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ECE 255: L3.2

Doped Semiconductors

(Sedra and Smith, 7th Ed., Sec. 3.2)

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Doping makes semiconductors useful

metal

gold (Au)

semiconductor

silicon (Si)

insulator

glass (SiO_2)

Doped semiconductors

1) The np product
2) Doping
3) Carrier concentration vs. doping density
4) Carrier concentration vs. temperature

The equilibrium np product

For intrinsic semiconductors: $n = p = n_i$ $n_i = 10^{10}\ \text{cm}^{-3}$

Silicon T = 300 K

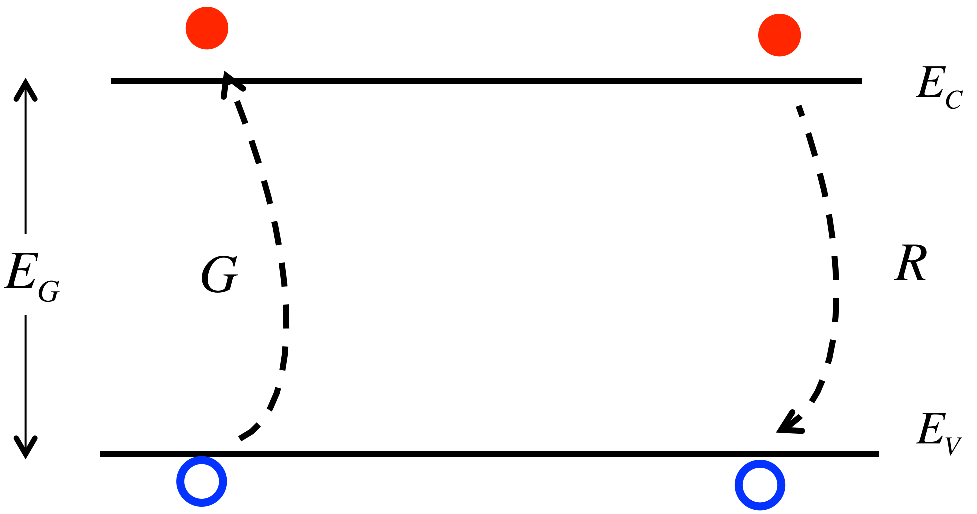
$$np = n_i^2$$

$$\boxed{n_i^2 \propto e^{-\frac{E_G}{k_B T}}}$$

n_i is typically **small at room temperature**

n_i can become **very large at high temperatures** and **very small at low temperatures**

