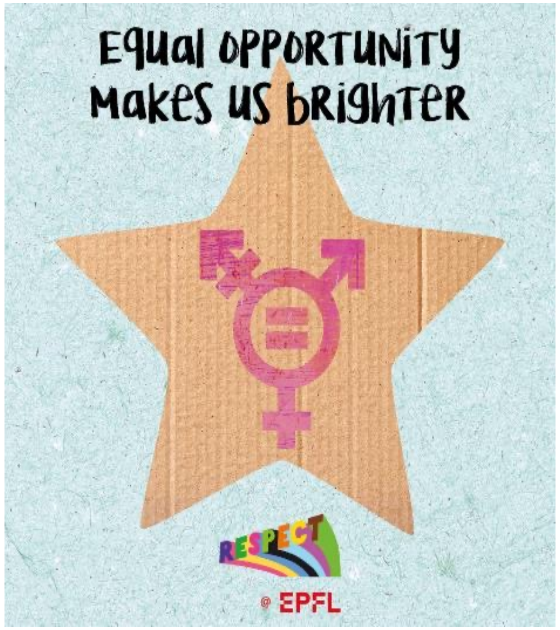
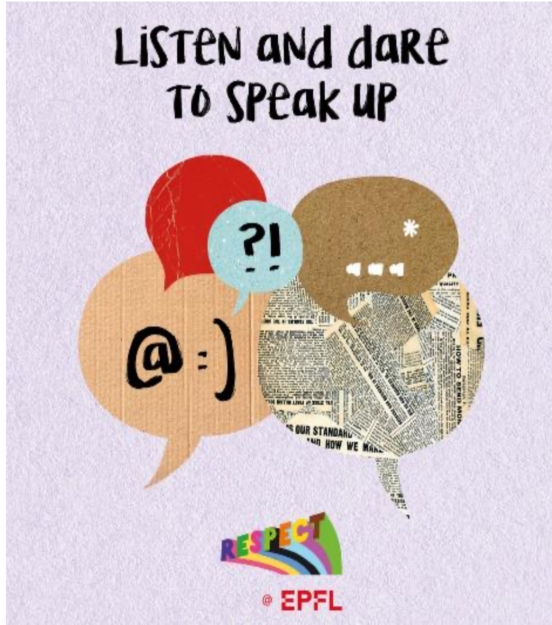
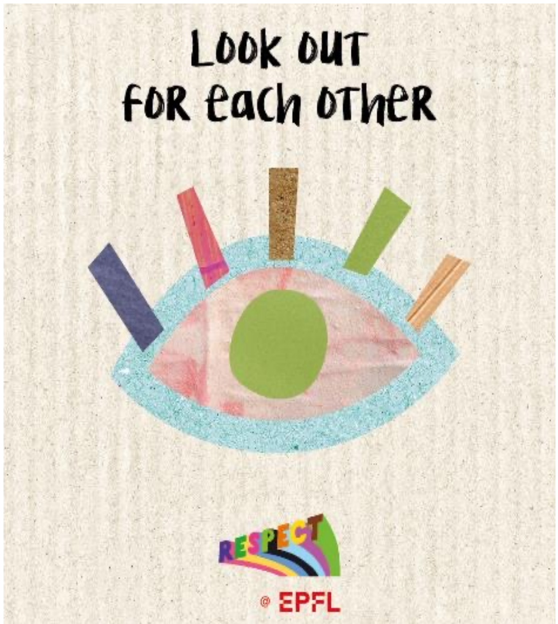
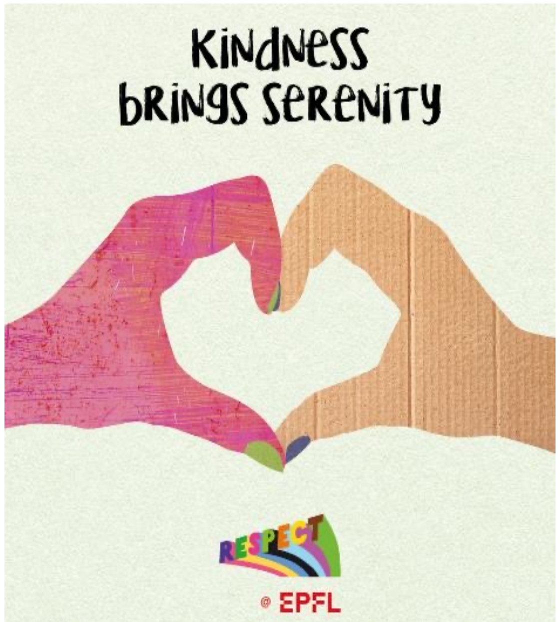
EPFL

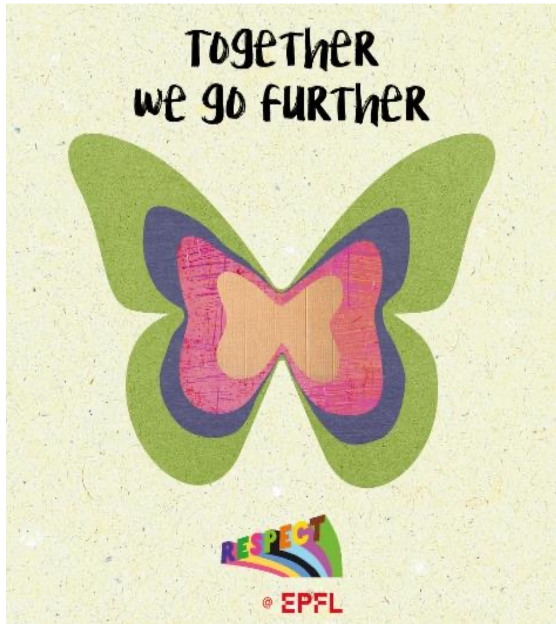

Equal opportunity
makes us brighter
RESPECT
EPFL


Diversity is
our strength
RESPECT
EPFL


Listen and dare
to speak up
?!
@ :)
RESPECT
EPFL


Look out
for each other
RESPECT
EPFL


Kindness
brings serenity
RESPECT
EPFL


Together
we go further
RESPECT
EPFL

EE-557
Semiconductor devices I

Doping and carrier concentration

Génie Electrique et Electronique
Master program
Prof. Elison Matioli

Outline of the lecture

1. Carrier concentration
2. Doping
3. Determining Fermi level

Read Chapter 2 of the reference book

References:

- J. A. del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/)
- C. Kittel, Introduction to Solid State Physics, John Wiley & Sons, 2005

Announcements

Exercise list 1 is online! Please try to solve it… next week we will solve it in class

This Friday there is a GREAT seminar about the **history of light emitters**:

IEM Distinguished Lecturers Seminar: The Search for Efficient Visible Light Emitters: Past, Present, Future

Event details

Date	06.10.2023
Hour	13:15 › 14:00
Speaker	Prof. Claude Weisbuch Materials Department, University of California, USA & Laboratoire de Physique de la Matière Condensée, École Polytechnique, CNRS, Institut Polytechnique de Paris, France
Location	ELA 2 Online
Category	Conferences - Seminars
Event Language	English

Summary of last lecture

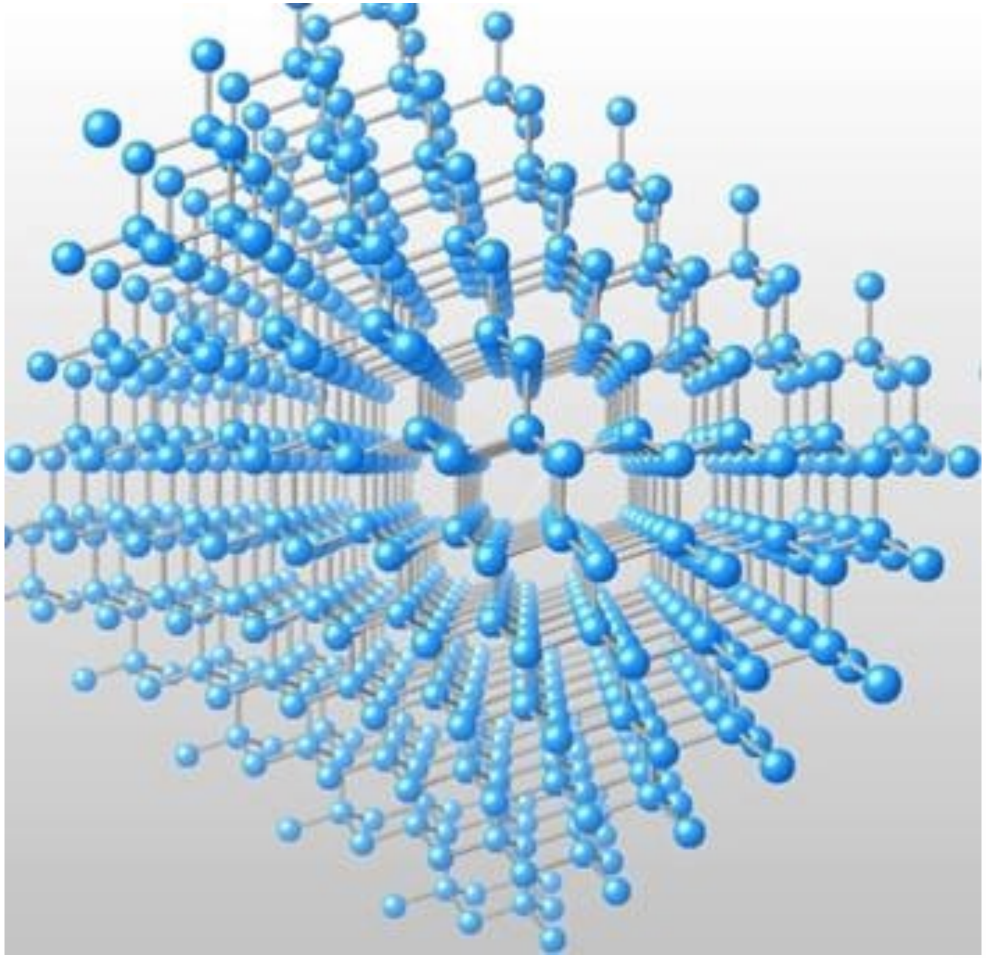
Key questions

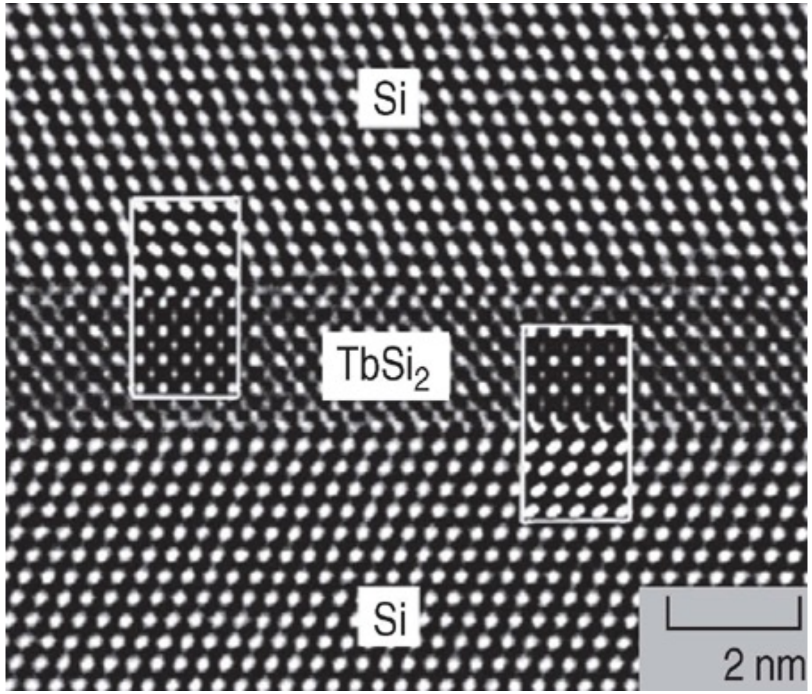
- What is doping?
- Where is the Fermi level in a doped semiconductor?

