Chapter 3-3.
Relating diffusion coefficients and mobilities

In this class, we will learn about:

Constancy of Fermi-level

- Indicates equilibrium conditions

Current flow under thermal equilibrium

- Net hole current (diffusion + drift) should be zero
- Net electron current (diffusion + drift) should be zero

Einstein relationship

- relates diffusion coefficient to mobility

Introduction to generation/recombination

Constancy of Fermi level

Under equilibrium conditions, $dE_F / dx = 0$; the Fermi level inside a material or a group of materials in intimate contact is invariant as a function of position.

E_F appears as a horizontal line on equilibrium energy band diagram.

If the Fermi level is not constant with position, charge transfer will take place resulting in a net current flow, in contrast to the assumption of equilibrium conditions.

Constancy of Fermi level

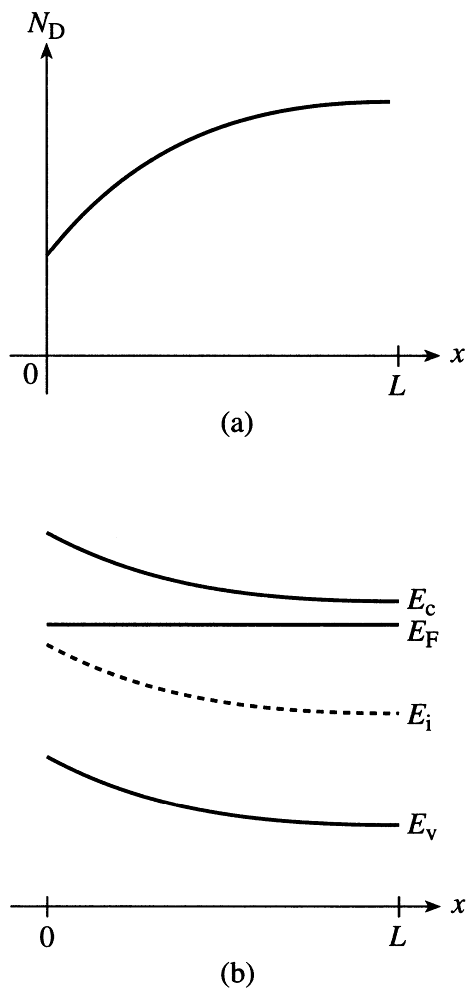


Figure 3.14

Doping concentration varies with position. This results in a gradient in carrier concentration. $E_C - E_F$ represents the change in carrier concentration with position.

The graph as drawn indicates that there will be an electric field. This field causes drift current. The concentration gradient gives diffusion current. These two currents exactly cancel each other so that the net current is zero.

A non-horizontal Fermi level means there will be a continuous movement of carriers from one side to the other, indicating current flow (against the assumption).

Current flow under equilibrium conditions

The total current under equilibrium conditions is equal to zero.

Total electron current, J_n and total hole current, J_p must also be zero. Why?

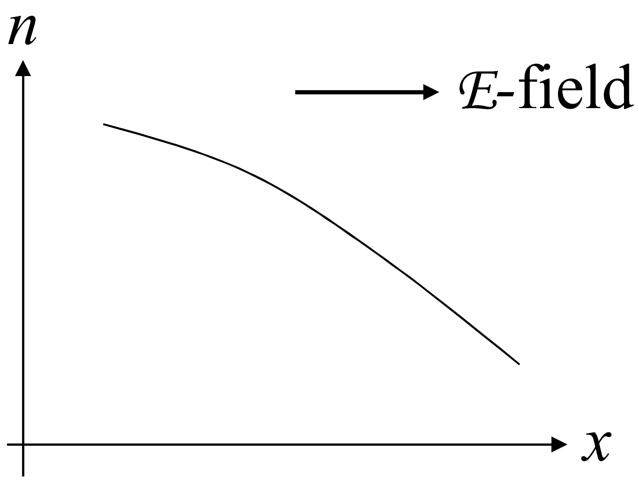
$$J_{n|diff} = -J_{n|drift} \quad \text{and} \quad J_{p|diff} = -J_{p|drift}$$

Under equilibrium conditions, both drift and diffusion components will vanish only if $\mathcal{E} = 0$ and $\mathrm{d}n / \mathrm{d}x = \mathrm{d}p / \mathrm{d}x = 0$

Even under thermal equilibrium conditions, non-uniform doping will give rise to carrier concentration gradient, a built-in $\mathcal{E}$*-field*, and non-zero current components.

