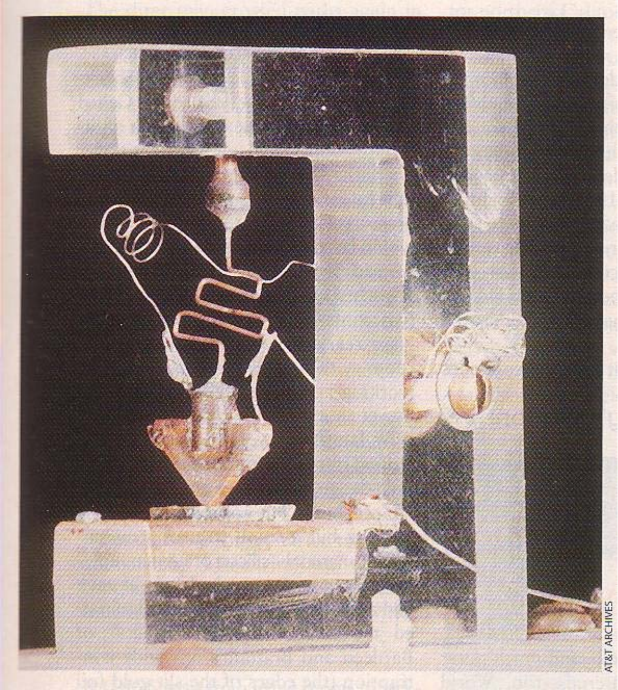
Lecture 1 - Outline

- 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, …)

- Semiconductor Fundamentals – Lecture 1
  - Semiconductor materials
  - Crystal structure
  - Valence bonds model
  - Energy bands model

Introduction

Birth of an era

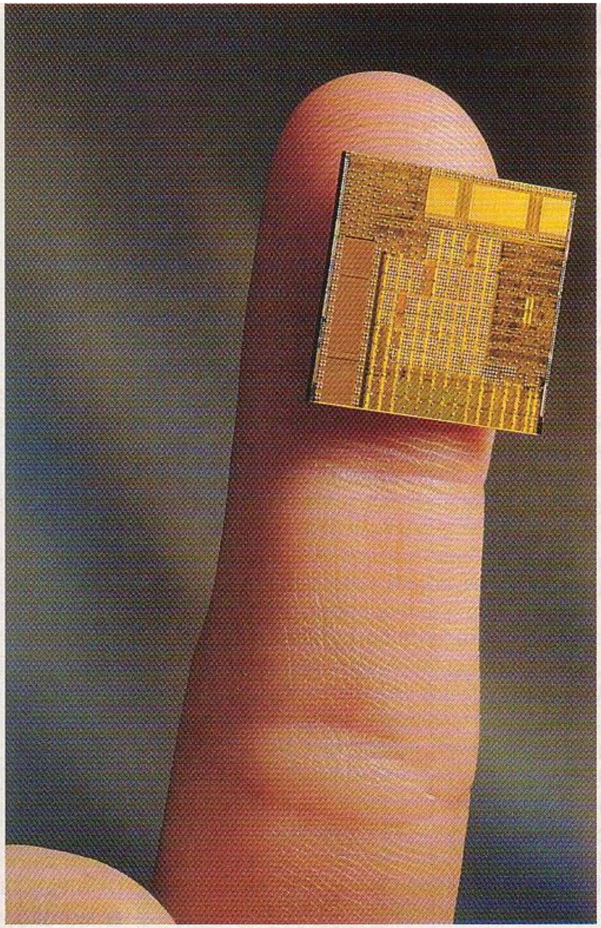


INVENTORS Shockley (*seated*), Bardeen (*left*) and Brattain (*right*) were the first to demonstrate a solid-state amplifier (*opposite page*).

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

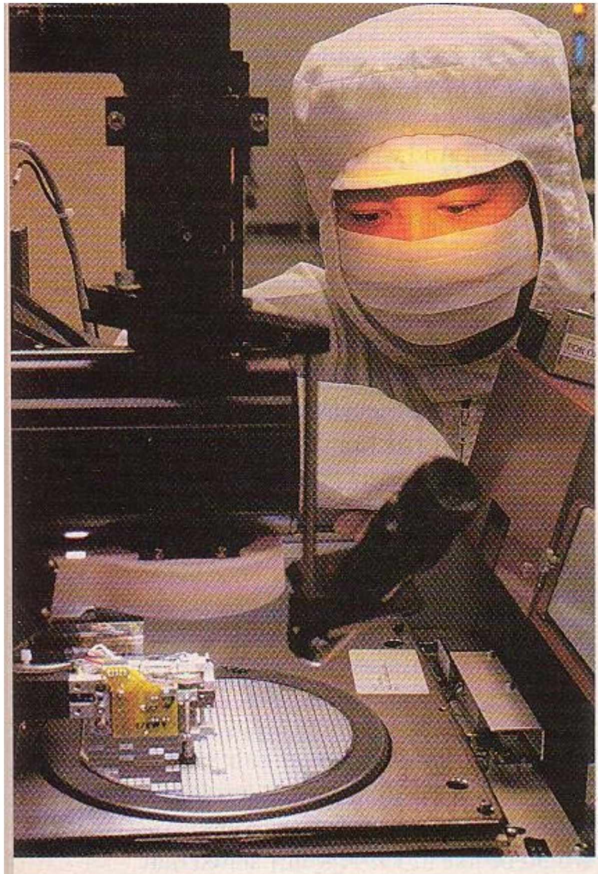
from: Scientific American, The Solid State Century, Special Issue, 1998

Present



SCOT HILL

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.



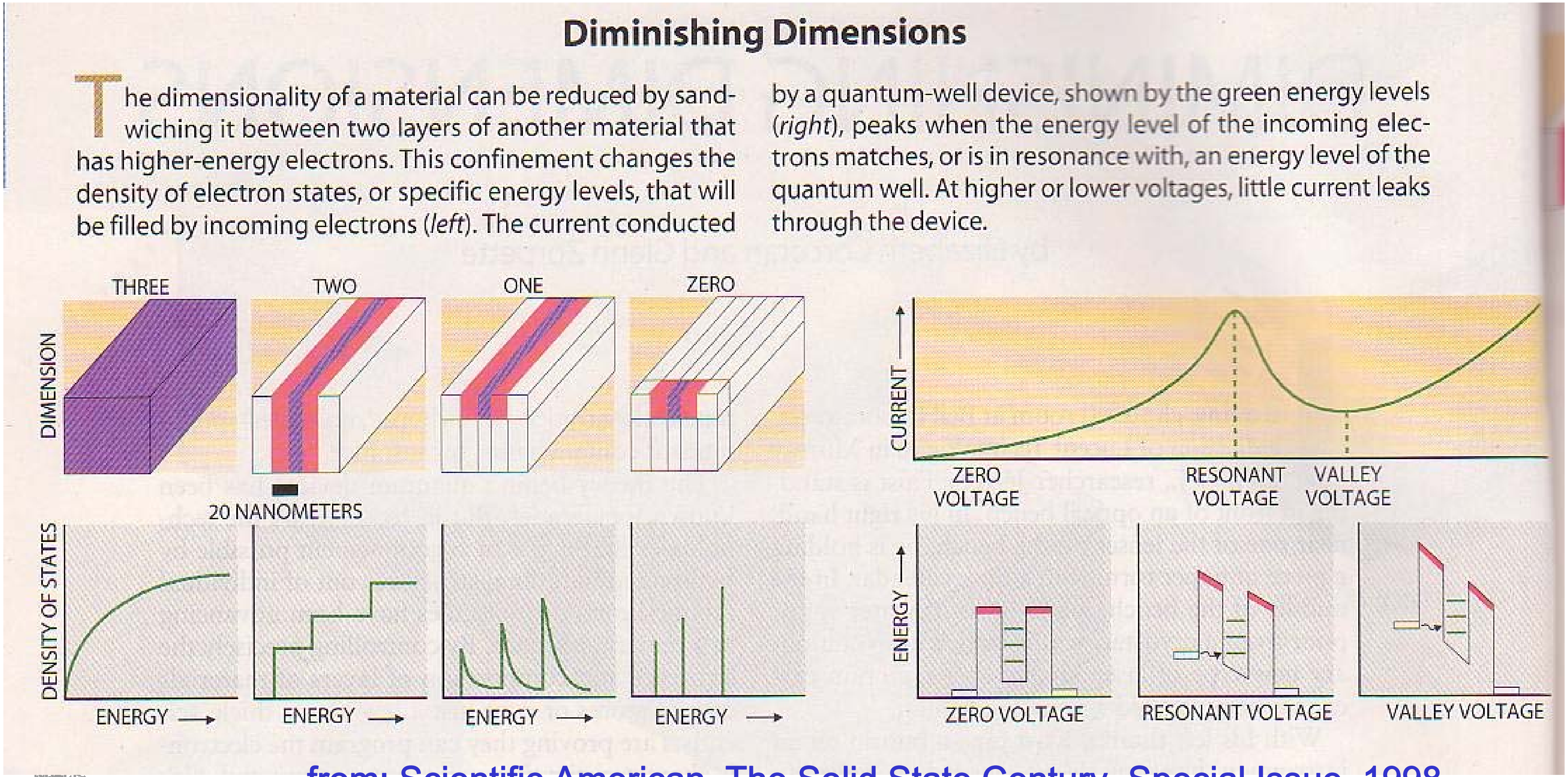
CHARLES O'REAR

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

Future ?

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



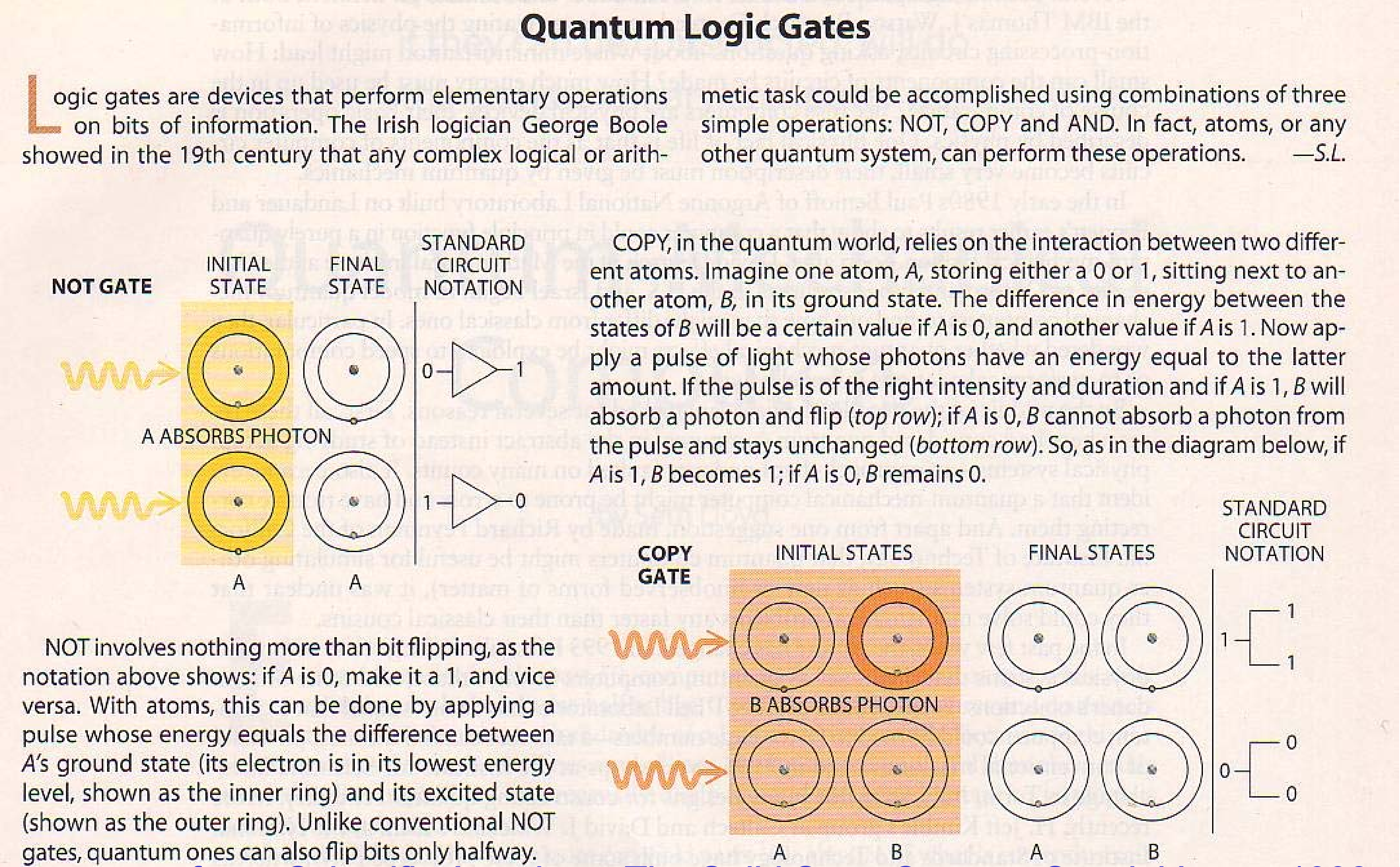
Diminishing Dimensions

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

Future ?

