Course 4

Monday, 23 September 2024 14:31

EE557Cours 4 - Doping

Equal opportunity makes us brighter
Diversity is our strength
Listen and dare to speak up
Look out for each other
Kindness brings serenity
Together we go further
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

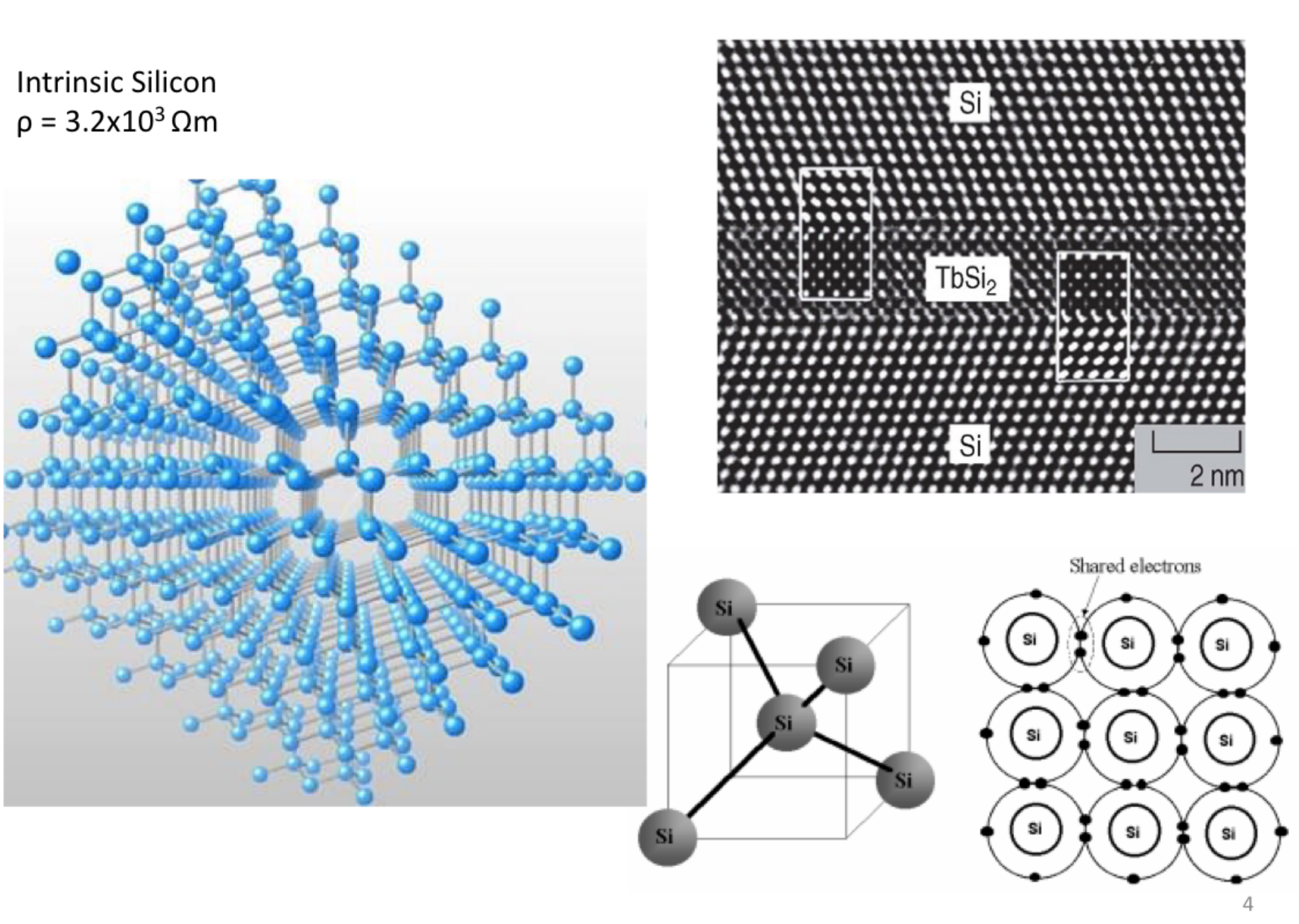
References:
- J. A. del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/)
- C. Kittel, Introduction to Solid State Physics, John Wiley & Sons, 2005

