University of Anbar
College of Science – Dept. of Physics

Lectures of Semiconductors #1

for 3th level of physics students

Lecture 9 : The Semiconductor in Equilibrium/2

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4.1.4 The Intrinsic Fermi-Level Position

Since the electron and hole concentrations are equal, setting Equations

$$n_0 = n_i = N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right]$$

$$p_0 = p_i = n_i = N_v \exp\left[\frac{-(E_{Fi} - E_v)}{kT}\right]$$

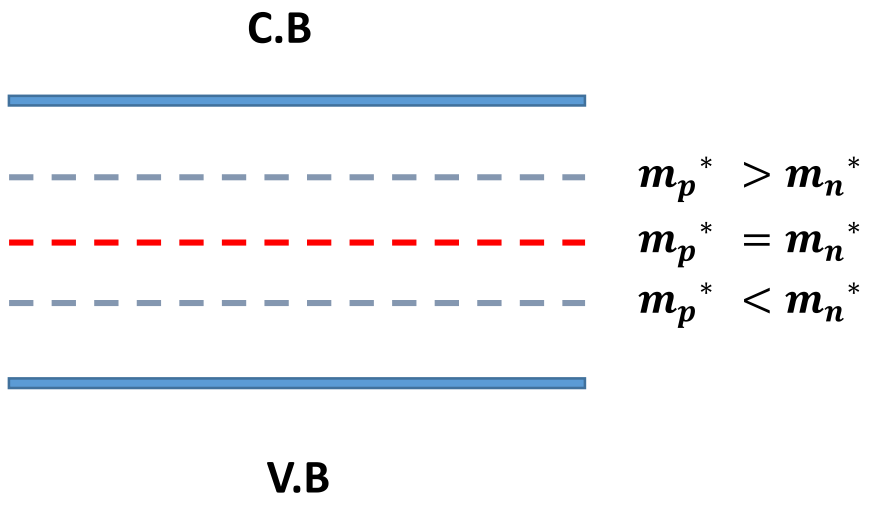
$$N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right] = N_v \exp\left[\frac{-(E_{Fi} - E_v)}{kT}\right]$$

$$E_{Fi} = \frac{1}{2}(E_c + E_v) + \frac{1}{2} kT \ln\left(\frac{N_v}{N_c}\right)$$

$$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} \qquad N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$$

$$E_{Fi} = \frac{1}{2}(E_c + E_v) + \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*}\right)$$

$$\boxed{E_{Fi} - E_{\text{midgap}} = \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*}\right)}$$



The density of states function is directly related to the carrier effective mass; thus, a larger effective mass means a larger density of states function.

Example:

Calculate the position of the intrinsic Fermi level with respect to the center of the bandgap in silicon at T 300 K.

The density of states effective carrier masses in silicon are $m_n^* = 1.08m_0$ and $m_p^* = 0.56m_0$.