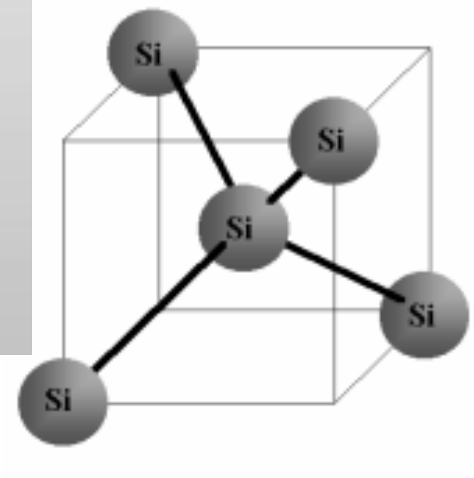
EPFL

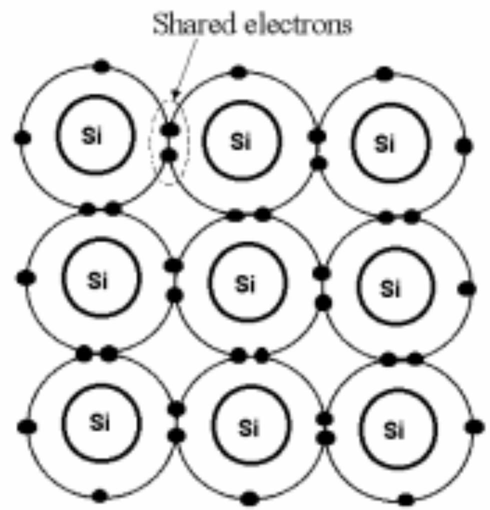
Intrinsic Silicon

$\rho = 3.2 \times 10^3 \ \Omega m$





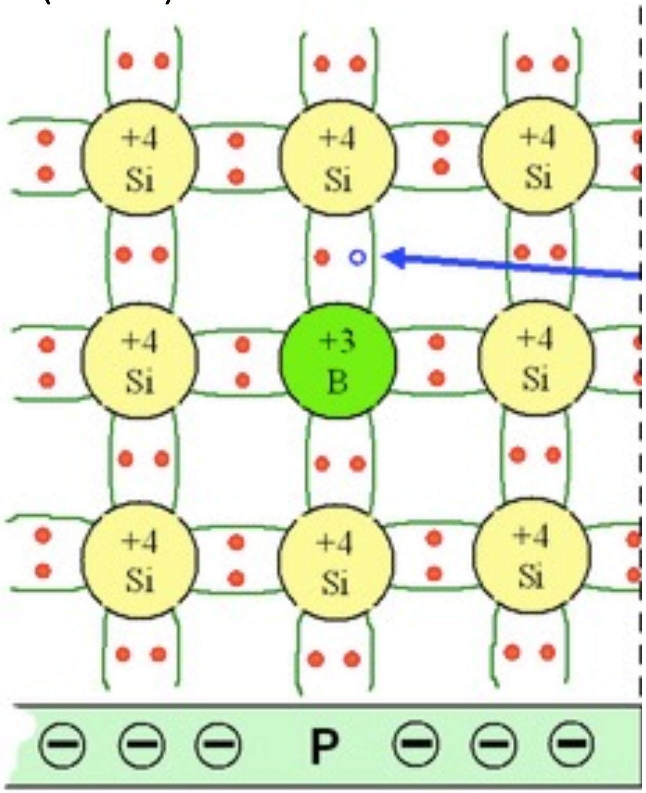


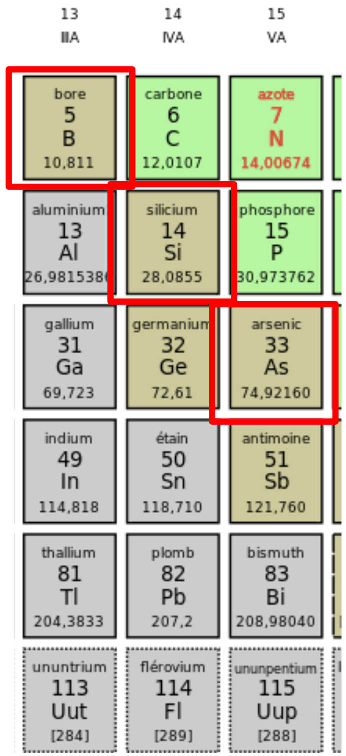


Doping

P-type doping with acceptors (Boron)

Silicon p-type:

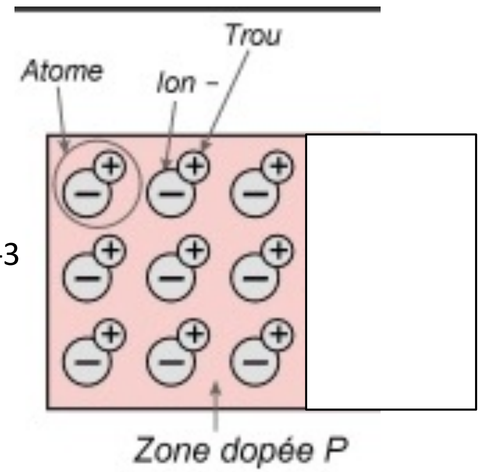


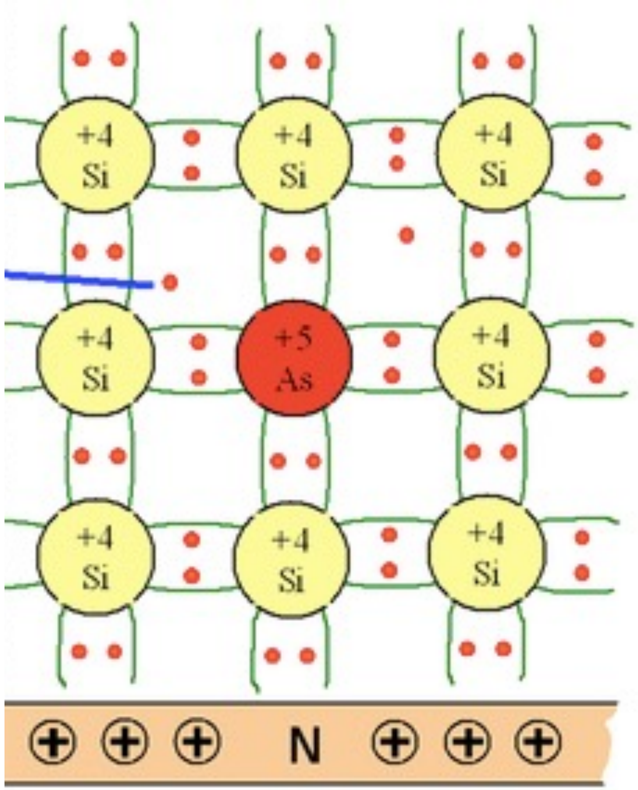


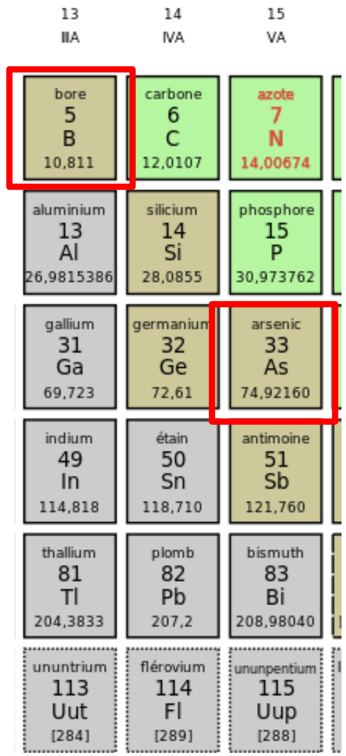
Silicon p-type:

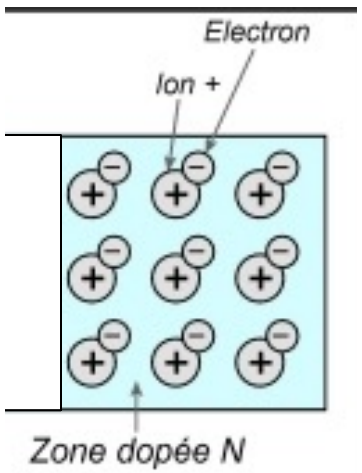
Concentration B = 10^{18} cm^{-3}

ρ = 0.04 Ωcm = 4×10^{-4} Ωm







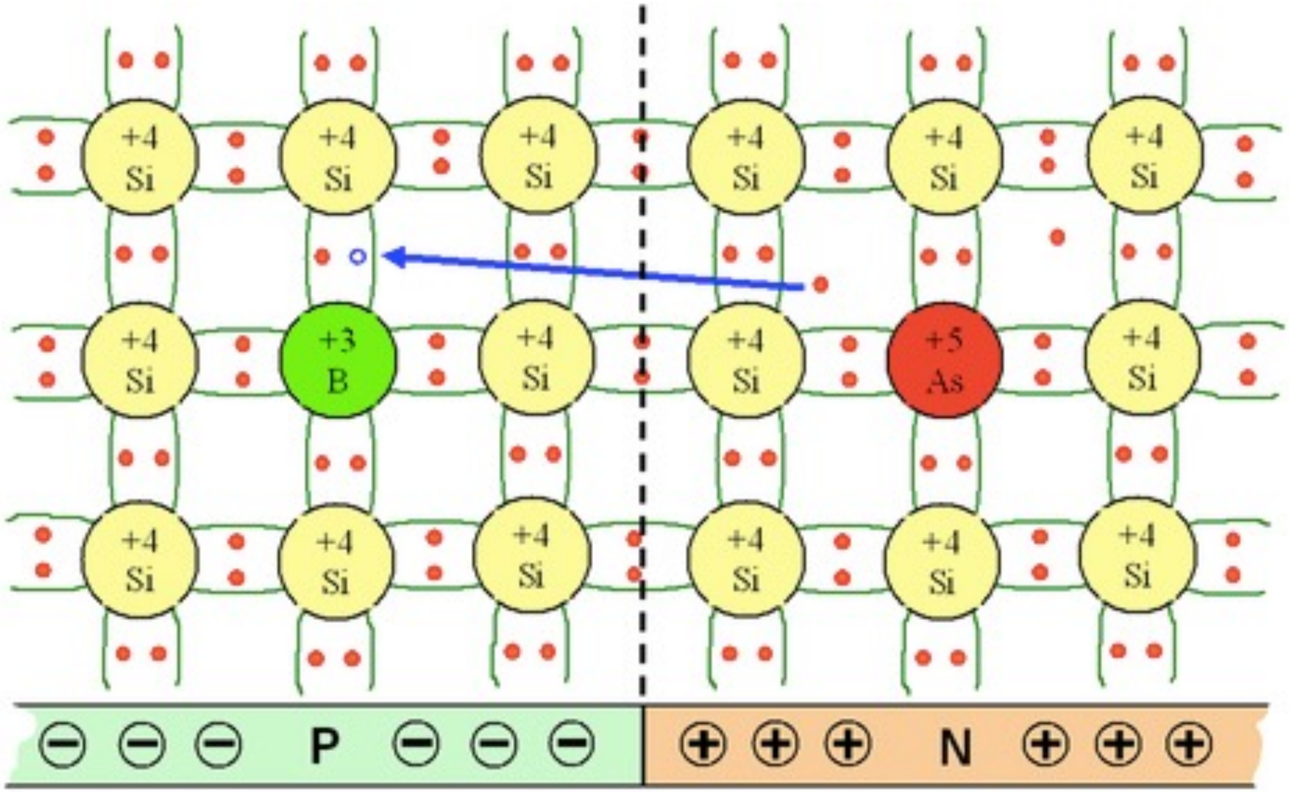


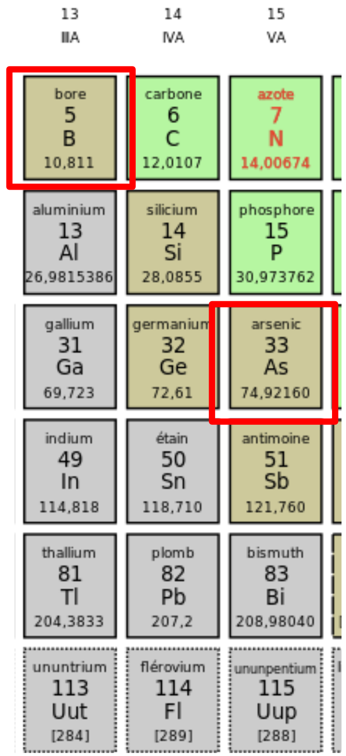
Silicon n-type:

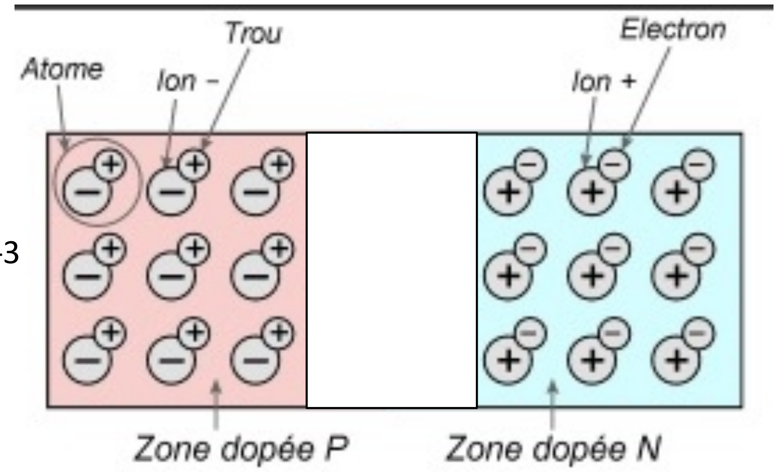
Concentration As = 10^{18} cm^{-3}

ρ = 0.02 Ωcm = 2x10^{-4} Ωm

Doping



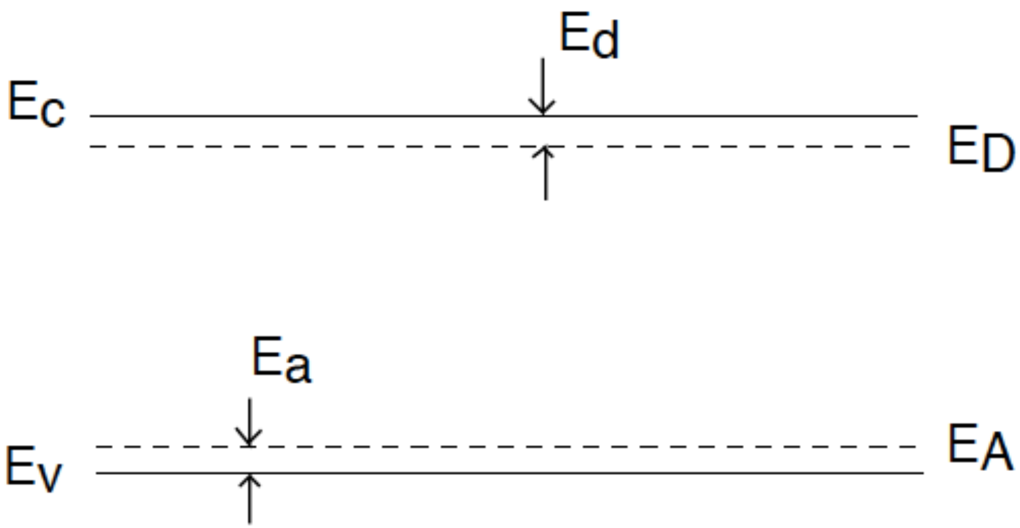




Silicon p-type:
Concentration B = 10^{18} cm^{-3}
ρ = 0.04 Ωcm = 4x10^{-4} Ωm

Silicon n-type:
Concentration As = 10^{18} cm^{-3}
ρ = 0.02 Ωcm = 2x10^{-4} Ωm

Representation of donor and acceptor states in energy band diagram:



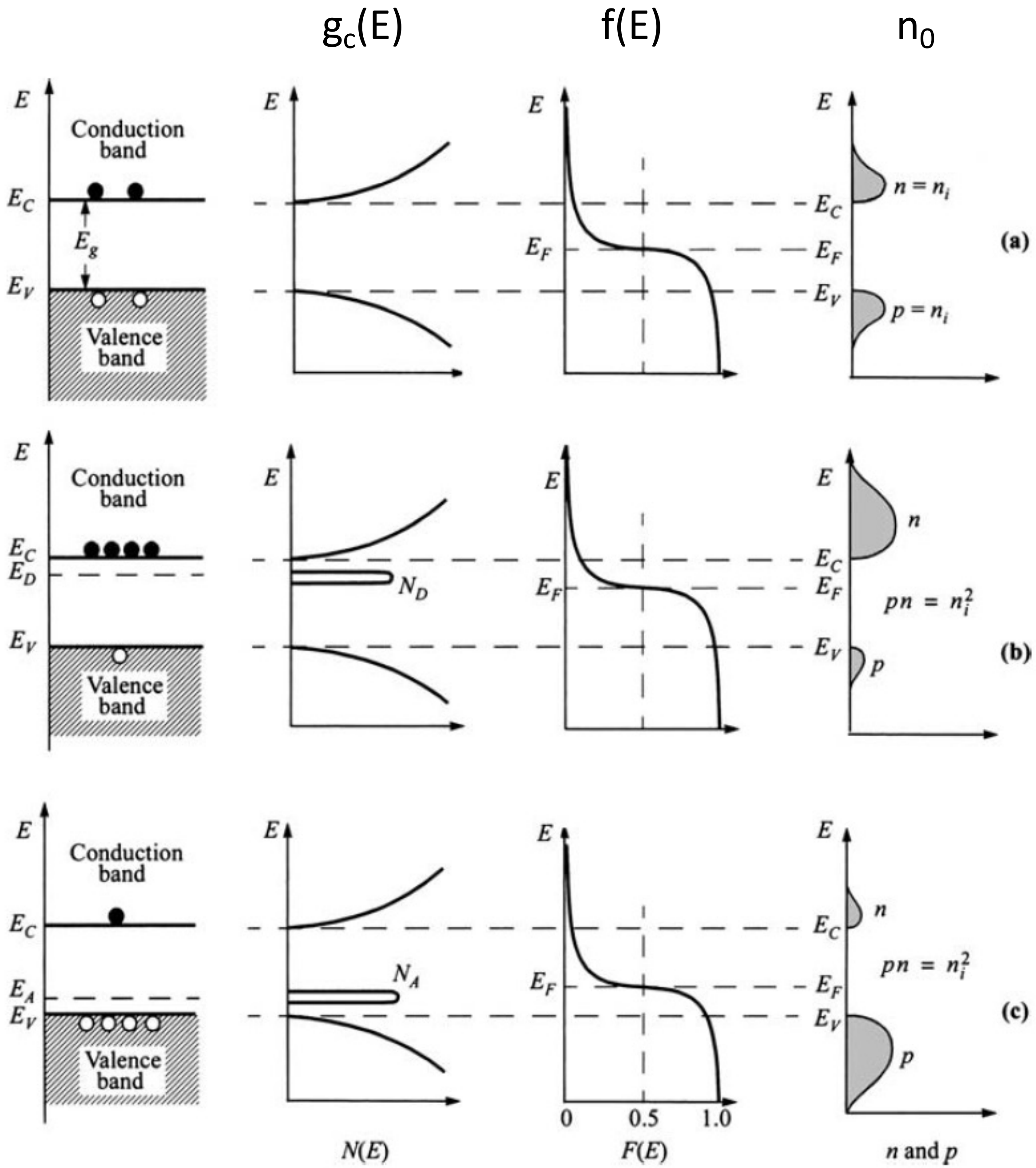
E_D,E_A ~40 −60 meV , for common dopants