Key questions

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

Doping

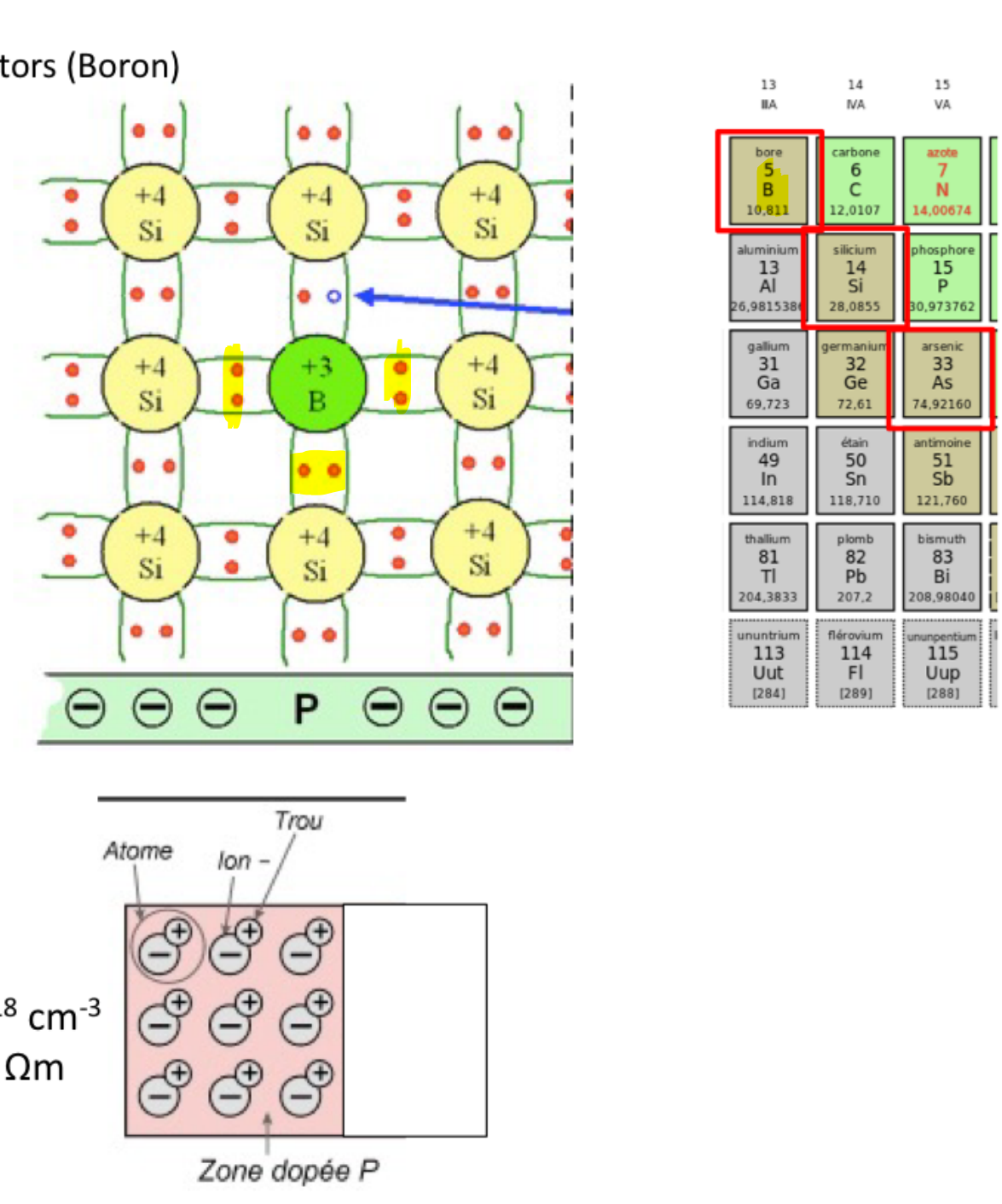
Intrinsic Silicon
ρ = 3.2x10³ Ωm


Si
TbSi₂
Si
2 nm
Si
Shared electrons

Doping

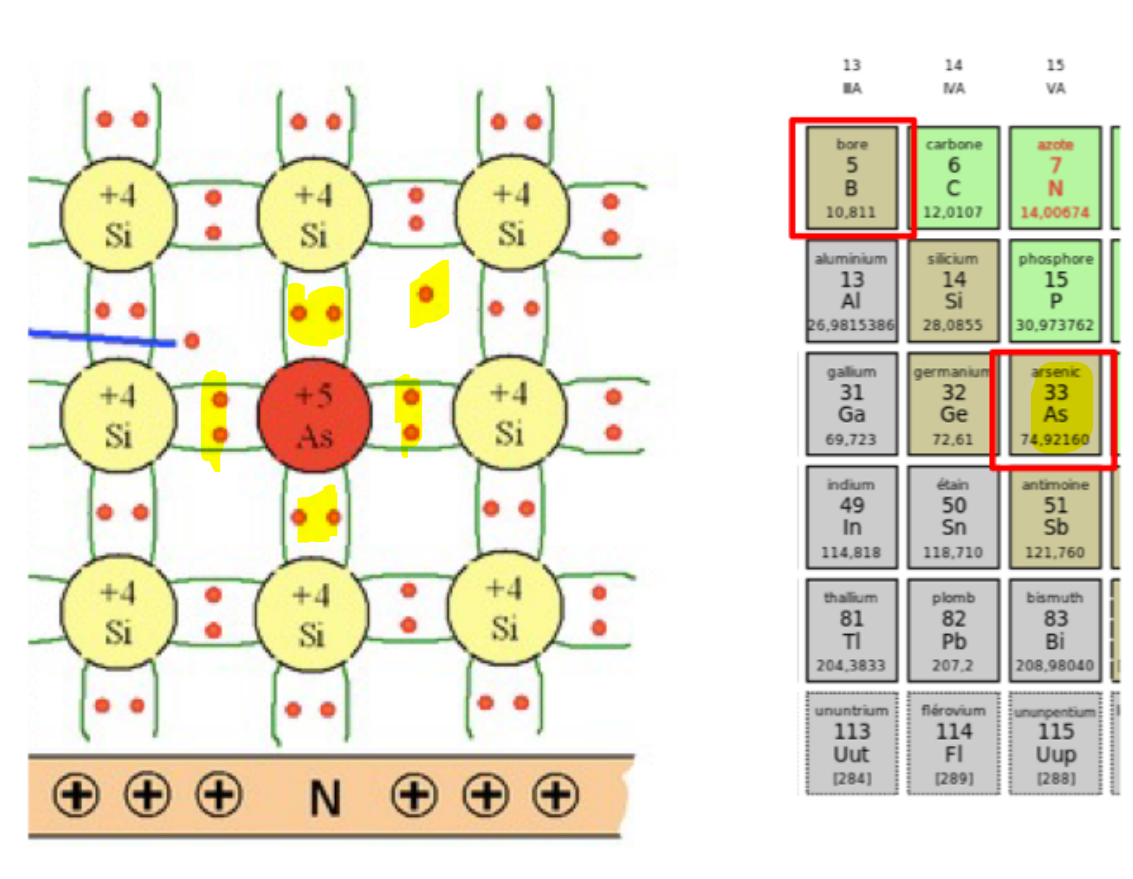
P-type doping with acceptors (Boron)

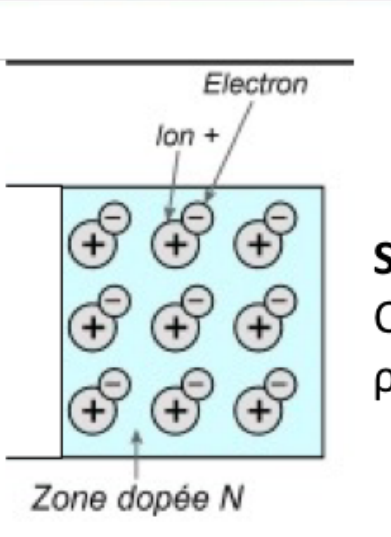
Silicon p-type:


+4 Si
+3 B
P
Atome
Ion –
Trou
Zone dopée P
bore 5 B
carbone 6 C
azote 7 N
aluminium 13 Al
silicium 14 Si
phosphore 15 P
gallium 31 Ga
germanium 32 Ge
arsenic 33 As
indium 49 In
étain 50 Sn
antimoine 51 Sb
thallium 81 Tl
plomb 82 Pb
bismuth 83 Bi
113 Uut
114 Fl
115 Uup

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

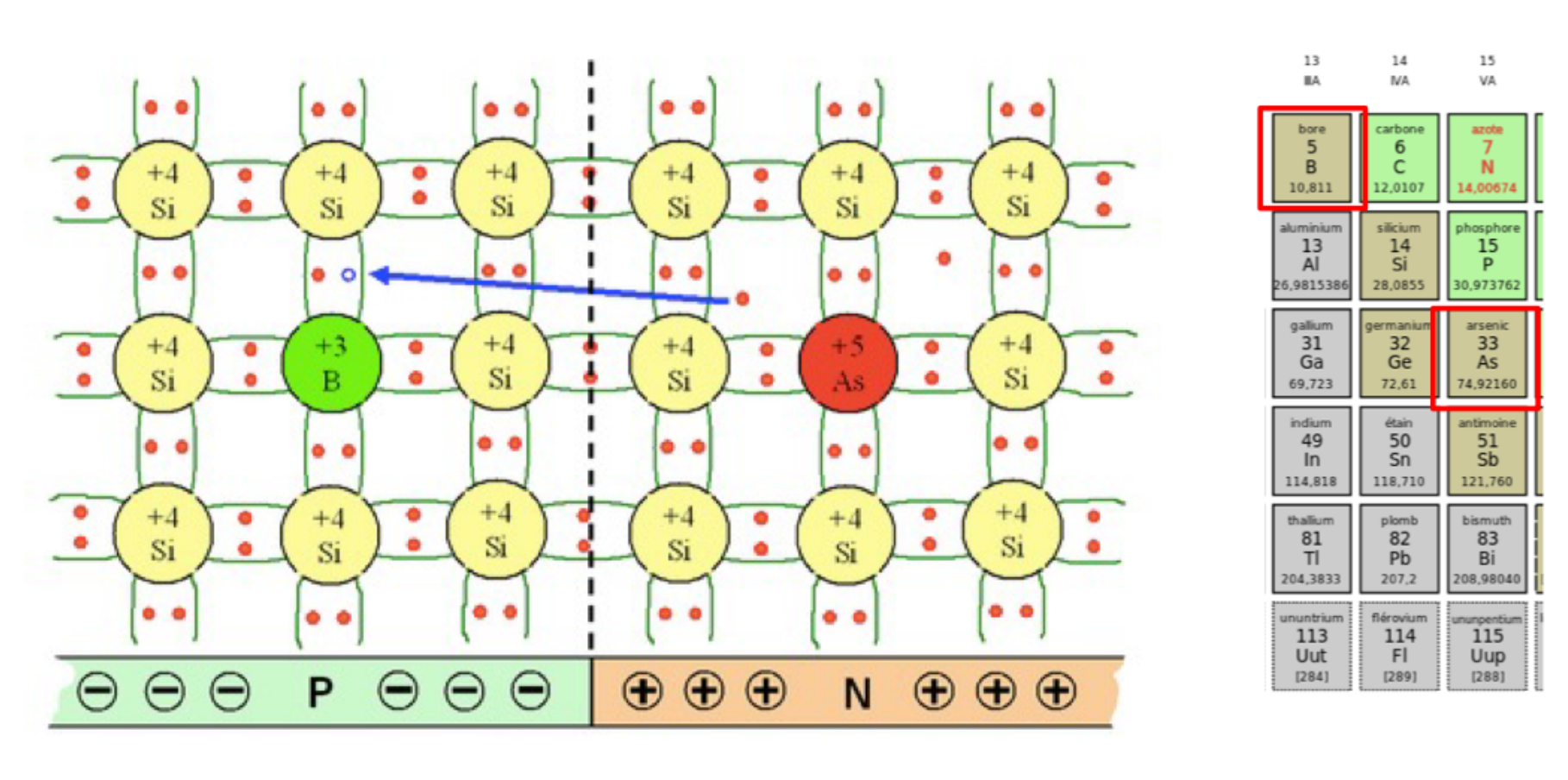
Doping

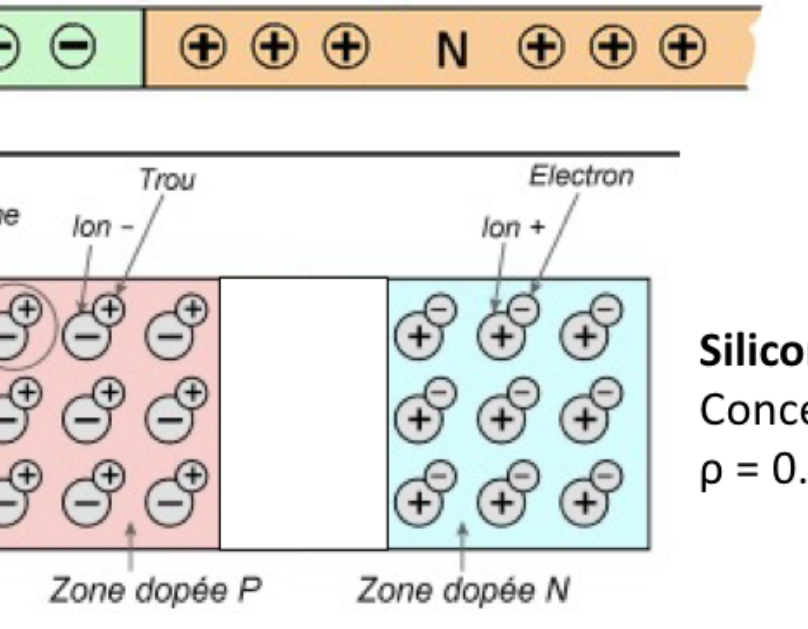

+4 Si
+5 As
N
bore 5 B
arsenic 33 As


Electron
Ion +