■ **Solution**

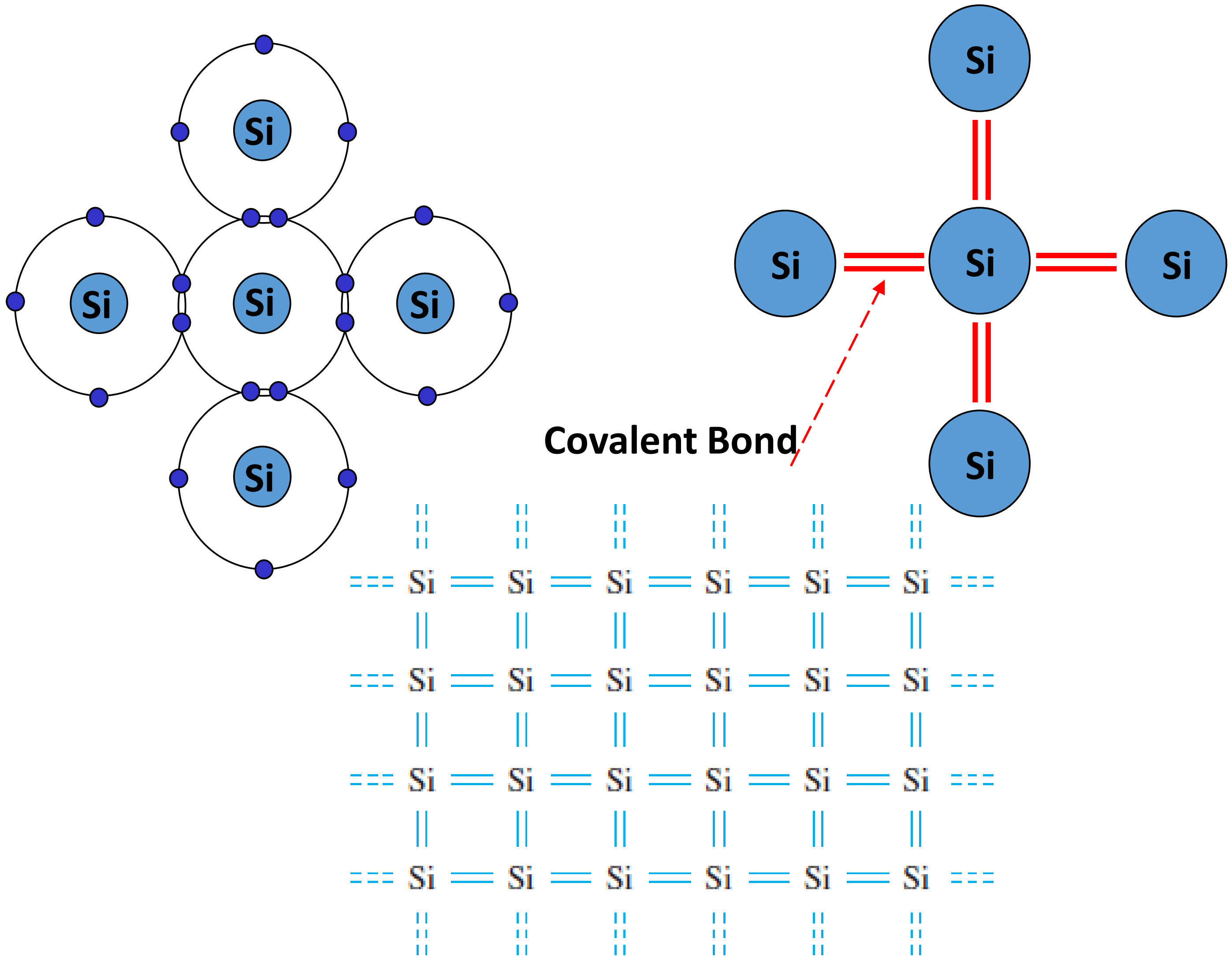
The intrinsic Fermi level with respect to the center of the bandgap is

$$E_{Fi} - E_{\text{midgap}} = \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*}\right) = \frac{3}{4}(0.0259)\ln\left(\frac{0.56}{1.08}\right)$$

or

$$E_{Fi} - E_{\text{midgap}} = -0.0128 \text{ eV} = -12.8 \text{ meV}$$

Qualitative Description

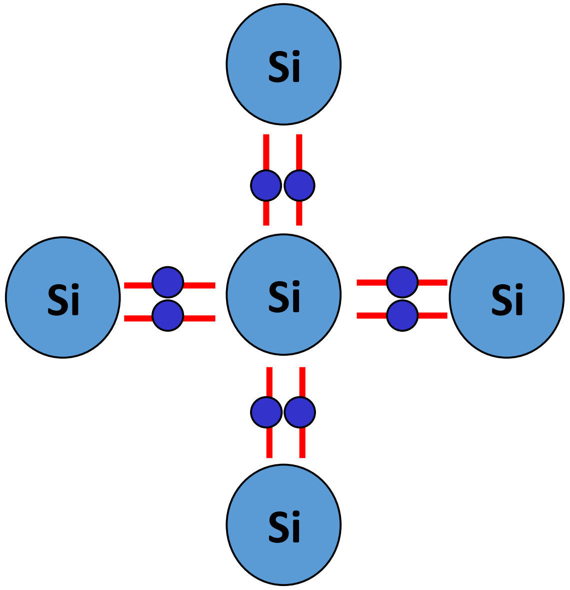


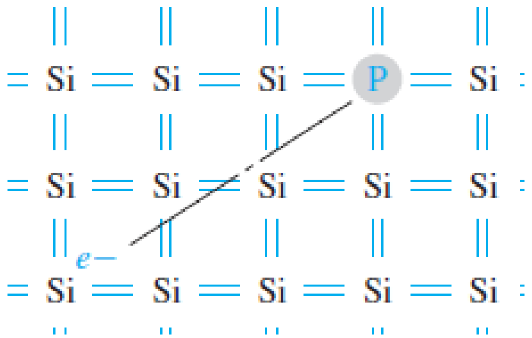
Adding a group V elements:

The group V element has five valence electrons. Four of these will contribute to the covalent bonding with the silicon atoms, leaving the fifth more loosely bound to the phosphorus atom.