- Quantum computing?



Quantum Logic Gates

Logic gates are devices that perform elementary operations on bits of information. The Irish logician George Boole showed in the 19th century that any complex logical or arithmetic task could be accomplished using combinations of three simple operations: NOT, COPY and AND. In fact, atoms, or any other quantum system, can perform these operations. —*S.L.*

NOT involves nothing more than bit flipping, as the notation above shows: if *A* is 0, make it a 1, and vice versa. With atoms, this can be done by applying a pulse whose energy equals the difference between *A*'s ground state (its electron is in its lowest energy level, shown as the inner ring) and its excited state (shown as the outer ring). Unlike conventional NOT gates, quantum ones can also flip bits only halfway.

COPY, in the quantum world, relies on the interaction between two different atoms. Imagine one atom, *A*, storing either a 0 or 1, sitting next to another atom, *B*, in its ground state. The difference in energy between the states of *B* will be a certain value if *A* is 0, and another value if *A* is 1. Now apply a pulse of light whose photons have an energy equal to the latter amount. If the pulse is of the right intensity and duration and if *A* is 1, *B* will absorb a photon and flip (*top row*); if *A* is 0, *B* cannot absorb a photon from the pulse and stays unchanged (*bottom row*). So, as in the diagram below, if *A* is 1, *B* becomes 1; if *A* is 0, *B* remains 0.

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

Chronology of a success story

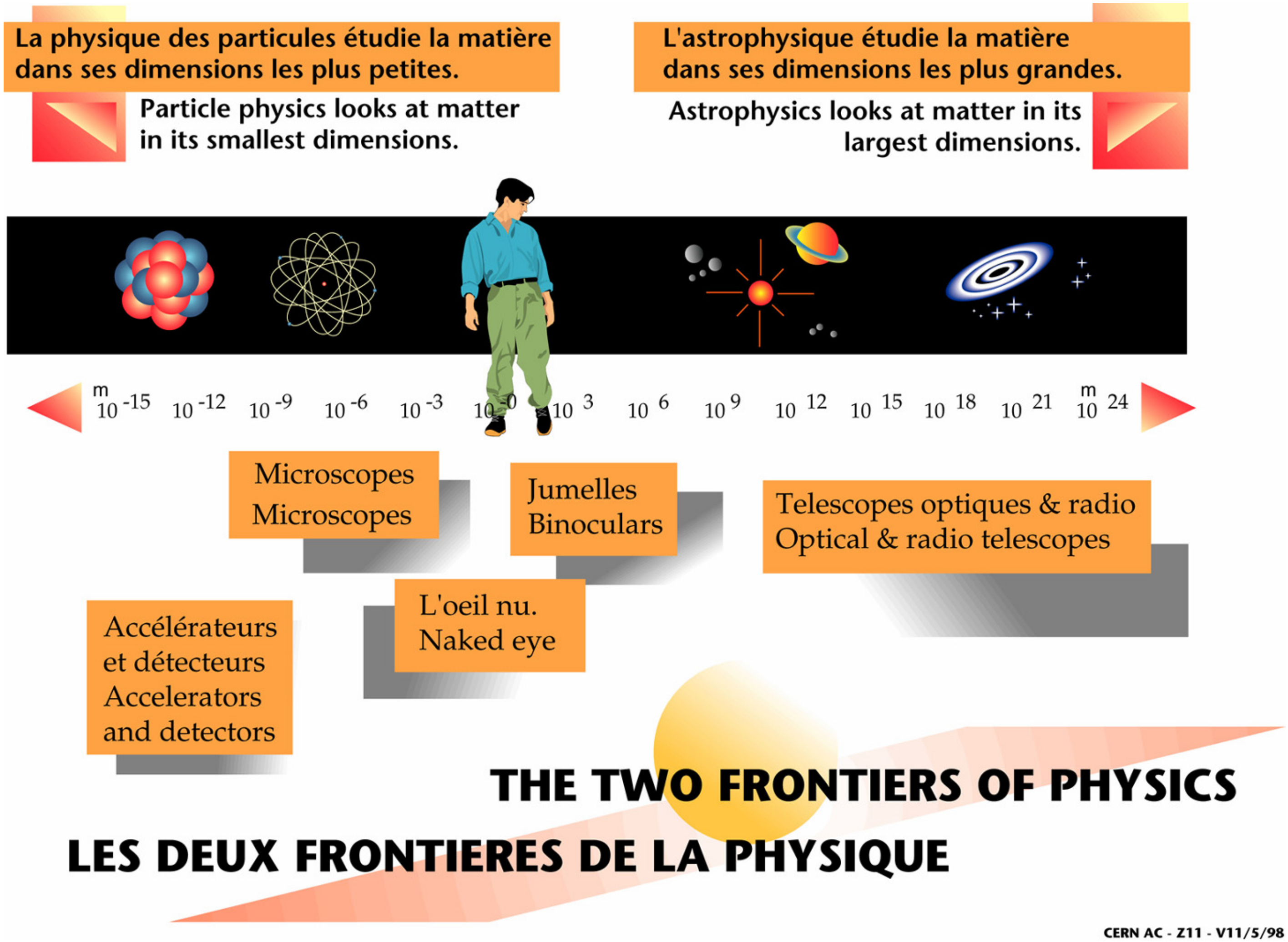
Year	event	notes
1947	bipolar transistor	Shockley-Brittain-Bardeen - Bell Labs
1956	Nobel Prize	
1954	bipolar transistor, grown junction technique	Texas Instruments
main difficulties: high purity material and doping technique; surface passivation		
1957-1958	diffusion doping technique	
1961	oxidation 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

Physics and Technology

Frontiers in Physics



La physique des particules étudie la matière dans ses dimensions les plus petites.

Particle physics looks at matter in its smallest dimensions.

L'astrophysique étudie la matière dans ses dimensions les plus grandes.

Astrophysics looks at matter in its largest dimensions.

Microscopes
Microscopes

Jumelles
Binoculars

Telescopes optiques & radio
Optical & radio telescopes

Accélérateurs et détecteurs
Accelerators and detectors

L'oeil nu.
Naked eye

THE TWO FRONTIERS OF PHYSICS

LES DEUX FRONTIERES DE LA PHYSIQUE

CERN AC - Z11 - V11/5/98

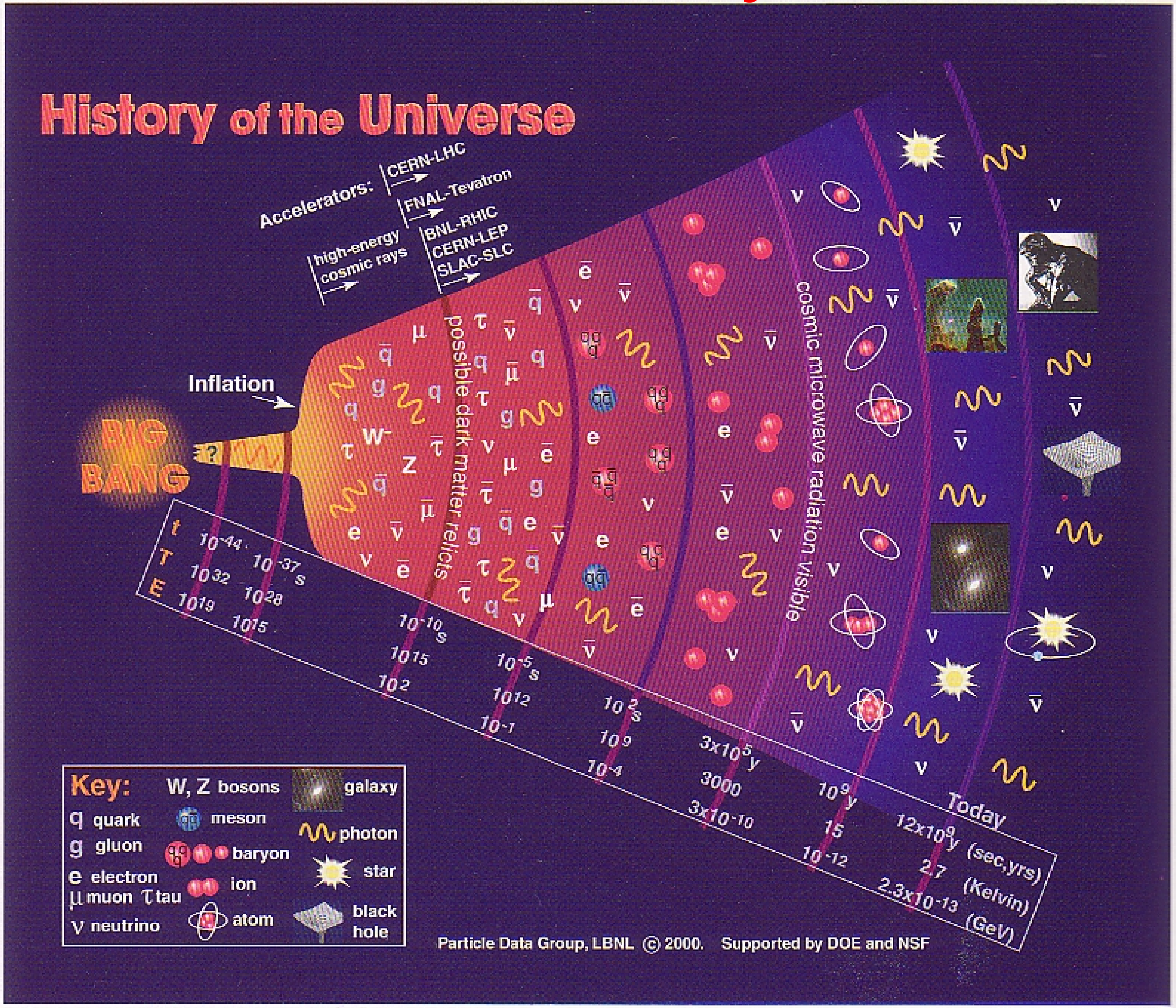
Frontiers in Physics

- 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 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”, …

Frontiers in Physics



Particle Data Group, LBNL © 2000. Supported by DOE and NSF

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) from the electrical conduction point of view
- 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?
  - Etc…

What is an amplifier?

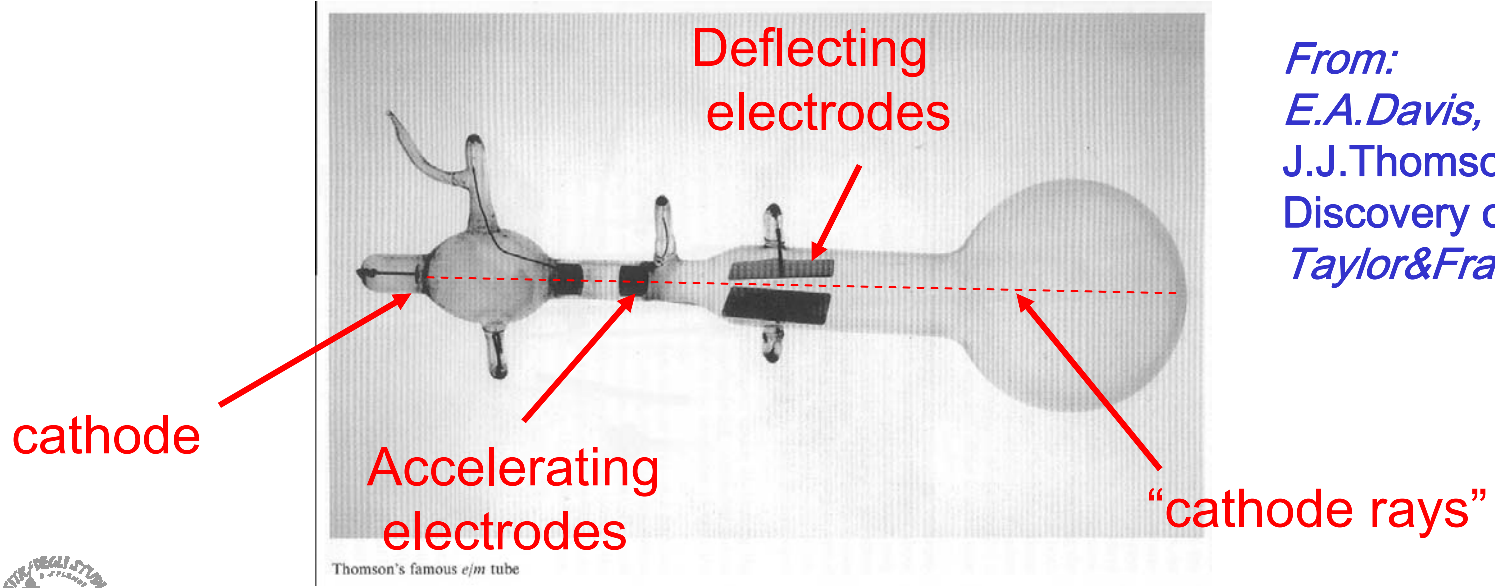
- Two centuries of industrial revolution
  - large effort in “power control” (power = work per unit time)
  - Progress in power control: getting better “amplifiers”
- What is an amplifier?
  - It is NOT just “a device to make something bigger” !
  - An amplifier is a device through which a large amount 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

What is an electron?

