

Chapter 6

Non-equilibrium Excess Carriers in Semiconductors

Outline

6.1 Carrier Generation and Recombination

6.2 Characteristics of Excess Carriers

6.3 Ambipolar Transport

6.4 Quasi-Fermi Energy Levels

6.5 Excess Carrier Lifetime

6.6 Surface Effects

6.1 CARRIER GENERATION AND RECOMBINATION

- In thermal equilibrium, these concentrations are independent of time
- electrons are continually being thermally excited from the valence band into the conduction band by the random nature of the thermal process
- electrons moving randomly through the crystal in the conduction band may come in close proximity to holes and “fall” into the empty states in the valence band

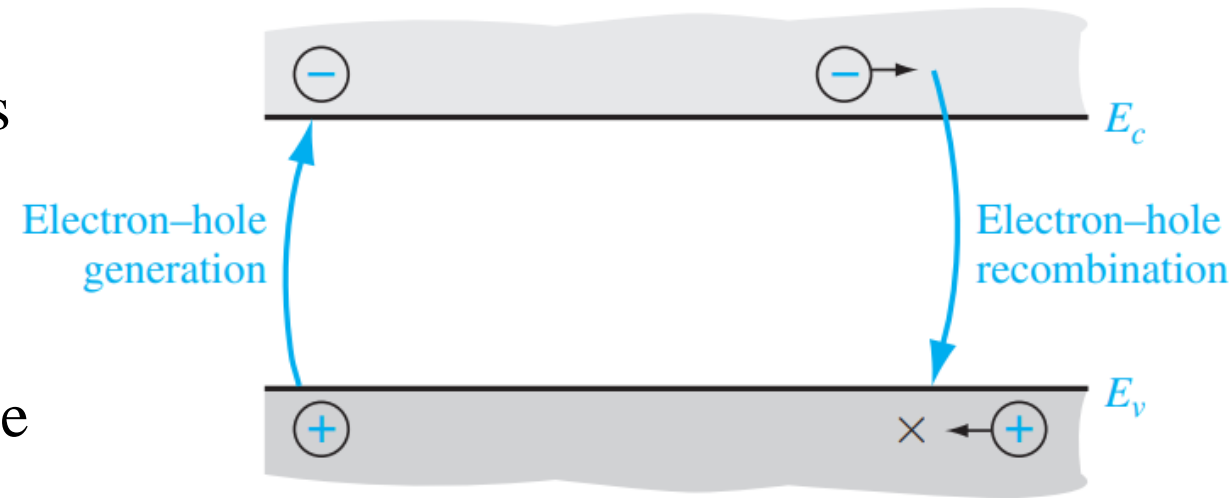


Figure 6.1 | Electron–hole generation and recombination.

$$G_{n0} = G_{p0} \left(\# / \text{cm}^3 - \text{s} \right)$$

$$R_{n0} = R_{p0}$$

In thermal equilibrium

$$G_{n0} = G_{p0} = R_{n0} = R_{p0}$$

Excess Carrier Generation and Recombination

Table 6.1 | Relevant notation used in Chapter 6

Symbol	Definition
n_0, p_0	Thermal-equilibrium electron and hole concentrations (independent of time and also usually position)
n, p	Total electron and hole concentrations (may be functions of time and/or position)
$\delta n = n - n_0$ $\delta p = p - p_0$	Excess electron and hole concentrations (may be functions of time and/or position)
g'_n, g'_p	Excess electron and hole generation rates
R'_n, R'_p	Excess electron and hole recombination rates
τ_{n0}, τ_{p0}	Excess minority carrier electron and hole lifetimes

For the direct band-to-band generation: $g'_n = g'_p$

Excess Carrier Generation and Recombination

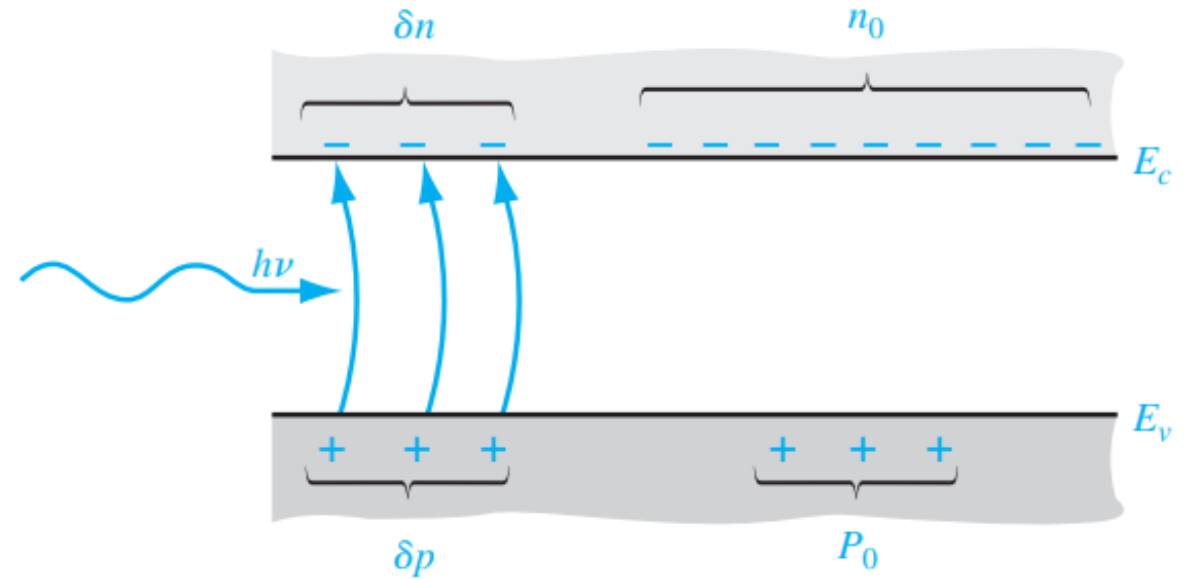
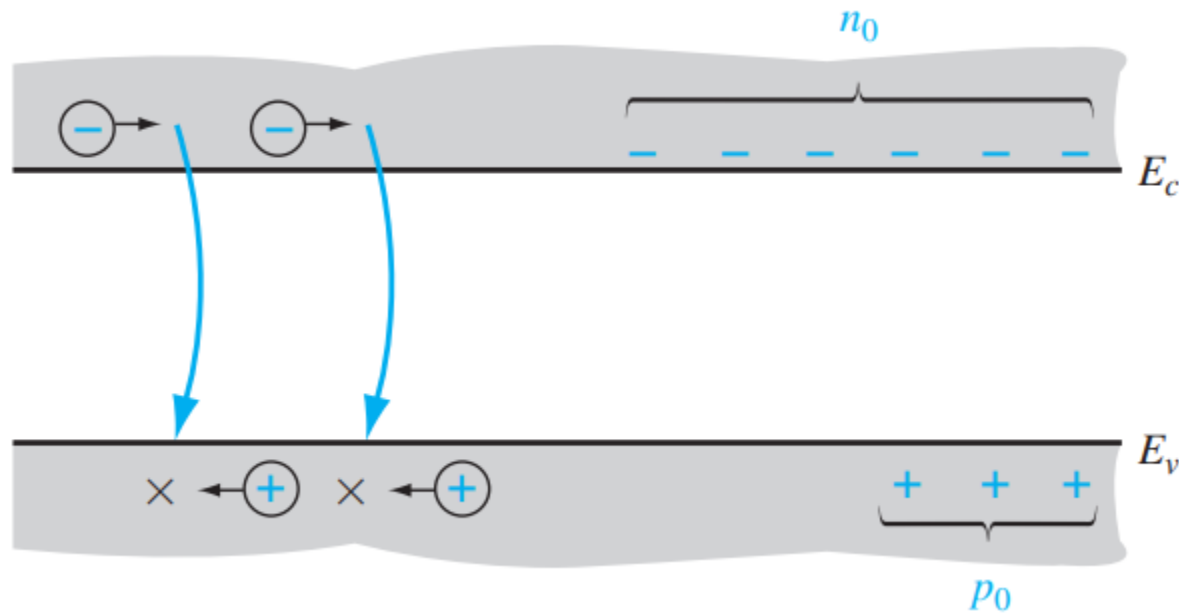