Zone dopée N

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

Doping


+4 Si
+3 B
+5 As
P
N

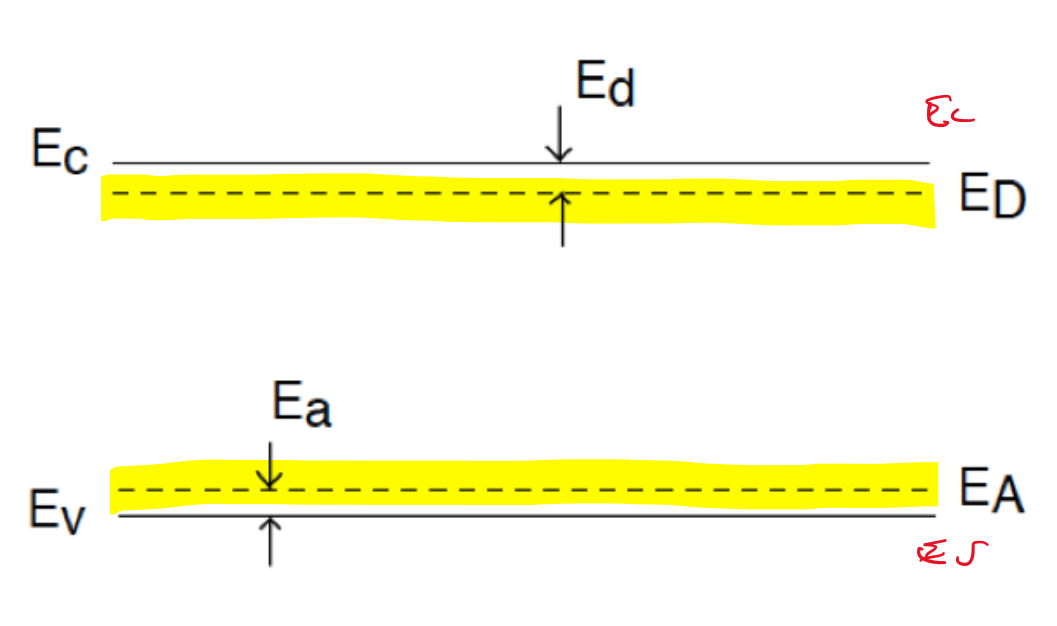

Atome
Ion –
Trou
Electron
Ion +
Zone dopée P
Zone dopée N

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

Carrier concentration

Representation of donor and acceptor states in energy band diagram:


Ec
Ed
ED
Ec
Ev
Ea
EA
Ev

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

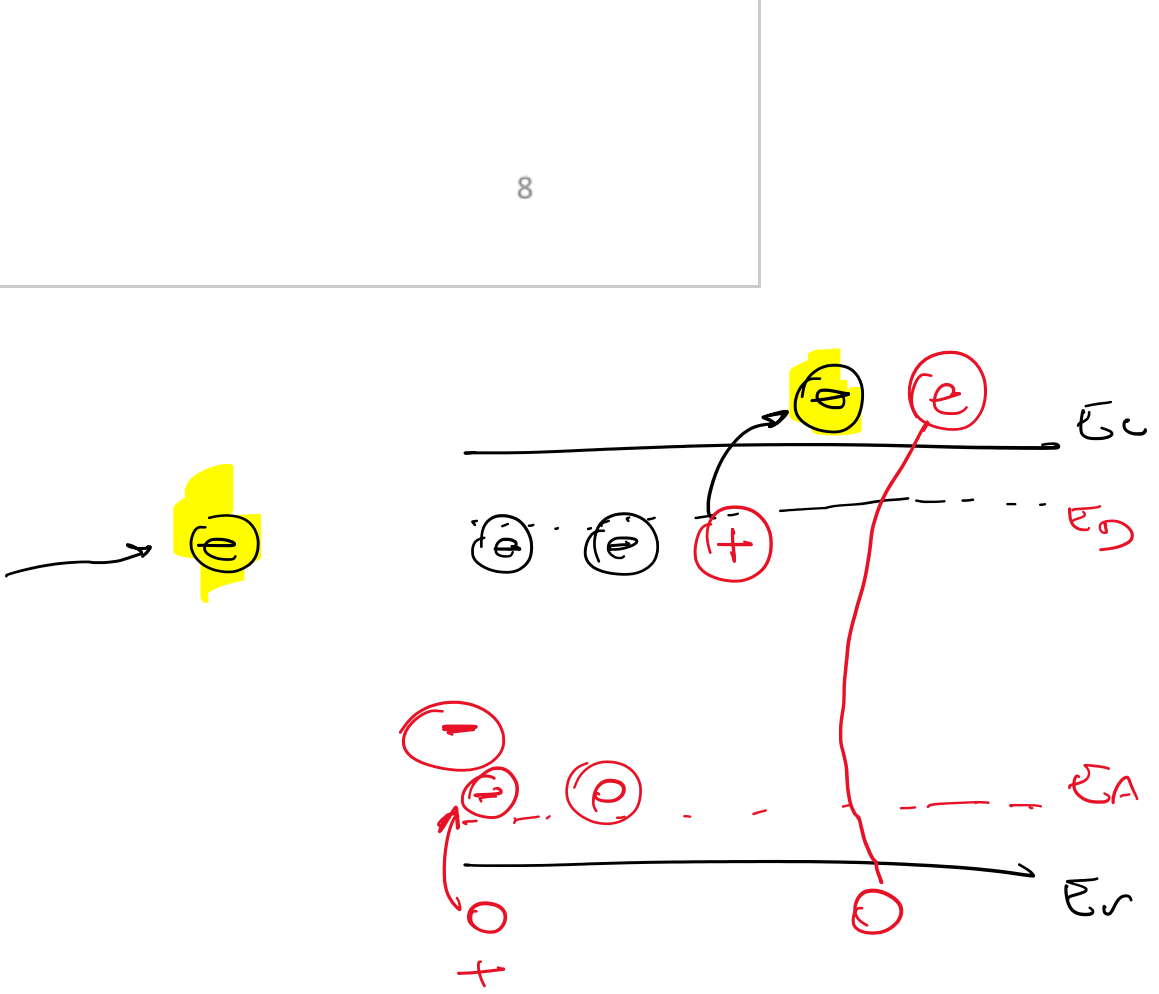
Doping:

Donor — neutral
— ionized (positive)

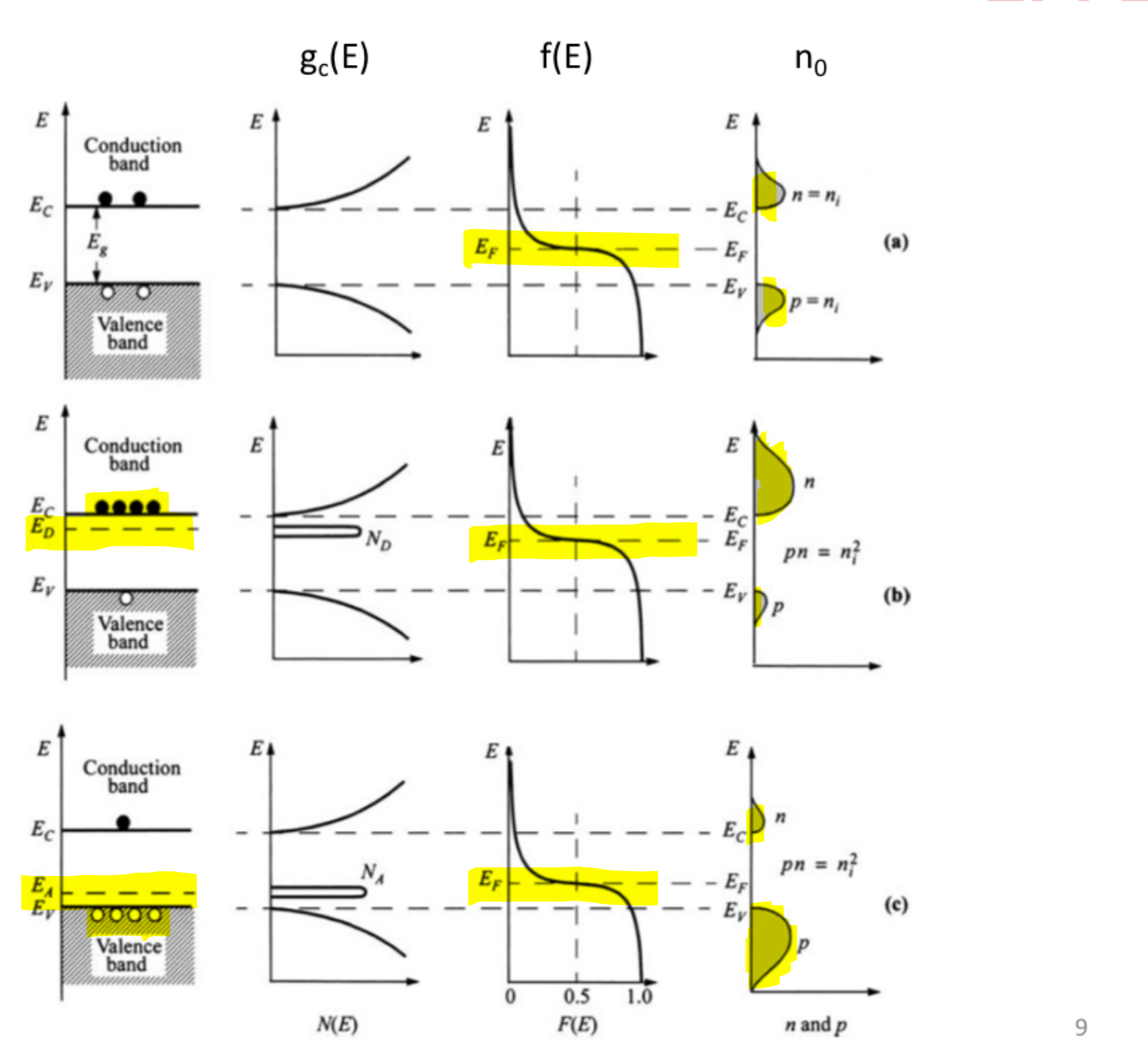
Acceptor — ionized (negative)
— neutral

: As : ⓔ

: As^+ : → ⓔ



Carrier concentration


gc(E)
f(E)
n0
E
Conduction band
Valence band
Ec
Eg
Ev
EF
ED
EA
ND
NA
n = ni
p = ni
pn = ni²
n
p
(a)
(b)
(c)
N(E)
F(E)
0
0.5
1.0
n and p