Generation and Recombination



$G_p = G_n = G > 0$

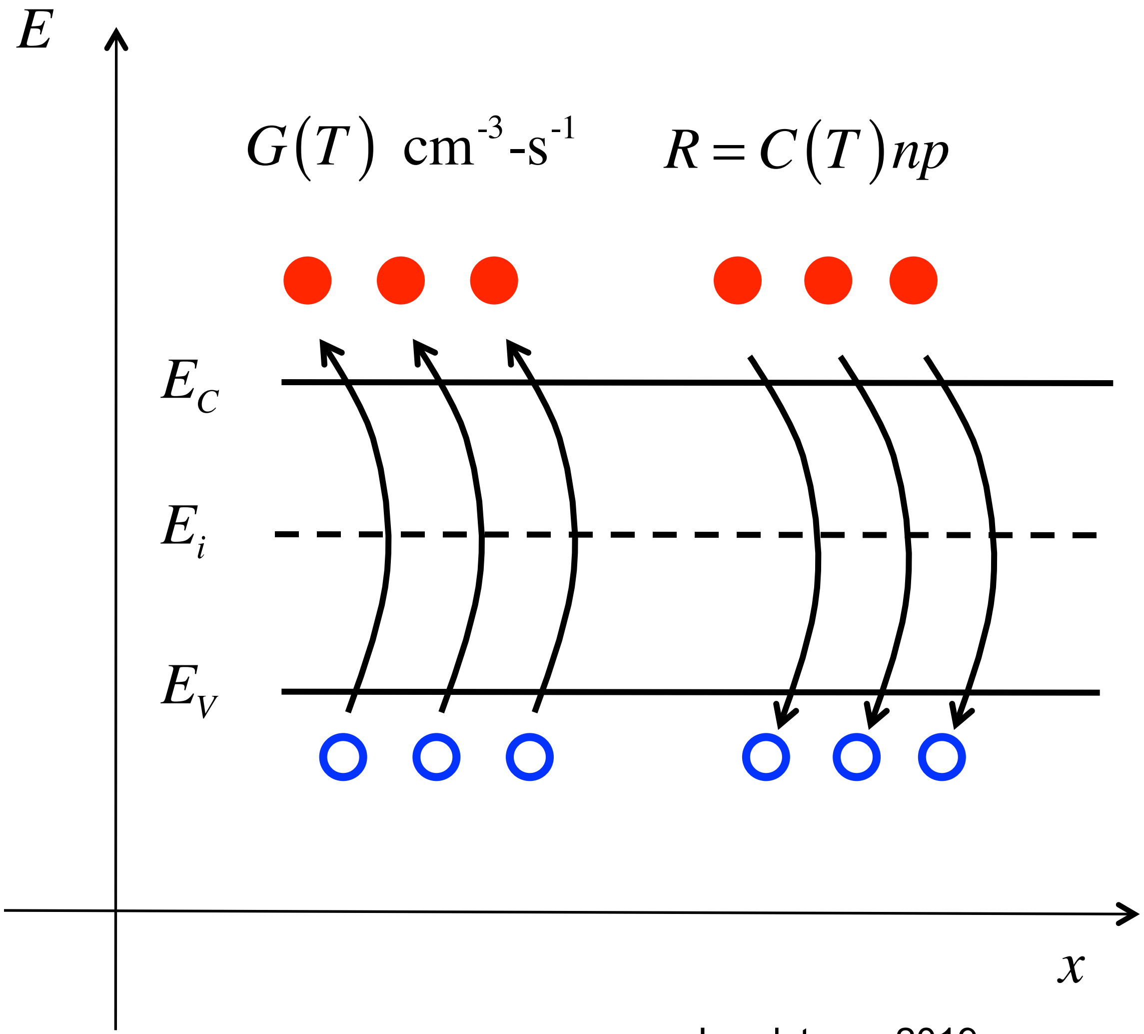
$R_p = R_n = R > 0$

requires energy to break covalent bonds

releases energy

In equilibrium: *G* = *R*

Why is $np = n_i^2$?



In equilibrium:

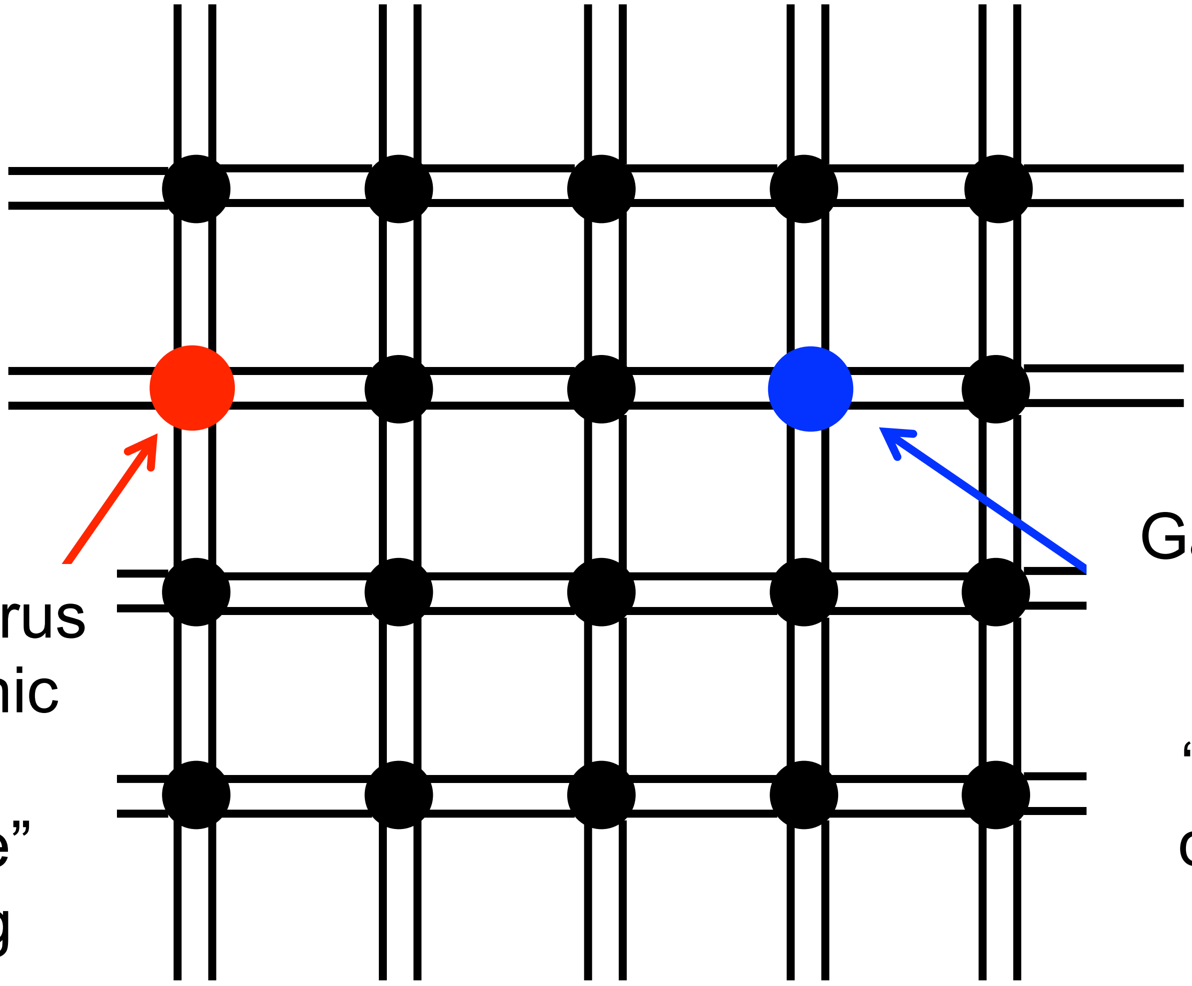
$$G = R$$

$$np = \frac{G(T)}{C(T)} = n_i^2(T)$$

$$\boxed{np = n_i^2(T)}$$

(equilibrium)

Doping a semiconductor



Phosphorus
or Arsenic

"N-type"
doping

Gallium or
boron

"P-type
doping"