Figure 6.2 | Creation of excess electron and hole densities by photons.

$$n = n_0 + \delta n \quad p = p_0 + \delta p$$

n_0, p_0 : thermal – equilibrium concentrations

$\delta n, \delta p$: excess electron and hole concentrations

$$np \neq n_0 p_0 = n_i^2$$

In a nonequilibrium condition:

$$np \neq n_0 p_0 = n_i^2$$

- As in the case of thermal equilibrium, an electron in the conduction band may “fall down” into the valence band, leading to the process of excess electron–hole recombination

Direct band-to-band recombination

$R'_n = R'_p$ (recombination rate for excess electrons/holes)

- In the direct band-to-band recombination the probability of an electron and hole recombining is constant with time
- The rate at which electrons recombine must be proportional to the electron concentration and must also be proportional to the hole concentration

The net rate of change in the electron concentration:

$$\frac{dn(t)}{dt} = \alpha_r [n_i^2 - n(t)p(t)]$$

$$n(t) = n_0 + \delta n(t)$$

$$p(t) = p_0 + \delta p(t)$$

$$\alpha_r n_i^2 \text{ (thermal – equilibrium generation rate)}$$

Since excess electrons and holes are created and recombine in pairs:

$$\delta n(t) = \delta p(t)$$

$$\Rightarrow \frac{d(\delta n(t))}{dt} = \alpha_r [n_i^2 - (n_0 + \delta n(t))(p_0 + \delta p(t))]$$

$$= -\alpha_r \delta n(t) [(n_0 + p_0) + \delta n(t)]$$

$$\frac{d(\delta n(t))}{dt} = -\alpha_r p_0 \delta n(t)$$

$$(\text{p-type } (p_0 \gg n_0), \text{ low level injection } (\delta n(t) \ll p_0))$$

$$\delta n(t) = \delta n(0) e^{-\alpha_r p_0 t} = \delta n(0) e^{-t/\tau_{n0}}$$

(τ_{n0} : excess minority carrier lifetime)

$$R'_n = R'_p = \frac{\delta n(t)}{\tau_{n0}}$$

same as n-type: $R'_n = R'_p = \frac{\delta n(t)}{\tau_{p0}}$

EXAMPLE 6.1

Objective: Determine the behavior of excess carriers as a function of time.

Assume that excess carriers have been generated uniformly in a semiconductor to a concentration of $\delta n(0) = 10^{15} \text{ cm}^{-3}$. The forcing function generating the excess carriers turns off at time $t = 0$. Assuming the excess carrier lifetime is $\tau_{n0} = 10^{-6} \text{ s}$, determine $\delta n(t)$ for $t > 0$.

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From Equation (6.11), we have

$$\delta n(t) = \delta n(0)e^{-t/\tau_{n0}} = 10^{15} e^{-t/10^{-6}} \text{ cm}^{-3}$$

For example, at: $t = 0$, $\delta n = 10^{15} \text{ cm}^{-3}$

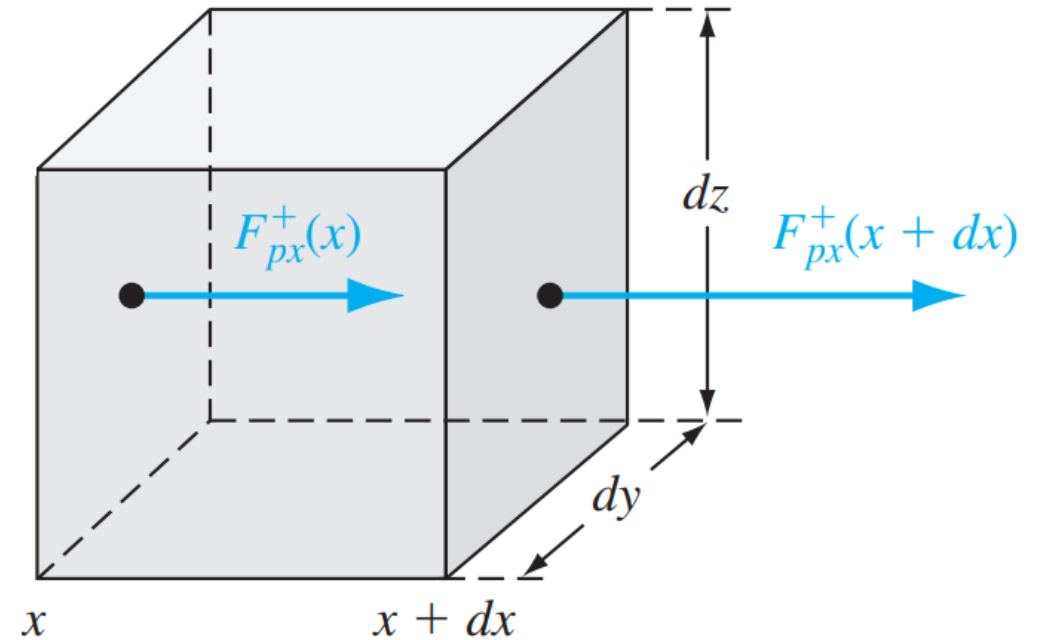
$$t = 1\mu\text{s}, \quad \delta n = 10^{15} e^{-1/1} = 3.68 \times 10^{14} \text{ cm}^{-3}$$

$$t = 4\mu\text{s}, \quad \delta n = 10^{15} e^{-4/1} = 1.83 \times 10^{13} \text{ cm}^{-3}$$

$$t = 10\mu\text{s}, \quad \delta n = 10^{15} e^{-10/1} = 4.54 \times 10^{10} \text{ cm}^{-3}$$

6.2 CHARACTERISTICS OF EXCESS CARRIERS

- The excess electrons and holes do not move independently of each other, but they diffuse and drift with the same effective diffusion coefficient and with the same effective mobility
- For an extrinsic semiconductor under low injection (this concept will be defined in the analysis), the effective diffusion coefficient and mobility parameters are those of the **minority carrier**