Einstein relationship

Consider a non-uniformly doped semiconductor under equilibrium.



$$\left.\begin{array}{l} \xrightarrow{\qquad\qquad} \; J_{\mathrm{n|drift}} \\[2em] \xleftarrow{\qquad\qquad} \; J_{\mathrm{n|diff}} \end{array}\right\} \; \text{Net current} = 0$$

$$J_{\mathrm{n|drift}} + J_{\mathrm{n|diff}} = q\mu_{\mathrm{n}} n \mathcal{E} + q D_{\mathrm{n}} \frac{\mathrm{d}n}{\mathrm{d}x} = 0$$

$$\mathcal{E} = \frac{1}{q}\frac{\mathrm{d}E_{\mathrm{i}}}{\mathrm{d}x} \quad \text{and} \quad n = n_{\mathrm{i}}\, \mathrm{e}^{(E_{\mathrm{F}} - E_{\mathrm{i}})/kT}$$

Under equilibrium: $E_{\mathrm{F}} = \text{const.}$ and $\left|J_{\mathrm{n|drift}}\right| = \left|J_{\mathrm{n|diff}}\right|$

Einstein relationship

Manipulation of the above equations leads to:

$$\boxed{\frac{D_{\mathrm{n}}}{\mu_{\mathrm{n}}} = \frac{kT}{q}}$$

