Primer on Semiconductors

Unit 1: Material Properties

Lecture 1.6: Doping

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Doping makes semiconductors useful

metal

semiconductor

insulator

gold (Au)

silicon (Si)

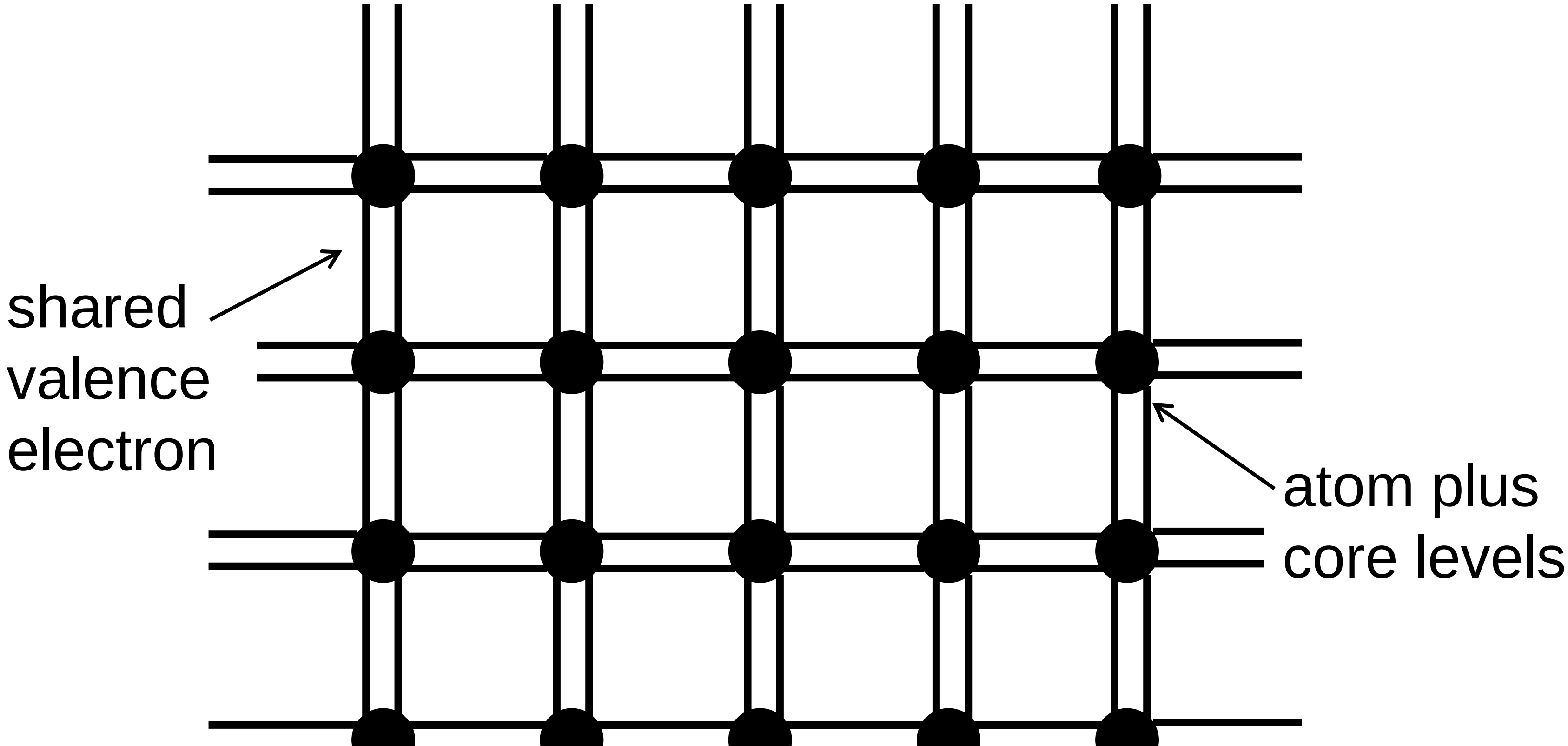
glass (SiO_2)

Things have changed

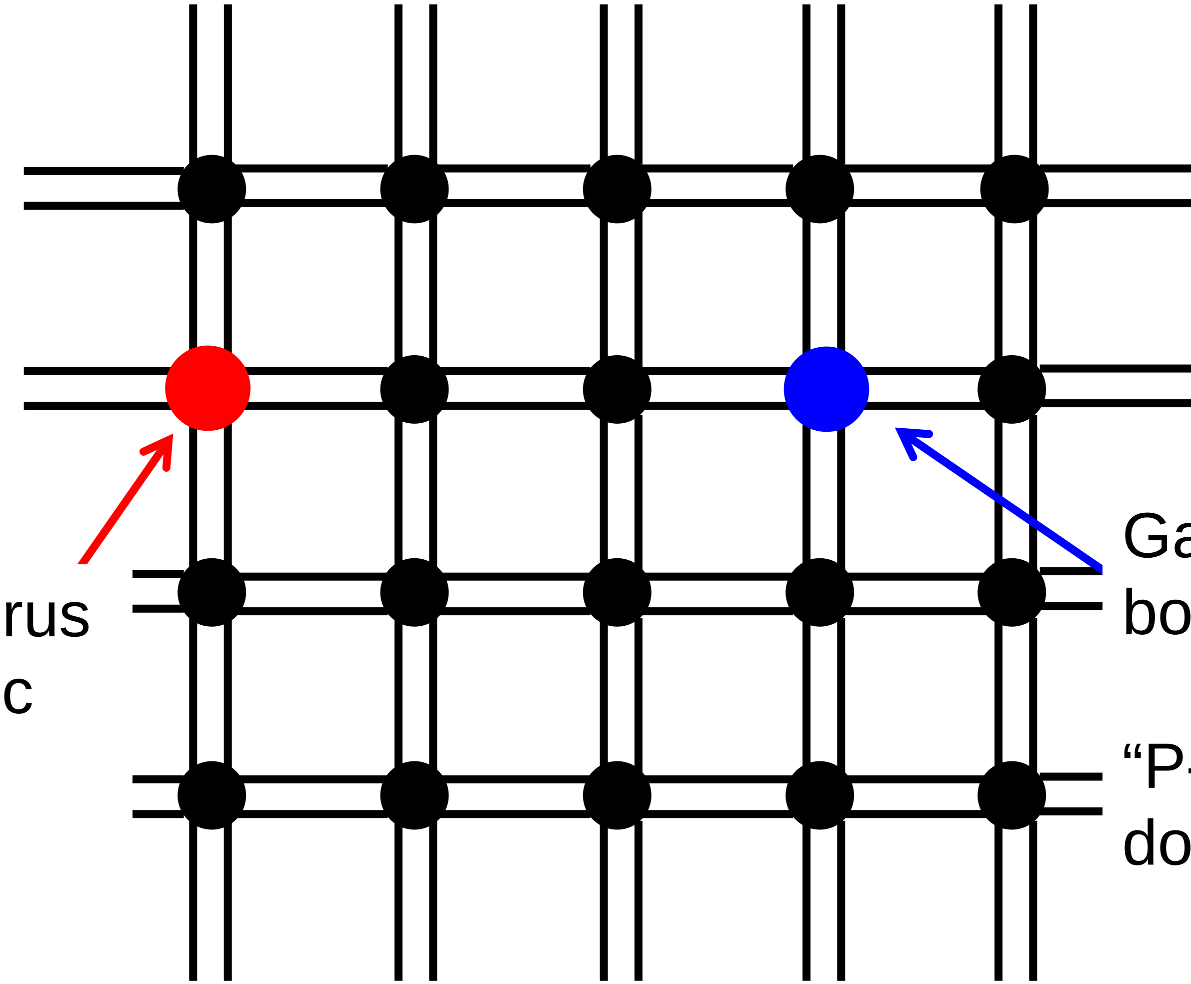
"One shouldn't work on semiconductors, that is a filthy mess; who knows whether any semiconductors exist."