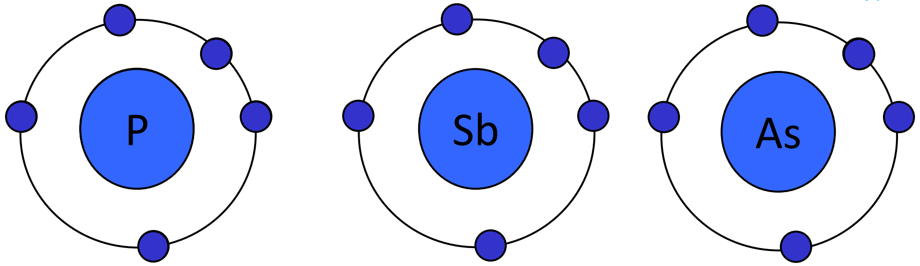
These atoms is called (called a donor *impurity atom*) and the fifth valence electron is called the donor electron.

n – type semiconductor

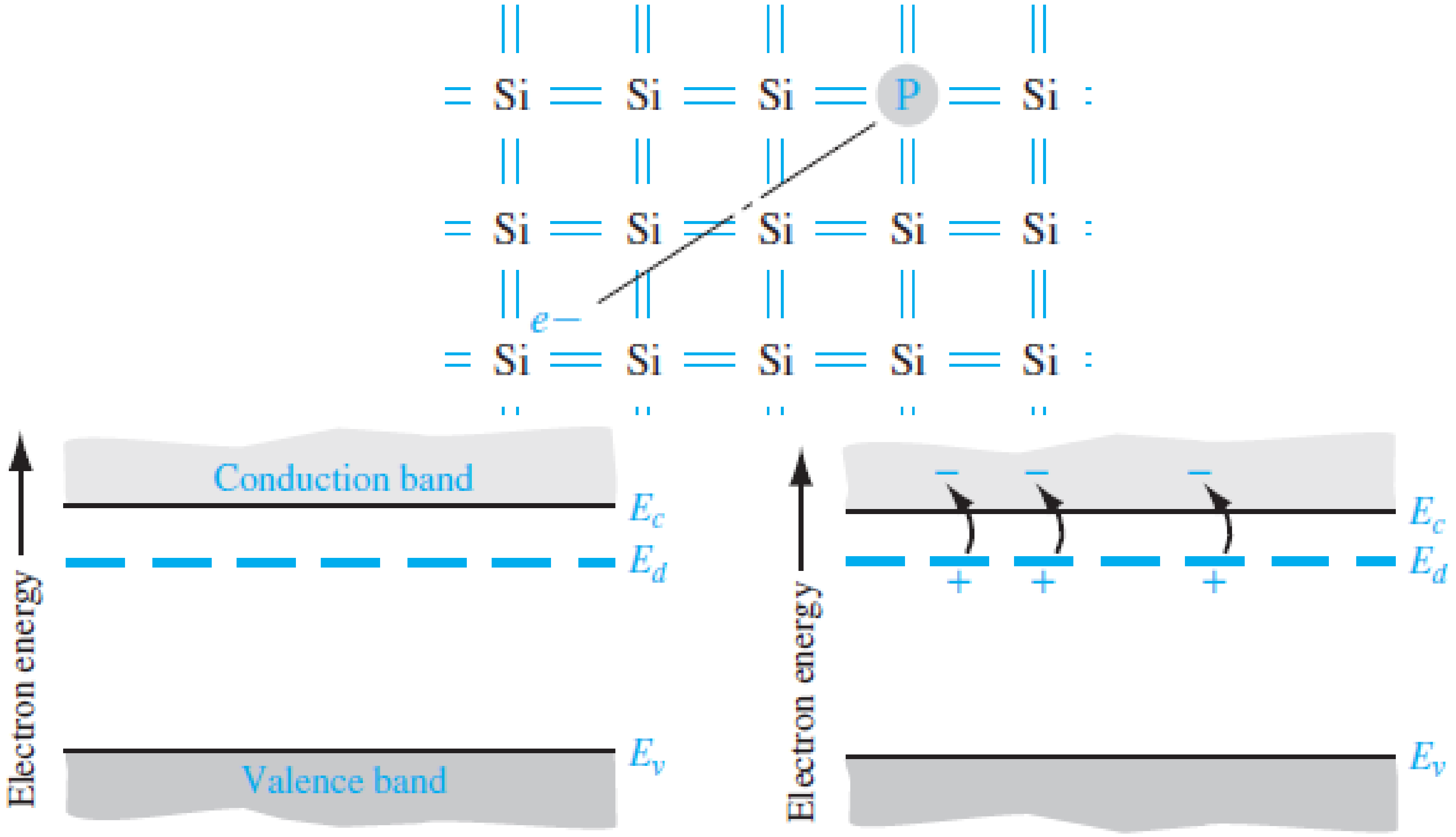


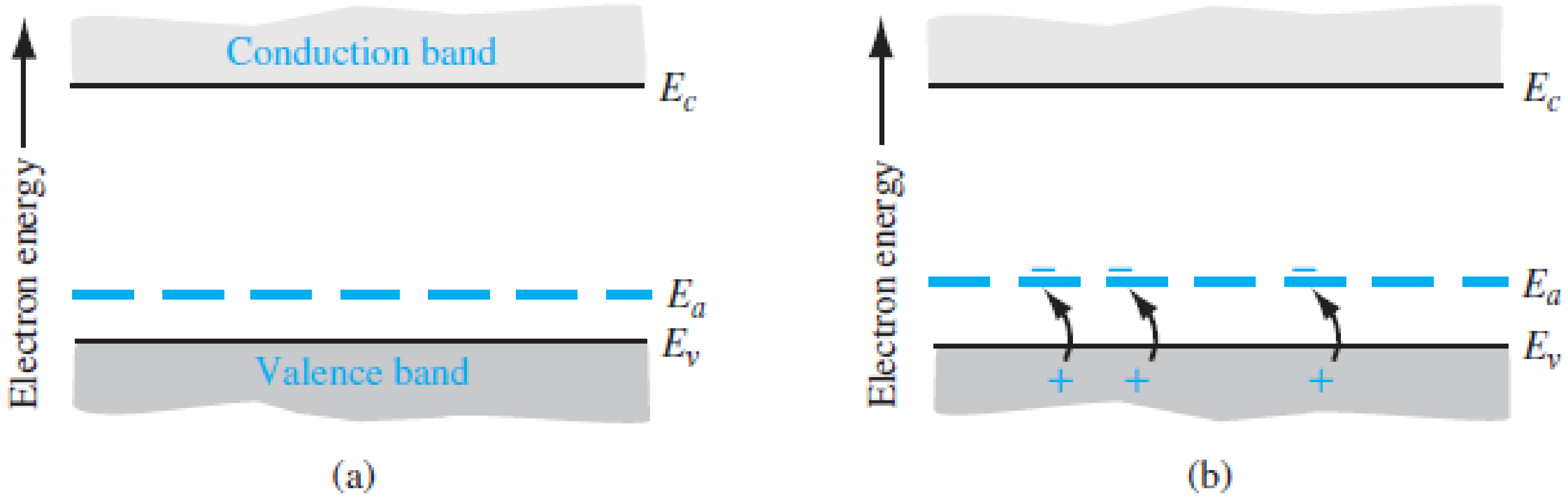


V equivalence



- The phosphorus atom without the donor electron is positively charged. At very low temperatures, the donor electron is bound to the phosphorus atom.
- that the energy required to elevate the donor electron into the conduction band is considerably less than that for the electrons involved in the covalent bonding.