- “Elementary particle”
  - Mass ≅ 10^{-27} grams ≅ 500000 eV ≅ 9 $\times 10^{-19}$ joules
  - 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 $\times 10^{-19}$ 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…

Electron as a particle

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

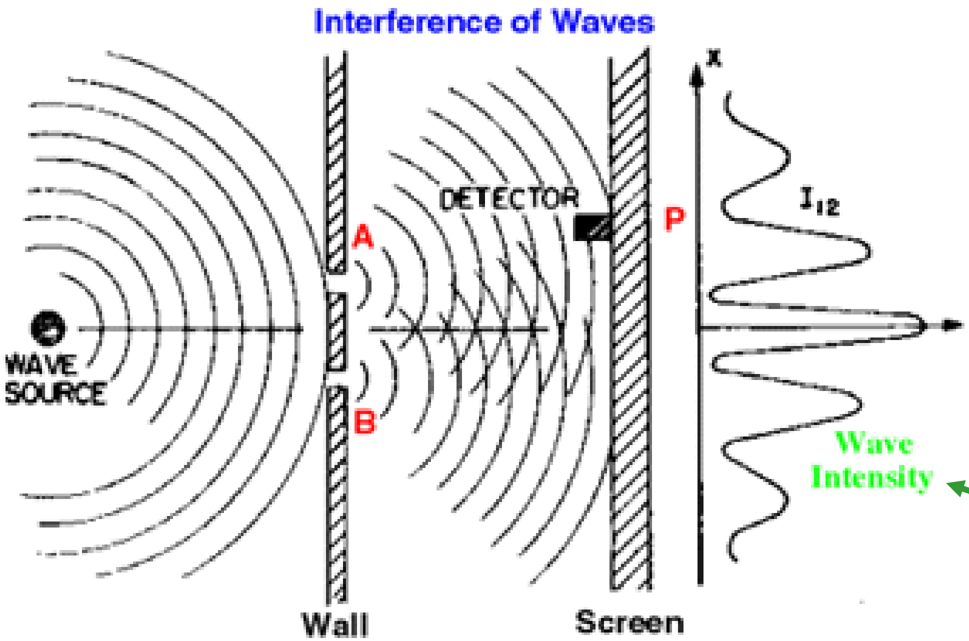


Thomson's famous *e/m* tube

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

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)

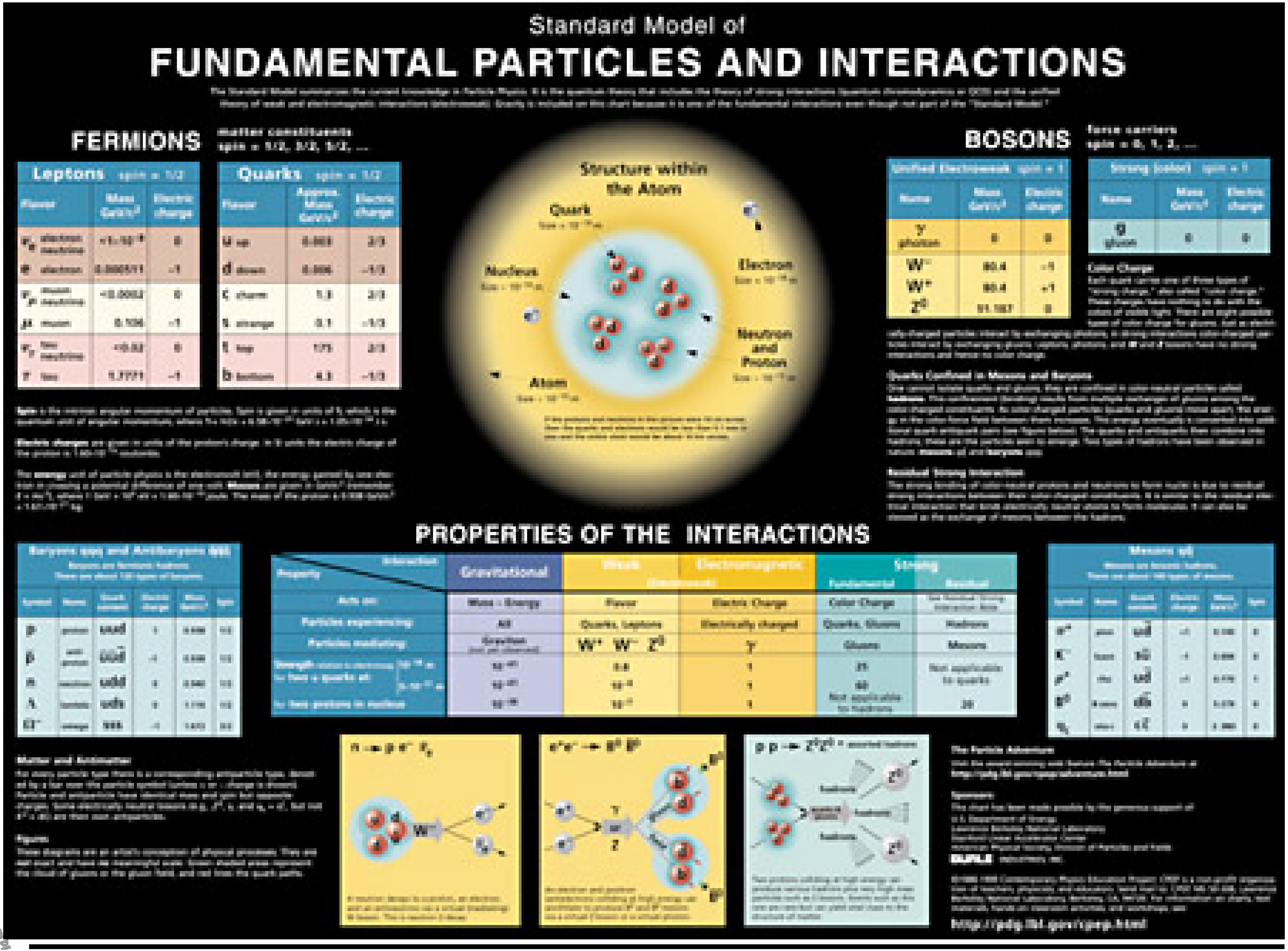
$$\langle I(\vec{r})\rangle_t=\vec{E}(\vec{r},t)\vec{E}^*(\vec{r},t)$$

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

Interactions, units and orders of magnitude

Interactions



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

FERMIONS

Leptons

Quarks

Structure within the Atom

BOSONS

PROPERTIES OF THE INTERACTIONS

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

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	*

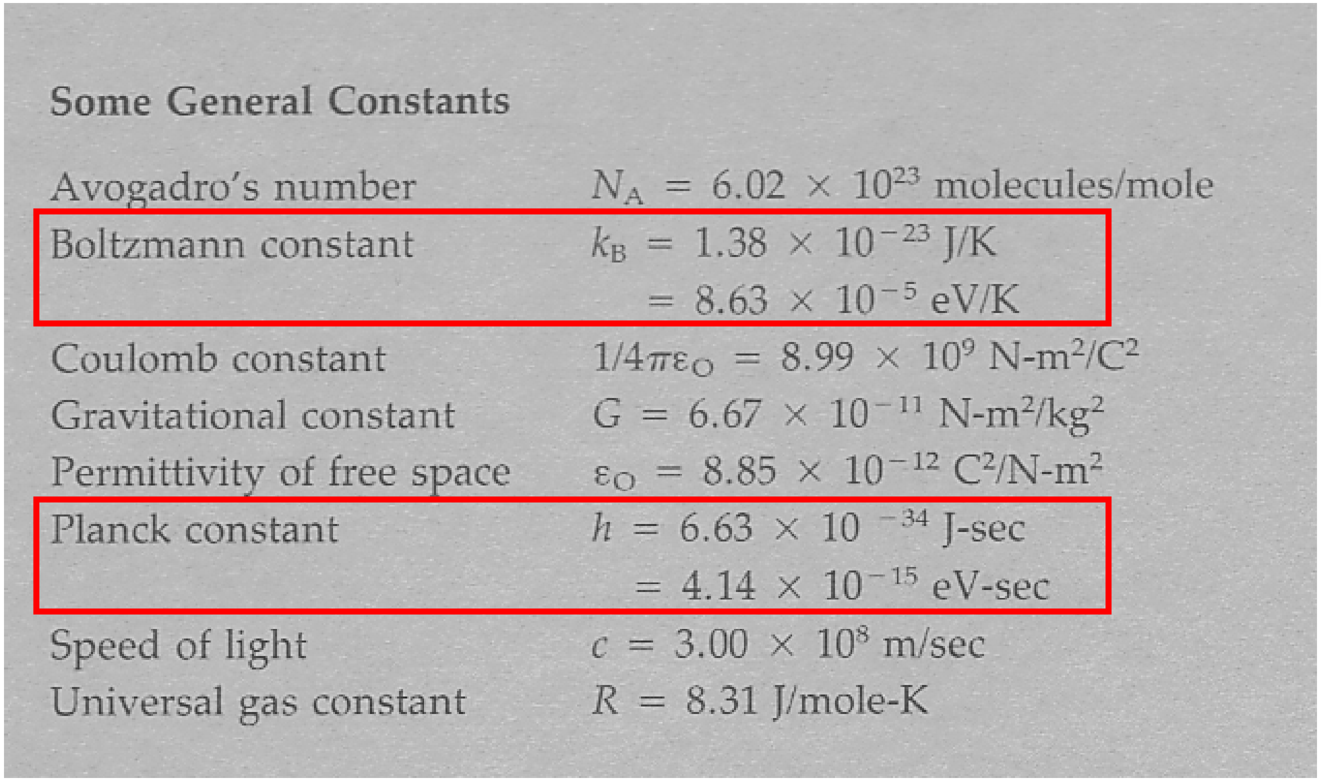
International System (SI), some other units

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, will be using mixed units, in particular for
- Energy (electronvolts instead of joules)
- Length (centimeters instead of meters)

Some constants and conversion factors

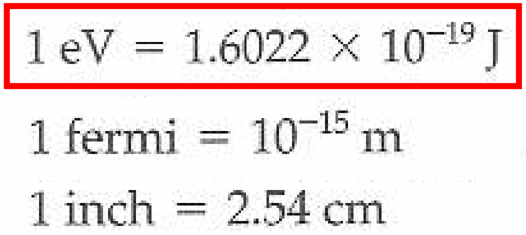


Some General Constants

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-m^2/C^2
Gravitational constant	$G = 6.67 \times 10^{-11}$ N-m^2/kg^2
Permittivity of free space	$\varepsilon_O = 8.85 \times 10^{-12}$ C^2/N-m^2
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:

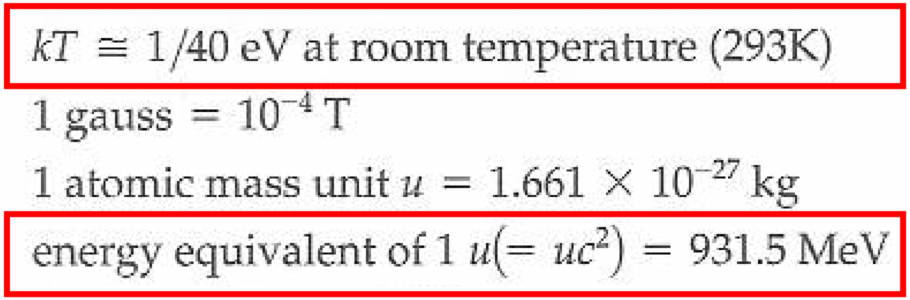
L.Anderson, ed.,
A Physicist's
Desk Reference,
AIP, New York



