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Physics of Electronic Materials and Devices

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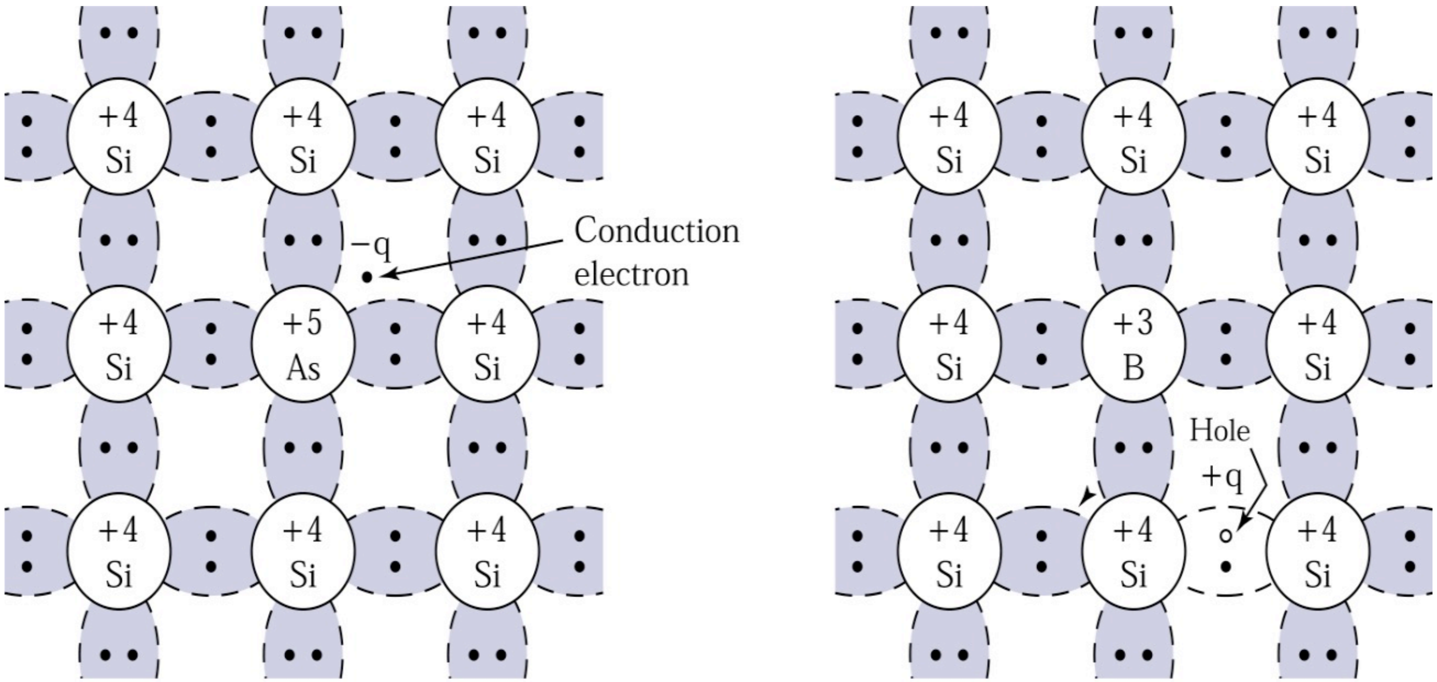
Lecture 7

Donors and Acceptors

- When a semiconductor is doped with some impurities, it becomes an ***extrinsic*** semiconductor.
- Also, its energy levels are changed.

Donors and Acceptors

- The figure shows schematic bond pictures for n-type (a) and p-type (b).



(a) (b)

Donors and Acceptors

Intrinstc

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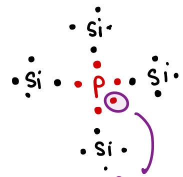
Ⅲ 3   IV 5



อะตอมสารเจือผู้รับ , เกิน ē ผู้ให้ donor

∴ Donor Impently - พาหะข้างมาก ē เพราะ เหลือ ē เยอะ

∴ อะตอมสารเจือผู้ให้ - พาหะข้างน้อย hole

- For n-type, atoms from group **V** impurity release electron for conduction as free charge carrier.
- An electron belonging to the impurity atom clearly needs far less energy to become available for conduction (or to be ionized).
- The impurity atom is called "**a donor**".
- The donor ionization energy is $\mathbf{E_C} - \mathbf{E_D}$ where $\mathbf{E_D}$ is donor level energy.