Wolfgang Pauli, 1931

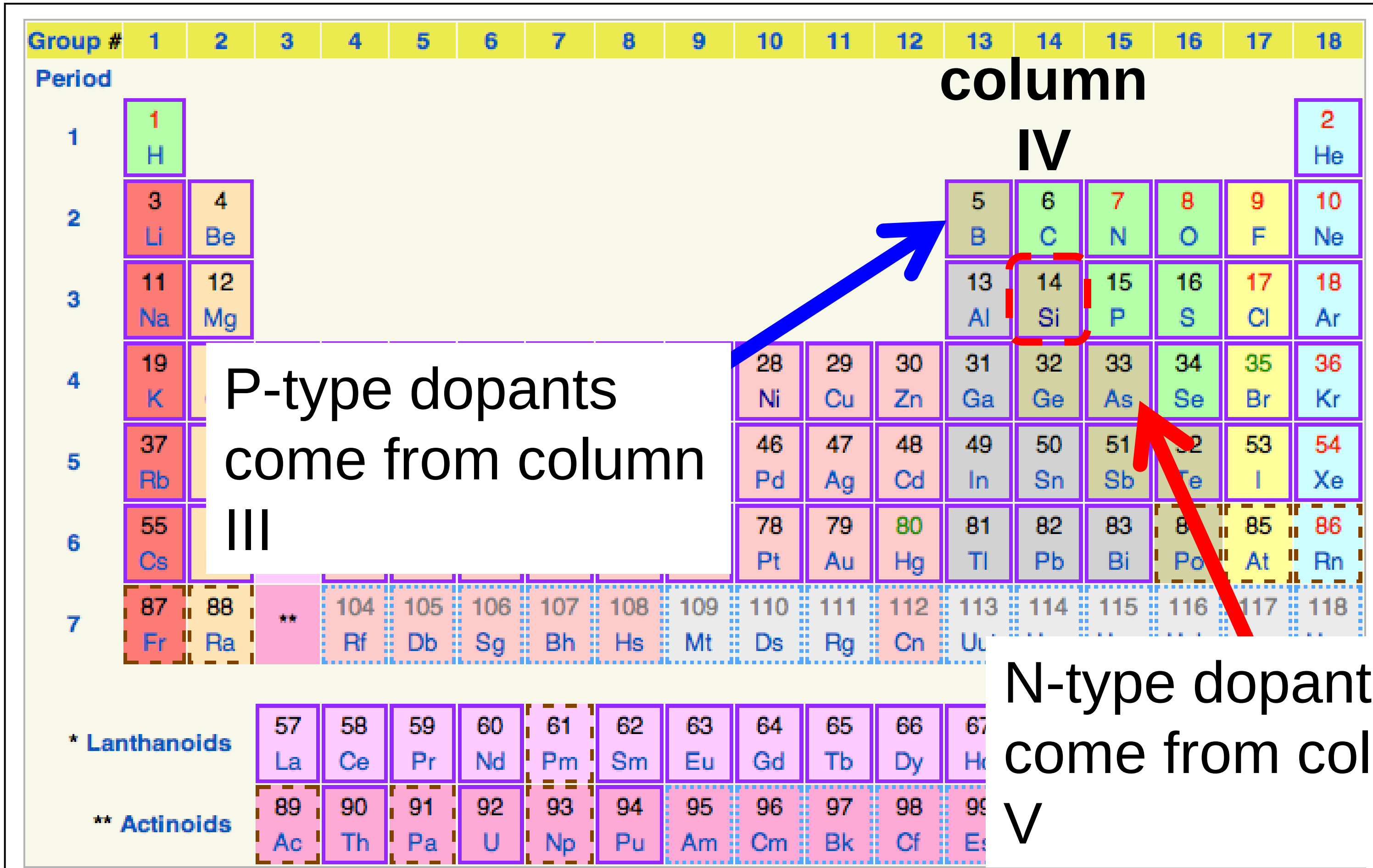
Recall: Bonding cartoon of Si lattice



Doping a semiconductor

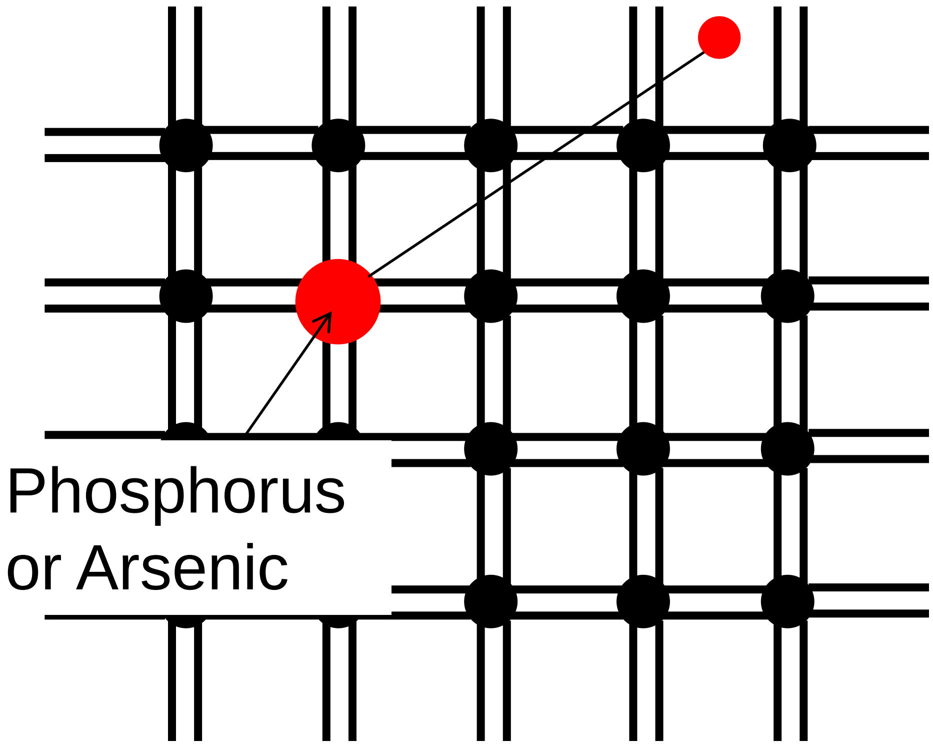


Dopants in Si



N-type doping

$$E_B \approx -0.1\,\mathrm{eV}$$

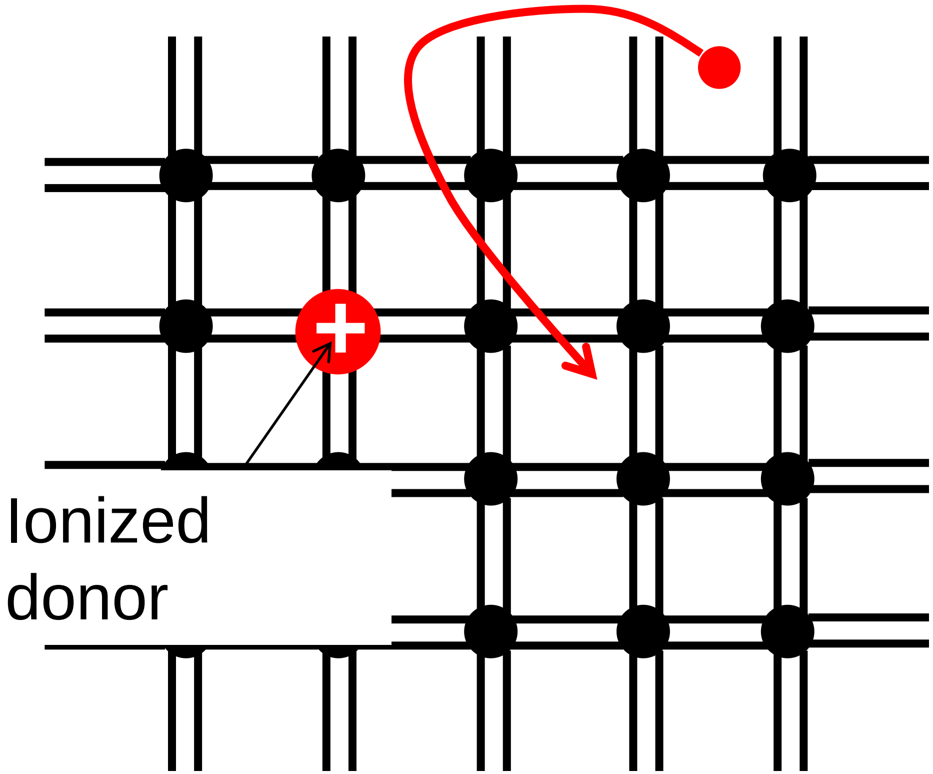


Weakly bound

Easily broken at room temperature

Produces an electron in the conduction band.

Ionized donor



Concentration of dopants:

$$N_D \ \text{cm}^{-3}$$

Concentration of ionized donors:

$$N_D^+ \ \text{cm}^{-3}$$

Concentration of electrons in the conduction band:

$$n \approx N_D^+ \ \text{cm}^{-3}$$

Be careful about units!

$$\boxed{n \approx N_D^+ \text{ cm}^{-3}}$$