… Einstein relationship for electrons

$$\boxed{\frac{D_{\mathrm{p}}}{\mu_{\mathrm{p}}} = \frac{kT}{q}}$$

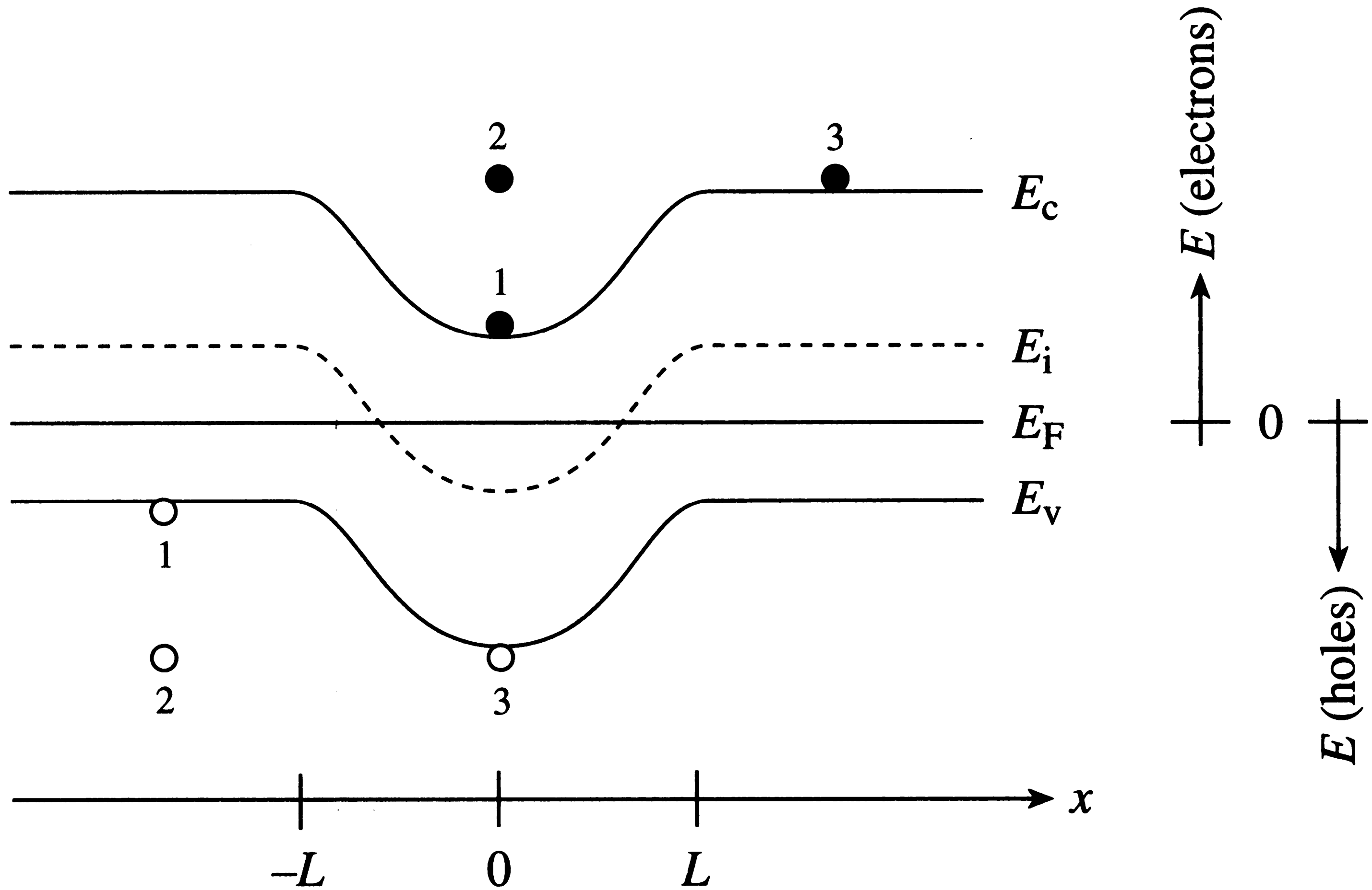
… Einstein relationship for holes

If $\mu_{\mathrm{n}} = 1350\ \mathrm{cm^2/(Vs)}$ then

Then $D_{\mathrm{n}} = (kT\,/\,q)\ \mu_{\mathrm{n}} = (0.0256\ \mathrm{V}) \times 1350\ \mathrm{cm^2/(Vs)} = 35\ \mathrm{cm^2/s}$

Always be careful about units!

Example 3-1: (Exercise 3.2) Plot electrostatic potential, V, and $\mathcal{E}$-field versus x for the case shown below



Example 3-2: Consider the diagram shown in example 3-1

(1) How can you say that the semiconductor is in equilibrium?

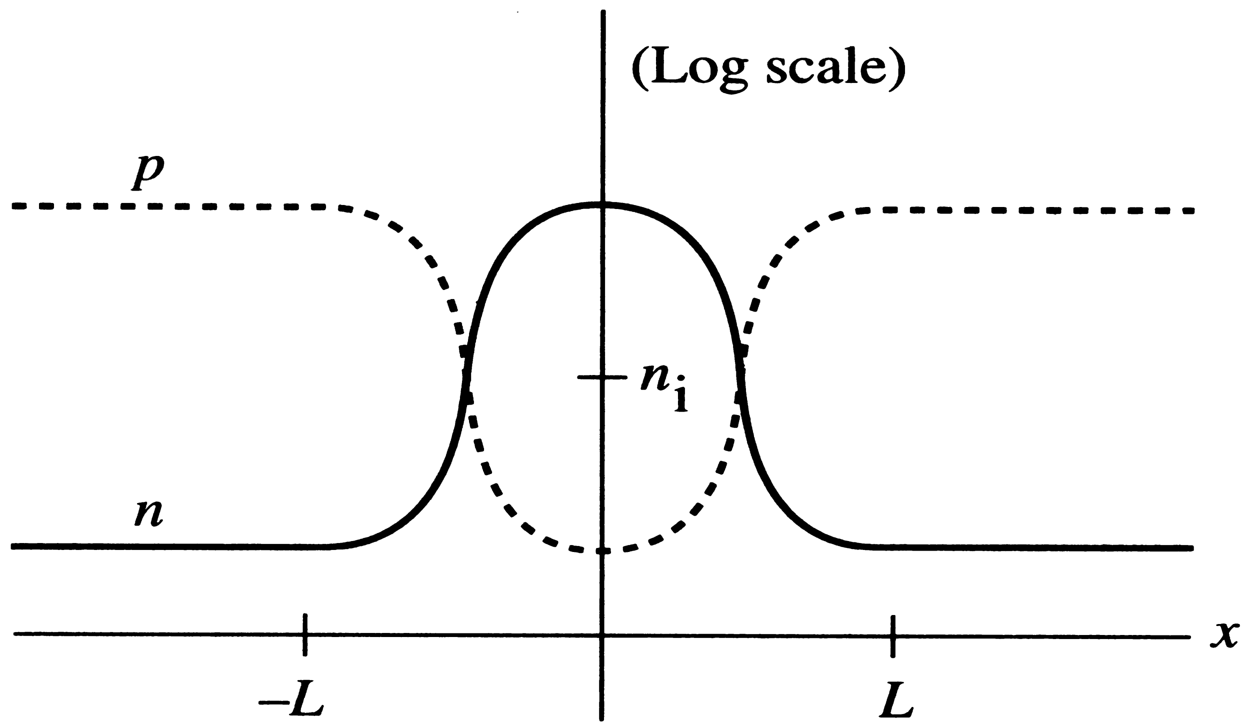
(2) What is the electron current density (J_n) and hole current density (J_p) at $x = \pm L/2$?