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

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

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



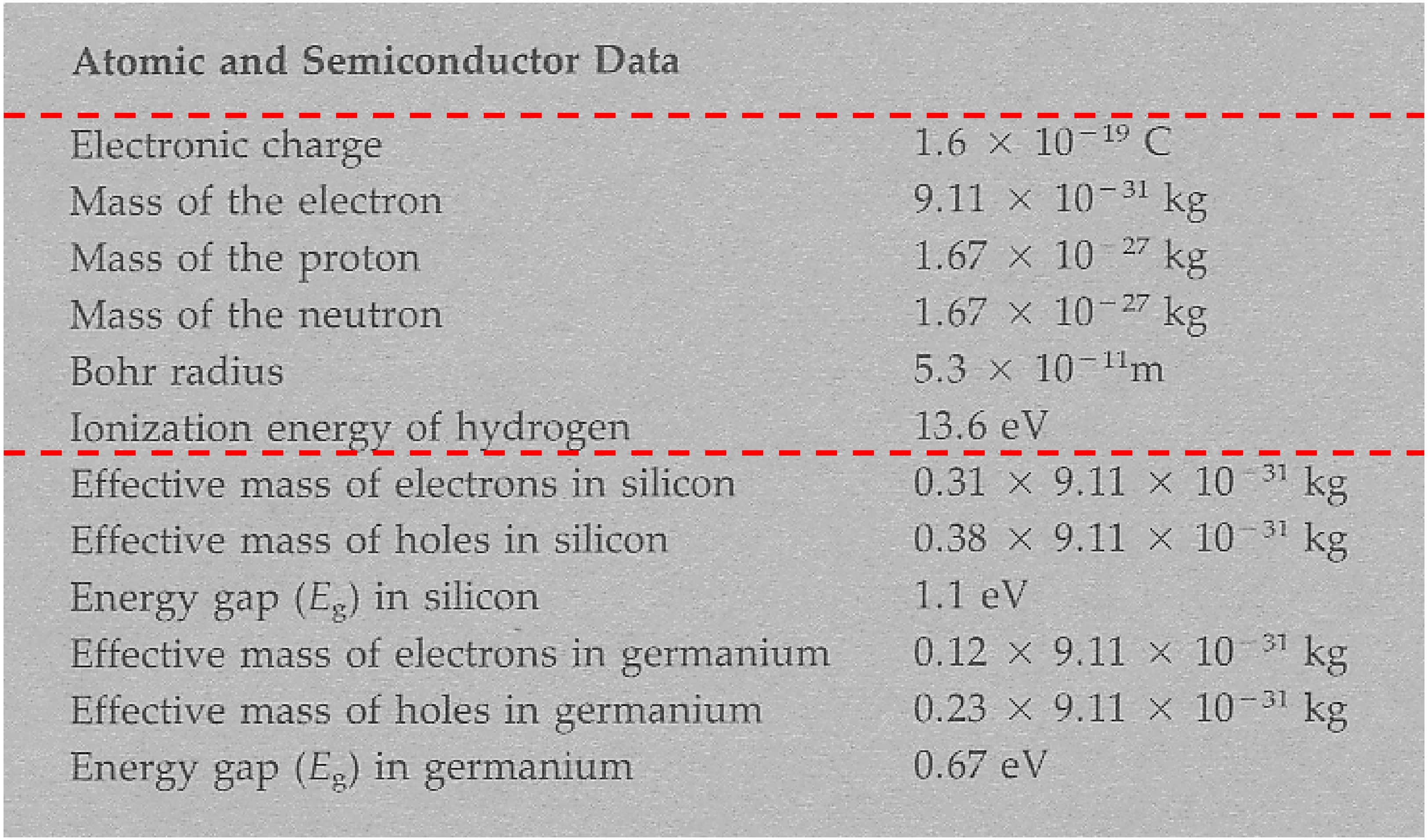
$kT \cong 1/40$ eV at room temperature (293K)

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

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

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

Other numbers we will often use…

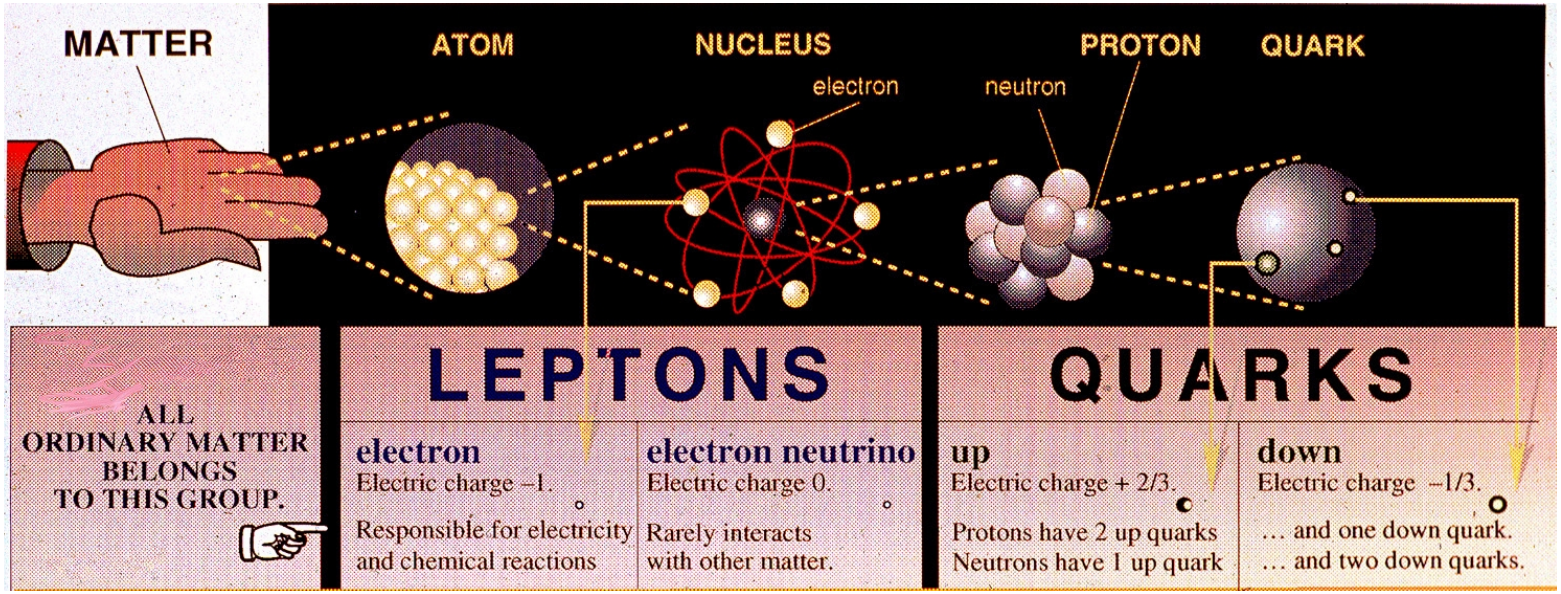


Atomic and Semiconductor Data

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	1Ǻ = 10^{-10}m	10 fm = 10^{-14}m	1 fm = 10^{-15}m
typical energy	1 eV	1 MeV = 10^{6} eV	1 GeV = 10^{9} eV
interaction	electromagnetic	strong	strong



Practical issues

Course outline and textbooks

- ¼ The physics of semiconductor devices: an introduction
  - *S.M.Sze*, Semiconductor Devices - Physics and Technology, *J.Wiley & Sons, 1985* : chapters 1, 2

- ½ Quantum Mechanics: an introduction
  - *J.Bernstein, P.H.Fishbane, S.Gasiorowicz*, Modern Physics, *Prentice-Hall, 2000* : chapters 4-12, 14

- ¼ Advanced semiconductor fundamentals
  - *R.F.Pierret*, Advanced Semiconductor Fundamentals, *Modular Series on Solid State Devices, Vol.VI, Prentice-Hall, 2nd ed., 2003* : Chapters 1-6

Documentation and exams

- The documentation for this course will be made available at:

  http://www.ts.infn.it/~lanceri/ComplementiFisica/

- The following ingredients will be taken into account for the final grading:
  - Homework during the course (assignments, seminars) ~ 1/4
  - Written final test (at home) ~ 1/4
  - Oral final exam
    - One subject chosen by you ~ 1/4
    - One subject chosen by me ~ 1/4

Introduction: summary

- “Modern” physics is relevant for technology
- Main motivation for this course: understand solid-state devices based on semiconductors
- Conduction:
  - Classical theory is not adequate: need quantum concepts
- In this course:
  - Simplified approach to semiconductors as an introduction
  - Basic Quantum Mechanics
  - Semiconductors revisited

Semiconductors: an introduction

Lecture 1

Course Outline - Reminder

- The physics of semiconductor devices: an introduction
  - Basic properties; energy bands, density of states (*this lecture*)
  - Equilibrium carrier concentration (“intrinsic”, “extrinsic”)
  - Carrier transport phenomena
    - Drift and Diffusion
    - Generation and Recombination
    - Continuity equations
- Quantum Mechanics: an introduction
- Advanced semiconductor fundamentals

Outline – Lecture 1

- Basic semiconductor properties
  - Semiconductor materials
  - Crystal structure
  - Valence bonds model
  - Energy bands model

Semiconductor materials

Insulators, semiconductors, conductors

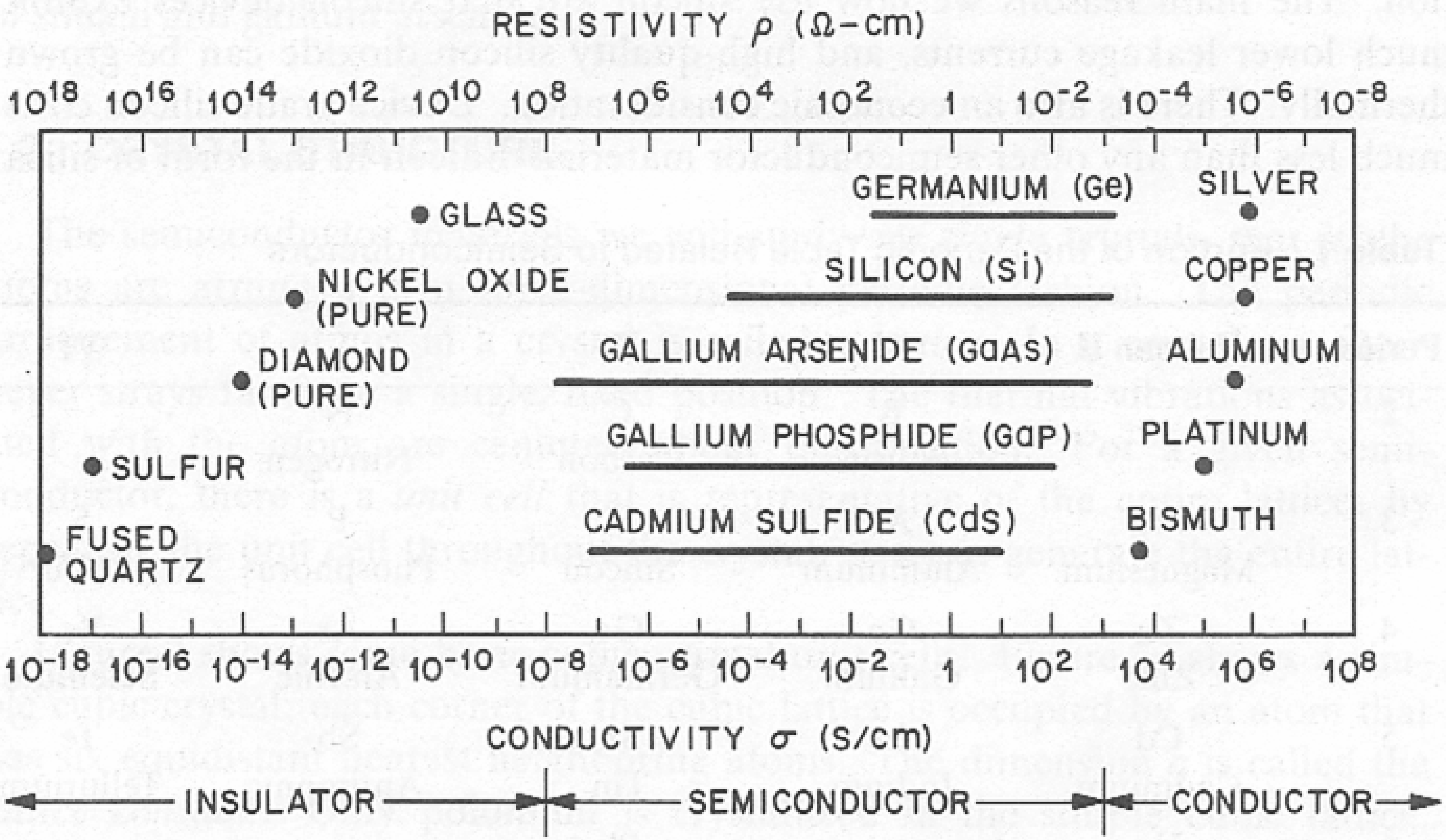


Fig. 1 Typical range of conductivities for insulators, semiconductors, and conductors.