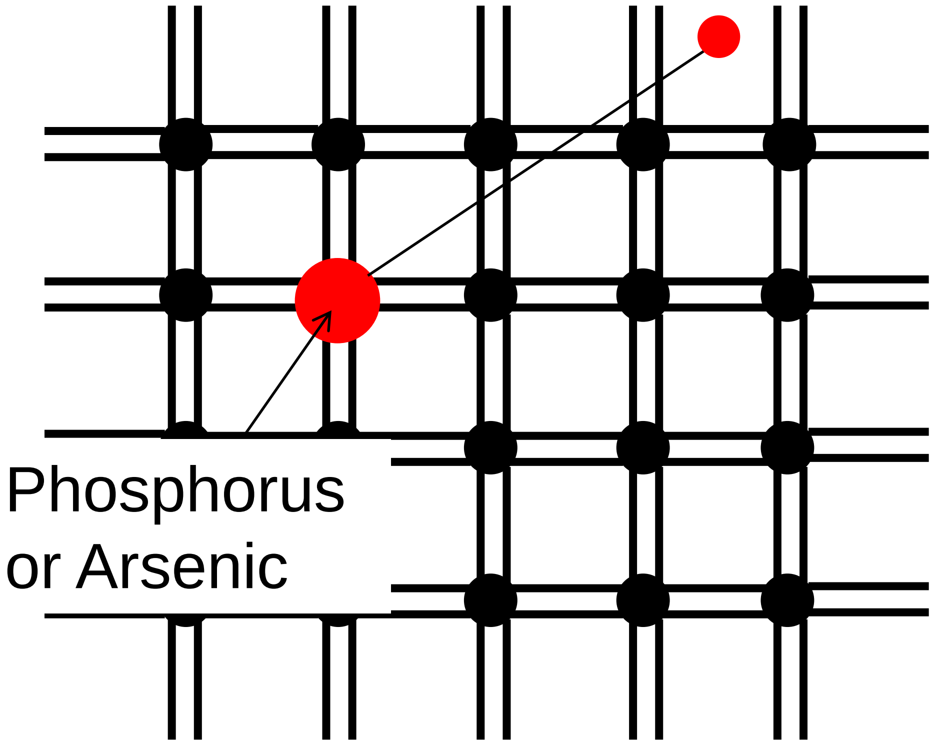
We will be working in SI (MKS) units. The carrier concentration should be given per cubic **meter**, but semiconductor people like to mix their units.

It is safest to do the calculations in SI units, and then convert to cubic cm.

$$n = 10^{26} \text{ m}^{-3} \rightarrow n = 10^{26} \frac{1}{m^3} \times \left(\frac{10^{-2}\text{m}}{\text{cm}} \right)^3 \rightarrow n = 10^{20} \text{ cm}^{-3}$$

Binding energy of the donor

$E_B \approx ?$



Hydrogen atom:

$$E_B = -\frac{m_0 q^4}{2\left(4\pi\varepsilon_0\hbar\right)^2}\ \mathrm{eV}$$

$$E_B = -13.6\ \mathrm{eV}$$

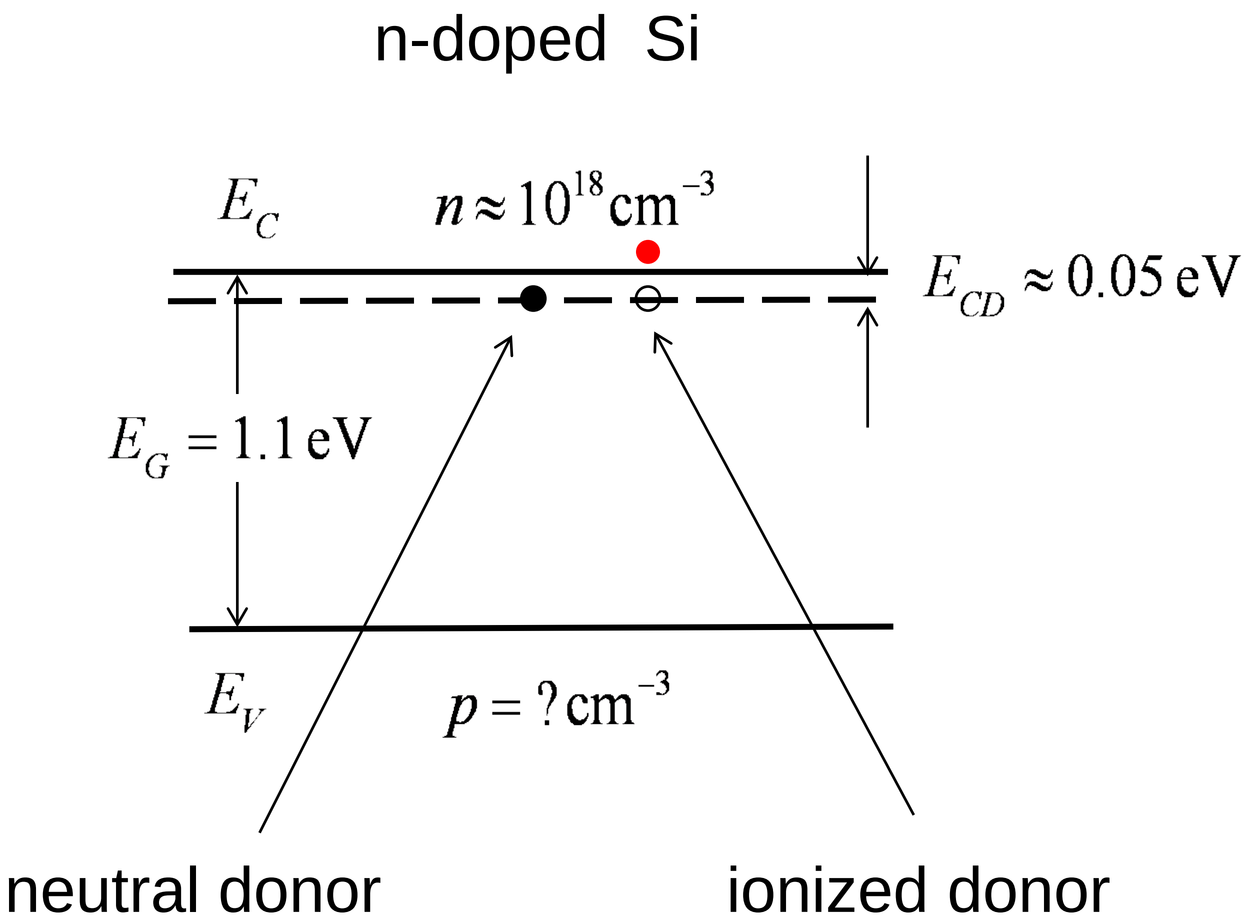
Donor in Si:

$$\varepsilon = K_S\varepsilon_0$$
$$= 11.8\times\left(8.854\times10^{-12}\ \mathrm{F/m}\right)$$

$$m_n^* = 1.18 m_0$$

$$E_B \approx -0.1\ \mathrm{eV}$$

Energy band view (n-type)



$$N_D = 10^{18}\,\text{cm}^{-3}$$

$$N_D^+ = 10^{18}\,\text{cm}^{-3}$$

$$n \approx N_D^+ = 10^{18}\,\text{cm}^{-3}$$

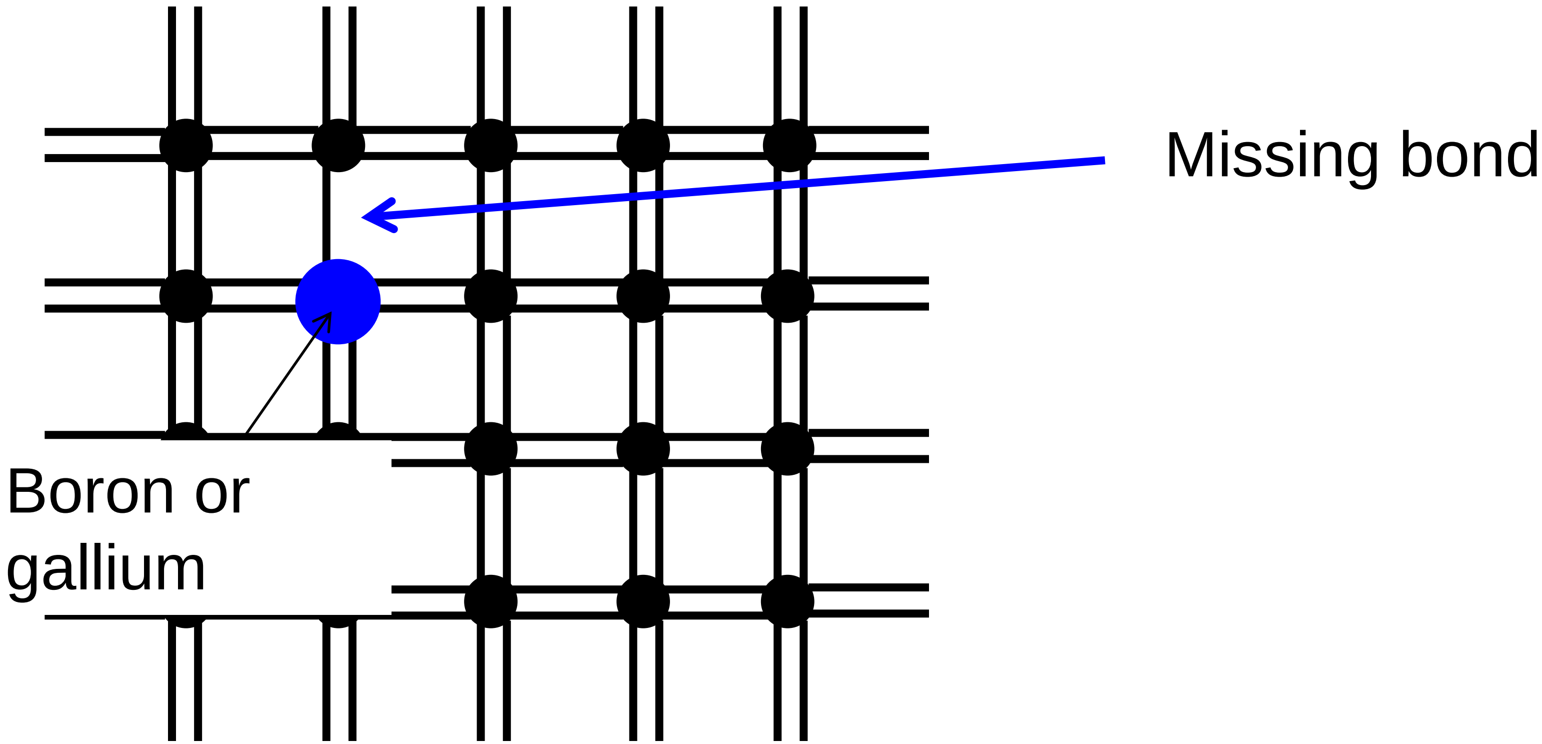
$$p \approx ?$$

(T = 300 K)

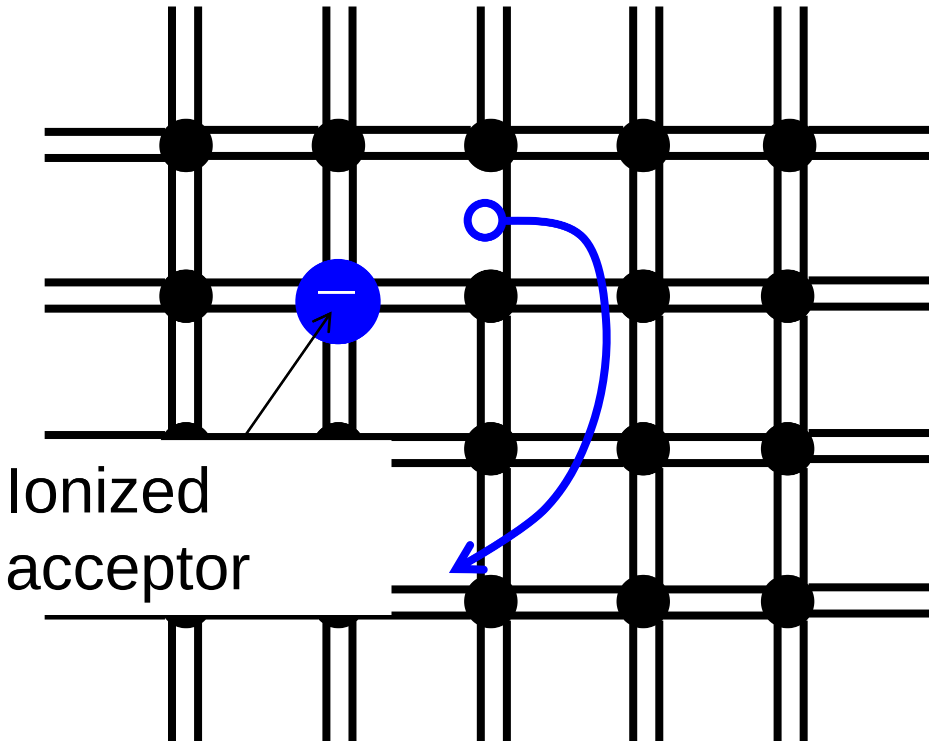
$$10^{14} \leq N_D \leq 10^{20}\ \text{cm}^{-3}$$

$$N_{atoms} \approx 5 \times 10^{22}\ \text{cm}^{-3}$$

P-type doping



Ionized acceptor



Concentration of dopants:

$$N_A \text{ cm}^{-3}$$

Concentration of ionized acceptors:

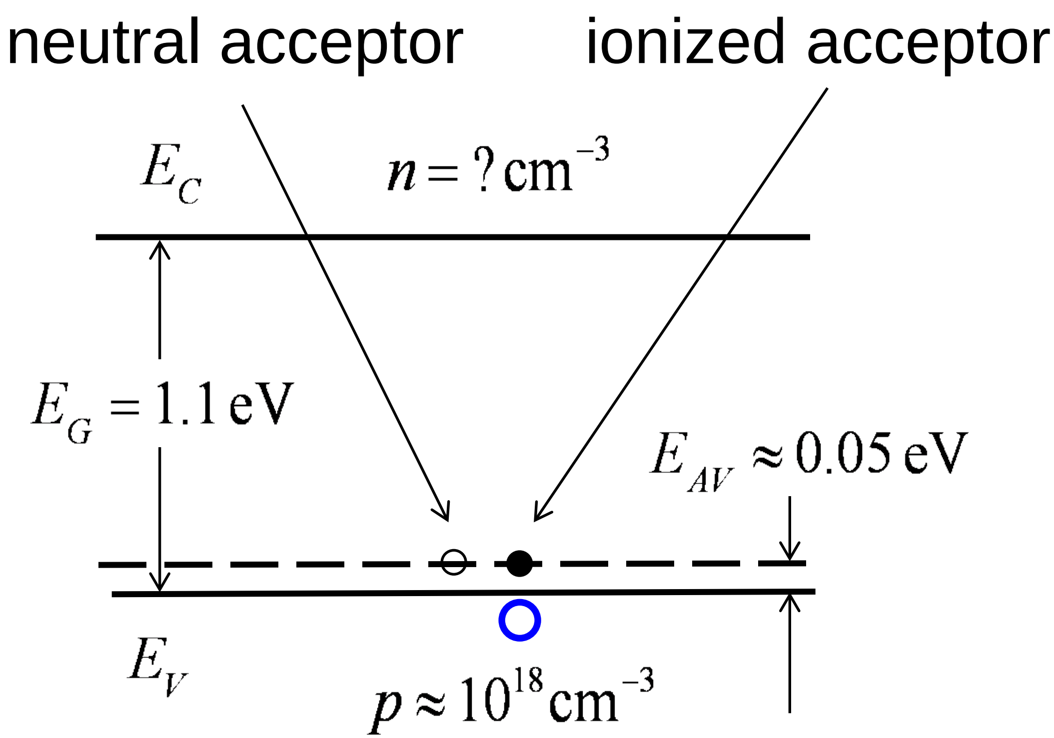
$$N_A^- \text{ cm}^{-3}$$

Concentration of “holes” in the valence band:

$$p \approx N_A^- \text{ cm}^{-3}$$

Energy band view (p-type)

p-doped Si



$$N_A = 10^{18}\,\text{cm}^{-3}$$

$$N_A^- = 10^{18}\,\text{cm}^{-3}$$

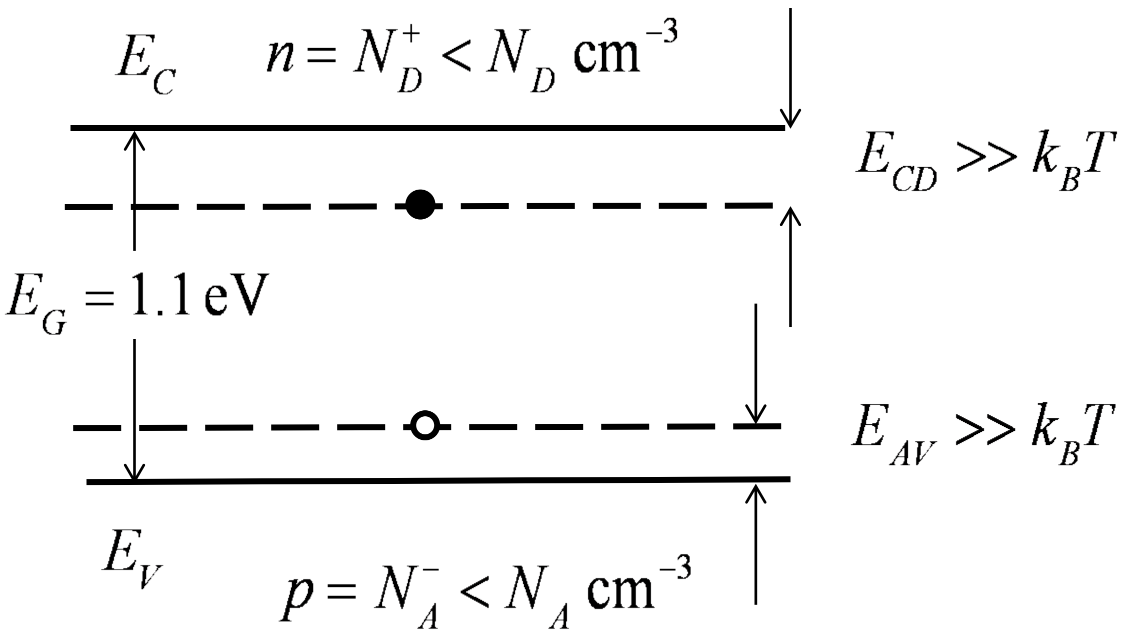
$$p \approx N_A^- = 10^{18}\,\text{cm}^{-3}$$

$$n \approx ?$$

(T = 300 K)

$$10^{14} \le N_A \le 10^{20}\ \text{cm}^{-3}$$

“Deep donors” and “deep acceptors”



“Shallow” donors and acceptors are fully ionized at room temperature.

If the donor or acceptor level is much larger than kT (at room temperature), we say that the level is “deep”).

Donors and acceptors will be partially ionized at room temperature.

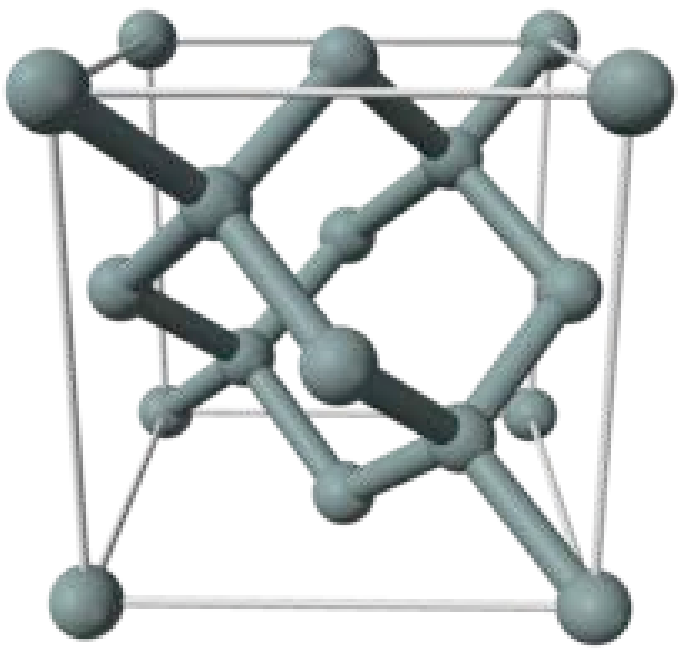
Question

1) What type of dopant is Si in GaAs?

   a) n-type
   b) p-type
   c) either n-type or p-type
   d) neither n-type nor p-type
   e) don’t know