Donors and Acceptors

- For p-type, atoms from group **III** capture electron from semiconductor valence band and produce hole as free charge carrier.
- $\mathbf{E_A}$ is called "**acceptor level**" and $\mathbf{E_A} - \mathbf{E_V}$ is called "acceptor ionization level energy".
- This acceptor ionization level energy is small since an acceptor impurity can readily accept an electron.

Donors and Acceptors

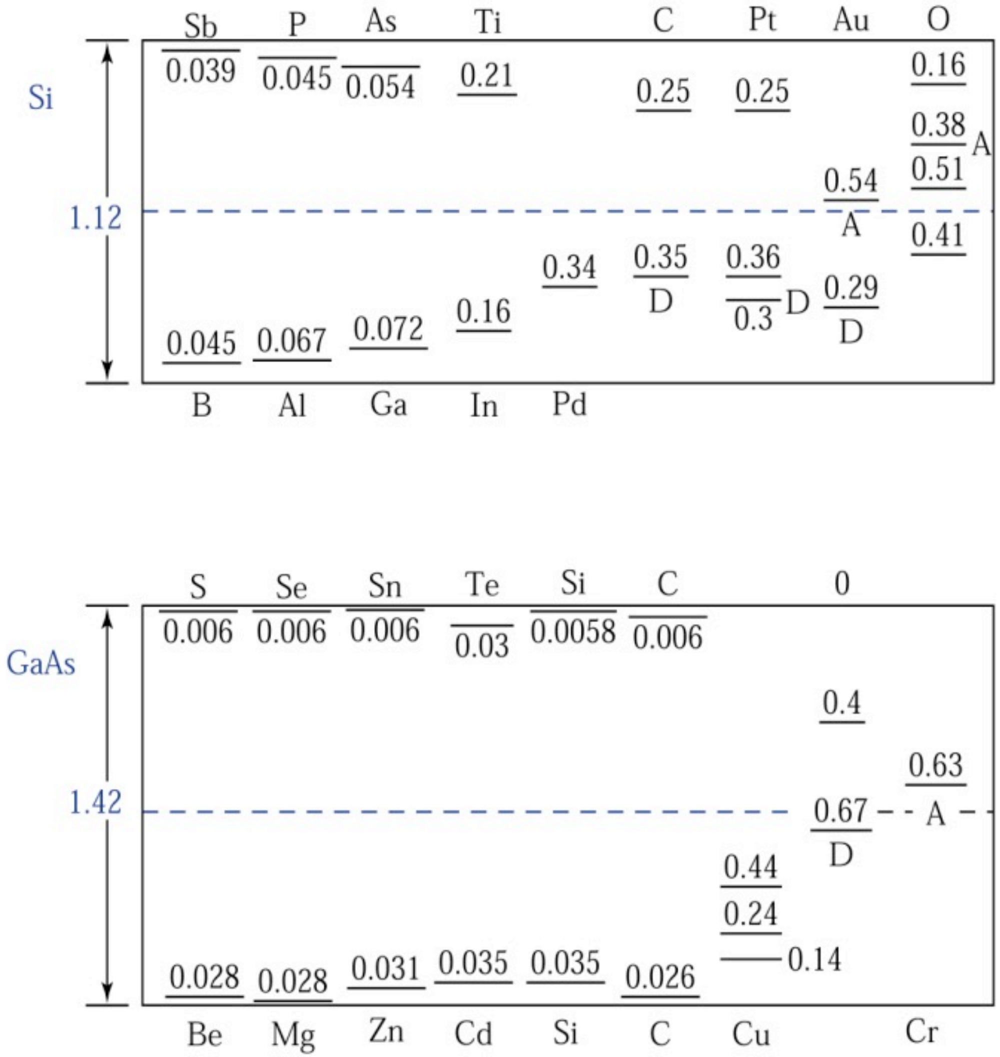
- The ionization energy or binding energy, producing a free charge carrier in semiconductor, can be approximately expressed by

$$E = \frac{-m^* e^4}{8\left(\varepsilon_0 \varepsilon_r\right)^2 h^2} \qquad \textbf{(1)}$$