(from SZE, fig.1-1)

Resistivity ρ, conductivity σ

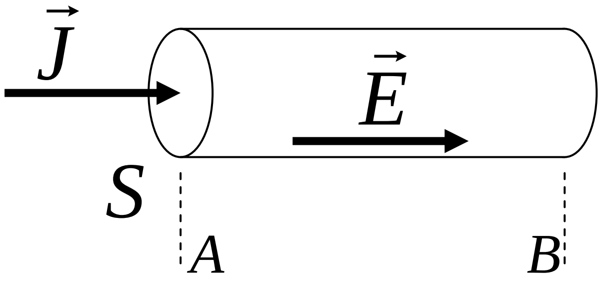
- Recall definitions: Ohm's law

$$\boxed{\vec{J} = \sigma\vec{E}}$$

$$I = \frac{\Delta V}{R} \qquad \Delta V = RI$$

$$R = \rho\frac{\Delta x}{S}, \quad I = \left(\vec{J}\bullet\hat{n}\right)S = JS$$

$$\Rightarrow \Delta V = \rho\frac{\Delta x}{S}JS = \rho J\Delta x$$



$$\Delta V = V_B - V_A < 0$$

$$\Delta x = x_B - x_A > 0$$

Current Density J

$$|J| = \frac{1}{\rho}\left|\frac{\Delta V}{\Delta x}\right| = \frac{1}{\rho}|E| = \sigma|E|$$

Electric Field E

Resistivity
Ω cm

Conductivity
S cm^{-1}

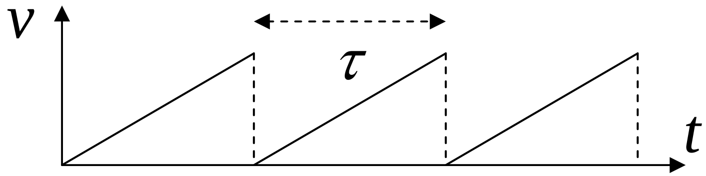
$$\boxed{\begin{aligned}\vec{E} &= -\vec{\nabla}V \\ E_x &= -\frac{dV}{dx}\end{aligned}}$$

Electric Potential V

Naïve microscopic interpretation

- Classical interpretation of Ohm's law:
  - Some electrons move "almost freely" in conductors
  - They are subject to some sort of "collision" on atoms (not clear how!)
  - Simplified picture:
    - electrons are accelerated by the external field E
    - on average, at *time intervals* τ electrons collide and "stop"
    - the kinetic energy gained due to E is dissipated as "heat"
    - The net resulting motion is a "drift" with *average velocity v*

$$\boxed{q_e = -|q|}$$



average drift velocity

mobility μ $cm^2 / (V\ s)$

$$v = a\tau = -\frac{|q|E}{m}\tau = -\boxed{\frac{|q|\tau}{m}}E = -\mu E \qquad \Rightarrow \qquad \tau = \frac{\mu m}{q}$$

$$J = -|q|nv = \boxed{|q|n\mu}E = \sigma E \qquad \Rightarrow \qquad \mu = \frac{\sigma}{|q|n} \qquad \Rightarrow \qquad \tau = \frac{\sigma m}{q^2 n}$$

Exercise 1.1: check dimensions and units for resistivity, conductivity, mobility

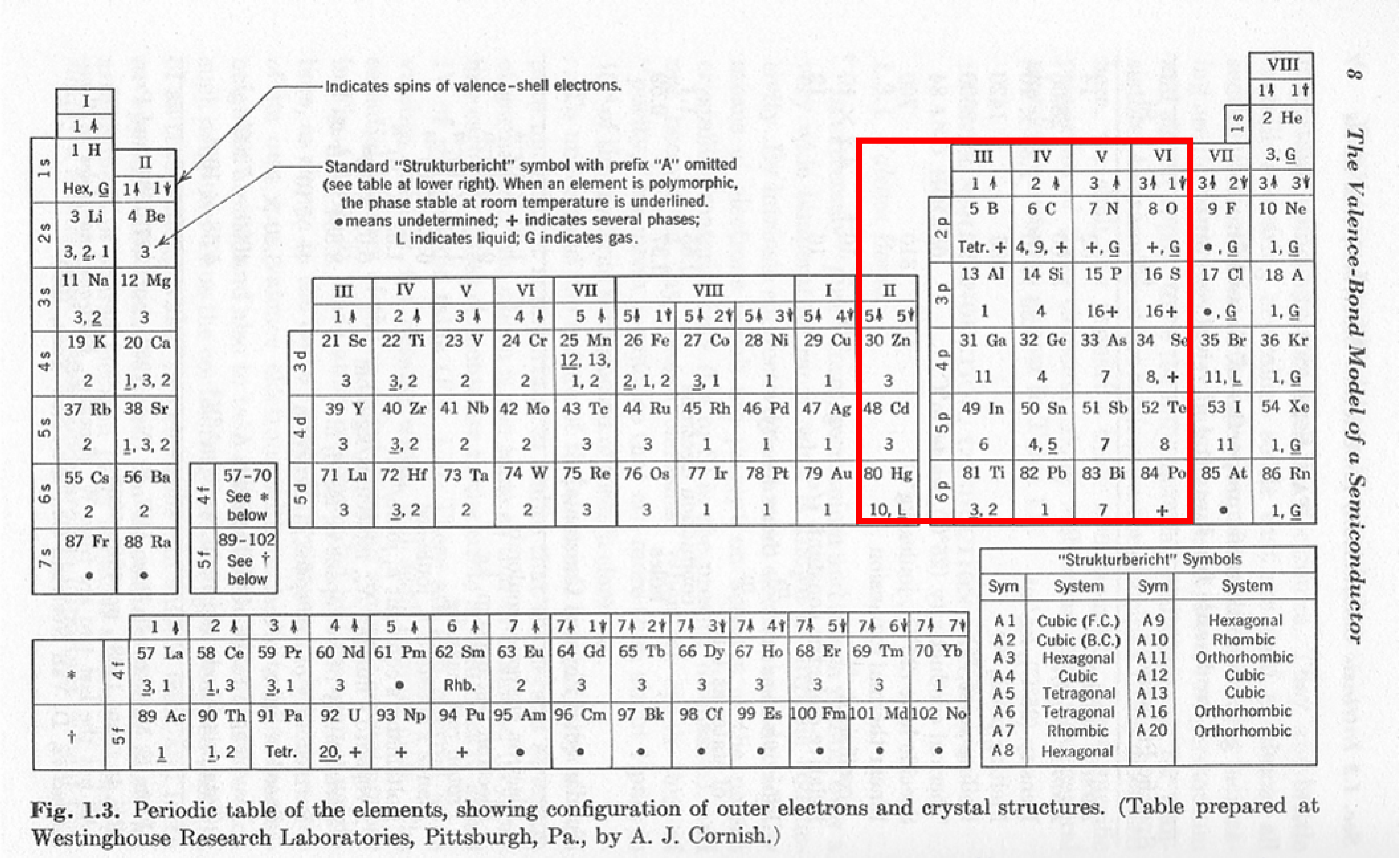
Several mysteries…

- The simplified picture is appealing and defines quantities (drift velocity, mobility) that can be indirectly measured and used to characterize materials, but:
  - Why do different materials behave differently?
  - Dependence on temperature in this model: completely wrong!
  - Computing the *"mean free path"* λ of electrons: surprise! much larger than the *average distance d* between atoms!

$$\lambda = v_{drift} \tau_{collision}$$

⇒ **Exercise 1.2:** for a typical conductor at room temperature, i.e. aluminum (Al): $\sigma = 4 \times 10^5\ (\Omega\ \mathrm{cm})^{-1}$), compare the drift velocity for a typical applied field with the thermal velocity, and find the orders of magnitude of μ, τ and λ

Periodic table of the elements



Indicates spins of valence-shell electrons.

Standard "Strukturbericht" symbol with prefix "A" omitted (see table at lower right). When an element is polymorphic, the phase stable at room temperature is underlined.
● means undetermined; + indicates several phases;
L indicates liquid; G indicates gas.

	I	II
	1 ↑	
1s	1 H Hex, G	II 1↑ 1↓
2s	3 Li 3, 2, 1	4 Be 3
3s	11 Na 3, 2	12 Mg 3
4s	19 K 2	20 Ca 1, 3, 2
5s	37 Rb 2	38 Sr 1, 3, 2
6s	55 Cs 2	56 Ba 2
7s	87 Fr ●	88 Ra ●

4f	57–70 See * below
5f	89–102 See † below

	III	IV	V	VI	VII	VIII			I	II
	1 ↑	2 ↑	3 ↑	4 ↑	5 ↑	5↑ 1↓	5↑ 2↓	5↑ 3↓	5↑ 4↓	5↑ 5↓
3d	21 Sc 3	22 Ti 3, 2	23 V 2	24 Cr 2	25 Mn 12, 13, 1, 2	26 Fe 2, 1, 2	27 Co 3, 1	28 Ni 1	29 Cu 1	30 Zn 3
4d	39 Y 3	40 Zr 3, 2	41 Nb 2	42 Mo 2	43 Tc 3	44 Ru 3	45 Rh 1	46 Pd 1	47 Ag 1	48 Cd 3
5d	71 Lu 3	72 Hf 3, 2	73 Ta 2	74 W 2	75 Re 3	76 Os 3	77 Ir 1	78 Pt 1	79 Au 1	80 Hg 10, L

	III	IV	V	VI	VII	VIII
						1↑ 1↓
1s						2 He 3, G
	1 ↑	2 ↑	3 ↑	3↑ 1↓	3↑ 2↓	3↑ 3↓
2p	5 B Tetr. +	6 C 4, 9, +	7 N +, G	8 O +, G	9 F ●, G	10 Ne 1, G
3p	13 Al 1	14 Si 4	15 P 16+	16 S 16+	17 Cl ●, G	18 A 1, G
4p	31 Ga 11	32 Ge 4	33 As 7	34 Se 8, +	35 Br 11, L	36 Kr 1, G
5p	49 In 6	50 Sn 4, 5	51 Sb 7	52 Te 8	53 I 11	54 Xe 1, G
6p	81 Ti 3, 2	82 Pb 1	83 Bi 7	84 Po +	85 At ●	86 Rn 1, G

		1 ↑	2 ↑	3 ↑	4 ↑	5 ↑	6 ↑	7 ↑	7↑ 1↓	7↑ 2↓	7↑ 3↓	7↑ 4↓	7↑ 5↓	7↑ 6↓	7↑ 7↓
*	4f	57 La 3, 1	58 Ce 1, 3	59 Pr 3, 1	60 Nd 3	61 Pm ●	62 Sm Rhb.	63 Eu 2	64 Gd 3	65 Tb 3	66 Dy 3	67 Ho 3	68 Er 3	69 Tm 3	70 Yb 1
†	5f	89 Ac 1	90 Th 1, 2	91 Pa Tetr.	92 U 20, +	93 Np +	94 Pu +	95 Am ●	96 Cm ●	97 Bk ●	98 Cf ●	99 Es ●	100 Fm ●	101 Md ●	102 No ●

"Strukturbericht" Symbols

Sym	System	Sym	System
A 1	Cubic (F.C.)	A 9	Hexagonal
A 2	Cubic (B.C.)	A 10	Rhombic
A 3	Hexagonal	A 11	Orthorhombic
A 4	Cubic	A 12	Cubic
A 5	Tetragonal	A 13	Cubic
A 6	Tetragonal	A 16	Orthorhombic
A 7	Rhombic	A 20	Orthorhombic
A 8	Hexagonal		

Fig. 1.3. Periodic table of the elements, showing configuration of outer electrons and crystal structures. (Table prepared at Westinghouse Research Laboratories, Pittsburgh, Pa., by A. J. Cornish.)

(from ADL, Fig1-3)

Periodic table and semiconductors

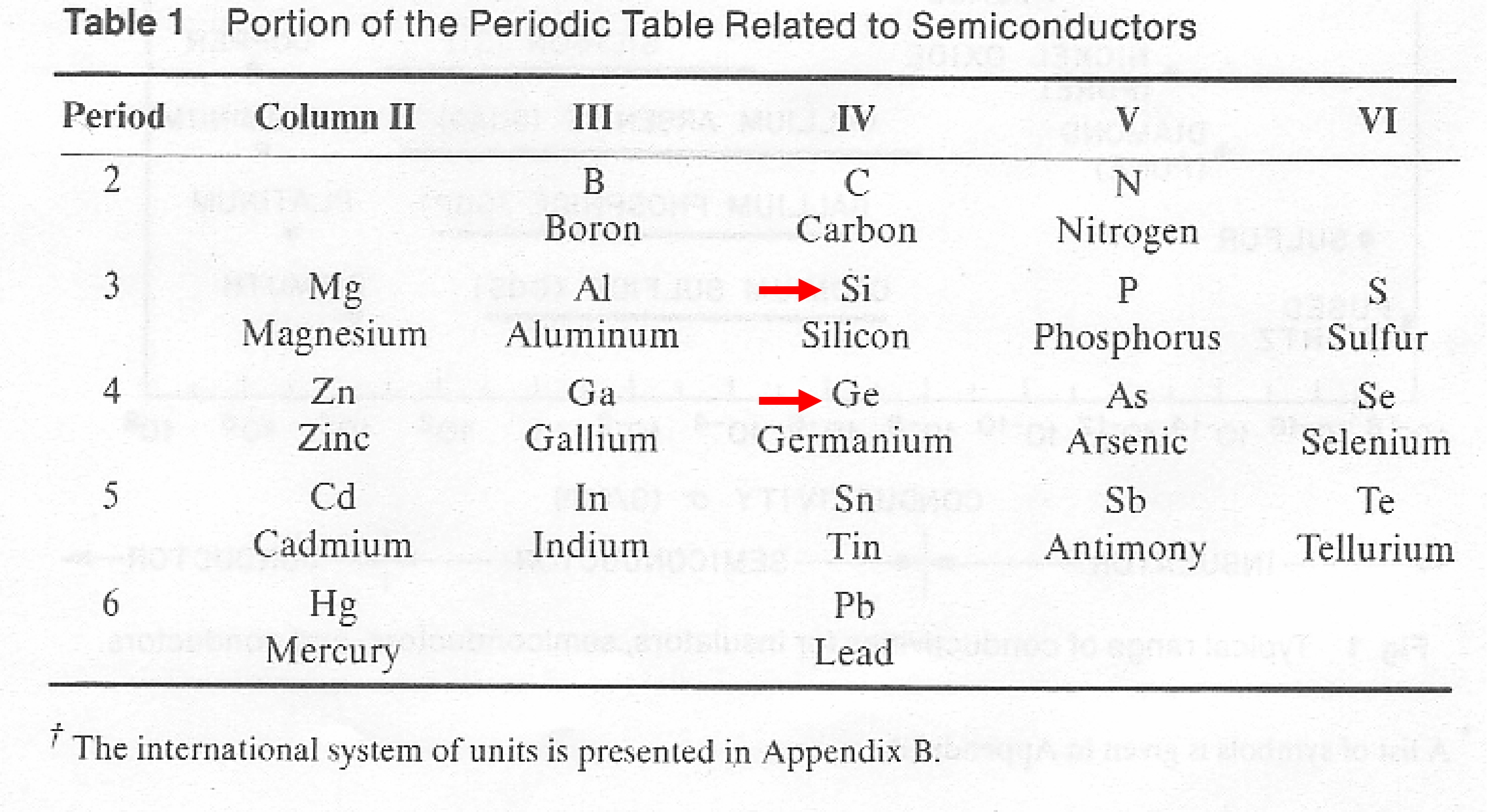


Table 1 Portion of the Periodic Table Related to Semiconductors

Period	Column II	III	IV	V	VI
2		B Boron	C Carbon	N Nitrogen	
3	Mg Magnesium	Al Aluminum	→ Si Silicon	P Phosphorus	S Sulfur
4	Zn Zinc	Ga Gallium	→ Ge Germanium	As Arsenic	Se Selenium
5	Cd Cadmium	In Indium	Sn Tin	Sb Antimony	Te Tellurium
6	Hg Mercury		Pb Lead		

† The international system of units is presented in Appendix B.