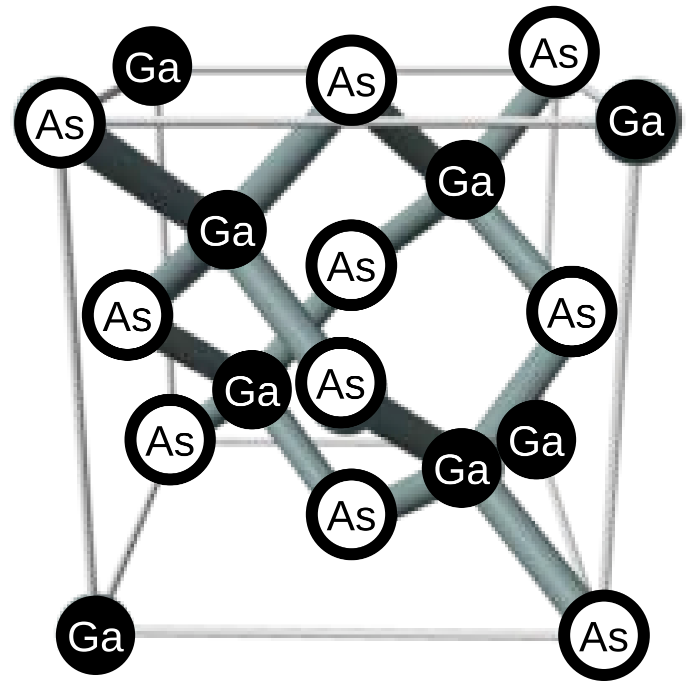
Si vs. GaAs crystals

Si



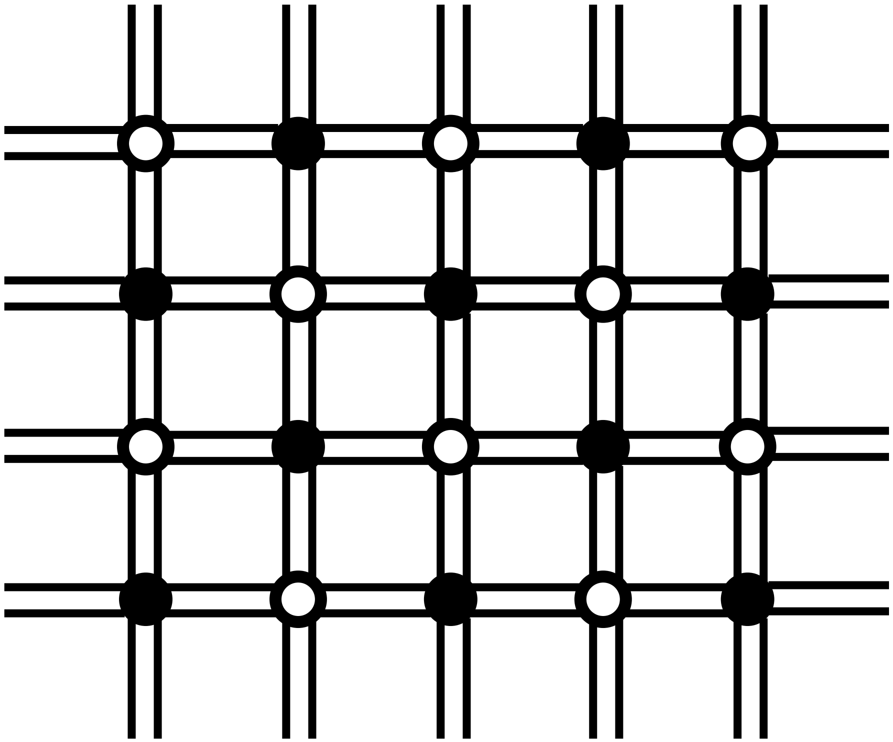
diamond lattice

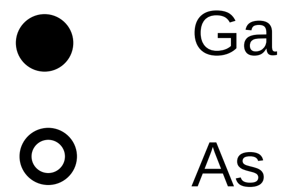
GaAs



zinc blende lattice

GaAs bonding cartoon

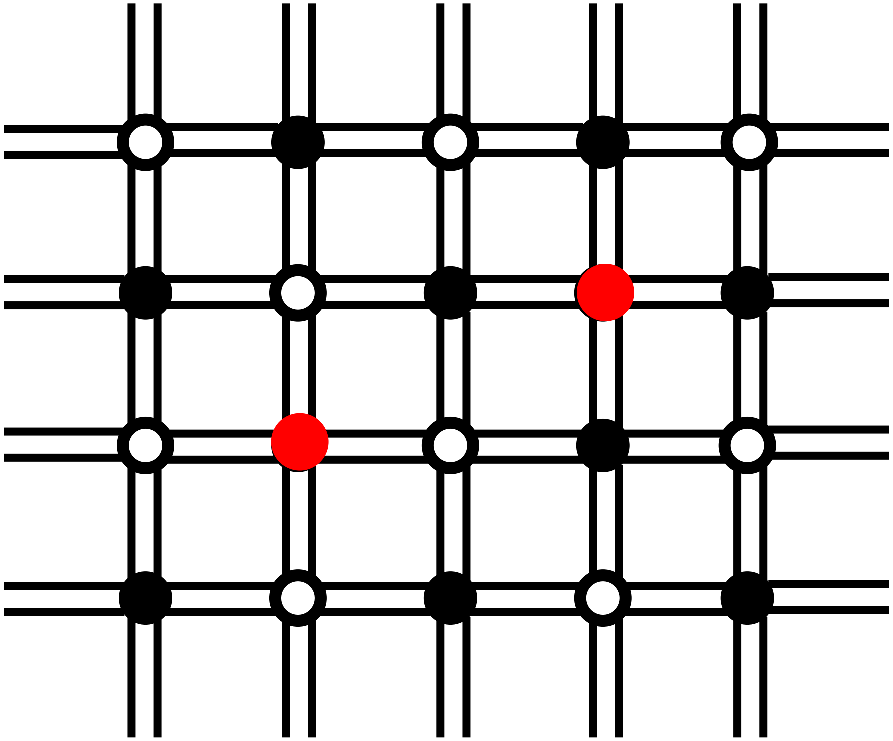


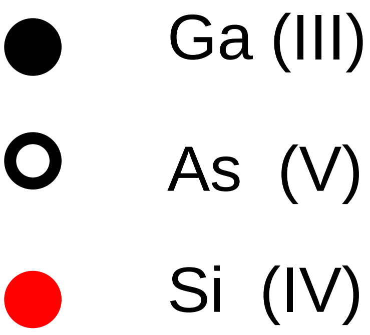


Every Ga atom has 4 NN As atoms.

Every As atom has 4 NN Ga atoms.

Si in GaAs: Two possibilities





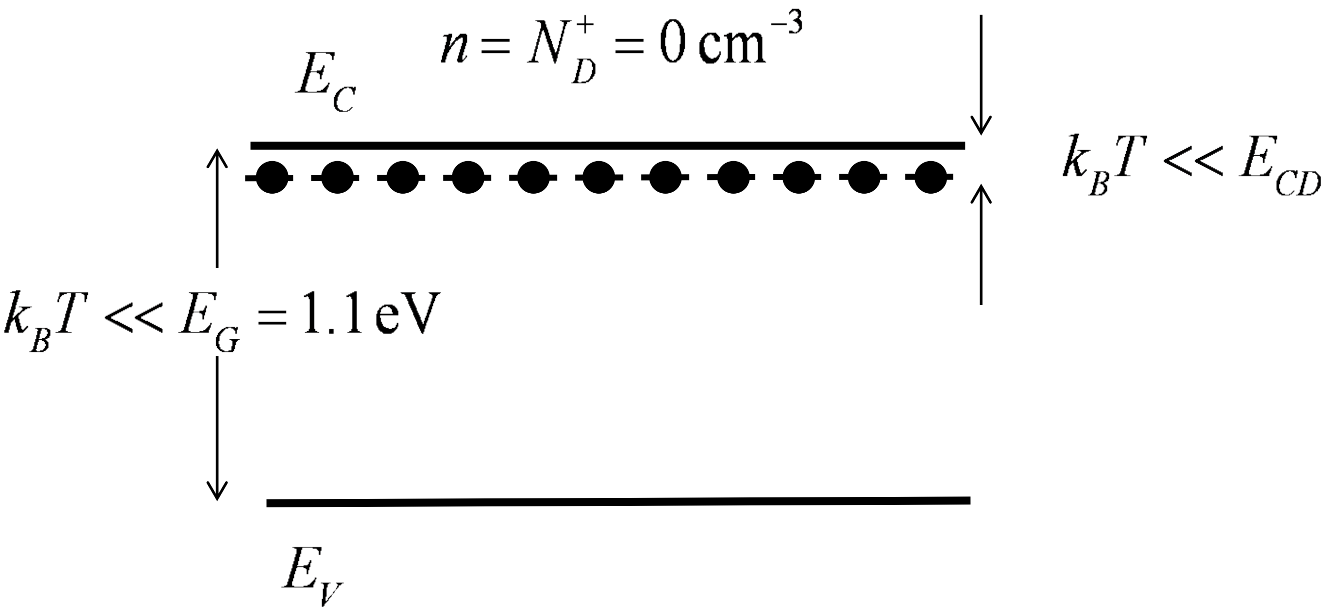
Si on a As site is an acceptor.