where $m^* = m_e^*$ for donor atoms

$m^* = m_h^*$ for acceptor atoms

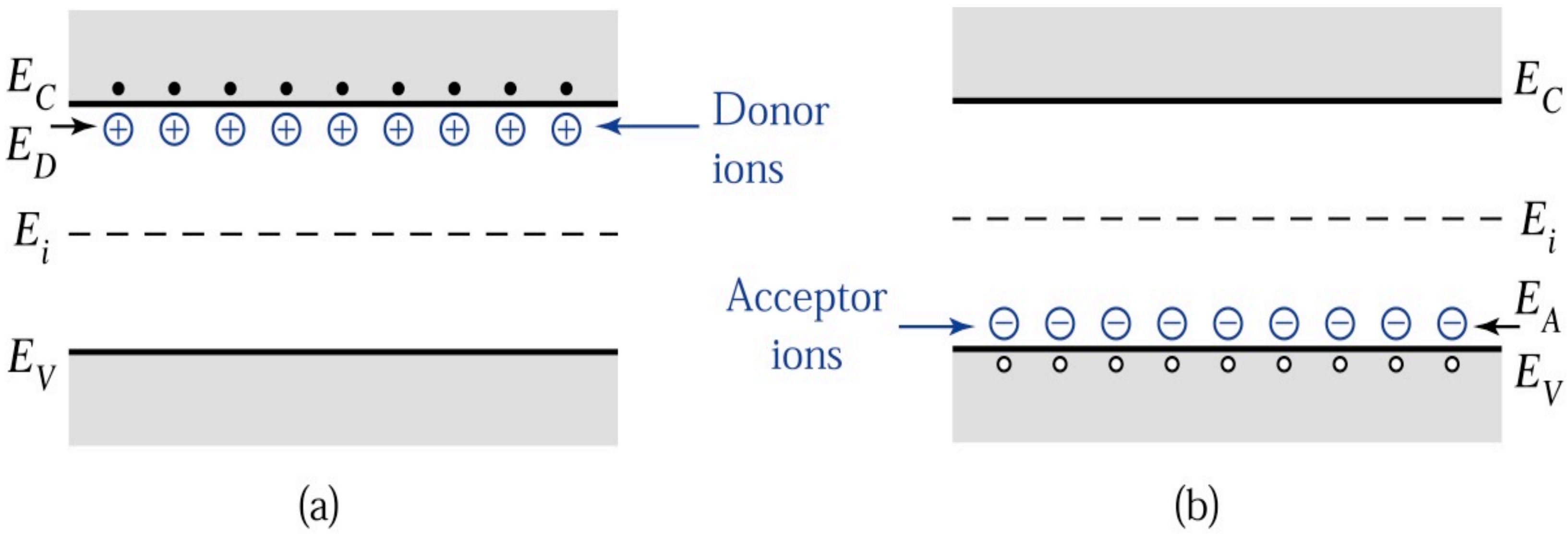
Donors and Acceptors



Example 1

- Calculate approximate binding energy for donors in Ge, given that $\varepsilon_r = 16$ and $m_e^* = 0.12m_o$.

Donors and Acceptors



(a) donor ions and (b) acceptor ions.

Donors and Acceptors

- Consider an ***n-type*** semiconductor, if N_D is the number of donor electrons at the energy level E_D, then we define to be the number of free electron carrier (number of N_D that have gone for conduction) or ionized donor atom density can be written as

$$N_D^+ = N_D\left[1 - F\left(E_D\right)\right] \quad \textbf{(2)}$$

Donors and Acceptors

- For a ***p-type***, the argument is similar. Therefore, free-hole density or ionized acceptor atom density is written as

$$N_A^- = N_A F\left(E_A\right) \qquad \textbf{(3)}$$

Donors and Acceptors

We can obtain the Fermi level dependence on temperature for three cases:

- Very low temperature
- Intermediate temperature
- Very high temperature.

Donors and Acceptors

- Very low temperature

$$E_F - E_D >> kT$$

$$n = N_D^+$$

$$N_C e^{-(E_C - E_F)/kT} = N_D \left[1 - \frac{1}{e^{(E_D - E_F)/kT} + 1} \right]$$

$$N_C e^{-(E_C - E_F)/kT} = N_D \left[\frac{1}{e^{(E_F - E_D)/kT} + 1} \right]$$

Donors and Acceptors

$$N_C e^{-(E_C - E_F)/kT} = N_D \left[\frac{1}{e^{(E_F - E_D)/kT}} \right]$$

Divding by N_C and taking ln

$$\frac{-(E_C - E_F)}{kT} = \ln\left(\frac{N_D}{N_C}\right) - \frac{(E_F - E_D)}{kT}$$

$$E_F = \left(\frac{E_C + E_D}{2}\right) + \frac{kT}{2} \ln\left(\frac{N_D}{N_C}\right)$$