(3) Roughly sketch n and p versus x inside the sample.

(4) Is there an electron diffusion current at $x = \pm L/2$? If so, what is its direction?

(5) Is there an electron drift current at $x = \pm L/2$? If so, what is its direction?

Example 3-2



	$x = -L/2$	$x = +L/2$
$J_{n\|diff}$	$\longrightarrow$	$\longleftarrow$
$J_{n\|drift}$	$\longleftarrow$	$\longrightarrow$

Recombination and generation processes

Recombination - a process whereby electrons and holes are destroyed or annihilated.

Generation - a process whereby electrons and holes are created.

Under equilibrium conditions, the generation rate and the recombination rate exactly cancel.

In the steady state, the generation rate and recombination rate can be different (Can you give an example?).

In both, equilibrium and steady state, there will be a steady-state carrier concentration.

Recombination-generation processes (R-G processes) play a major role in shaping the characteristics exhibited by a device.

Various R-G processes

Band-to-band recombination

generally results in light emission

Band-to-band generation

direct thermal generation

generation by light absorption (photo-generation)

R-G center recombination/generation

Involves an R-G center (indirect generation / recombination)

Auger recombination

Generation via impact ionization

Various R-G processes

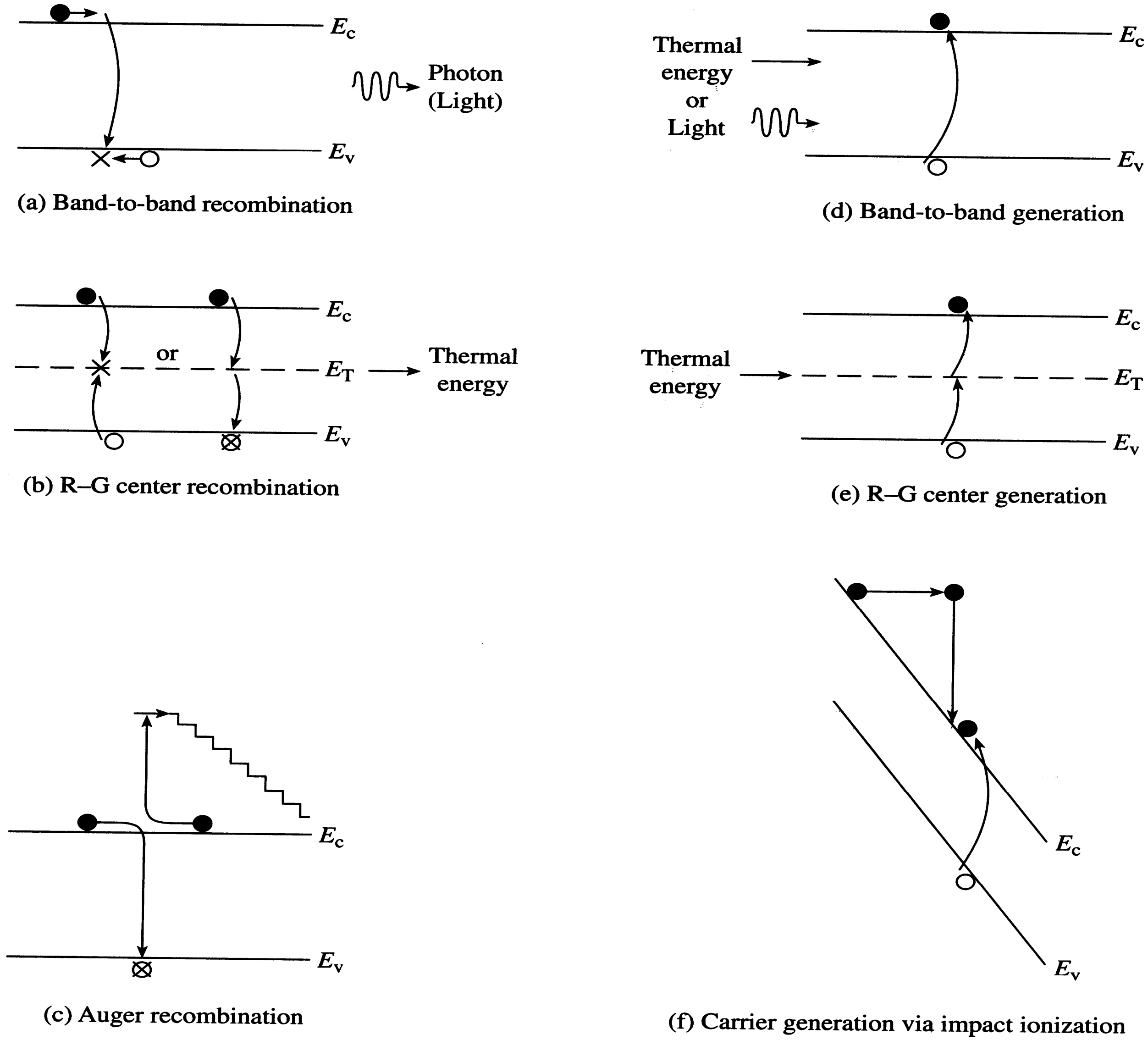


Figure 3.15

Mid-gap energy levels due to atomic impurities

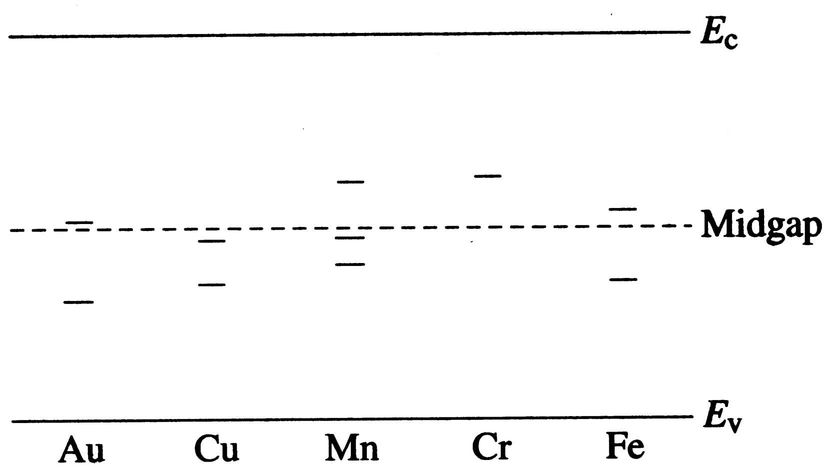


Figure 3.16

Recombination in Si is mainly via R-G centers introduced by various unwanted impurities.