(from SZE, Table1-1)

Element and compound semiconductors

Practical considerations: most frequently used in standard devices:

- (Ge)… Si, GaAs

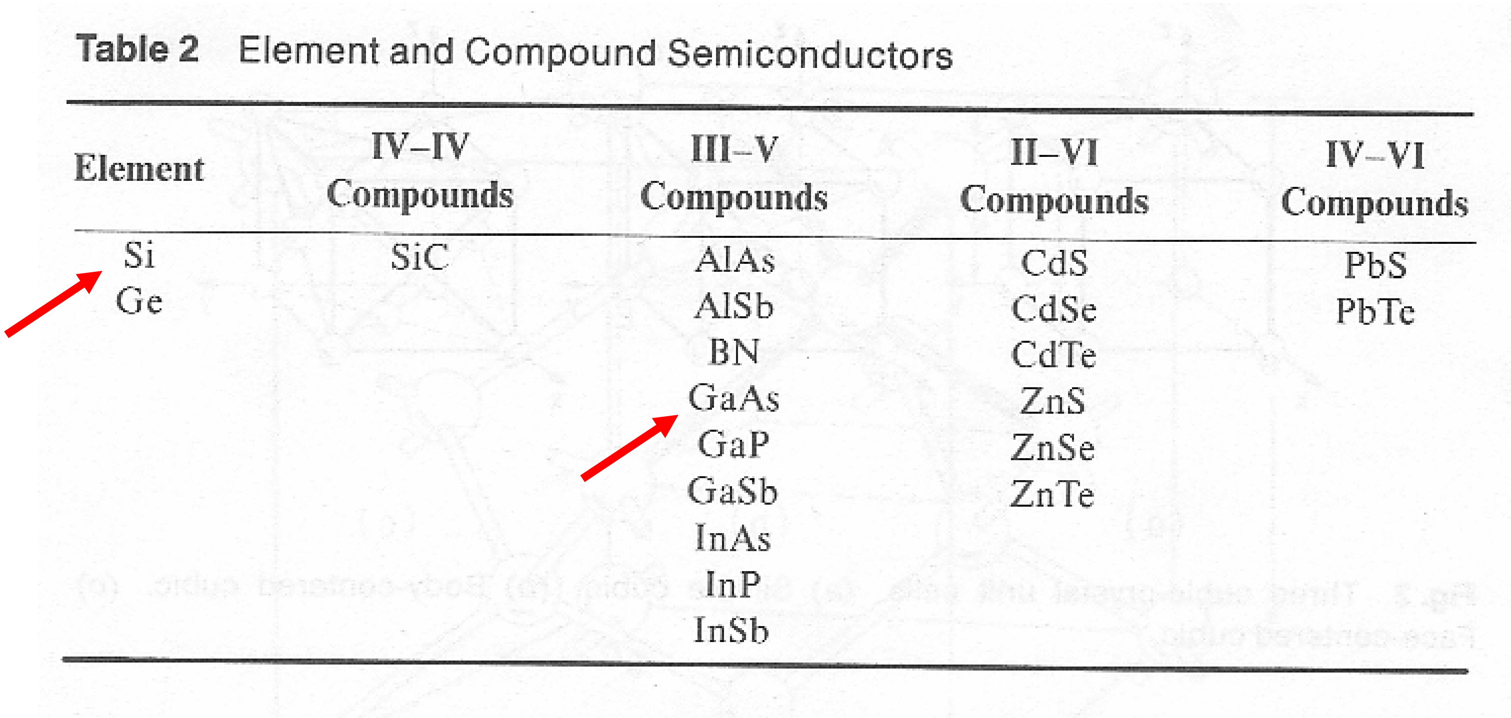


Table 2 Element and Compound Semiconductors

Element	IV–IV Compounds	III–V Compounds	II–VI Compounds	IV–VI Compounds
Si	SiC	AlAs	CdS	PbS
Ge		AlSb	CdSe	PbTe
		BN	CdTe	
		GaAs	ZnS	
		GaP	ZnSe	
		GaSb	ZnTe	
		InAs		
		InP		
		InSb		

(from SZE, Table1-2)

Crystal structure

Crystal lattice and unit cell

- Two-dimensional periodic arrangement of atoms

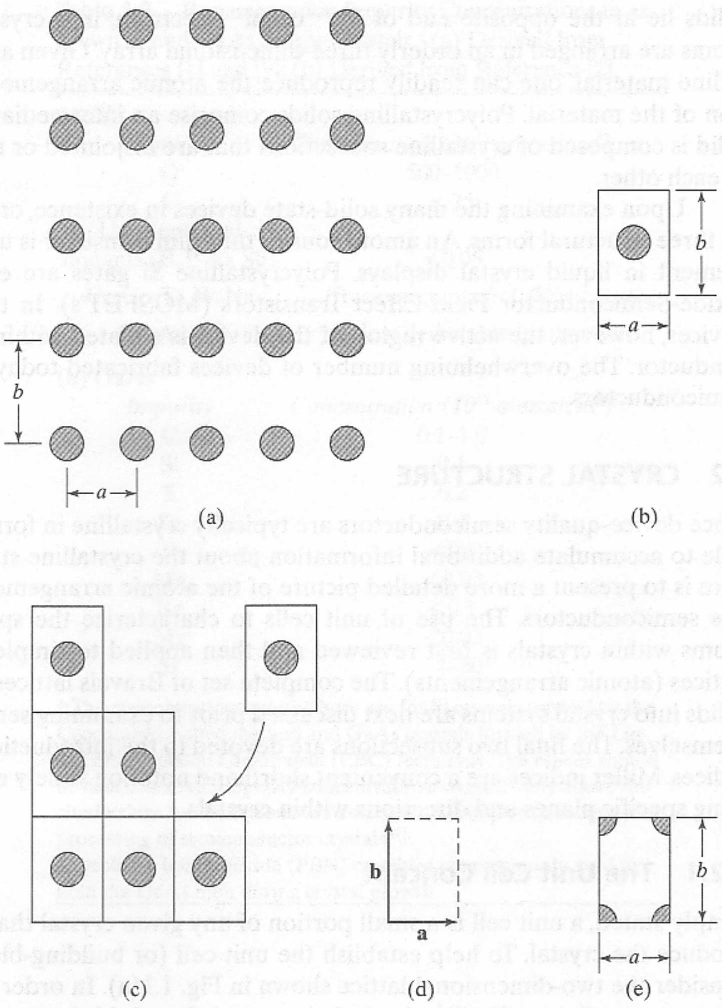


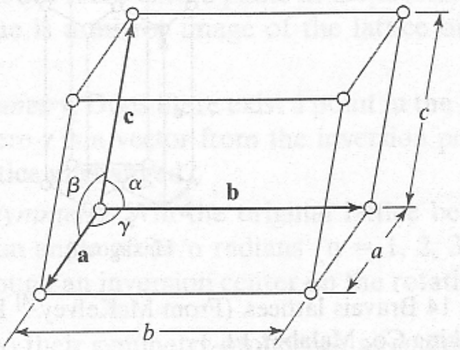
Figure 1.1 Introduction to the unit cell method of describing atom arrangements within crystals. (a) Sample two-dimensional lattice. (b) Unit cell corresponding to the part (a) lattice. (c) Reproduction of the original lattice. (d) Basis vectors. (e) An alternative unit cell.

(from PIER, Fig.1-1)

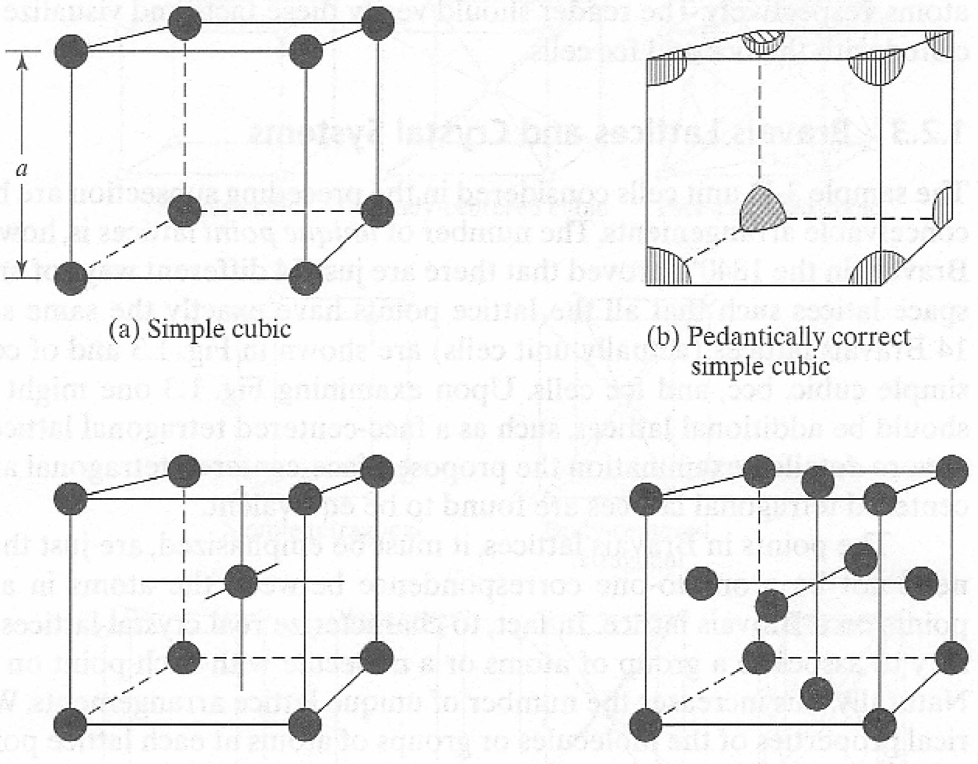
Crystal lattice and unit cell

Three-dimensional periodic arrangement of atoms; an example

Crystallography:
classification
of all possible
configurations
(14 Bravais cells,
230 possible patterns)



(from PIER, Fig.1-4)



(a) Simple cubic

(b) Pedantically correct simple cubic

(c) bcc

(d) fcc

Figure 1.2 Simple three-dimensional unit cells. (a) Simple cubic unit cell. (b) Pedantically correct simple cubic unit cell including only the fractional portion (1/8) of each corner atom actually within the cell cube. (c) Body-centered cubic unit cell. (d) Face-centered cubic unit cell (After Pierret.[3])

(from PIER, Fig.1-2)

Si and GaAs unit cells

“Diamond lattice”: Si, Ge

Lattice constant: a = 5.43 Å (Si)
a = 5.64 Å (Ge)

Exercise 1.3:
What is the distance between nearest neighbours in Si crystals?