Donors and Acceptors

- Intermediate temperature

$$E_F - E_D < kT << E_g$$

In this case, all donors are ionized

$$n = N_D$$

$$N_C e^{-(E_C - E_F)/kT} = N_D$$

Donors and Acceptors

$$-\frac{(E_C - E_F)}{kT} = \ln\left(\frac{N_D}{N_C}\right)$$

$$E_F = E_C + kT\ln\left(\frac{N_D}{N_C}\right)$$

$$E_F = E_C - kT\ln\left(\frac{N_C}{N_D}\right) \qquad \textbf{(4)}$$

Donors and Acceptors

- *Very high temperature*
  - In this case, all donors are ionized and electrons are excited from valence band to conduction band.
  - This is acting like an intrinsic semiconductor or $E_F = E_i$.
  - It may be useful to express electron and hole densities in terms of intrinsic concentration n_i and the intrinsic Fermi level E_i.

Donors and Acceptors

For ***n-type***, from $n = N_C \exp\left[-(E_C - E_F)/kT\right]$,

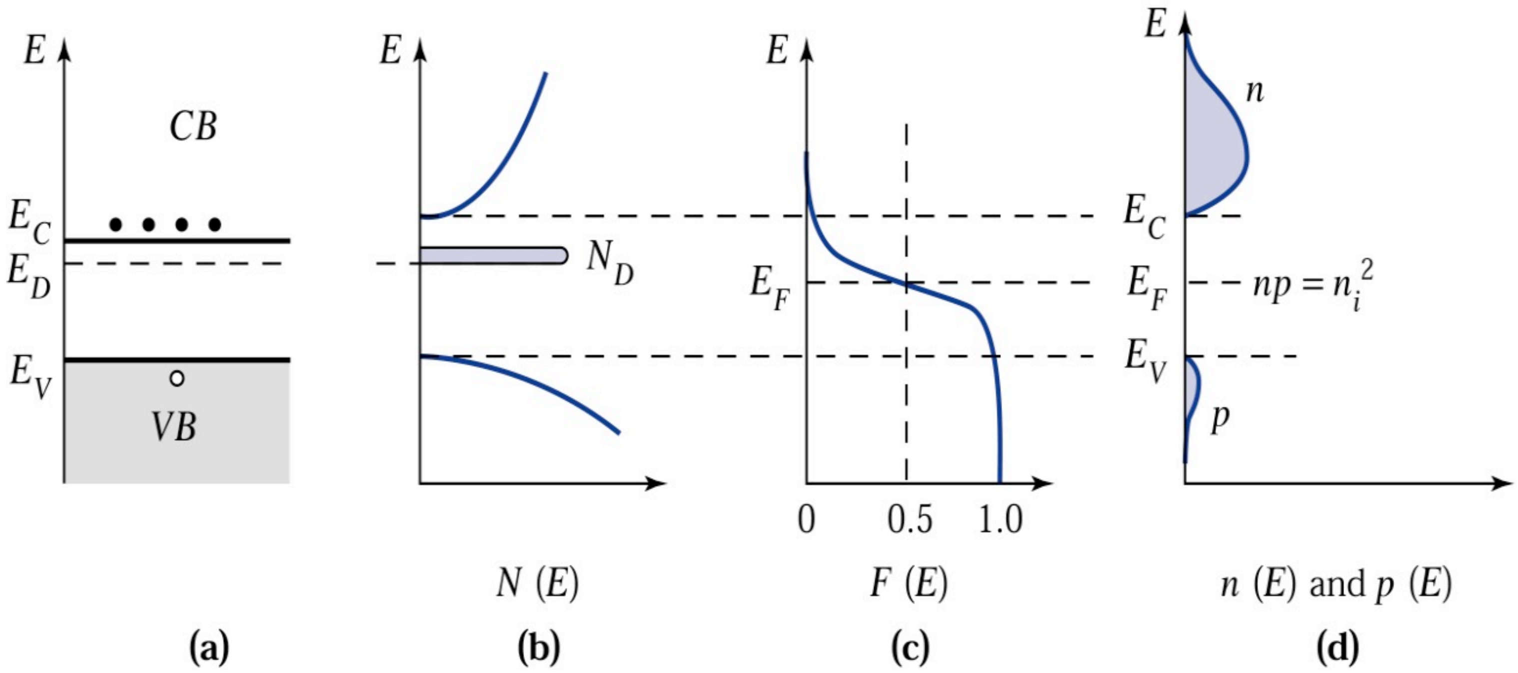
$$n = N_C \exp\left[-(E_C - E_F)/kT\right]$$
$$= N_C \exp\left[-(E_C - E_i)/kT\right]\exp\left[(E_F - E_i)/kT\right]$$
$$n = n_i \exp\left[(E_F - E_i)/kT\right] \qquad \textbf{(5)}$$