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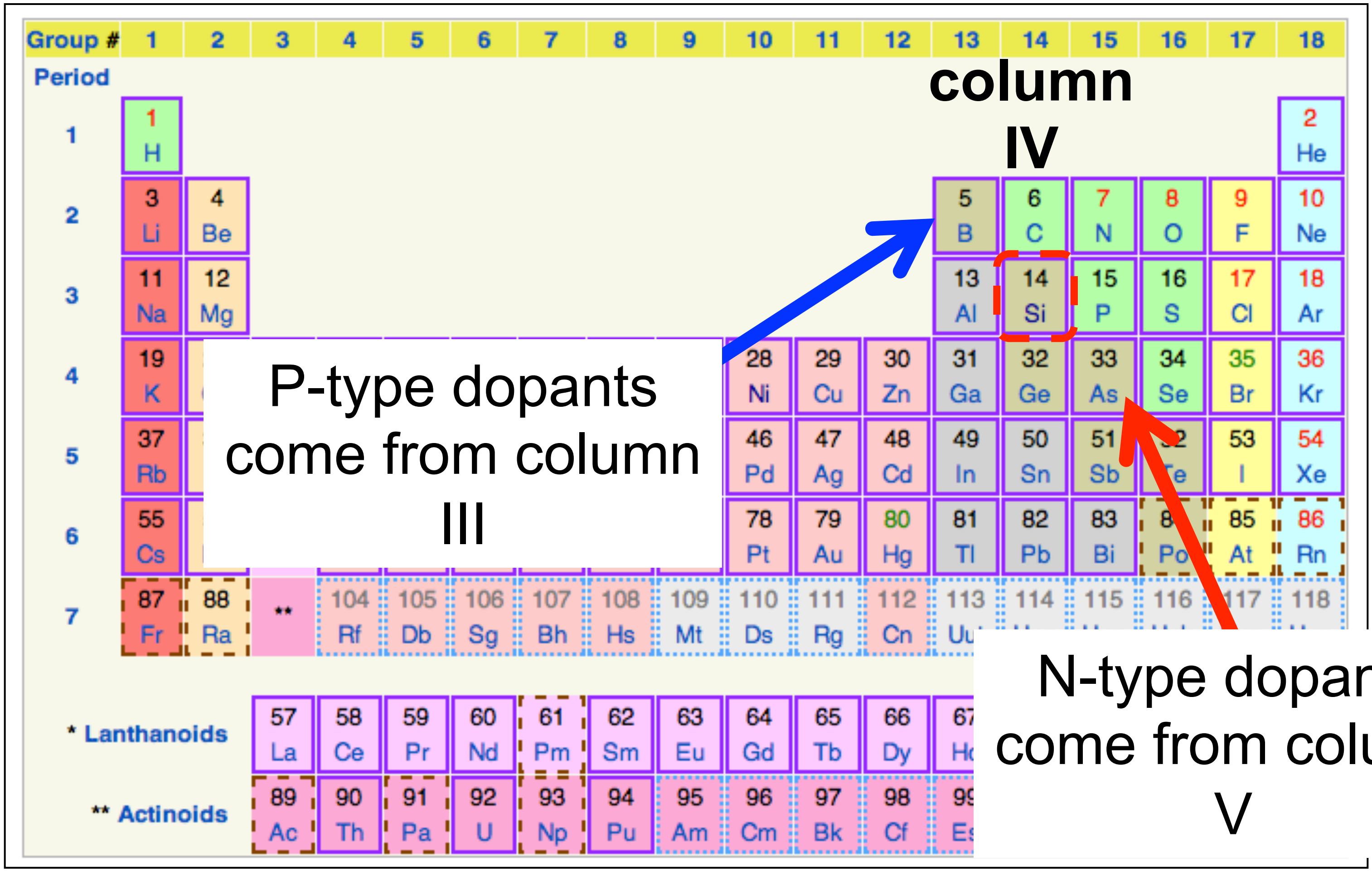
Dopants in Si