6.3 AMBIPOLAR TRANSPORT

- If a pulse of excess electrons and a pulse of excess holes are created at a particular point in a semiconductor with an applied electric field, the excess holes and electrons will tend to drift in opposite directions
- If a pulse of excess electrons and a pulse of excess holes are created at a particular point in a semiconductor with an applied electric field, the excess holes and electrons will tend to drift in opposite directions

$$E = E_{app} + E_{int}$$

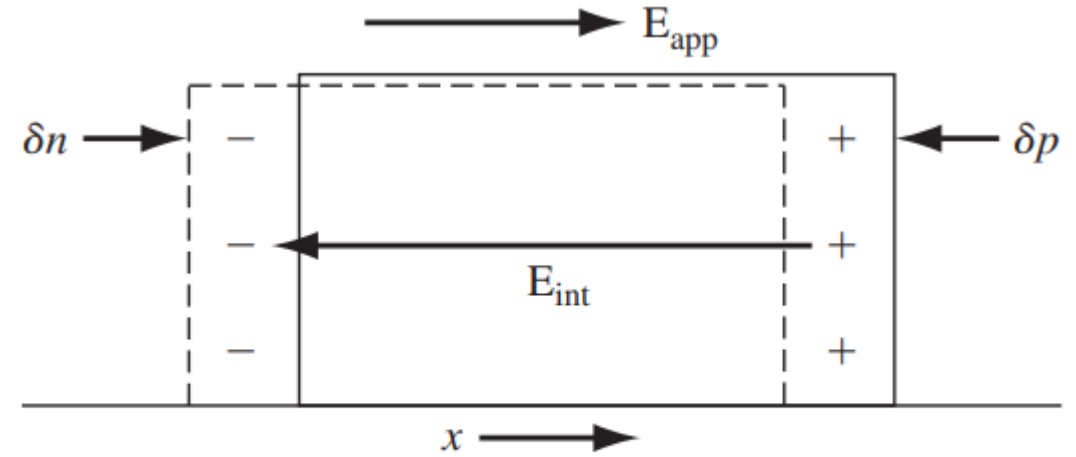


Figure 6.5 | The creation of an internal electric field as excess electrons and holes *tend* to separate.

Limits of Extrinsic Doping and Low Injection(補)

- The ambipolar transport equation may be simplified and linearized by considering an extrinsic semiconductor and by considering low-level injection
 - It is important to note that for an extrinsic p-type semiconductor under low injection, the ambipolar diffusion coefficient and the ambipolar mobility coefficient reduce to the minority carrier electron parameter values, which are constants
- $$D' = \frac{D_n D_p \left[(n_0 + \delta n) + (p_0 + \delta n) \right]}{D_n (n_0 + \delta n) + D_p (p_0 + \delta n)}$$

For p-type ,low injection

($n_0 \ll p_0$ and $\delta n \ll p_0$, D_n 、 D_p same order)

$$D' = D_n$$

$$\mu' = \mu_n$$

For n-type ,low injection

($n_0 \gg p_0$ and $\delta n \ll n_0$, D_n 、 D_p same order)

$$D' = D_p$$

$$\mu' = -\mu_p$$

Limits of Extrinsic Doping and Low Injection(補)

$$g - R = g_n - R_n = (G_{n0} + g'_n) - (R_{n0} + R'_n)$$

G_{n0} : thermal-equilibrium electron generation rates

g'_n : excess electron generation rates

For thermal equilibrium :

$$G_{n0} = R_{n0}$$

$$g - R = g'_n - R'_n = g'_n - \frac{\delta n}{\tau_n}$$

same as hole:

$$g - R = g'_p - R'_p = g'_p - \frac{\delta p}{\tau_p}$$

$$D_n \frac{\partial^2 \delta n}{\partial x^2} + \mu_n E \frac{\partial \delta n}{\partial x} + g'_n - \frac{\delta n}{\tau_{n0}} = \frac{\partial \delta n}{\partial t}$$

$$D_p \frac{\partial^2 \delta p}{\partial x^2} - \mu_p E \frac{\partial \delta p}{\partial x} + g'_p - \frac{\delta p}{\tau_{p0}} = \frac{\partial \delta p}{\partial t}$$

- describe the drift, diffusion, and recombination of excess minority carriers as a function of spatial coordinates and as a function of time
- the excess minority carrier concentration is equal to the excess majority carrier concentration
- The excess majority carriers, then, diffuse and drift with the excess minority carriers

Common ambipolar transport equation simplifications

Specification	Effect
Steady state	$\frac{\partial(\delta n)}{\partial t} = 0, \quad \frac{\partial(\delta p)}{\partial t} = 0$
Uniform distribution of excess carriers (uniform generation rate)	$D_n \frac{\partial^2(\delta n)}{\partial x^2} = 0, \quad D_p \frac{\partial^2(\delta n)}{\partial x^2} = 0$
Zero electric field	$E \frac{\partial(\delta n)}{\partial x} = 0, \quad E \frac{\partial(\delta p)}{\partial x} = 0$
No excess carrier generation	$g' = 0$
No excess carrier recombination (infinite lifetime)	$\frac{\delta n}{\tau_{n0}} = 0, \quad \frac{\delta p}{\tau_{p0}} = 0$

Applications of the Ambipolar Transport Equation

Objective: Determine the time behavior of excess carriers as a semiconductor returns to thermal equilibrium.

Consider an infinitely large, homogeneous n-type semiconductor with zero applied electric field. Assume that at time $t = 0$, a uniform concentration of excess carriers exists in the crystal, but assume that $g' = 0$ for $t > 0$. If we assume that the concentration of excess carriers is much smaller than the thermal-equilibrium electron concentration, then the low-injection condition applies. Calculate the excess carrier concentration as a function of time for $t \geq 0$.

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$$D_p \frac{\partial^2(\delta p)}{\partial x^2} - \mu_p E \frac{\partial(\delta p)}{\partial x} + g' - \frac{\delta p}{\tau_{p0}} = \frac{\partial(\delta p)}{\partial t}$$

$$\frac{\partial^2(\delta p)}{\partial x^2} = \frac{\partial(\delta p)}{\partial x} = 0$$

$$g' = 0$$

condition

$$\frac{d(\delta p)}{dt} = -\frac{\delta p}{\tau_{p0}}$$

$$\delta p(t) = \delta p(0)e^{-t/\tau_{p0}}$$

EXAMPLE 6.3

Objective: Determine the time dependence of excess carriers in reaching a steady-state condition.

Again consider an infinitely large, homogeneous n-type semiconductor with a zero applied electric field. Assume that, for $t < 0$, the semiconductor is in thermal equilibrium and that, for $t \geq 0$, a uniform generation rate exists in the crystal. Calculate the excess carrier concentration as a function of time assuming the condition of low injection.

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Again consider an infinitely large, homogeneous n-type semiconductor with a zero applied electric field. Assume that, for $t < 0$, the semiconductor is in thermal equilibrium and that, for $t \geq 0$, a uniform generation rate exists in the crystal. Calculate the excess carrier concentration as a function of time assuming the condition of low injection.