Similarly to ***p-type***, we have

$$p = n_i \exp\left[(E_i - E_F)/kT\right] \qquad \textbf{(6)}$$

This $n.p = n_i^2$ is valid for both intrinsic and extrinsic semiconductors under thermal equilibrium.

n-type semiconductor



(*a*) Schematic band diagram. (*b*) Density of states.
(*c*) Fermi distribution function (*d*) Carrier concentration.

Note that $np = n_i^2$.

Donors and Acceptors

- We have learned how to find new position of Fermi level for extrinsic semiconductors.
- Now let us consider the new electron density in case of both donors $\boldsymbol{N_D}$ and acceptors $\boldsymbol{N_A}$ are present simultaneously.
- The Fermi level will adjust itself to preserve overall charge neutrality as

$$n + N_A^- = p + N_D^+ \tag{7}$$

Donors and Acceptors

- By solving (7) with $n.p = n_i^2$, the equilibrium electron and hole concentrations in an n-type semiconductors yield

$$n_n = \frac{1}{2}\left[N_D^+ - N_A^- + \sqrt{\left(N_D^+ - N_A^-\right)^2 + 4n_i^2} \right] \qquad (8)$$

$$p_n = \frac{n_i^2}{n_n} \qquad (9)$$

Donors and Acceptors

- Similarly to p-type semiconductors, the electron and hole concentrations are expressed as

$$p_p = \frac{1}{2}\left[N_A^- - N_D^+ + \sqrt{\left(N_D^+ - N_A^-\right)^2 + 4n_i^2} \right] \qquad (10)$$