Near room temperature, most dopants are ionized:

$$N_D^+ \simeq N_D \qquad N_A^- \simeq N_A$$

Typical doping levels: N_A,N_D ~10^{15} −10^{20} cm−3

Carrier concentration



Ionization energies

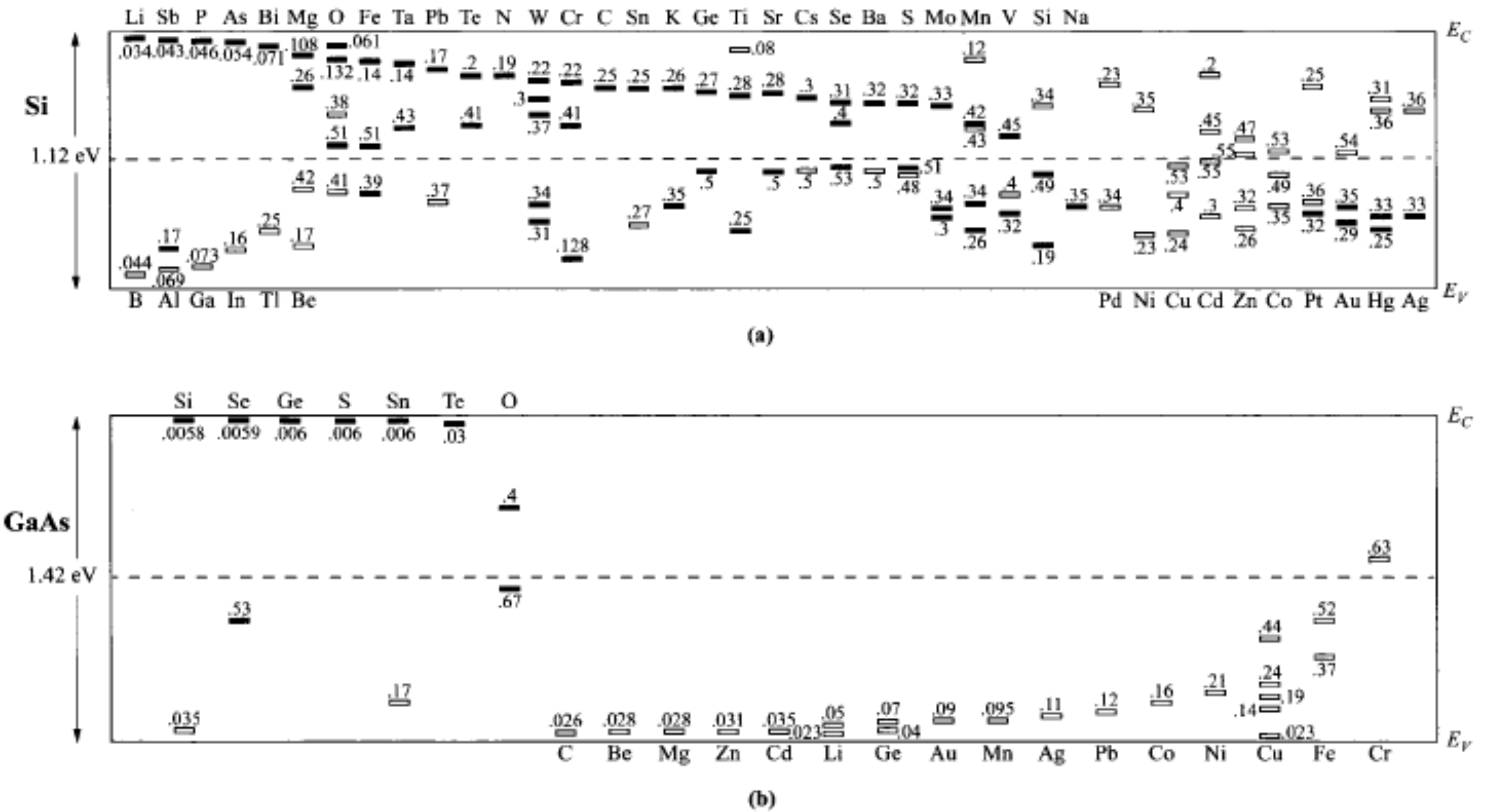
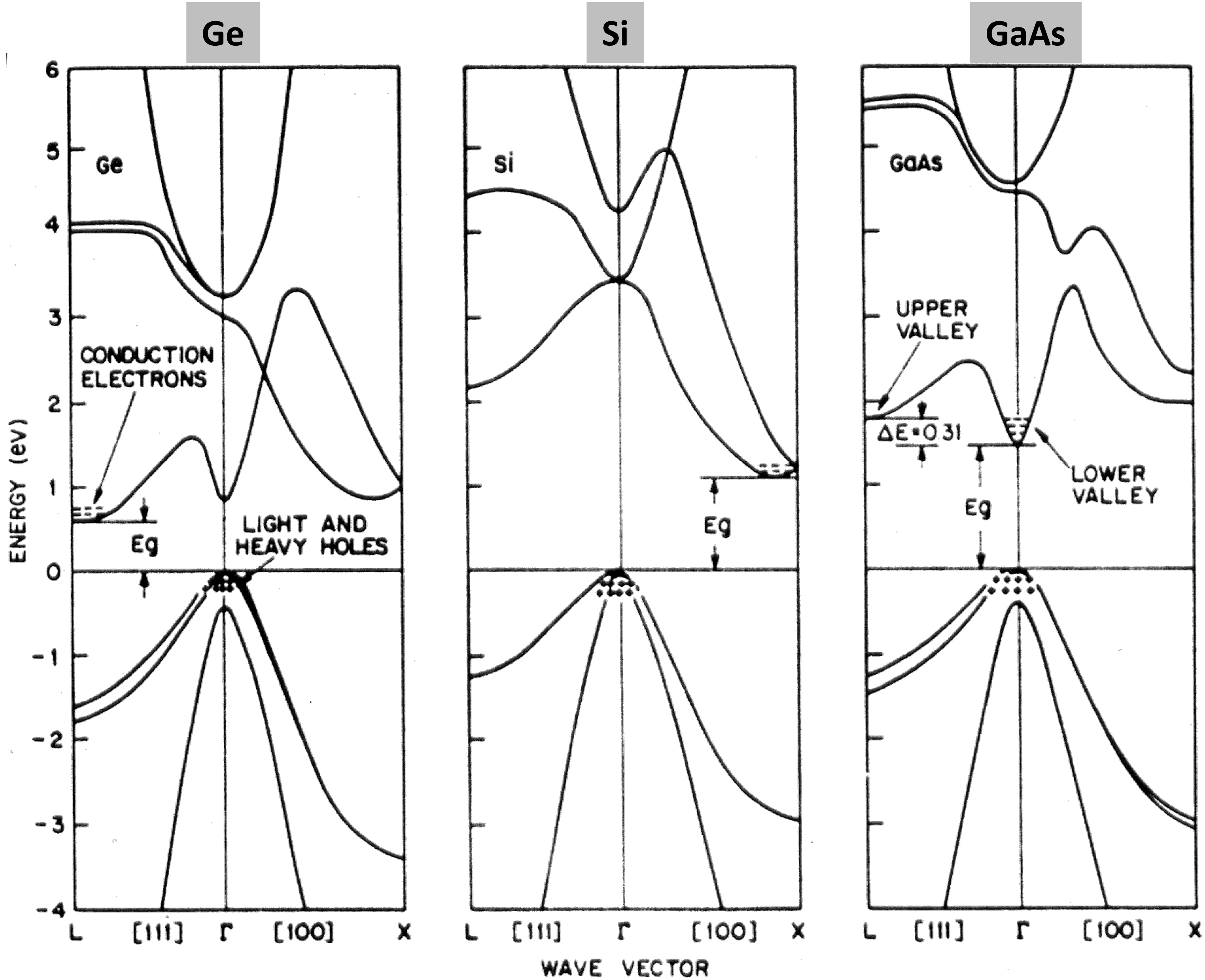