■ Solution

The condition of a uniform generation rate and a homogeneous semiconductor again implies that $\partial^2(\delta p)/\partial x^2 = \partial(\delta p)/\partial x = 0$ in Equation (6.56). The equation, for this case, reduces to

$$D_p \frac{\partial^2(\delta p)}{\partial x^2} - \mu_p E \frac{\partial(\delta p)}{\partial x} + g' - \frac{\delta p}{\tau_{p0}} = \frac{\partial(\delta p)}{\partial t}$$

$$\partial^2(\delta p)/\partial x^2 = \partial(\delta p)/\partial x = 0$$

condition

$$g' - \frac{\delta p}{\tau_{p0}} = \frac{d(\delta p)}{dt}$$

$$\delta p(t) = g' \tau_{p0} (1 - e^{-t/\tau_{p0}})$$

EXAMPLE 6.4

Objective: Determine the steady-state spatial dependence of the excess carrier concentration.

Consider a p-type semiconductor that is homogeneous and infinite in extent. Assume a zero applied electric field. For a one-dimensional crystal, assume that excess carriers are being generated at $x = 0$ only, as indicated in Figure 6.6. The excess carriers being generated at $x = 0$ will begin diffusing in both the $+x$ and $-x$ directions. Calculate the steady-state excess carrier concentration as a function of x .

$$D_n \frac{\partial^2(\delta n)}{\partial x^2} + \mu_n E \frac{\partial(\delta n)}{\partial x} + g' - \frac{\delta n}{\tau_{n0}} = \frac{\partial(\delta n)}{\partial t}$$

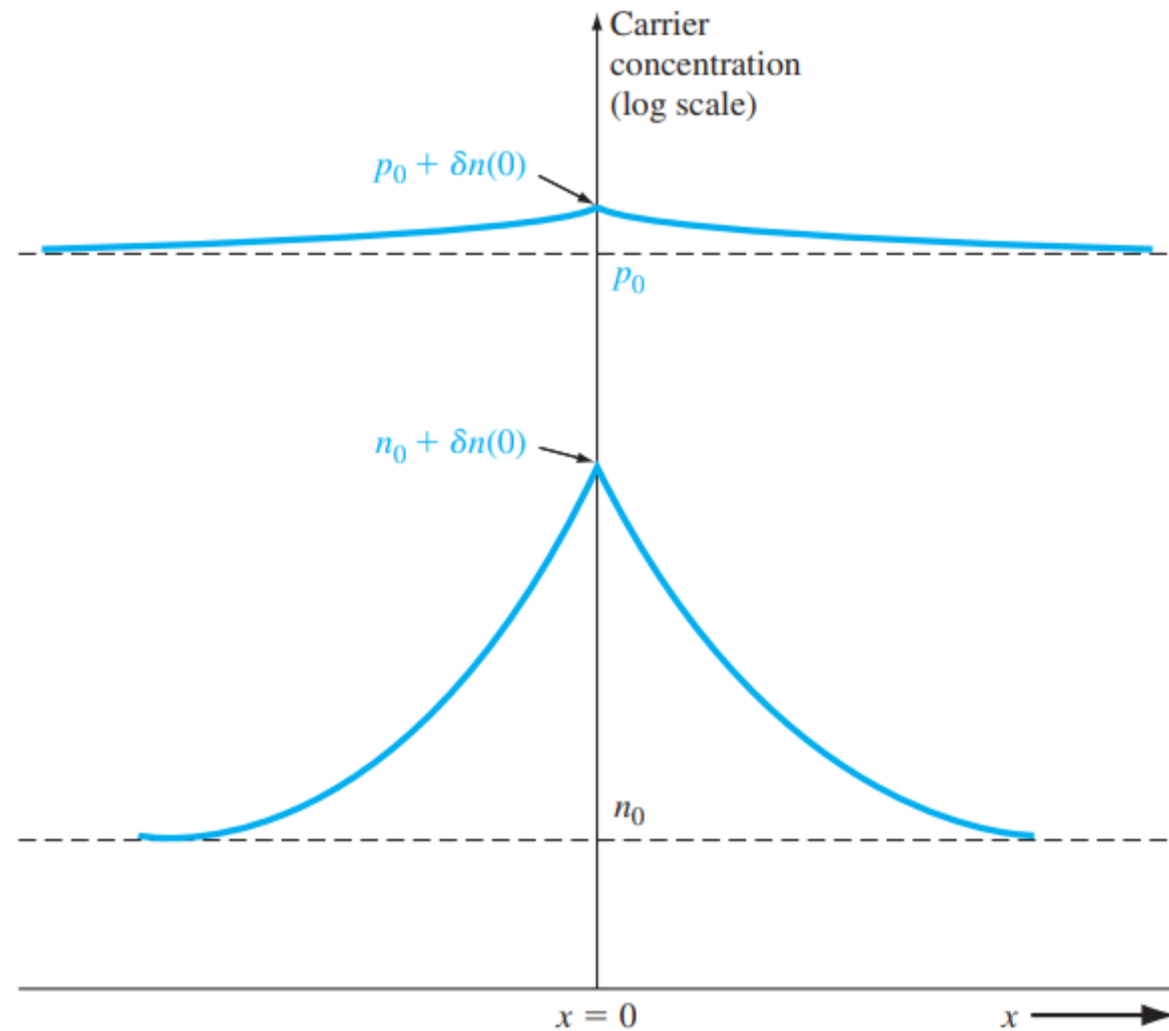
$E = 0, g' = 0 \text{ for } x \neq 0$
 $\partial(\delta n)/\partial t = 0$
condition

$(L_n = D_n \tau_{n0})$
 $D_n \frac{d^2(\delta n)}{dx^2} - \frac{\delta n}{\tau_{n0}} = 0$
 \downarrow
 $\delta n(x) = Ae^{-x/L_n} + Be^{x/L_n}$
 \leftarrow

$\delta n(x) = \delta n(0)e^{-x/L_n} \quad x \geq 0$

$\delta n(x) = \delta n(0)e^{+x/L_n} \quad x \leq 0$

EXAMPLE 6.4



$$\delta n(x) = \delta n(0)e^{-x/L_n} \quad x \geq 0$$

$$\delta n(x) = \delta n(0)e^{+x/L_n} \quad x \leq 0$$

Figure 6.7 | Steady-state electron and hole concentrations for the case when excess electrons and holes are generated at $x = 0$.

EXAMPLE 6.5

Objective: Determine both the time dependence and spatial dependence of the excess carrier concentration.

Assume that a finite number of electron–hole pairs is generated instantaneously at time $t = 0$ and at $x = 0$, but assume $g' = 0$ for $t > 0$. Assume we have an n-type semiconductor with a constant applied electric field equal to E_0 , which is applied in the $+x$ direction. Calculate the excess carrier concentration as a function of x and t .