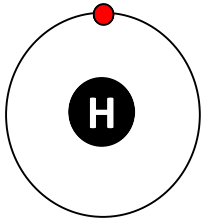
- **The pure single-crystal semiconductor material is called an intrinsic material.**

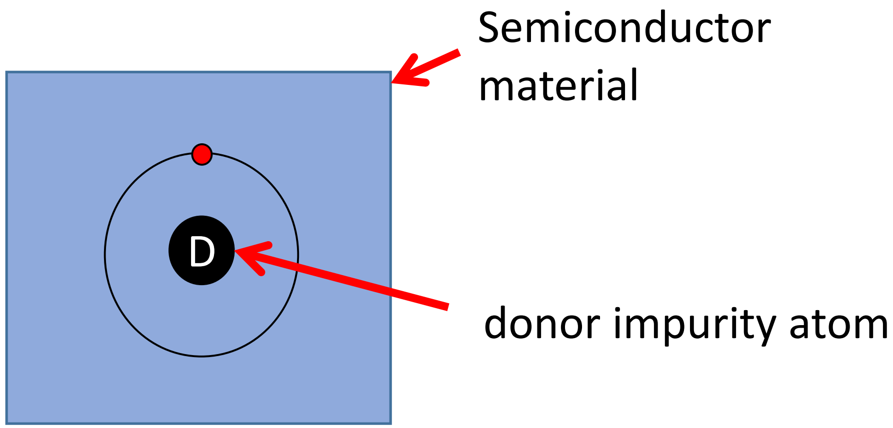
- **Adding controlled amounts of dopant atoms, either donors or acceptors creates a material called an extrinsic semiconductor. An extrinsic semiconductor will have either a preponderance of electrons (n-type) or a preponderance of holes (p-type).**

Ionization Energy

the approximate distance of the donor electron from the donor impurity ion, and also the approximate energy required to elevate the donor electron into the conduction band can be calculated. This energy is referred to as ***ionization energy***.

Using the Bohr model of the hydrogen atom:





$$\frac{e^2}{4\pi\epsilon_o {r_n}^2} = \frac{mv^2}{r_n}$$

$$\frac{e^2}{4\pi\epsilon\, {r_n}^2} = \frac{m^* v^2}{r_n}$$

$$\frac{e^2}{4\pi\epsilon\, {r_n}^2} = \frac{m^* v^2}{r_n}$$

where v is the magnitude of the velocity
r_n is the radius of the orbit.

angular momentum is $m^* \, r_n v = n\hbar$

The Bohr radius i

$$r_n = \frac{n^2 \hbar^2 4\pi\,\epsilon}{m^* e^2} \Longrightarrow a_0 = \frac{4\pi\epsilon_0 \hbar^2}{m_0 e^2} = 0.53\ \text{Å}$$

$$\frac{r_n}{a_0} = n^2 \epsilon_r \left(\frac{m_0}{m^*}\right)$$

where ϵ_r is the relative dielectric constant of the semiconductor material, m_0 is the rest mass of an electron, and m^* is the conductivity effective mass of the electron in the semiconductor.[3]

The total energy of the orbiting electron is given by

$$E = T + V$$

the kinetic energy

$$T = \frac{1}{2} m^* v^2$$

$$T = \frac{m^* e^4}{2(n\hbar)^2(4\pi\epsilon)^2}$$

the potential energy

$$V = \frac{-e^2}{4\pi\epsilon r_n} = \frac{-m^* e^4}{(n\hbar)^2(4\pi\epsilon)^2}$$

$$E = T + V = \frac{-m^* e^4}{2(n\hbar)^2(4\pi\epsilon)^2}$$

For silicon, the ionization energy is $E = -25.8\ meV$

- It is much less than the bandgap energy of silicon.
- This energy is the approximate ionization energy of the donor atom, or the energy required to elevate the donor electron into the conduction band.

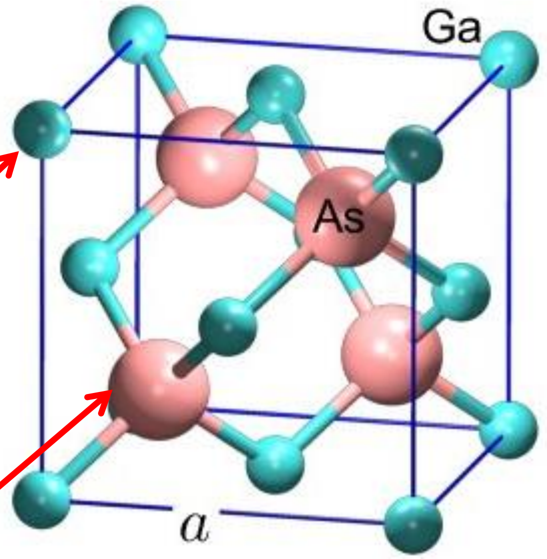
Why the energies of both Si and Ge are differ?