$$n_p = \frac{n_i^2}{p_p} \qquad (11)$$

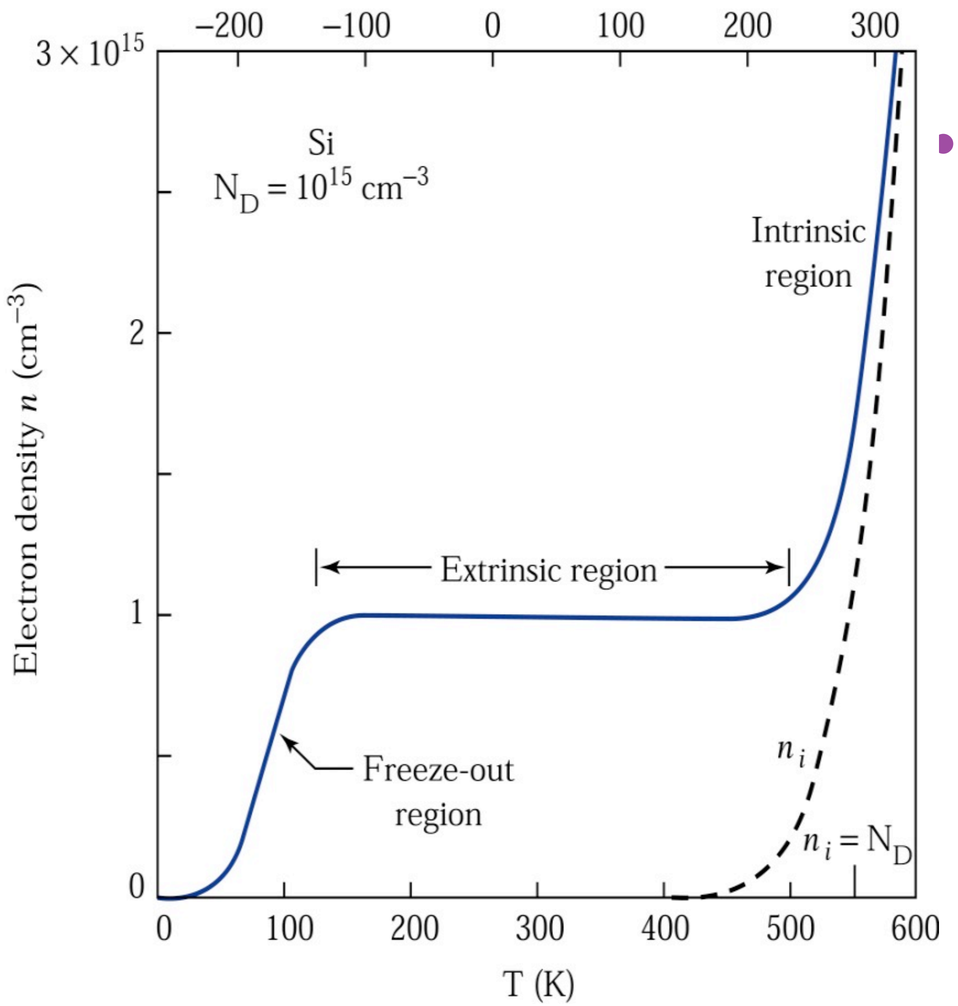
Donors and Acceptors

- Generally, in case of all impurities are ionized, the net impurity concentration $N_D - N_A$ is larger than the intrinsic carrier concentration n_i; therefore, we may simply rewrite the above relationship as,

$$n_n \approx N_D - N_A \quad \text{if} \quad N_D > N_A$$

$$p_p \approx N_A - N_D \quad \text{if} \quad N_A > N_D$$

Donors and Acceptors



- The figure shows electron density in Si as a function of temperature for a donor concentration of $N_D = 10^{15}$ cm^{-3}.

Donors and Acceptors

- At low temperature, not all donor impurities could be ionized and this is called "**Freeze-out region**" since some electrons are frozen at the donor level.
- As the temperature increased, all donor impurities are ionized and this remains the same for a wide range of temperature.
- This region is called "**Extrinsic region**".

Donors and Acceptors

- Until the temperature is increased even higher and it reaches a point where electrons are excited from valence band.

- This makes the intrinsic carrier concentration becomes comparable to the donor concentration.

- At this region, the semiconductors act like **an intrinsic one.**

Degenerate semiconductor

- If the semiconductors are heavily doped for both n- or p-type, E_F will be higher than E_C or below E_V, respectively.
- The semiconductor is referred to as ***degenerate*** semiconductor.
- This also results in the reduction of the bandgap.

Degenerate semiconductor

- The bandgap reduction ΔE_g for Si at room temperature is expressed by

$$\Delta E_g = 22\sqrt{\frac{N}{10^{18}}}\ \text{meV} \qquad (12)$$

where the doping N is in the unit of cm^{-3}.

Example 2

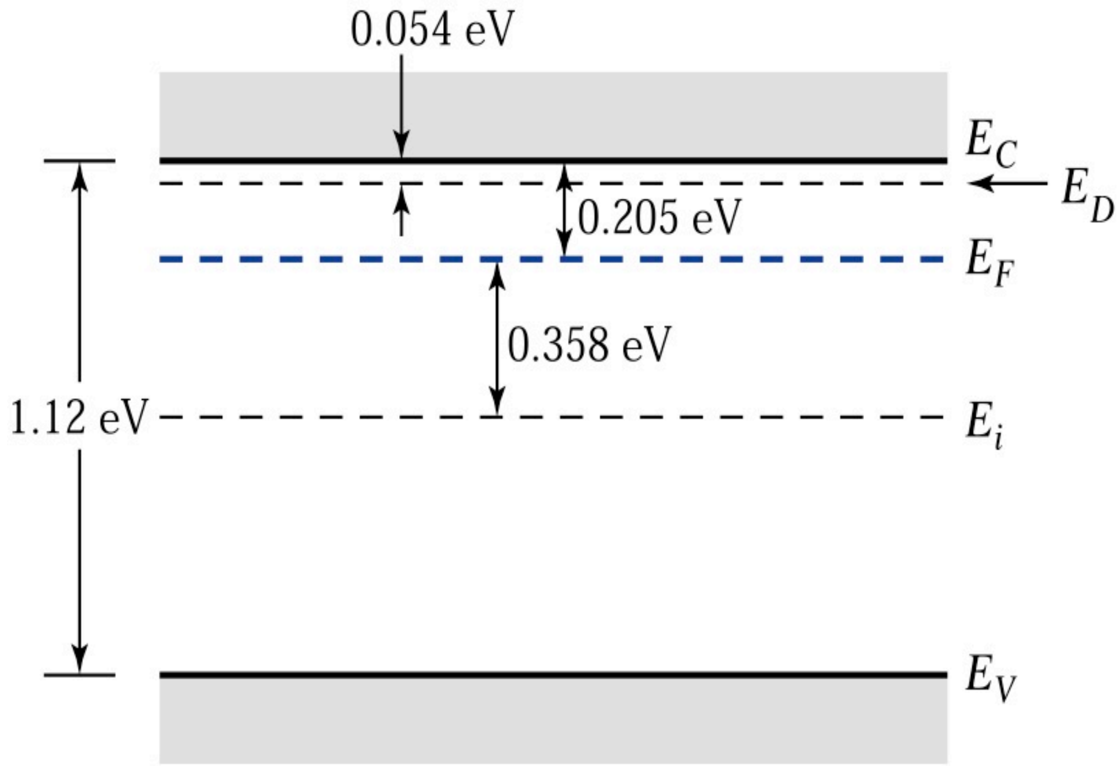
- Si is doped with 10^{16} arsenic atoms/cm^3. Find the carrier concentration and the Fermi level at room temperature (300K).