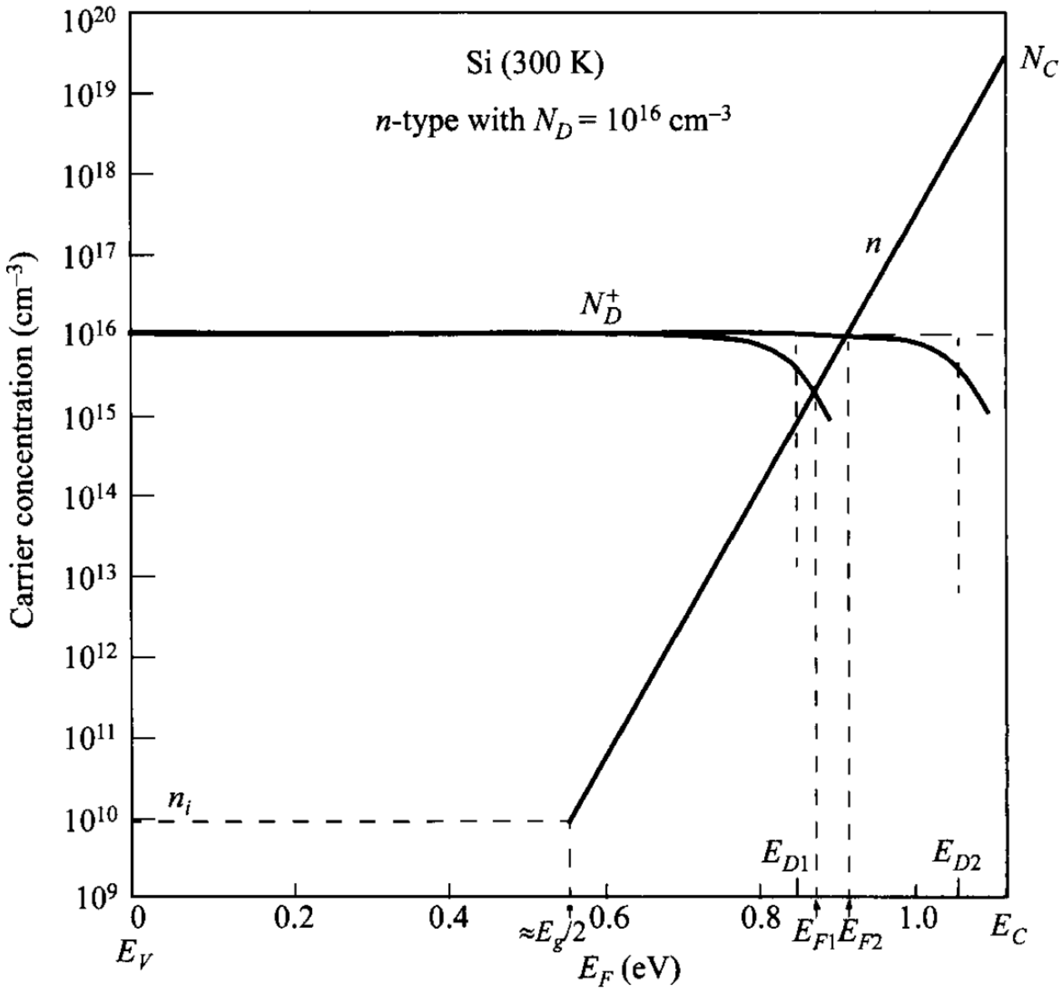
Fig. 10 Measured ionization energies for varies impurities in (a) Si and (b) GaAs. Levels below the gap center are measured from E_V. Levels above the gap center are measured from E_C. Solid bars represent donor levels and hollow boxes represent acceptor levels. (After Refs. 29, 31, 34, and 35.)