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$$D_p \frac{\partial^2(\delta p)}{\partial x^2} - \mu_p E_0 \frac{\partial(\delta p)}{\partial x} - \frac{\delta p}{\tau_{p0}} = \frac{\partial(\delta p)}{\partial t} \qquad \delta p(x, t) = p'(x, t)e^{-t/\tau_{p0}}$$

$$D_p \frac{\partial^2 p'(x, t)}{\partial x^2} - \mu_p E_0 \frac{\partial p'(x, t)}{\partial x} = \frac{\partial p'(x, t)}{\partial t} \longrightarrow p'(x, t) = \frac{1}{(4\pi D_p t)^{1/2}} \exp\left[\frac{-(x - \mu_p E_0 t)^2}{4D_p t}\right]$$

$$\delta p(x, t) = \frac{e^{-t/\tau_{p0}}}{(4\pi D_p t)^{1/2}} \exp\left[\frac{-(x - \mu_p E_0 t)^2}{4D_p t}\right]$$

EXAMPLE 6.5

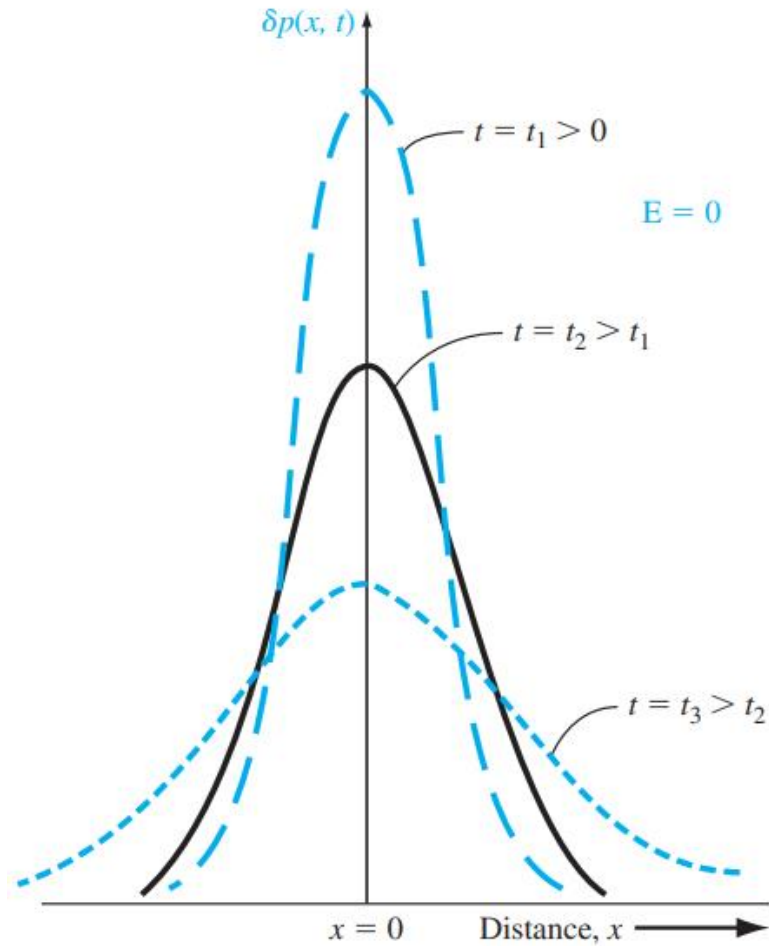


Figure 6.8 | Excess hole concentration versus distance at various times for zero applied electric field.

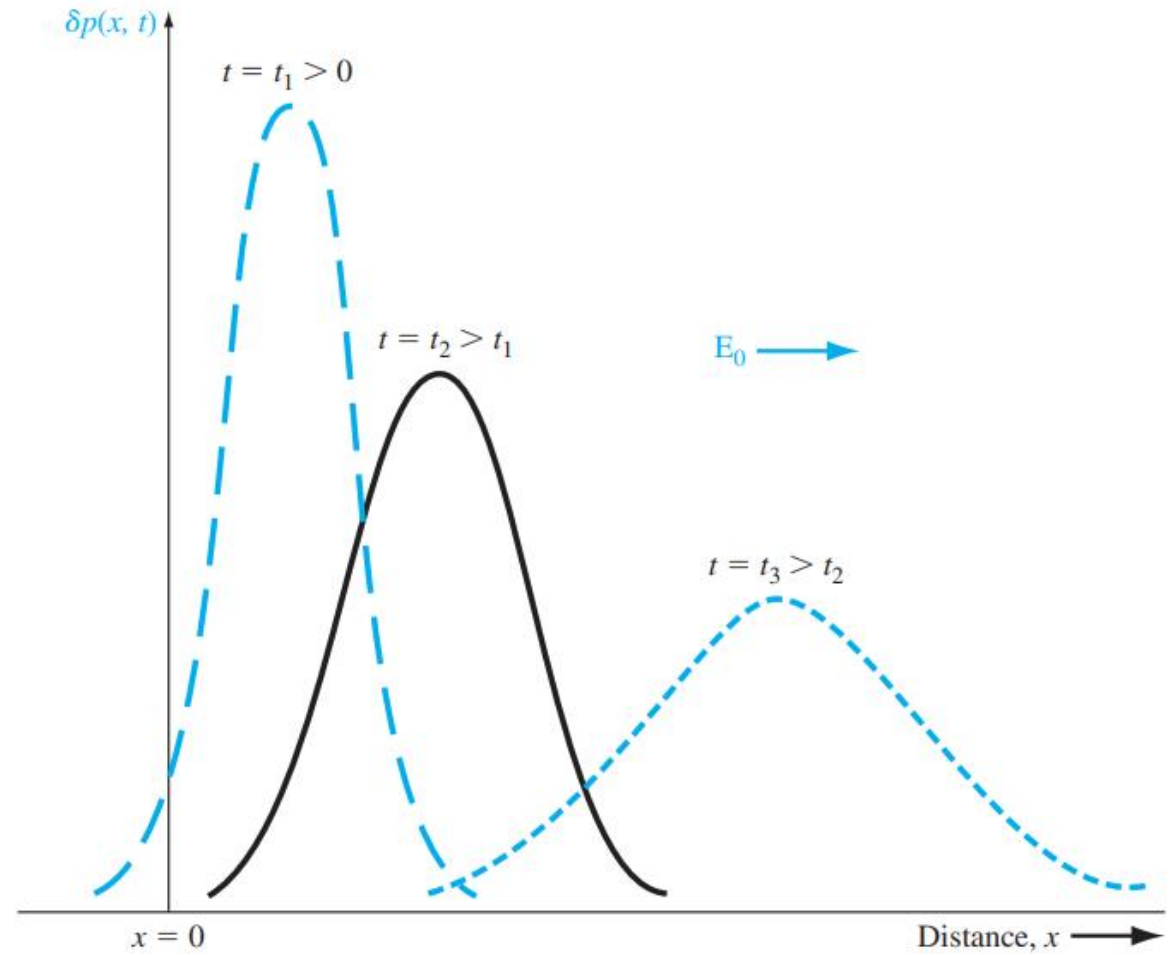


Figure 6.9 | Excess hole concentration versus distance at various times for a constant applied electric field.