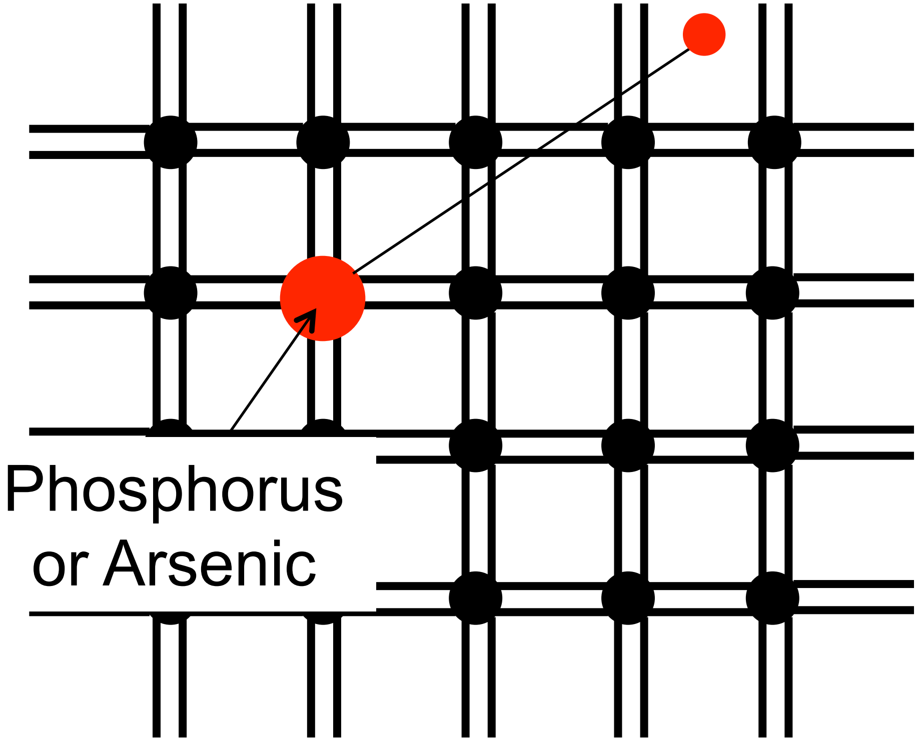


column IV

P-type dopants come from column III

N-type dopants come from column V

Donors: N-type doping



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

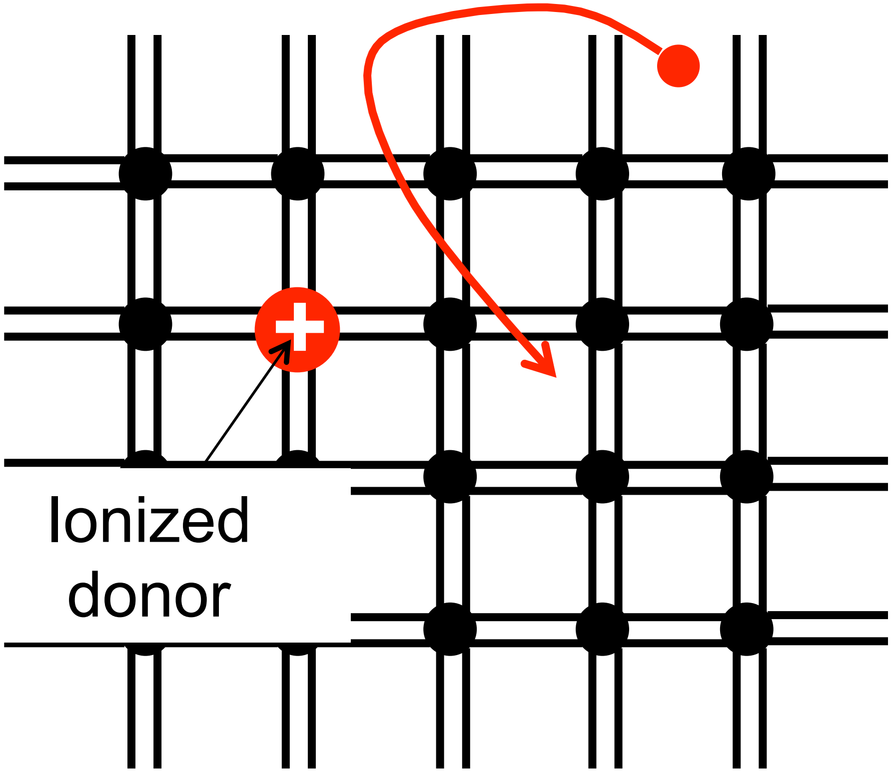
$$E_B \approx -0.05\ \mathrm{eV}$$

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:

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

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Carrier concentrations

$n \approx N_D^+ \approx N_D \text{ cm}^{-3}$ Phosphorous or arsenic doped Si at 300 K

Example:

$N_D = 10^{16} \text{ cm}^{-3}$

$n = 10^{16} \text{ cm}^{-3} >> n_i = 10^{10} \text{ cm}^{-3}$

extrinsic semiconductor

$p \neq 10^{10} \text{ cm}^{-3}$

$np = n_i^2 = 10^{20} \text{ cm}^{-3}$

$$p = \frac{n_i^2}{n} = \frac{10^{20}}{10^{16}} = 10^4 \text{ cm}^{-3}$$

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.