Si is an “amphoteric” dopant in GaAs.

Si on a Ga site is a donor.

How does the carrier concentration vary with T?

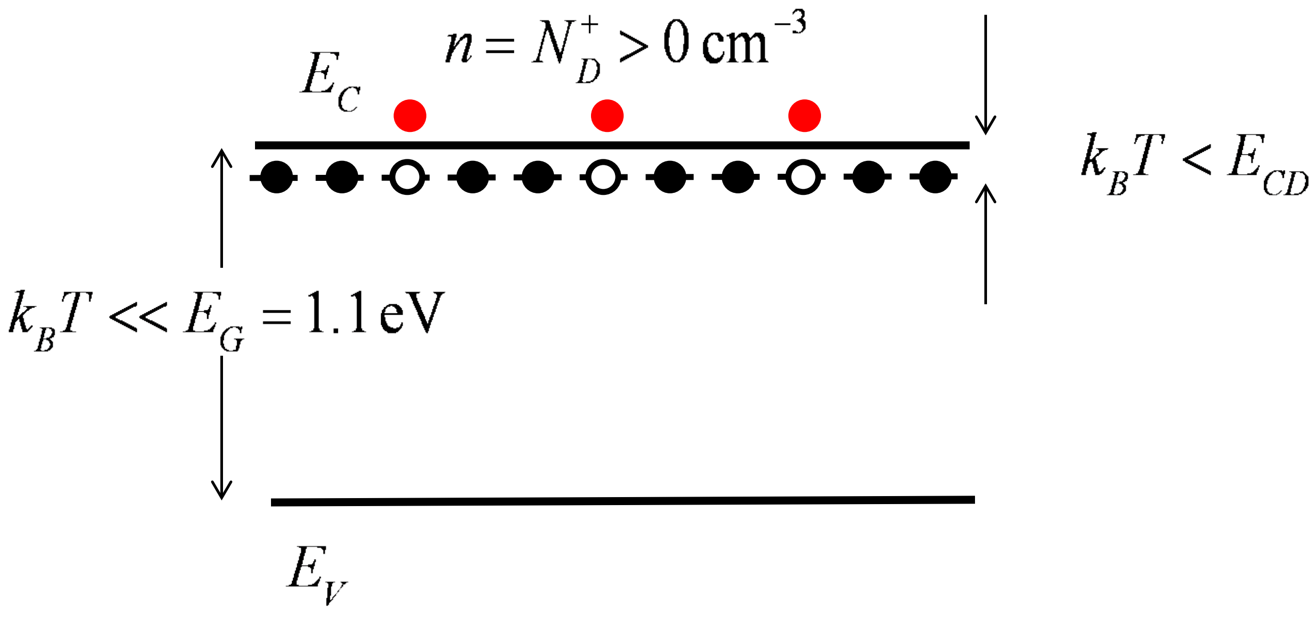
T = 0 K



No extrinsic carriers due to doping, and no intrinsic carriers due to thermal excitation across the band gap.

Low temperature

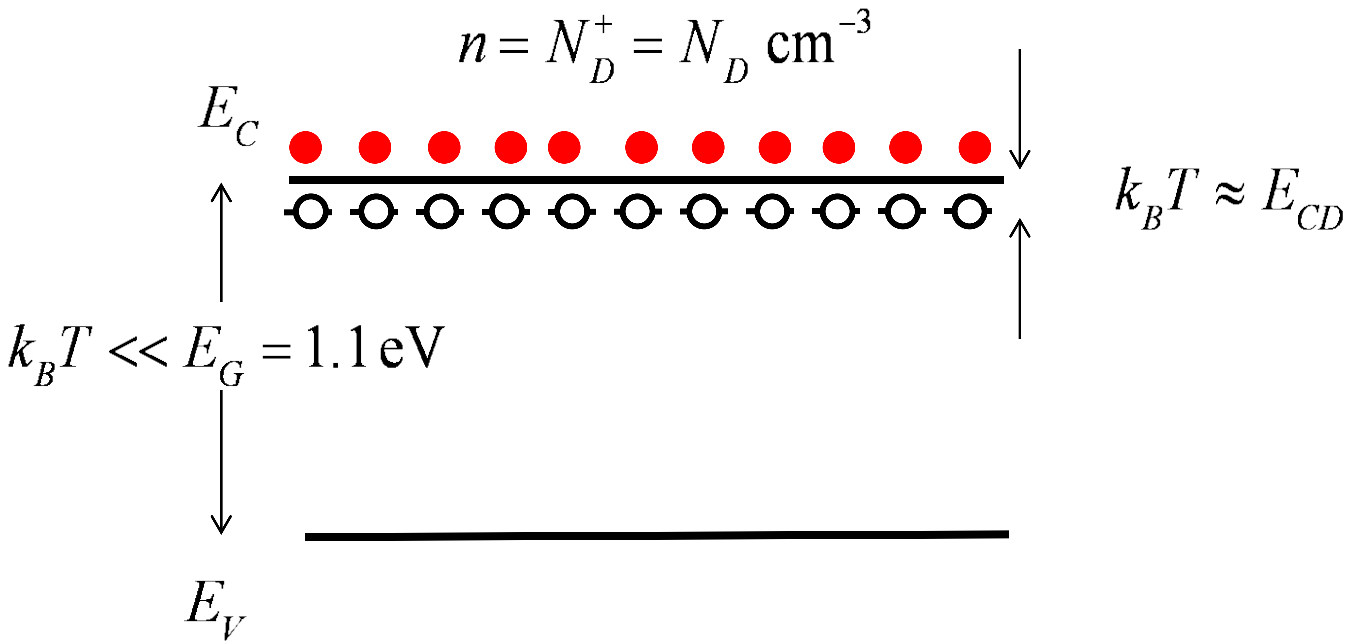
$T > 0$ K



A few extrinsic carriers due to doping, but no intrinsic carriers due to thermal excitation across the band gap.