“Zincblende lattice”: GaAs

Lattice constant: a = 5.63 Å (GaAs)

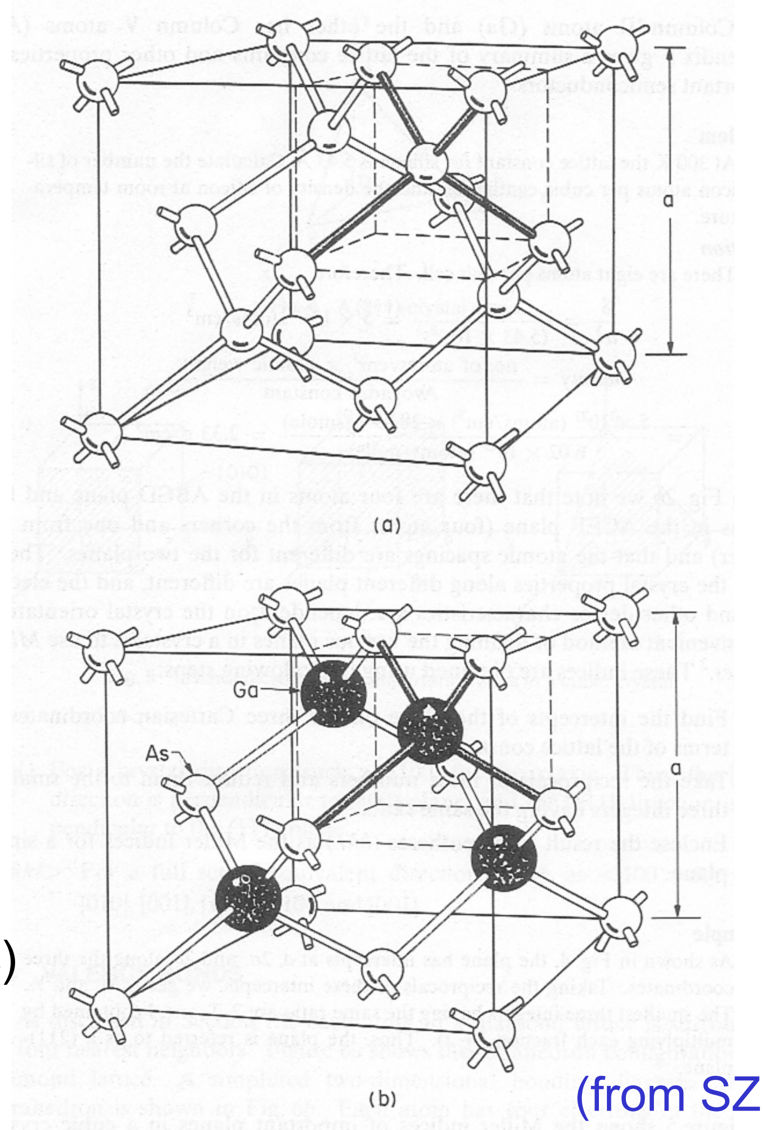


Fig. 3 (*a*) Diamond lattice. (*b*) Zincblende lattice.

(from SZE, fig.1-3)

Miller indices

- Miller indices (i j k)
    - Intercepts of the plane on the three cartesian axes, in units of lattice constants
    - Reciprocals, reduced to the smallest integers having the same ratio
- Other conventions and "Wafer flats"
    - See "advanced" topics

- On planes of different orientation in the crystal:
    - Different number of atoms and atom spacing
    - Different crystal properties (mechanical, electrical)

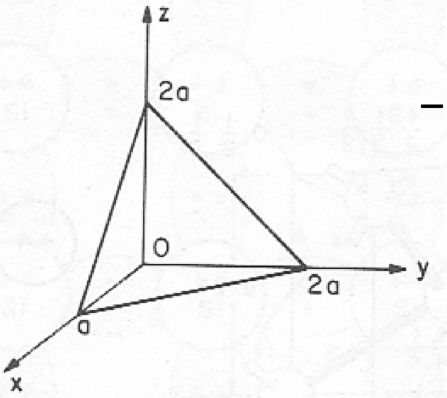


Fig. 4 A (211)-crystal plane.

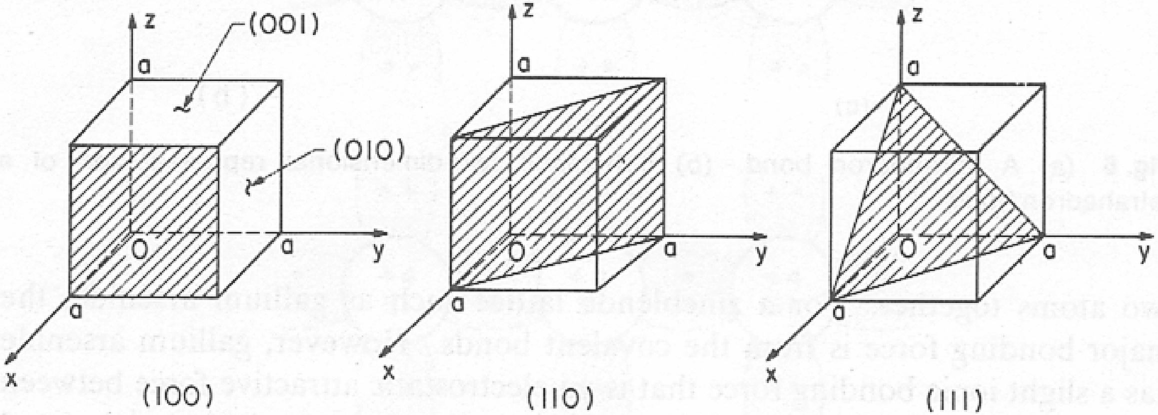


Fig. 5 Miller indices of some important planes in a cubic crystal.

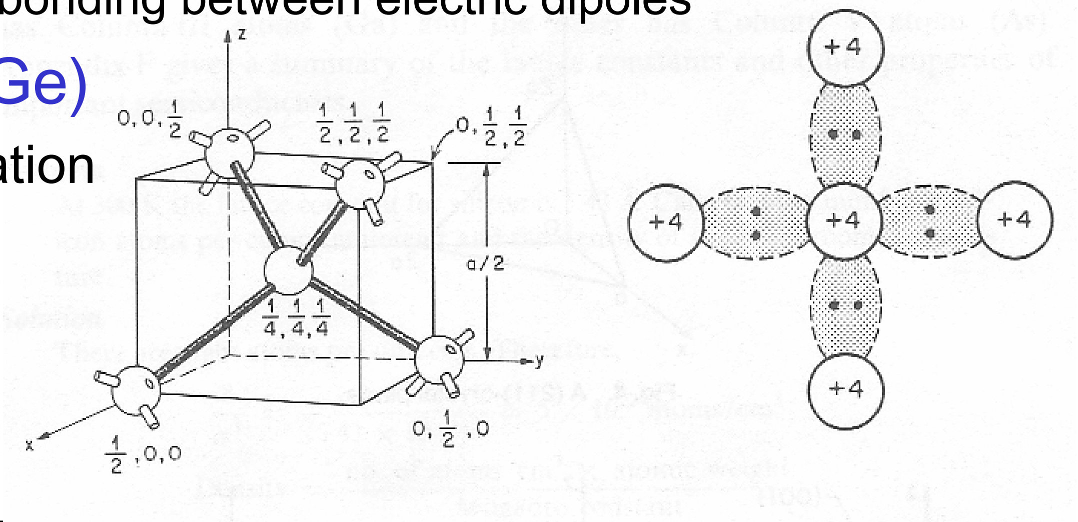
Exercise 1.4:
If a plane has intercepts 2a, 3a, 4a along the three axes, find its Miller indices

Exercise 1.5:
Find the number of atoms Per cm^2 in Si in the (100), (110), and (111) planes

Valence bonds model

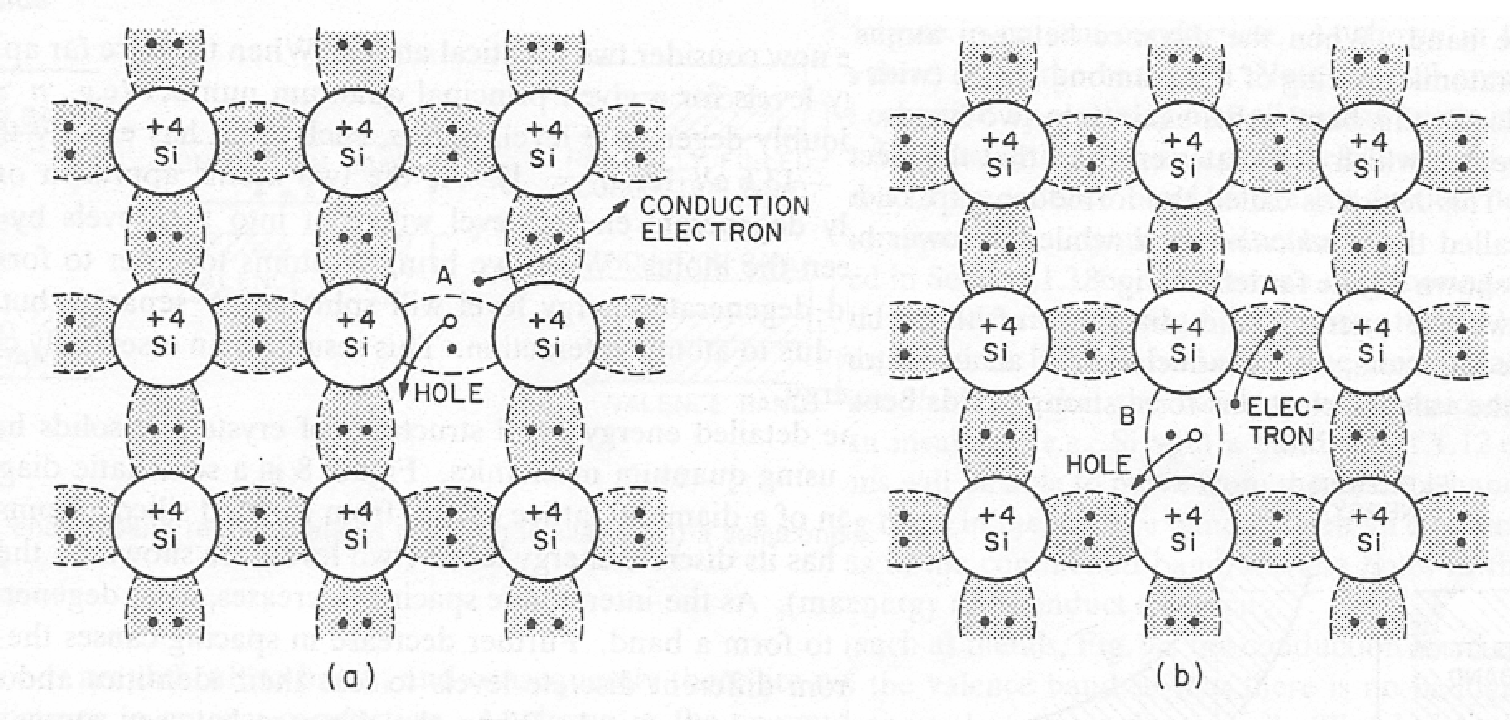
Atoms bonding

- Classification (recall from Chemistry courses?)
  - Ionic: "low affinity": lose electrons, "high affinity": absorb electrons; negatively and positively charged ions attract each other
  - Metallic: "sea" of loosely bound (almost free) outer electrons keep together the positive ions left behind (found in good *conductors*)
  - Covalent: energetically stable configuration with outer electrons "shared" between neighbour atoms, when "shells" fully occupied (very stable, found in *semiconductors* and *insulators*)
  - Van der Waals: weak bonding between electric dipoles
- Covalent bonds (Si, Ge)
  - Schematic representation



Broken bonds: electrons and holes

Basic bond model of “intrinsic” (= “pure”) Silicon



a broken bond at position A, resulting in a conduction electron and a “hole”

deficiency filled by one of the neighboring electrons (in B), resulting in a shift of the “hole” from A to B

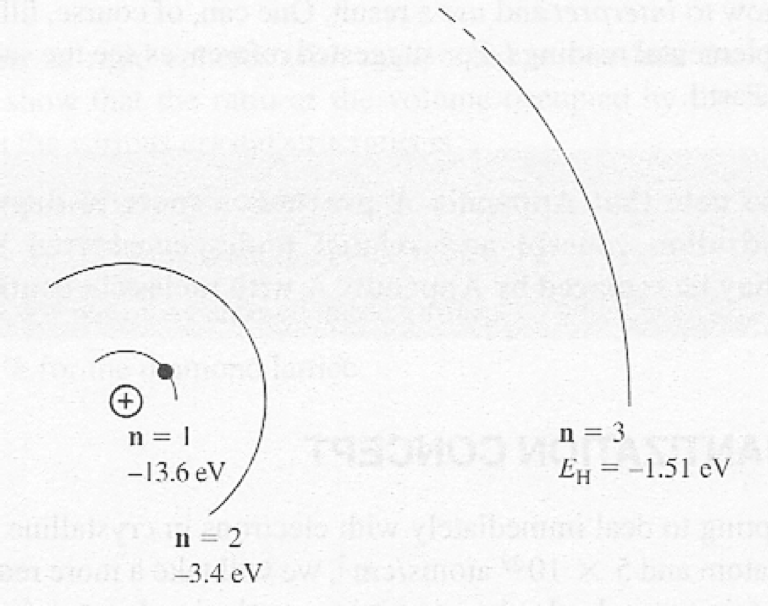
Energy band model

Isolated atoms: energy levels

Hydrogen atom (Z=1)

Idealized representation of the first three allowed Bohr orbits and their quantized energy levels