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

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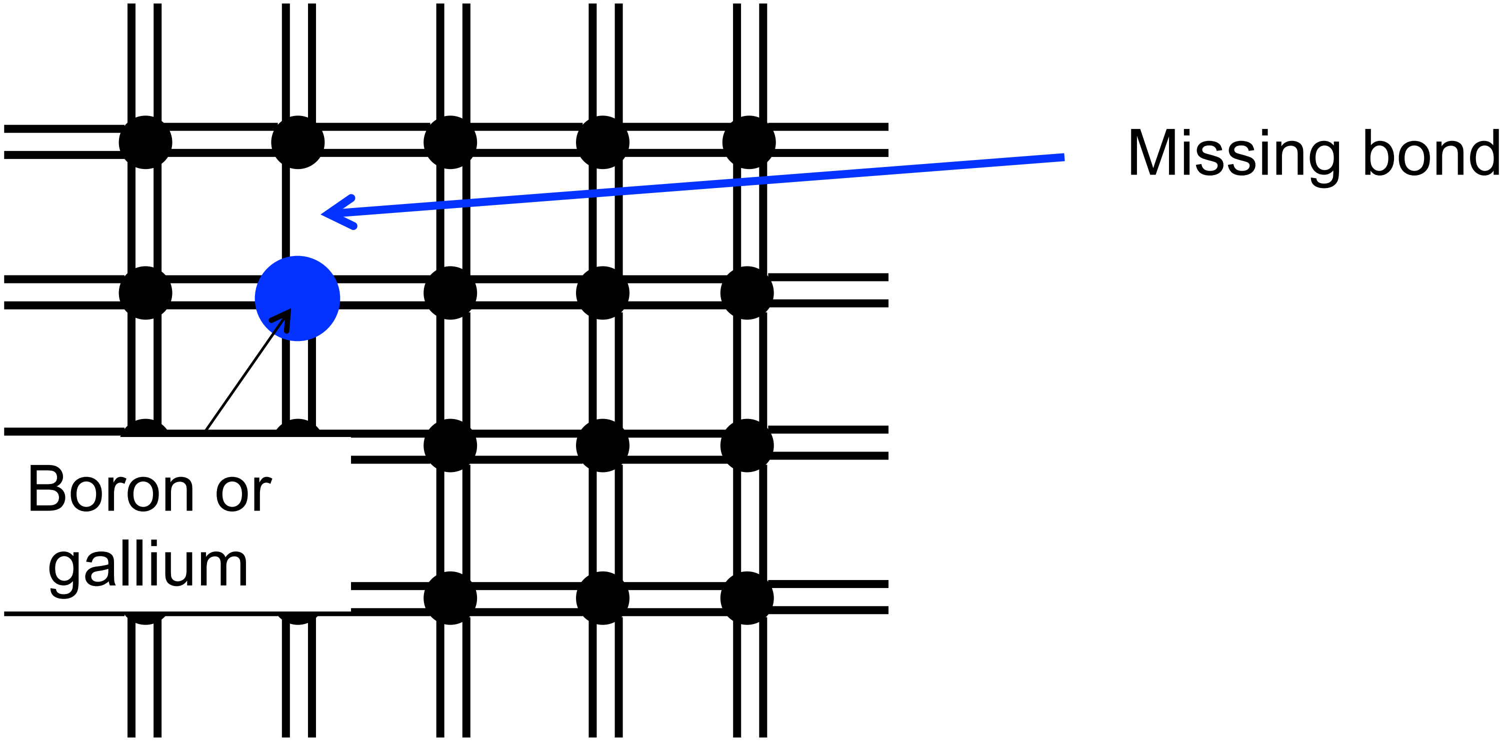
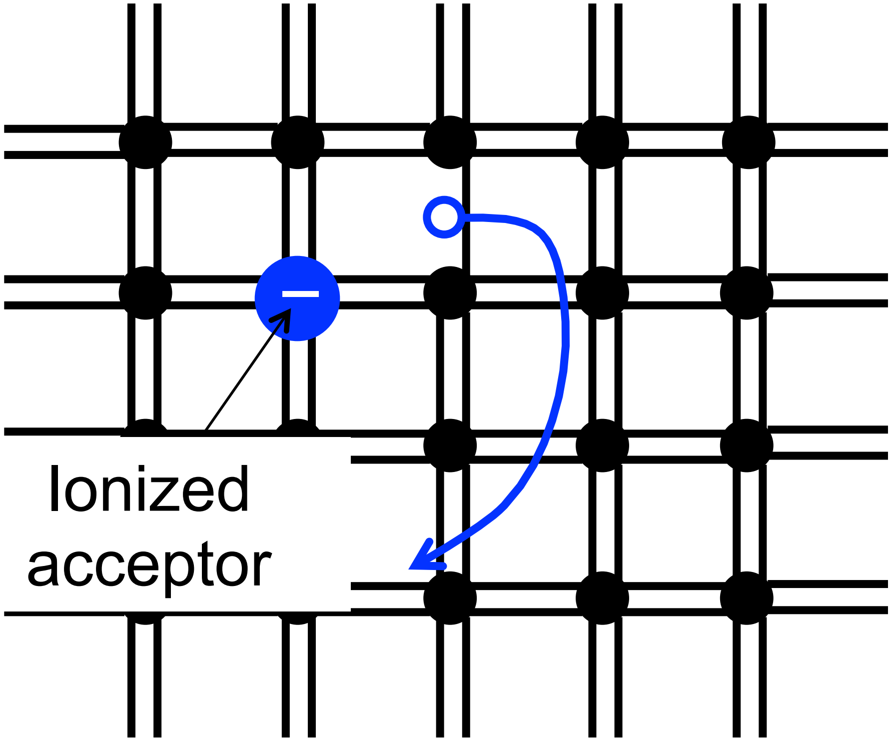
Acceptors: P-type doping



Ionized acceptor



Concentration of dopants:

N_A cm^{-3}

Concentration of ionized acceptors:

N_A^- cm^{-3}

Concentration of "holes" in the valence band:

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

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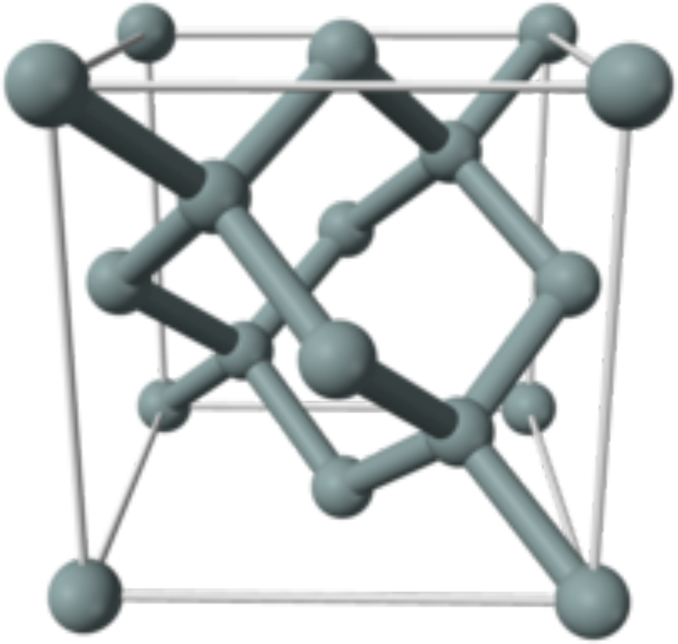
Question