<u>Sol</u>n

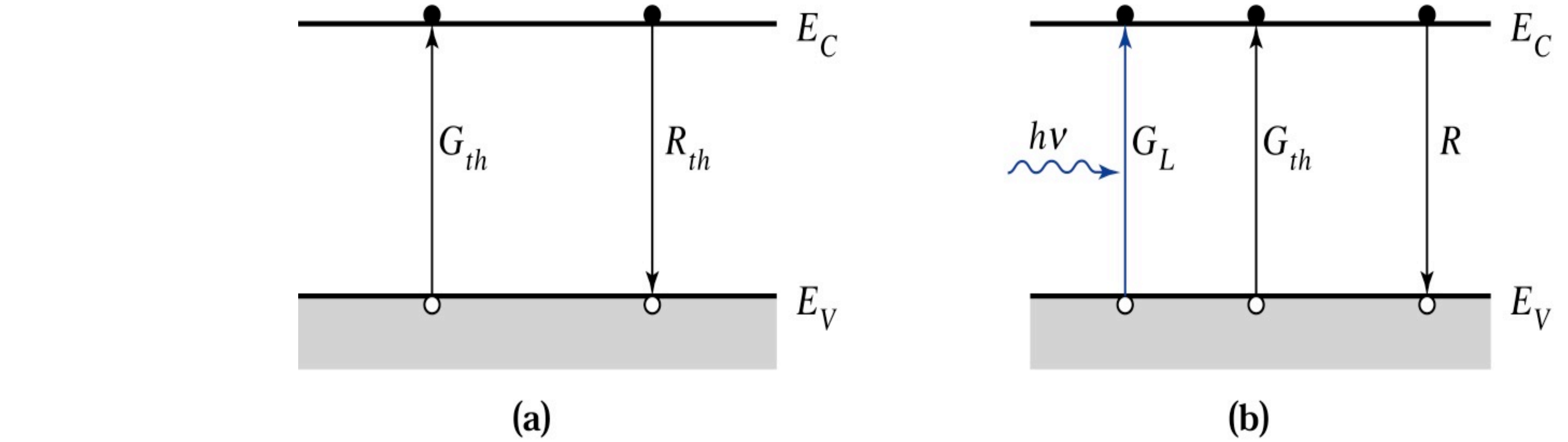
At room temperature, complete ionization of impurity atoms is highly possible, then we have $n = N_D = 10^{16}$ cm^{-3}.

Example 2

- Sol^n
- The Fermi level measured from the intrinsic Fermi level is



Direct recombination



- When a bond between neighboring atoms is broken, an electron-hole pair is generated.
- The valence electron moves upward to the conduction band due to getting thermal energy.
- This results in a hole being left in the valence band.

Direct recombination

- This process is called ***carrier generation*** with the generation rate G_{th} (number of electron-hole pair generation per unit volume per time).

- When an electron moves downward from the conduction band to the valence band to recombine with the hole, this reverse process is called ***recombination***.

- The recombination rate represents by R_{th}.

Direct recombination

- Under thermal equilibrium, the generation rate G_{th} equals to the recombination rate R_{th} to preserve the condition of

$$pn = n_i^2 \tag{13}$$

- The direct recombination rate R can be expressed as

$$R = \beta np \tag{14}$$

where β is the proportionality constant.

Direct recombination

- Therefore, for an n-type semiconductor, we have

$$G_{th} = R_{th} = \beta n_{n0} p_{n0} \qquad (15)$$

where n_{n0} and p_{n0} represent electron and hole densities at thermal equilibrium.