Dielectric Relaxation Time Constant

A uniform concentration of holes δp
is suddenly injected into a portion of the surface of a semiconductor
How is charge neutrality achieved and how fast

$$\text{Poisson equation: } \nabla \cdot E = \frac{\rho}{\varepsilon}$$

$$\text{Current equation: } J = \sigma E$$

$$\nabla \cdot J = -\frac{\partial \rho}{\partial t} = \sigma \nabla \cdot E = \frac{\sigma \rho}{\varepsilon}$$

$$\frac{d\rho}{dt} + \frac{\sigma}{\varepsilon} \rho = 0$$

$$\rho(t) = \rho(0)e^{-(t/\tau_d)} \quad (\tau_d : \text{dielectric relaxation time constant})$$

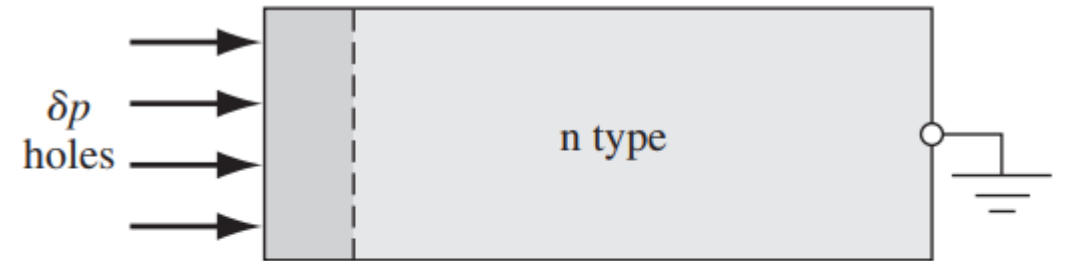


Figure 6.10 | The injection of a concentration of holes into a small region at the surface of an n-type semiconductor.

EXAMPLE 6.6

Objective: Calculate the dielectric relaxation time constant for a particular semiconductor.
Consider n-type silicon with a donor impurity concentration of $N_d = 10^{16} \text{ cm}^{-3}$.

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The conductivity is found as

$$\sigma \approx e\mu_n N_d = (1.6 \times 10^{-19})(1200)(10^{16}) = 1.92 (\Omega\text{-cm})^{-1}$$

where the value of mobility is the approximate value found from Figure 5.3. The permittivity of silicon is

$$\epsilon = \epsilon_r \epsilon_0 = (11.7)(8.85 \times 10^{-14}) \text{ F/cm}$$

The dielectric relaxation time constant is then

$$\tau_d = \frac{\epsilon}{\sigma} = \frac{(11.7)(8.85 \times 10^{-14})}{1.92} = 5.39 \times 10^{-13} \text{ s}$$

or

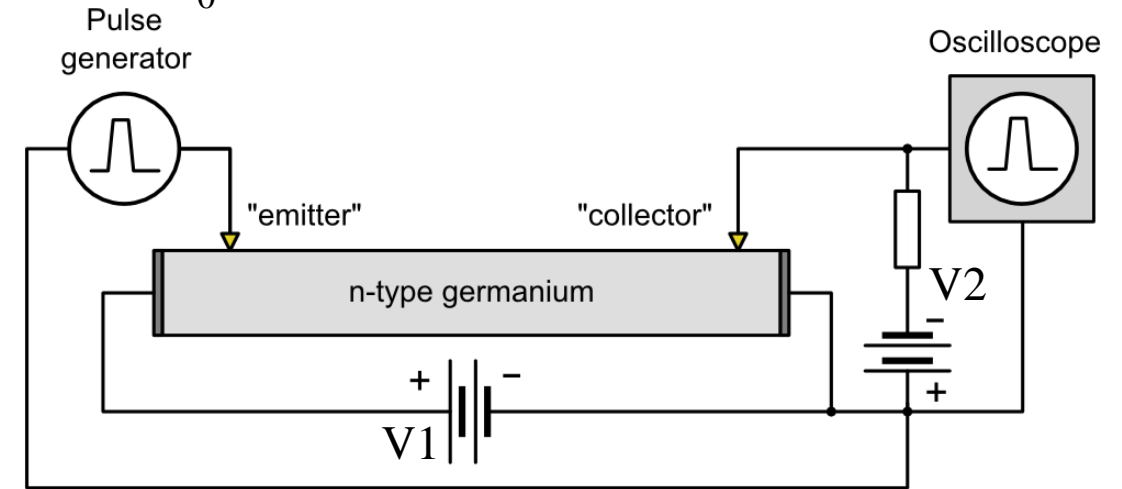
$$\tau_d = 0.539 \text{ ps}$$

Haynes–Shockley Experiment

The voltage source V_1 establishes an applied electric field E_0 in the $+x$ direction in the n – type

Excess carriers are effectively injected into the semiconductor at contact emitter
Contact collector is a rectifying contact that is under reverse bias by the voltage source V_2

The contact collector will collect a fraction of the excess carriers as they drift through the semiconductor



Haynes–Shockley Experiment

determine mobility : $x - \mu_p E_0 t = 0$

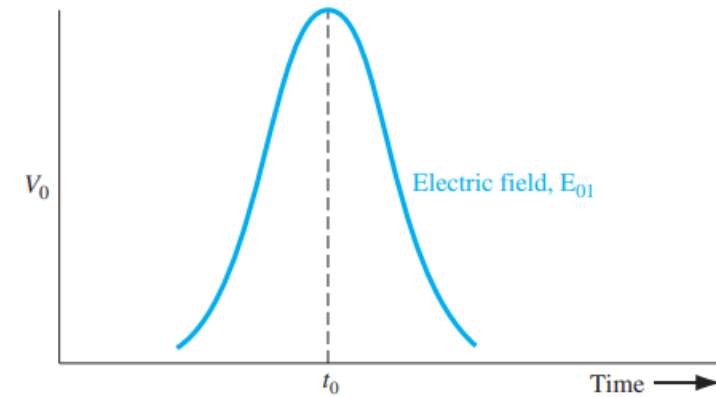
determine diffusion coefficient: $(d - \mu_p E_0 t)^2 = 4D_p t$.

determine the minority carrier lifetime:

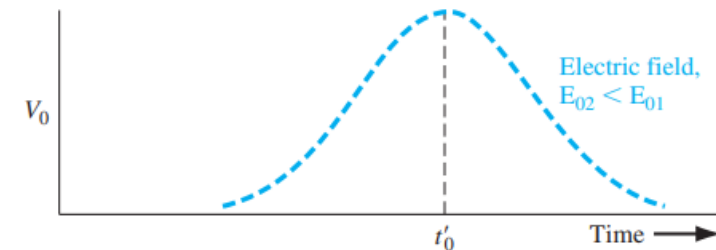
$$S(\text{area under curve}) = K \exp\left(\frac{-d}{\mu_p E_0 \tau_{p0}}\right)$$



(a)



(b)



(c)

6.4 QUASI-FERMI ENERGY LEVELS

The thermal-equilibrium electron and hole concentrations are functions of the Fermi energy level