Reminder: valence bands are often degenerated at K = 0 (g_A = 2x2)



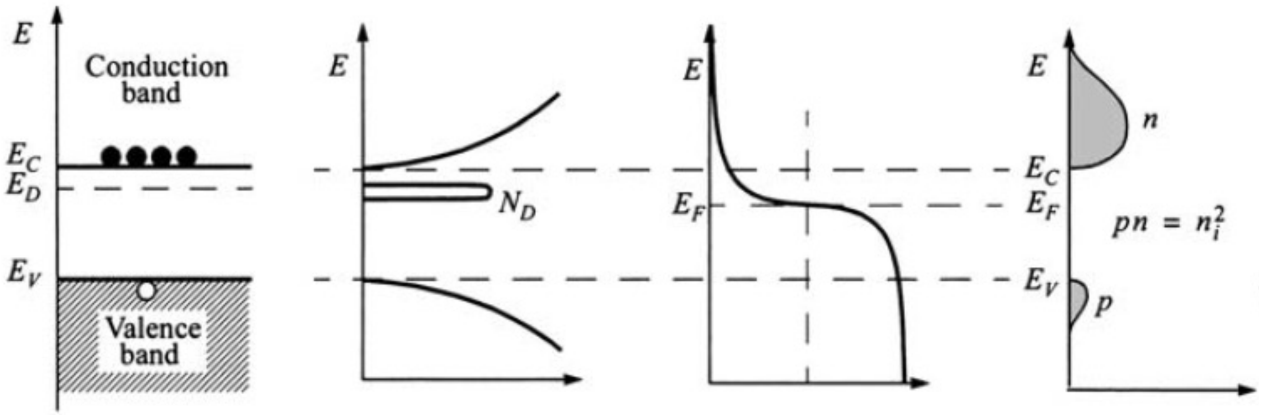
Graphical method:
Determine the Fermi energy level E_F and electron concentration n, when ionization is not complete.

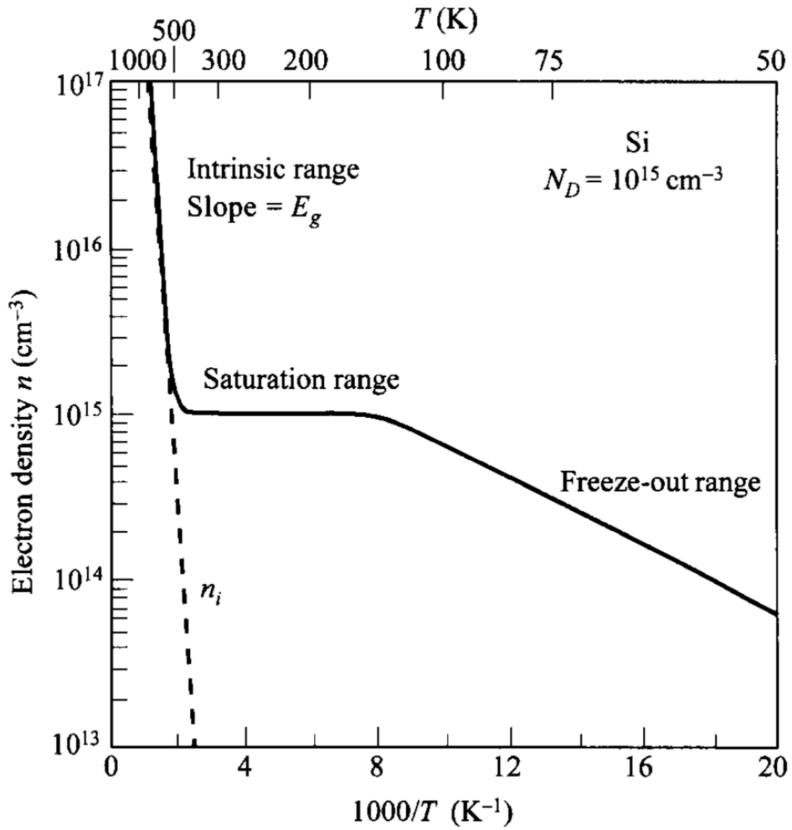
Examples with two different values of impurity levels E_D are shown below:



Ionization energies

Electron density as a function of temperature for a Si sample with donor impurity concentration of 10^{15} cm^{-3}





Key conclusions

Distinct feature of semiconductors: at 0 K, quantum state filling ends up with full band separated from next empty band by ~1-3eV bandgap at around 300 K, some electrons populate next band above bandgap.

System in thermal equilibrium:

- isolated from outside world and in steady state.
- In thermal equilibrium, E_F is independent of position: it is constant!

Occupation probability of quantum systems in thermal equilibrium governed by Fermi-Dirac distribution function:

$$f(E) = \frac{1}{1 + \exp \frac{E - E_F}{kT}}$$

Density of states give us the number of states per volume available at a give energy

In 3D:
$$g_c(E) = 4\pi \left(\frac{2m^*_{de}}{h^2}\right)^{3/2} \sqrt{E - E_c} \qquad E \geq E_c$$

$$g_v(E) = 4\pi \left(\frac{2m^*_{dh}}{h^2}\right)^{3/2} \sqrt{E_v - E} \qquad E \leq E_v$$

Key conclusions

Non-degenerate semiconductor:

$$n_o = N_c \exp \frac{E_F - E_c}{kT}, \qquad p_o = N_v \exp \frac{E_v - E_F}{kT}$$

Intrinsic semiconductor: ideally pure semiconductor.

$$n_o = p_o = n_i = \sqrt{N_c N_v} \exp - \frac{E_g}{2kT}$$

In non-degenerate semiconductor $n_o p_o$ $\qquad n_o p_o = n_i^2$

In intrinsic semiconductor, E_F is close to middle of E_g.

In extrinsic semiconductor, E_F location depends on doping level:

n-type non-degenerate semiconductor:

$$n_o \simeq N_D, \qquad E_F - E_c \simeq kT \ln \frac{N_D}{N_c}$$

p-type non-degenerate semiconductor:

$$p_o \simeq N_A, \qquad E_F - E_v \simeq kT \ln \frac{N_v}{N_A}$$