	Ionization energy (eV)	
Impurity	Si	Ge
Donors		
Phosphorus	0.045	0.012
Arsenic	0.05	0.0127
Acceptors		
Boron	0.045	0.0104
Aluminum	0.06	0.0102

Group III–V Semiconductors

GaAs | InP | GaP | GaN

Acceptor Impurities



III group
Beryllium (Be), zinc (Zn), and cadmium (Cd)

Donor Impurities

VI group
Selenium (Se) and Tellurium (Te)

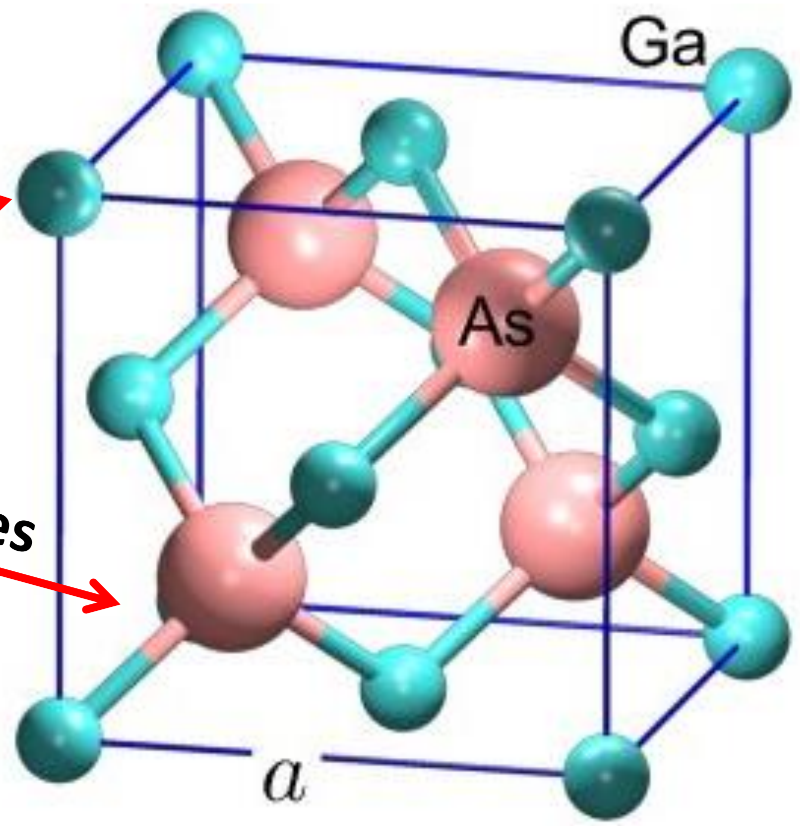
The corresponding ionization energies for these impurities are smaller than those for the impurities in silicon. The ionization energies for the donors in gallium arsenide are also smaller than those for the acceptors, because of the smaller effective mass of the electron compared to that of the hole.

IV group

Si	Ge

Donor impurities

Acceptor Impurities



These impurities are called amphoteric

Impurity	Ionization energy (eV)
Donors	
Selenium	0.0059
Tellurium	0.0058
Silicon	0.0058
Germanium	0.0061
Acceptors	
Beryllium	0.028
Zinc	0.0307
Cadmium	0.0347
Silicon	0.0345
Germanium	0.0404

Impurity ionization energies in gallium arsenide

Example:

Calculate the ionization energy and radius of the donor electron in germanium using the Bohr theory. (use the density of states effective mass as a first approximation.)

Solution

We have $\frac{r_1}{a_o} = \epsilon_r \left(\frac{m_o}{m^*}\right)$

For Germanium, $\epsilon_r = 16$, $m^* = 0.55 m_o$

Then

$$r_1 = (16)\left(\frac{1}{0.55}\right)a_o = 29(0.53)$$

so

$$\underline{r_1 = 15.4\ \mathring{A}}$$

The ionization energy can be written as

$$E = \left(\frac{m^*}{m_o}\right)\left(\frac{\epsilon_o}{\epsilon_s}\right)^2 (13.6) \quad eV$$

$$= \frac{0.55}{(16)^2}(13.6) \Rightarrow \underline{E = 0.029\ eV}$$