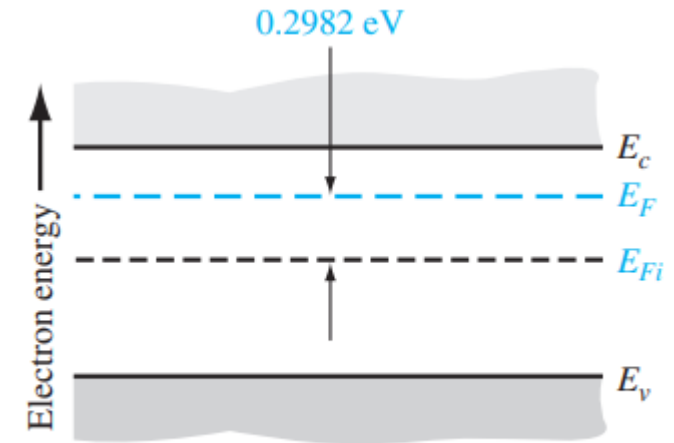
$$n_0 = n_i \exp\left(\frac{E_F - E_{Fi}}{kT}\right)$$

$$p_0 = n_i \exp\left(\frac{E_{Fi} - E_F}{kT}\right)$$

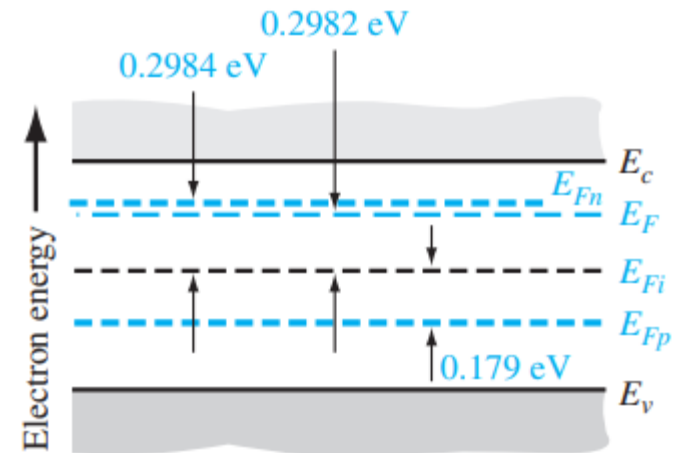
If excess carriers are created in a semiconductor, we are no longer in thermal equilibrium and the Fermi energy is strictly no longer defined

$$n_0 + \delta n = n_i \exp\left(\frac{E_{Fn} - E_{Fi}}{kT}\right)$$

$$p_0 + \delta p = n_i \exp\left(\frac{E_{Fi} - E_{Fp}}{kT}\right)$$



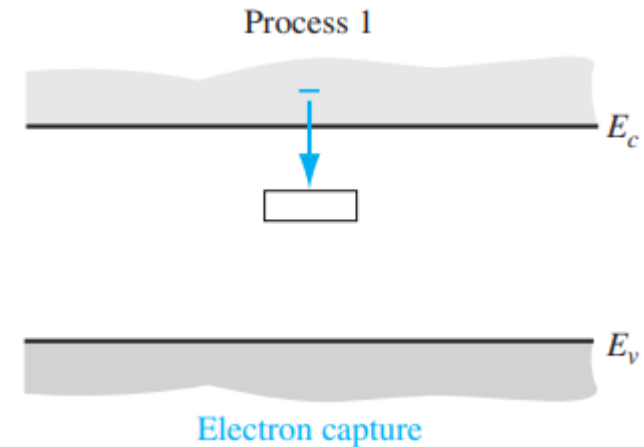
(a)
Thermal-equilibrium



(b)
Quasi-Fermi levels

6.5 EXCESS CARRIER LIFETIME

- We have been considering an ideal semiconductor in which electronic energy states do not exist within the forbidden-energy bandgap
- In a real semiconductor material, defects occur within the crystal and disrupt the perfect periodic-potential function
- If the density of these defects is not too great, the defects will create discrete electronic energy states within the forbidden-energy band. These allowed energy states may be the dominant effect in determining the mean carrier lifetime



Shockley–Read–Hall Theory of Recombination

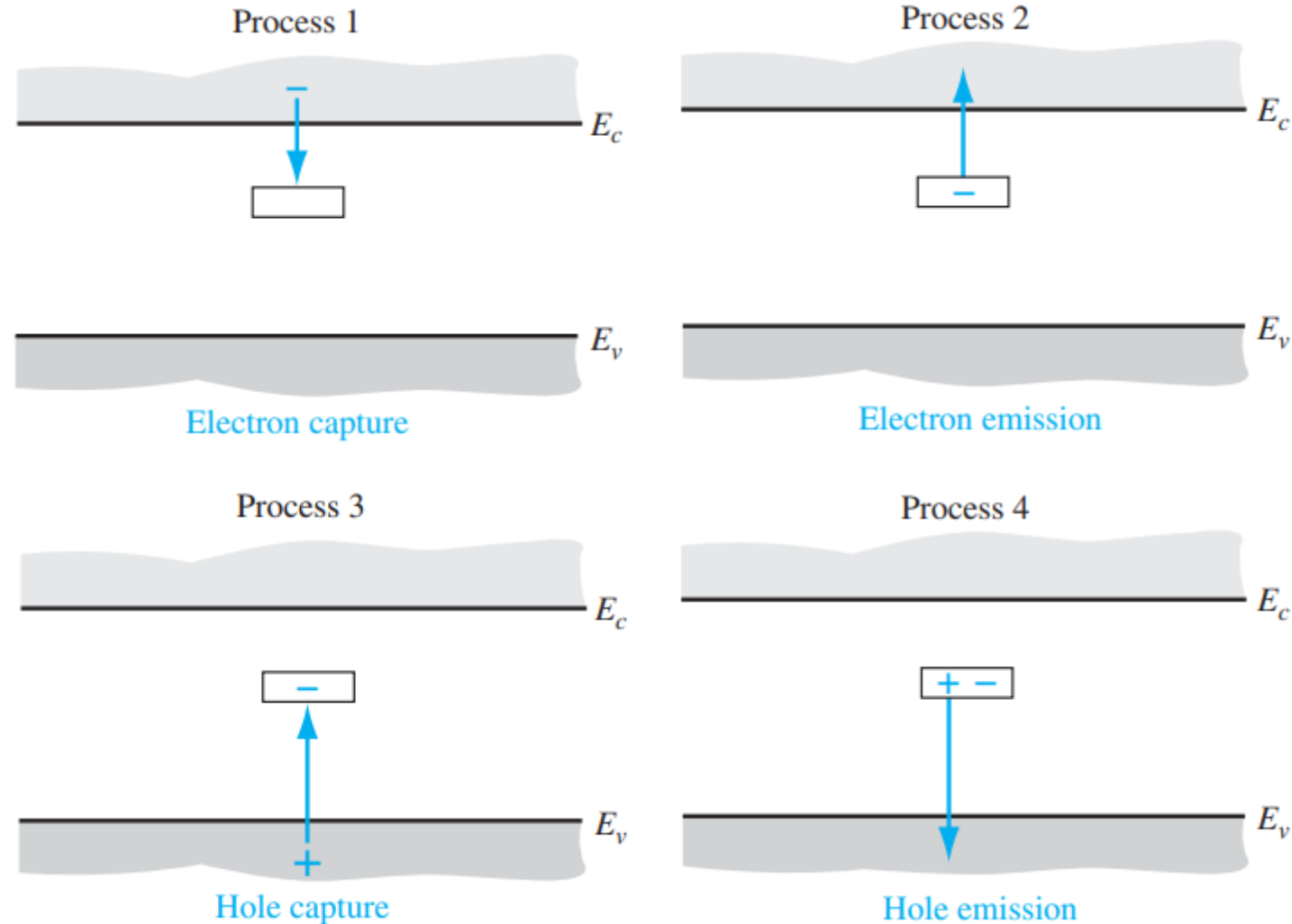
- Assume that the trap is an acceptor-type trap(it is negatively charged when it contains an electron and is neutral when it does not contain an electron)

Process 1: The capture of an electron from the conduction band by an initially neutral empty trap

Process 2: The inverse of process 1—the emission of an electron that is initially occupying a trap level back into the conduction band

Process 3: The capture of a hole from the valence band by a trap containing an electron. (Or we may consider the process to be the emission of an electron from the trap into the valence band.)