Direct recombination

- If the light is applied on the semiconductor, it produces electron-hole pairs at a rate G_L, the carrier concentrations are above their equilibrium values.
- The generation and recombination rates become

$$G = G_L + G_{th} \qquad R = \beta n_n p_n = \beta \left(n_{n0} + \Delta n \right) \left(p_{n0} + \Delta p \right)$$

(16) (17)

where Δn and Δp are the excess carrier concentrations

Direct recombination

$$\Delta n = n_n - n_{n0} \qquad (18a)$$

$$\Delta p = p_n - p_{n0} \qquad (18b)$$

- $\Delta n = \Delta p$ to maintain the overall charge neutrality.
- The net rate of change of hole concentration is expressed as

$$\frac{dp_n}{dt} = G - R = G_L + G_{th} - R \qquad (19)$$

Direct recombination

- In steady-state, $dp_n/dt = 0$. From **(19)** we have

$$G_L = R - G_{th} \equiv U \qquad (20)$$

where **U is the net recombination rate**.

Substituting **(15)** and **(17)** into **(20)**, this yields

$$U = \beta\left(n_{n0} + p_{n0} + \Delta p\right)\Delta p \qquad (21)$$

Direct recombination

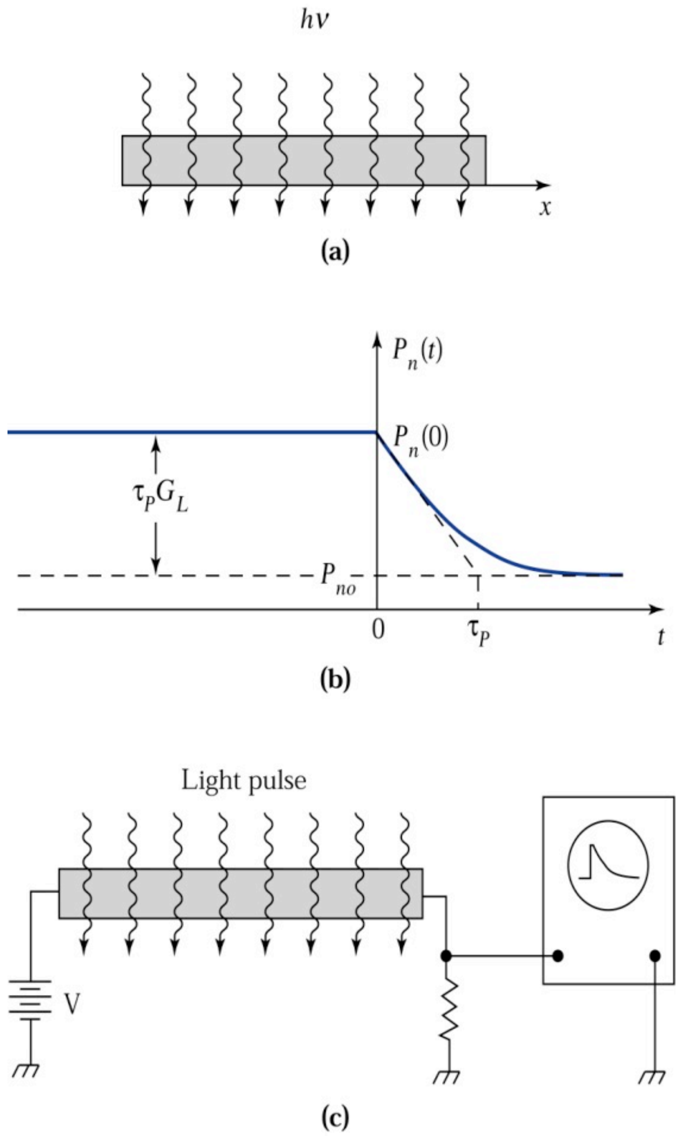
- For low-level injection Δp, $p_{n0} << n_{n0}$, **(21)** becomes

$$U \approx \beta n_{n0} \Delta p = \frac{p_n - p_{n0}}{1/\beta n_{n0}} = \frac{p_n - p_{n0}}{\tau_p} \qquad (22)$$

- where τ_p is called excess minority carrier lifetime .

$$p_n = p_{n0} + \tau_p G_L \qquad (23)$$

Direct recombination



- We may write p_n in the function of t as

$$p_n(t) = p_{n0} + \tau_p G_L \exp\left(-t/\tau_p\right)$$

(24)

Example 3

- A Si sample with $n_{n_0} = 10^{14}$ cm^{-3} is illuminated with light and 10^{13} electron-hole pairs/cm^3 are created every microsecond. If $\tau_n = \tau_p = 2$ μs, find the change in the minority carrier concentration.