Momentum considerations

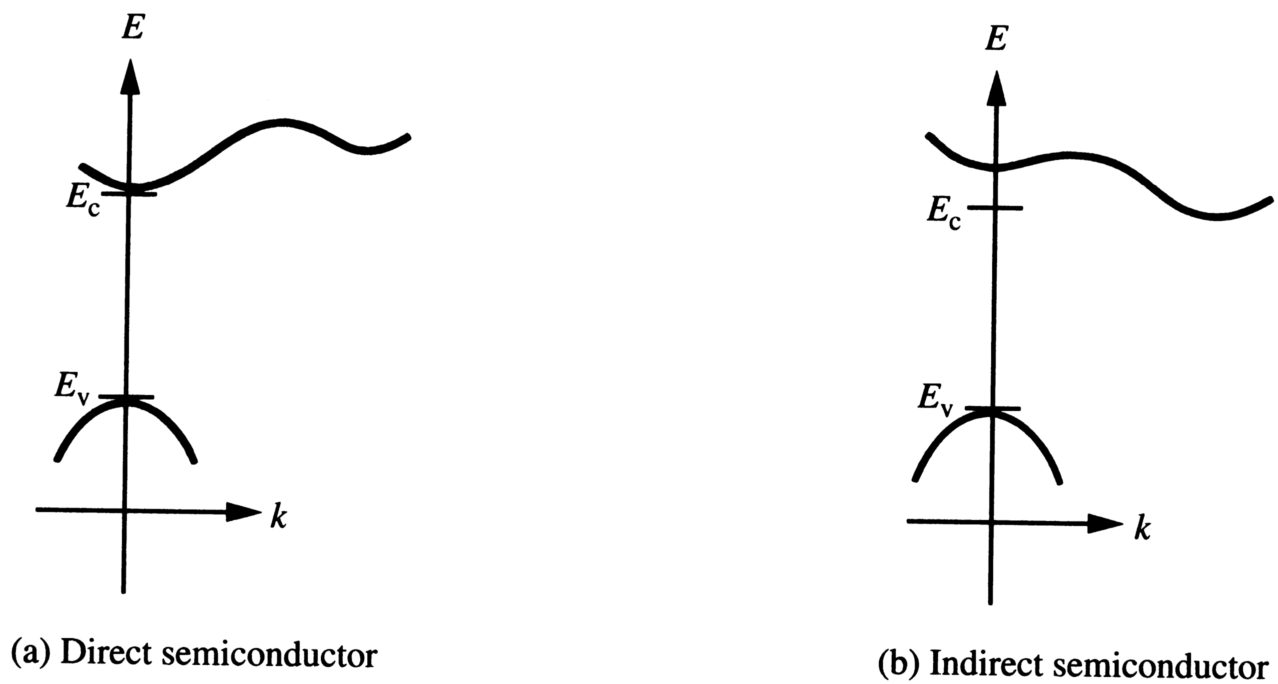
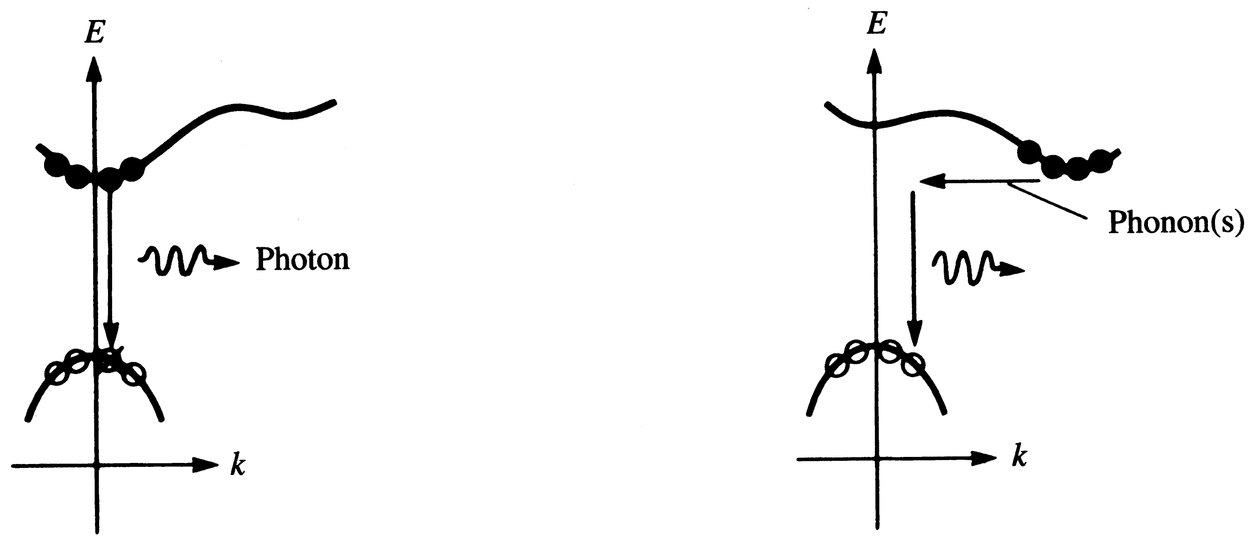


Figure 3.17

E vs. k diagrams for direct and indirect semiconductors.

E-*k* visualizations of recombination in direct and indirect semiconductors



(a) Direct semiconductor

(b) Indirect semiconductor

Figure 3.18