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

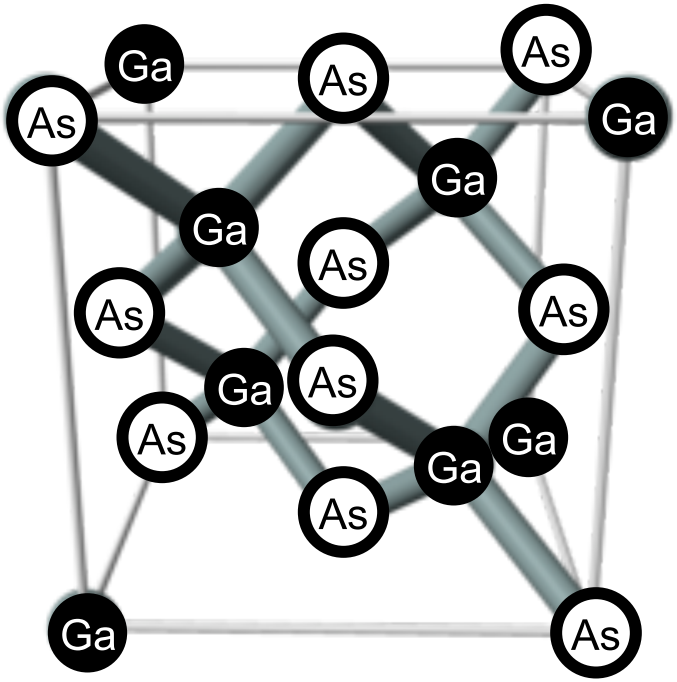
Si vs. GaAs crystals

Si



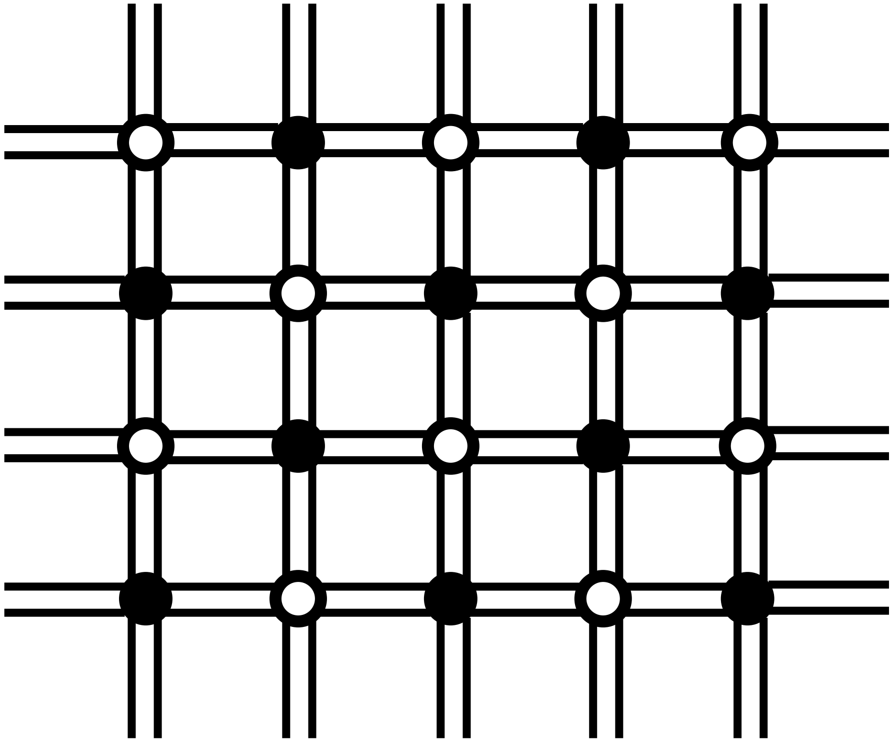
diamond lattice

GaAs



zinc blende lattice

GaAs bonding cartoon



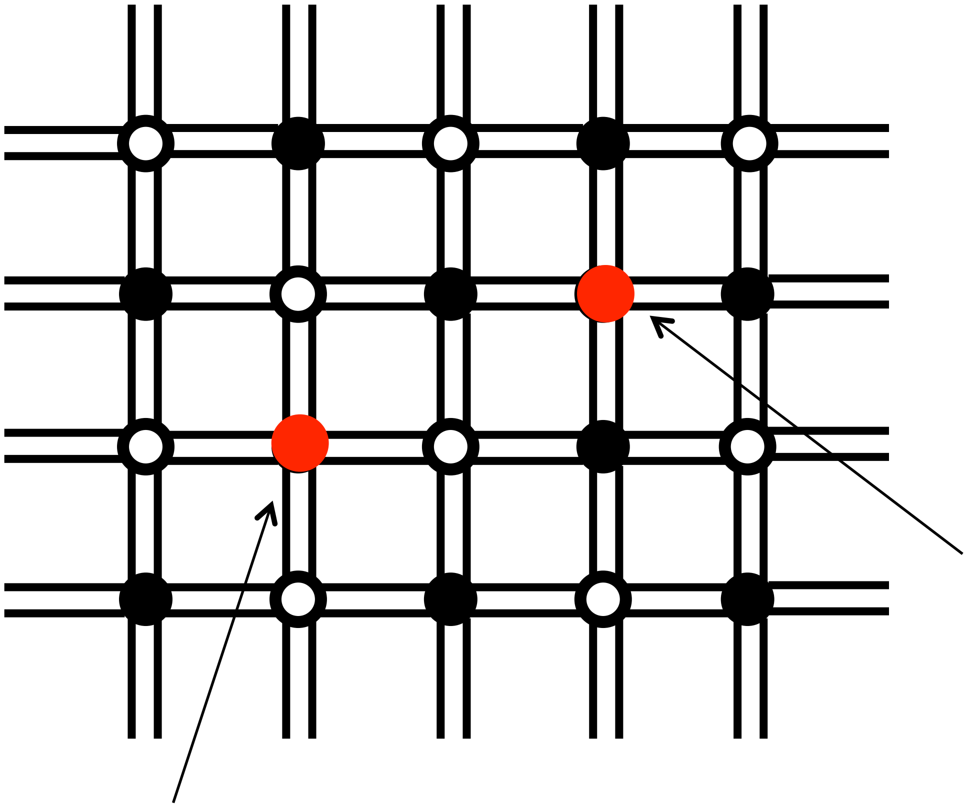
● Ga

○ As

Every Ga atom has 4 NN As atoms.