Ionization energies

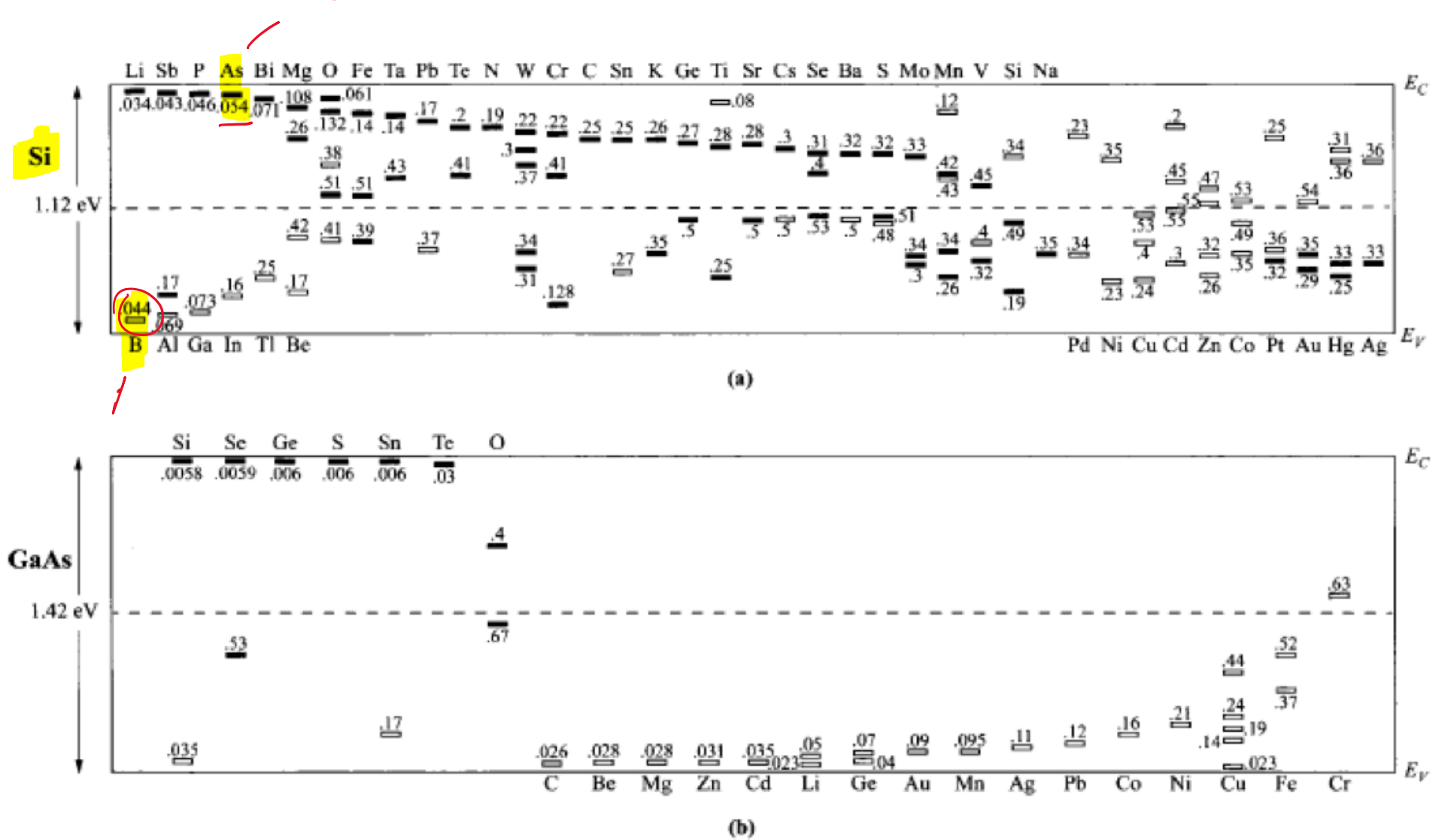


Fig. 10 Measured ionization energies for varies impurities in (a) Si and (b) GaAs. Levels below the gap center are measured from E_V. Levels above the gap center are measured from E_C. Solid bars represent donor levels and hollow boxes represent acceptor levels. (After Refs. 29, 31, 34, and 35.)

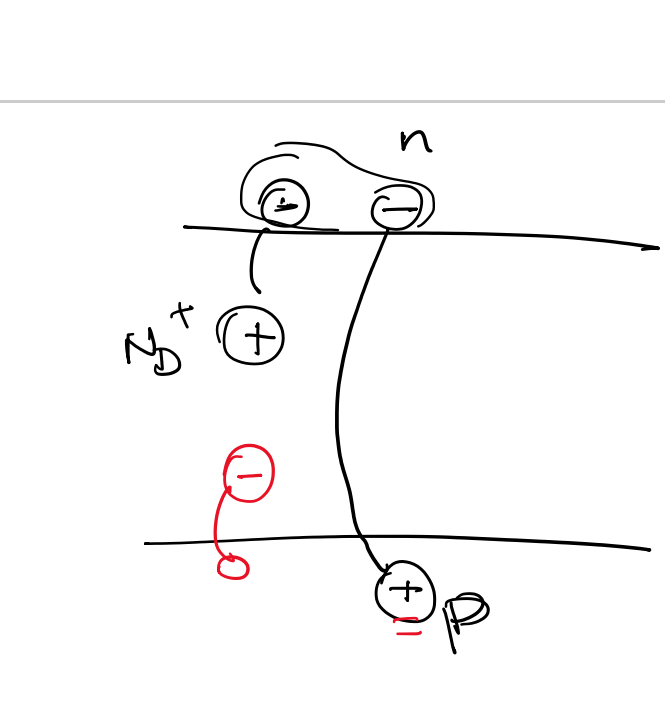
Not all dopants are necessarily ionized:

$$N_D^+ = \frac{N_D}{1 + g_D \cdot \exp\left(-\frac{E_D - E_F}{kT}\right)}$$

g_D: degeneracy of the E_C ⇒ $g_D = 2$ (2 spins)

$$N_A^- = \frac{N_A}{1 + g_A \exp\left(\frac{E_A - E_F}{kT}\right)}$$

$\boxed{g_A = 4}$ = 2 spins × 2 bands



Due to charge neutrality:

$$n + N_A^- = p + N_D^+$$

for n-type Si: ($N_A = 0$)