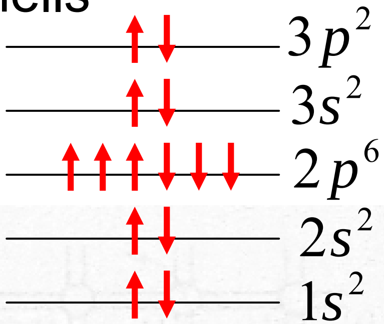
$$E_n = -\frac{13.6\,\text{eV}}{n^2}$$

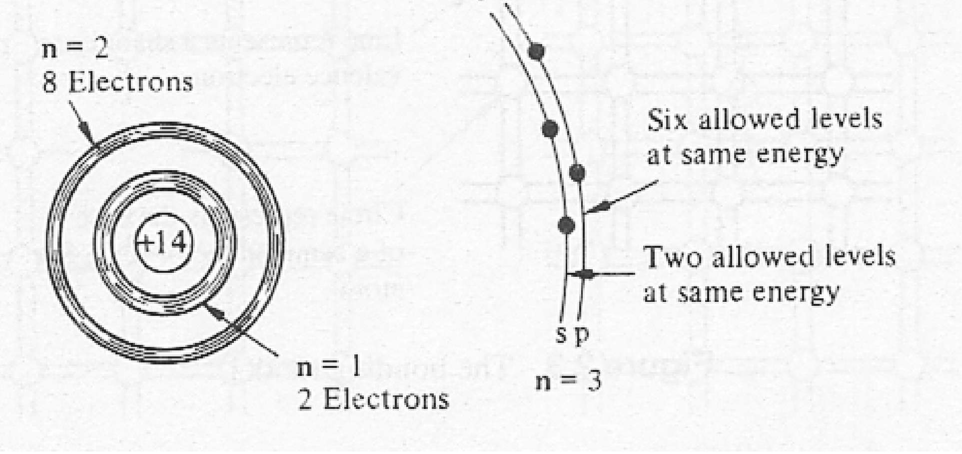


Silicon atom (Z=14)

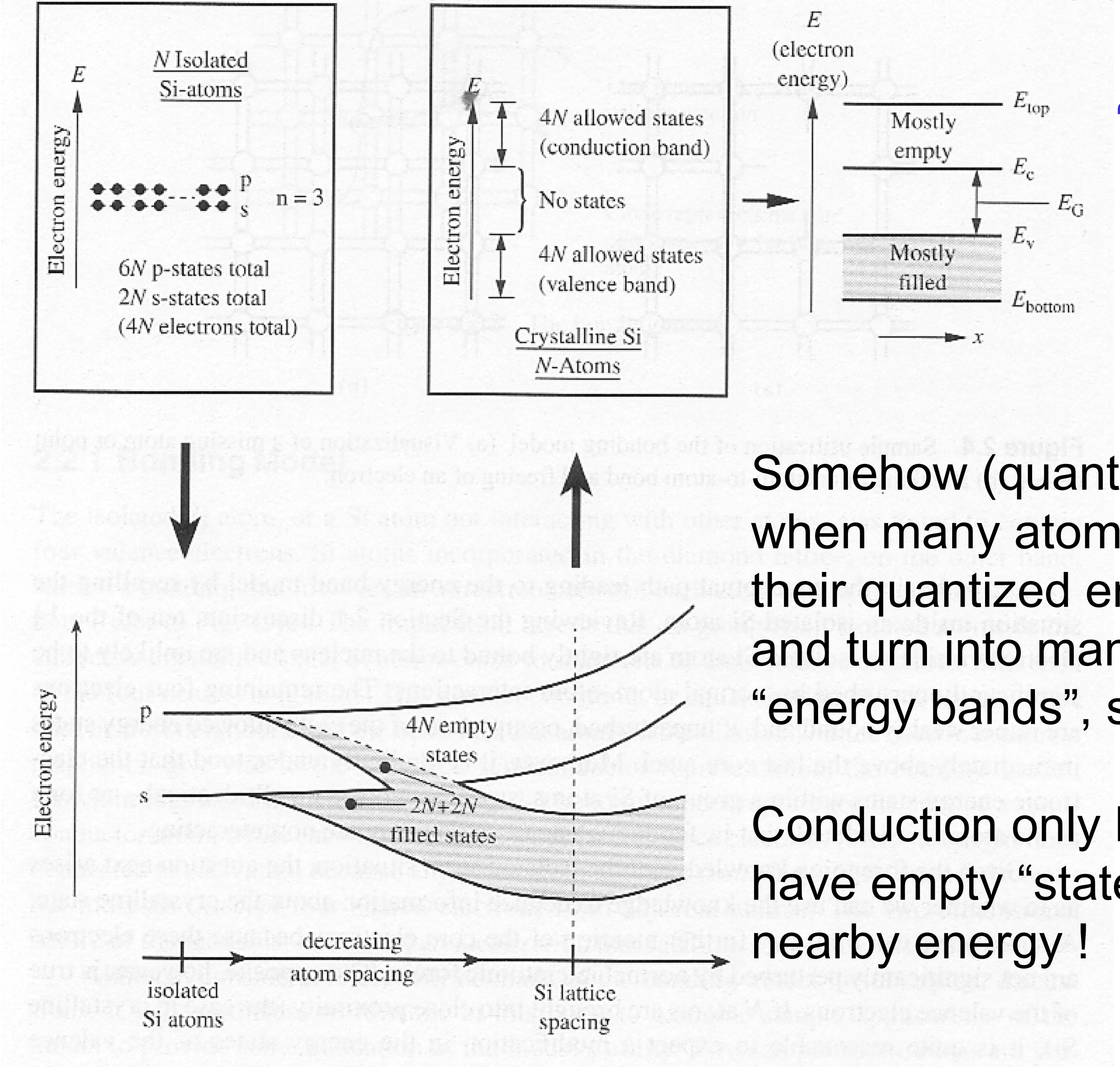
Schematic representation of how the 14 electrons fill the lowest available "shells"

4 electrons needed to complete the 3p shell





From energy levels to energy bands



“Conduction Band”

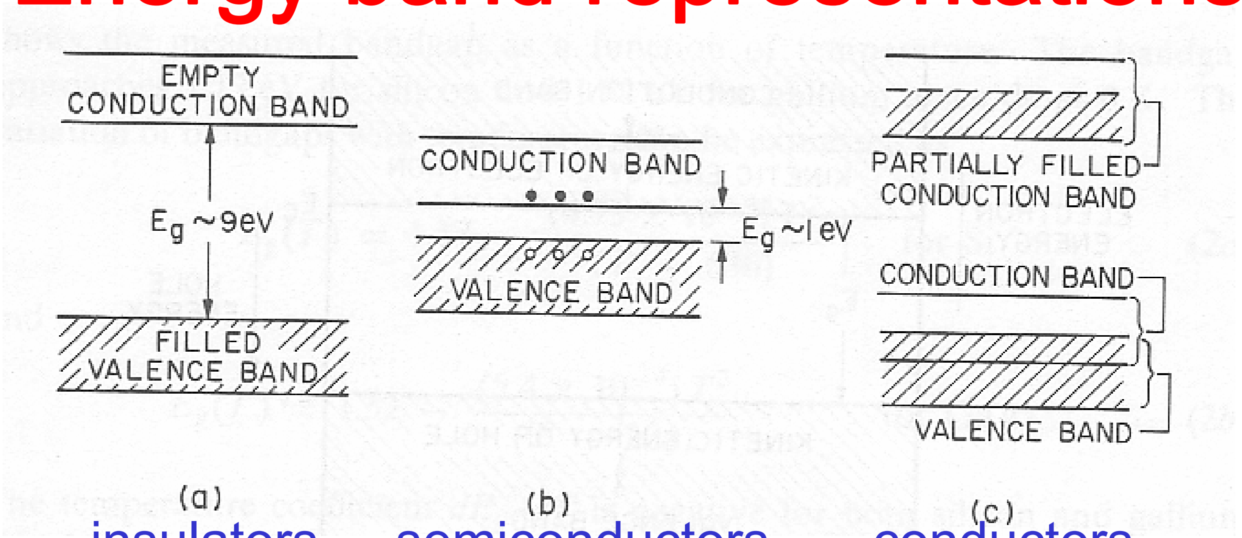
“Gap”

“Valence Band”

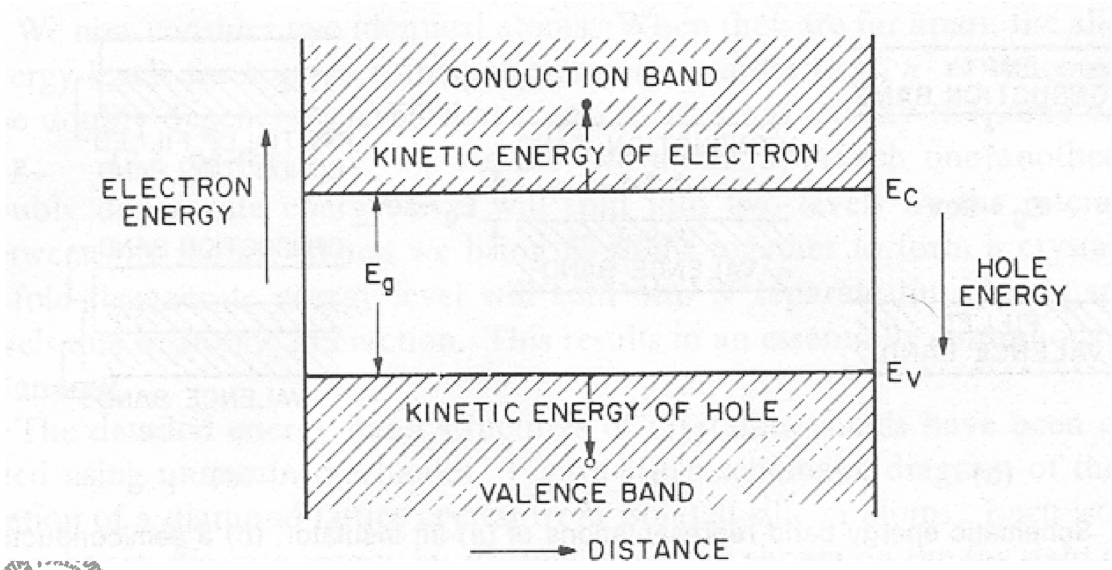
Somehow (quantum mechanics !), when many atoms get close together their quantized energy levels split and turn into many states grouped in “energy bands”, see diagrams

Conduction only happens if electrons have empty “states” available at nearby energy !

Energy band representations



insulators semiconductors conductors



kinetic energy and potential energy for electrons and holes (= for “carriers”)

Lecture 1 - summary

- Motivated by the goal of describing and understanding conduction in semiconductors for device applications, we introduced (or recalled):
  - Resistivity, conductivity, electron mobility, average collision time, mean free path between collisions
  - Some rudiments of crystallography, Miller indices
  - The bond model of semiconductors and of the mechanism of conduction by electrons and holes (together: “carriers”)
  - The energy band model and its qualitative characterization of electrons and holes energies
- Next steps (extended to semiconductors with impurities):
  - Quantitative description of the density of states available for carriers, their population, their kinematical properties;
  - Then: carrier transport phenomena (drift, diffusion, generation, recombination; transport equations) relevant for conduction, and their relations with measurable quantities

Lecture 1 – Items to be understood…

- Many items require a deeper explanation!
  - What is the nature of the collisions of electrons in crystals?
  - Can one predict mobilities, free path etc. for different materials and temperatures?
  - What is the logic behind the Periodic Table? Why do element semiconductors belong to column IV of the Table ?
  - How do we know the arrangement of atoms in crystals?
  - What is the explanation/prediction for different types of bonds? Why are covalent bonds directional?
  - Why only some energy levels are permitted in an atom?
  - What is the origin of energy bands? Can they be computed using first principles? How does one measure them in the laboratory?
  - Etc… (add your own questions: “perche`…?” !)

Lecture 1 - Glossary

Introduction

amplifier	amplificatore	
particle	particella	
wave	onda	
semiconductor	semiconduttore	
conduction	conduzione	
quantum well	pozzo quantistico	
quantum dot	punto quantistico	
passivation	passivazione	
doping	drogaggio	
power	potenza	
work	lavoro	
diffraction	diffrazione	

Basic properties…

resistivity	resistivita`	
conductivity	conducibilita`	
mobility	mobilita`	
mean free path	cammino libero medio	
lattice	reticolo	
drift	deriva	
diffusion	diffusione	
valence	valenza	
conduction	conduzione	
bond	legame	
energy band	banda energetica	
hole	lacuna	
carrier	portatore	

Lecture 1 - exercises

- Exercise 1.1: review dimensions and units for the electric field and electric potential; check the dimensions and units given for resistivity, conductivity, mobility.
- Exercise 1.2: for a typical conductor at room temperature, (i.e. aluminum (Al): $\sigma = 4 \times 10^5\ (\Omega\ \text{cm})^{-1}$), compare the thermal velocity with the drift velocity for a typical applied electric field, and find the orders of magnitude of μ, τ and λ
- Exercise 1.3: What is the distance between nearest neigbours in Si crystals?
- Exercise 1.4: If a plane has intercepts 2a, 3a, 4a along the three axes, find its Miller indices.
- Exercise 1.5: Find the number of atoms per cm^2 in Si in the (100), (110), and (111) planes.