Every As atom has 4 NN Ga atoms.

Si in GaAs: Two possibilities



● Ga (III)

○ As (V)

🔴 Si (IV)

Si on a As site is an acceptor.

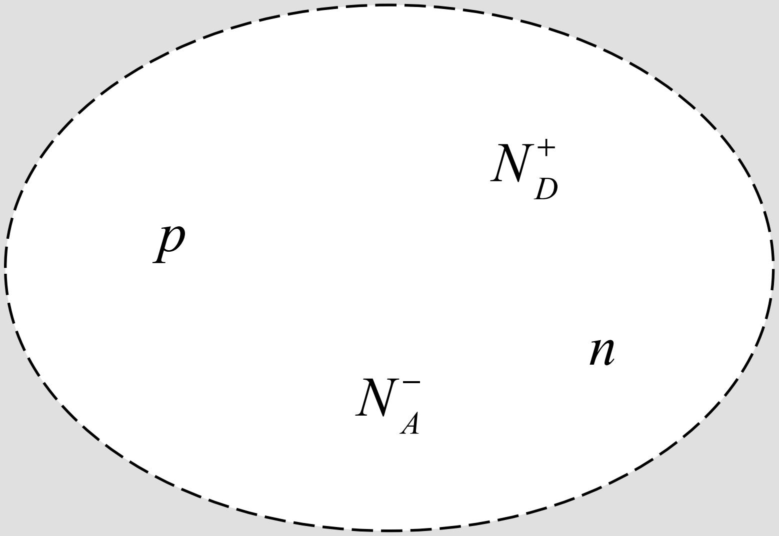
Si is an “amphoteric” dopant in GaAs.

Si on a Ga site is a donor.

Space charge density

What is the net charge in this region?

$$\rho = q\left[p - n + N_D^+ - N_A^- \right] \quad \mathrm{C/m^3}$$



bulk, uniform semiconductor

Space charge neutrality

“Nature abhors a vacuum.” Nature also abhors a charge.

Mobile charges (electrons and holes) will be attracted to the immobile ionized dopants), so that the net charge is zero.

$$\rho = q\left[p - n + N_D^+ - N_A^- \right] = 0$$

Almost uniform semiconductors will be nearly neutral, but with strong non-uniformities (e.g. PN junctions), there will be a space charge.

Space charge neutrality + np product

$$\rho = q\left[p - n + N_D^+ - N_A^- \right] = 0$$

$$np = n_i^2$$

Always true in equilibrium − even for doped semiconductors.

These are two equations in two unknowns − *p* and *n*.

Solving for the carrier density

1) charge neutrality: $p - n + N_D^+ - N_A^- = 0$

2) eq. np product: $np = n_i^2$

3) result:

$$\frac{n_i^2}{n} - n + N_D^+ - N_A^- = 0$$

$$p - \frac{n_i^2}{p} + N_D^+ - N_A^- = 0$$

N-type extrinsic semiconductors at **moderate** temps

$$n = \frac{N_D^+ - N_A^-}{2} + \left[\left(\frac{N_D^+ - N_A^-}{2}\right)^2 + n_i^2\right]^{1/2}$$

$$p = \frac{n_i^2}{n}$$

Extrinsic semiconductors:

$$N_D^+ = N_D \qquad N_A^- = N_A \qquad N_D - N_A >> n_i$$

$$n = N_D - N_A$$

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Example 1

Consider Si doped with phosphorus at N_D = 2.00 x 10^{15} cm^{-3} The temperature is 300 K. What are *n* and *p*?

Recall that at 300 K in Si, n_i = 1.00 x 10^{10} cm^{-3}

Assume that the donors are fully ionized.

$$n = \frac{N_D - N_A}{2} + \left[\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2\right]^{1/2} = \frac{N_D}{2} + \left[\left(\frac{N_D}{2}\right)^2 + n_i^2\right]^{1/2}$$

$$N_D >> n_i \qquad n = N_D = 2.00 \times 10^{15} \text{ cm}^{-3}$$

$$p = n_i^2 / n \qquad p = \left(10^{10}\right)^2 / 2 \times 10^{15} = 5 \times 10^4 \text{ cm}^{-3}$$

Example 2

Consider Si doped with phosphorus at N_D = 2.00 x 10^{15} cm^{-3} **and Boron** at N_A = 1.00 x 10^{15} cm^{-15}.
The temperature is 300 K. What are *n* and *p*?

$$n = \frac{N_D - N_A}{2} + \left[\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2\right]^{1/2}$$

$$N_D - N_A >> n_i \qquad n = N_D - N_A$$

$$p = n_i^2 / n$$

$$\boxed{\begin{aligned} &n = 1.00 \times 10^{15}\ \text{cm}^{-3} \\ &p = \left(10^{10}\right)^2 / 1 \times 10^{15} = 1 \times 10^{5}\ \ \text{cm}^{-3} \end{aligned}}$$