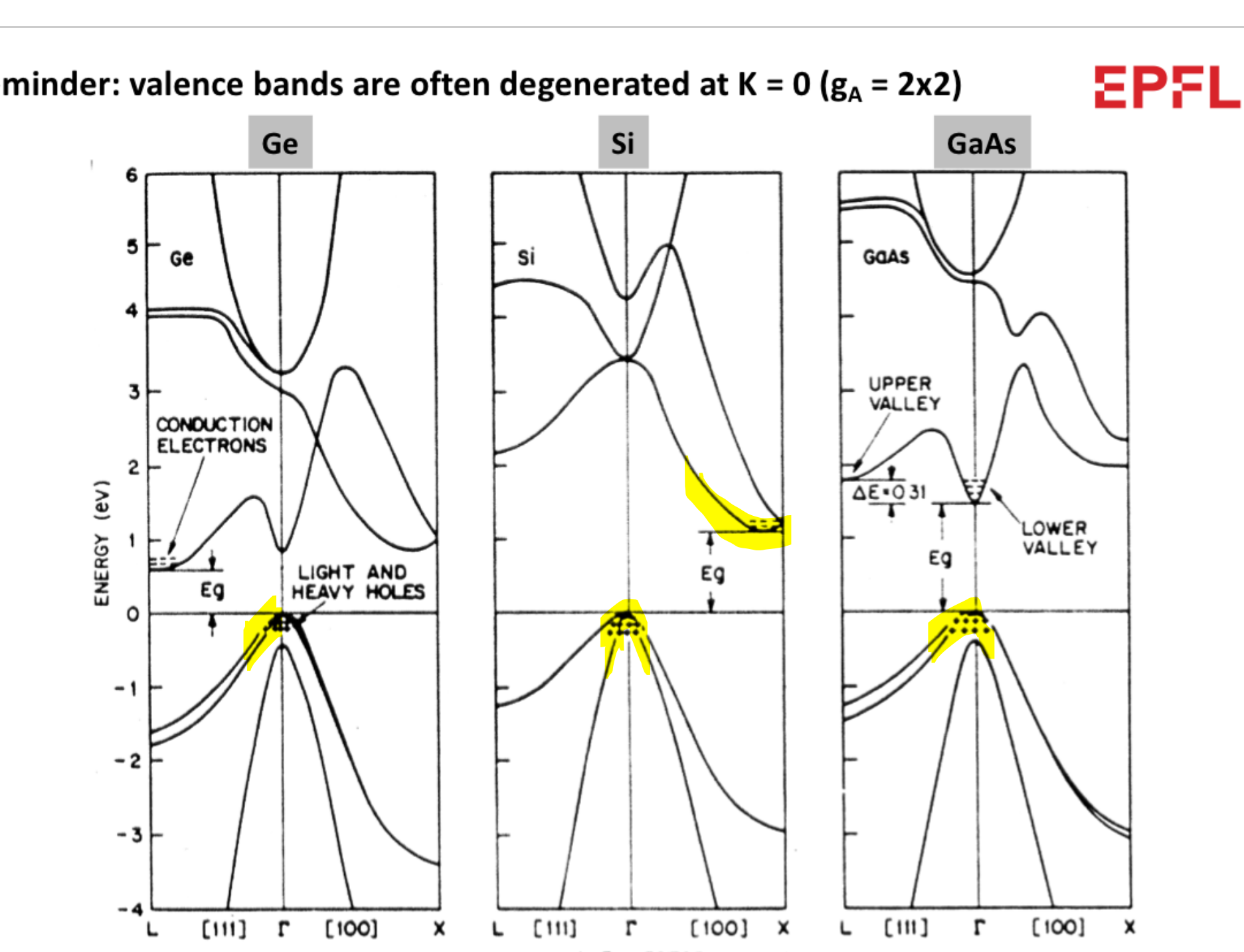
$$n = p + N_D^+ = N_D^+$$

$N_D = 10^{18}$ cm^{-3}
$p = 10^{10}$ cm^{-3}

Assuming non-degenerate case:

$$\underset{(1)}{N_C \cdot \exp\left(-\frac{E_C - E_F}{kT}\right)} \simeq \underset{(2)}{\frac{N_D}{1 + 2\exp\left(-\frac{E_D - E_F}{kT}\right)}}$$

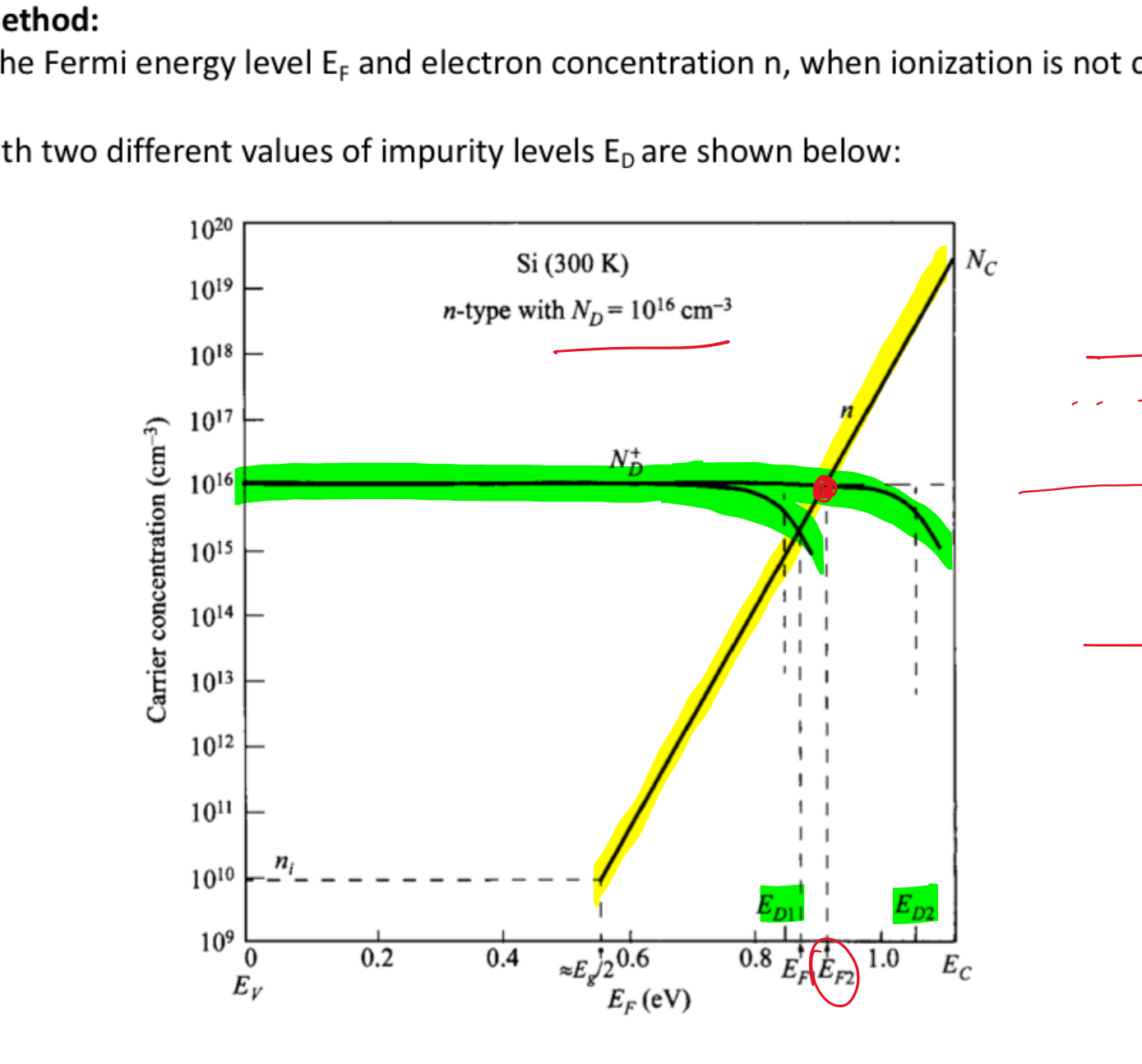
Reminder: valence bands are often degenerated at K = 0 (g_A = 2x2)