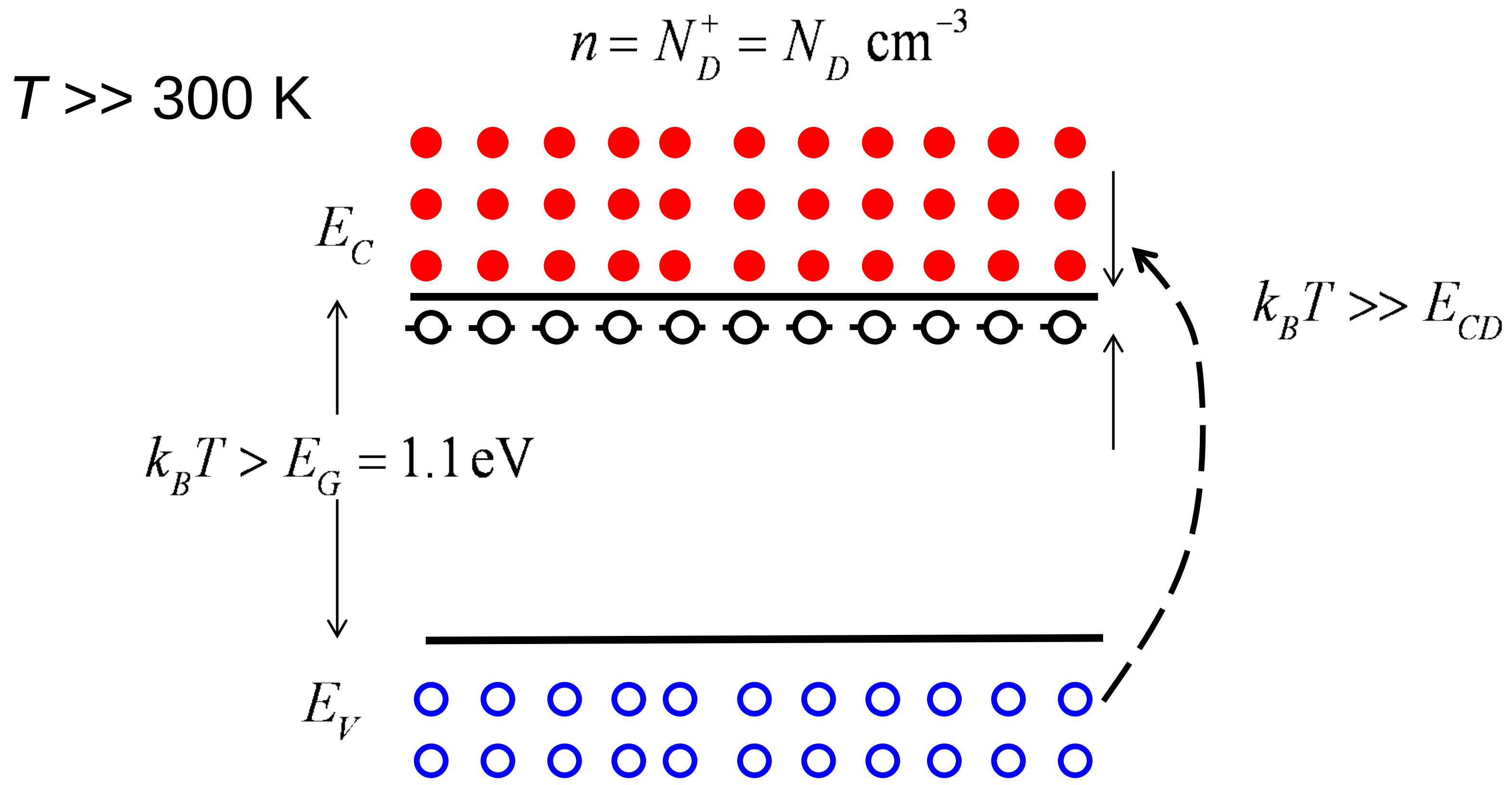
Room temperature (shallow dopants)

T = 300 K



Many extrinsic carriers due to doping, but very few intrinsic carriers due to thermal excitation across the band gap.

High temperature



Extrinsic carriers due to doping, but also many intrinsic carriers due to thermal excitation across the band gap. Also many holes in the valence band now.

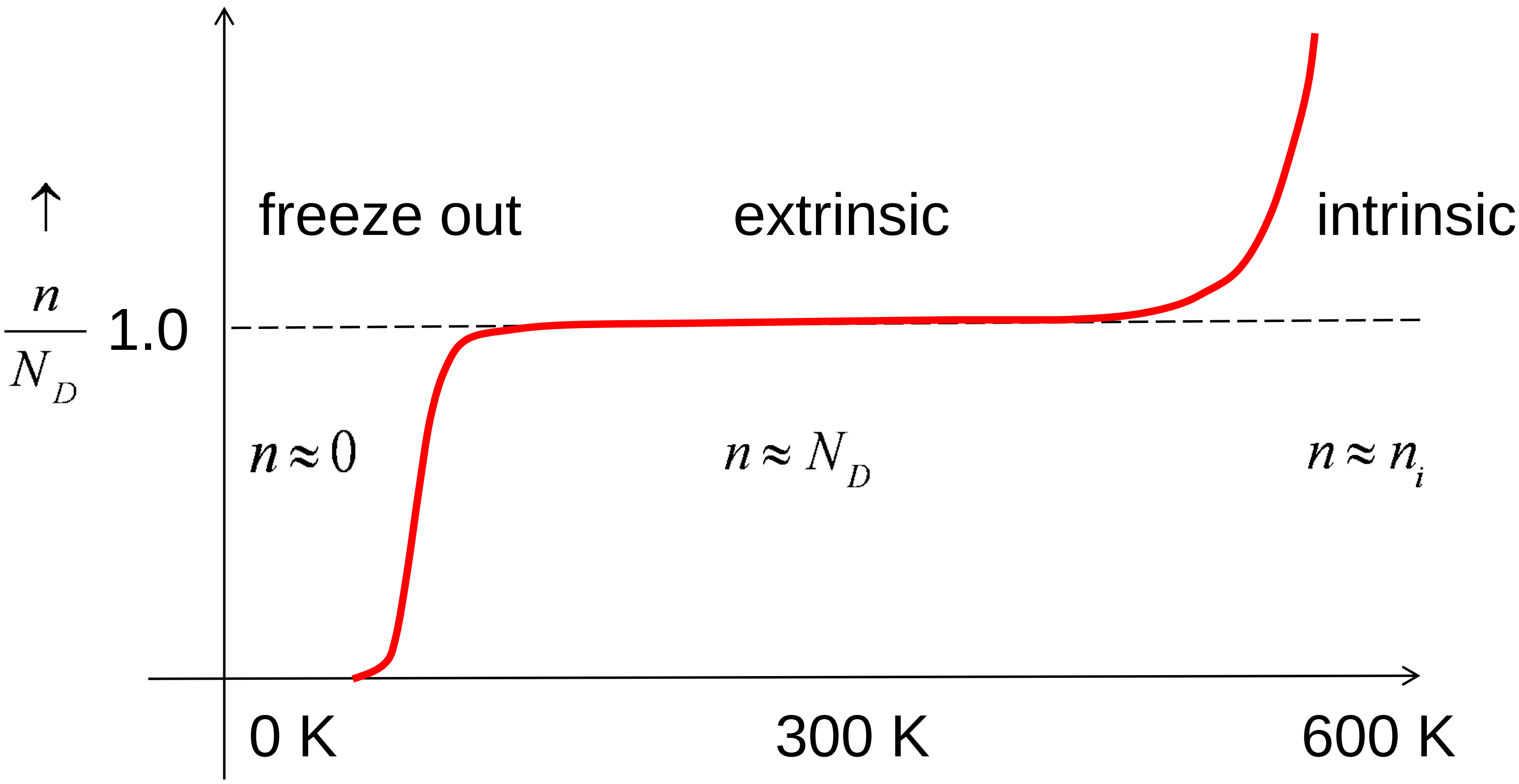
Comment

At high temperatures, the intrinsic carriers produced by thermal excitation across the bandgap overwhelm the extrinsic carriers produced by doping.

Because semiconductor devices are produced by selective doping, the device ceases to operate.

Semiconductor devices for operation at high temperature should be made with materials with large band gaps, such as SiC and GaN.

Carrier concentration vs. temperature



Summary

To dope a semiconductor, we replace a few atoms with atoms from a different column of the periodic table.

Ionized dopants produce electrons in the conduction band or holes in the valence band.

Dopants can be energetically shallow or deep.

The carrier concentration vs. temperature characteristic has freeze out, extrinsic, and intrinsic regions.

A low temperatures, semiconductors become insulators.