N-type semiconductors at **high** temps

$$n = \frac{N_D^+ - N_A^-}{2} + \left[\left(\frac{N_D^+ - N_A^-}{2}\right)^2 + n_i^2\right]^{1/2}$$

$$p = \frac{n_i^2}{n}$$

Intrinsic semiconductors:

$$N_D^+ = N_D \qquad N_A^- = N_A \qquad n_i >> N_D - N_A$$

$$n = p = n_i$$

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N-type semiconductors at **low** temperatures

$$n = \frac{N_D^+ - N_A^-}{2} + \left[\left(\frac{N_D^+ - N_A^-}{2}\right)^2 + n_i^2\right]^{1/2}$$

$$p = \frac{n_i^2}{n}$$

Freeze out::

$$N_D^+ = 0 \qquad N_A^- = 0 \qquad n_i \approx 0$$

$$n = p = 0$$

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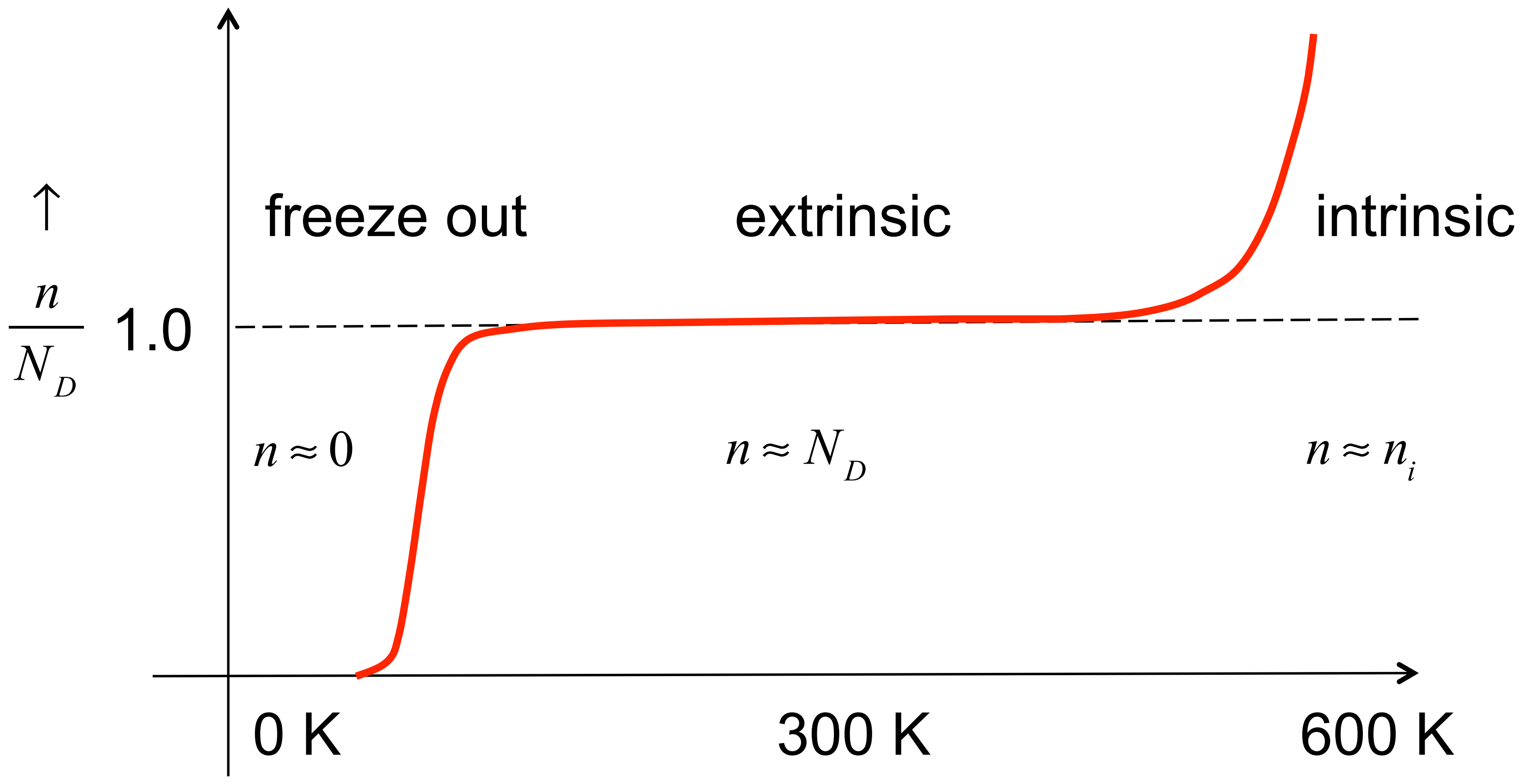
Carrier concentration vs. temperature



P-type semiconductors

1) charge neutrality: $p - n + N_D^+ - N_A^- = 0$

2) np product: $np = n_i^2$

3) quadratic eqn. for p: $p - \dfrac{n_i^2}{p} + N_D^+ - N_A^- = 0$

$$p = \frac{N_A^- - N_D^+}{2} + \left[\left(\frac{N_A^- - N_D^+}{2}\right)^2 + n_i^2\right]^{1/2}$$

Exercise: repeat the n-type examples for a p-type semiconductor

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.

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

A low temperatures, semiconductors become insulators.

A high temperatures, doped semiconductors become intrinsic.

Doped semiconductors

1) The np product
2) Doping
3) Carrier concentration vs. doping density
4) Carrier concentration vs. temperature