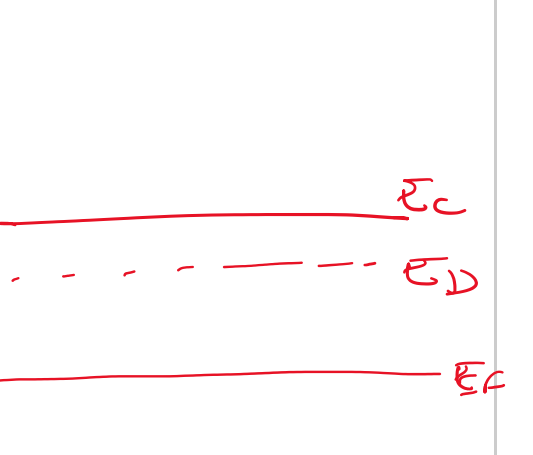


Ionization energies

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

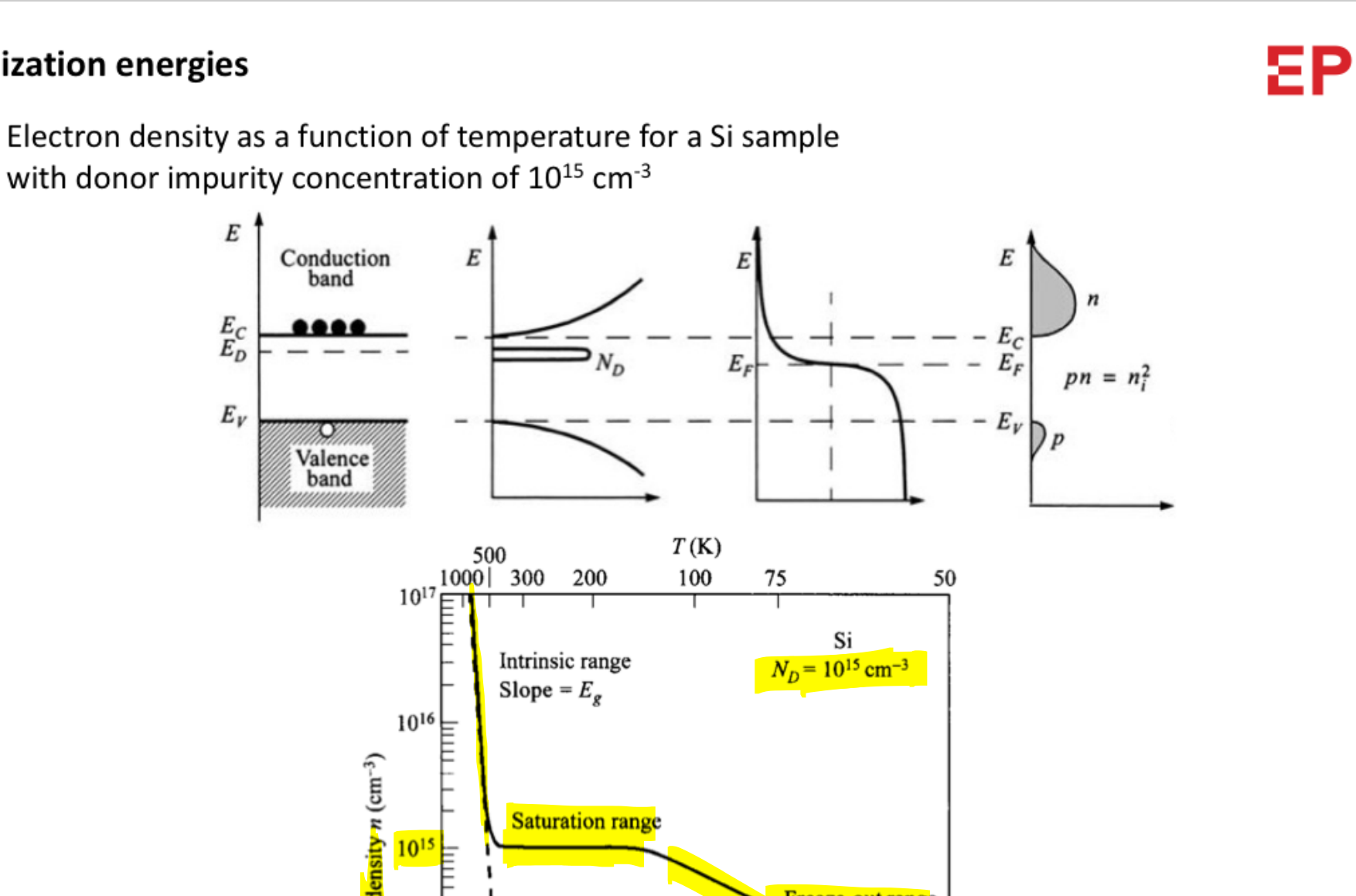
Examples with two different values of impurity levels E_D are shown below:





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:

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