Process 4: The inverse of process 3—the emission of a hole from a neutral trap into the valence band. (Or we may consider this process to be the capture of an electron from the valence band.)



Shockley–Read–Hall Theory of Process 1

- the rate at which electrons from the conduction band are captured by the traps is proportional to the density of electrons in the conduction band and proportional to the density of empty trap states

$$R_{cn} = C_n N_t [1 - f_F(E_t)] n$$

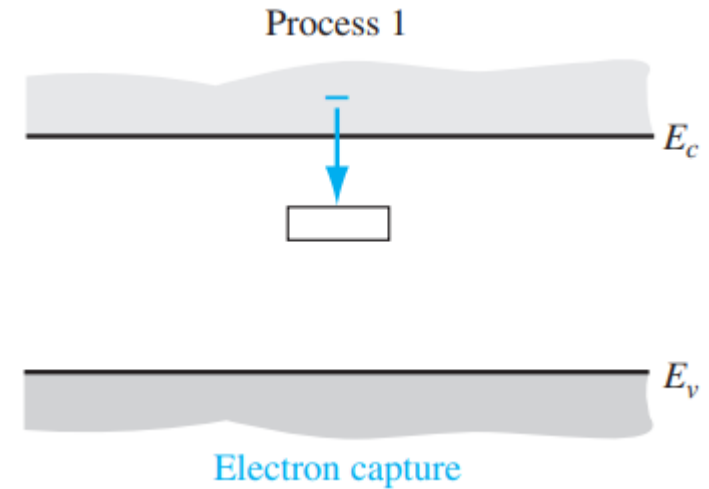
$$R_{cn} = \text{capture rate}(\#/\text{cm}^3 - \text{s})$$

C_n = constant proportional to electron
–capture cross section

N_t = total concentration of trapping centers

n = electron concentration in the conduction band

$f_F(E_t)$ = Fermi function at the trap energy



$$f_F(E_t) = \frac{1}{1 + \exp\left(\frac{E_t - E_F}{kT}\right)}$$

Shockley–Read–Hall Theory of Process 2

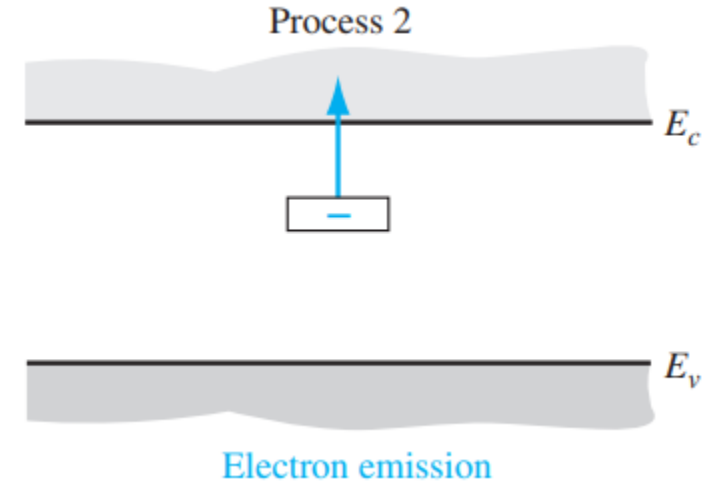
- the rate at which electrons are emitted from filled traps back into the conduction band is proportional to the number of filled traps

$$R_{en} = E_n N_t f_F(E_t)$$

$$R_{en} = \text{emission rate}(\# / \text{cm}^3 - \text{s})$$

$$E_n = \text{constant}$$

$$f_F(E_t) = \text{probability that the trap is occupied}$$



Theory of Recombination at thermal equilibrium

In thermal equilibrium:

$$R_{en} = R_{cn}$$

$$E_n N_t f_{F0}(E_t) = C_n N_t [1 - f_{F0}(E_t)] n_0$$

$$E_n = N_c \exp\left[\frac{-(E_c - E_t)}{kT}\right] C_n = n' C_n$$

In nonequilibrium:

$$R_n = R_{cn} - R_{en}$$

$$= C_n N_t [1 - f_F(E_t)] n - E_n N_t f_F(E_t)$$

$$= C_n N_t [n(1 - f_F(E_t)) - n' f_F(E_t)]$$

consider process 3 and process 4

$$R_p = R_{cp} - R_{ep}$$

$$= C_p N_t [p f_F(E_t) - p' [1 - f_F(E_t)]]$$

$$p' = N_v \exp\left(\frac{-(E_t - E_v)}{kT}\right)$$

$$f_F(E_t) = \frac{C_n n + C_p p'}{C_n (n + n') + C_p (p + p')}$$

$$R_n = R_p = \frac{C_n C_p N_t (np - n_i^2)}{C_n (n + n') + C_p (p + p')} \equiv R$$

Limits of Extrinsic Doping and Low Injection

Consider an n – type semiconductor under low injection

$$n_0 \gg p_0, n_0 \gg \delta p, n_0 \gg n', n_0 \gg p'$$

imply that the trap level energy is near midgap

$$R = \frac{C_n C_p N_t (np - n_i^2)}{C_n (n + n') + C_p (p + p')} = C_p N_t \delta p = \frac{\delta p}{\tau_{p0}}$$

Similarly in p-type:

$$p_0 \gg n_0, p_0 \gg \delta n, p_0 \gg n', p_0 \gg p'$$

$$R = C_n N_t \delta n = \frac{\delta n}{\tau_{n0}}$$

EXAMPLE 6.8

Objective: Determine the excess carrier lifetime in an intrinsic semiconductor.

If we substitute the definitions of excess carrier lifetimes from Equations (6.103) and (6.104) into Equation (6.99), the recombination rate can be written as

$$R = \frac{(np - n_i^2)}{\tau_{p0}(n + n') + \tau_{n0}(p + p')} \quad (6.105)$$

Consider an intrinsic semiconductor containing excess carriers. Then $n = n_i + \delta n$ and $p = n_i + \delta n$. Also assume that $n' = p' = n_i$.

EXAMPLE 6.8

Objective: Determine the excess carrier lifetime in an intrinsic semiconductor.

If we substitute the definitions of excess carrier lifetimes from Equations (6.103) and (6.104) into Equation (6.99), the recombination rate can be written as

$$R = \frac{(np - n_i^2)}{\tau_{p0}(n + n') + \tau_{n0}(p + p')} \quad (6.105)$$

Consider an intrinsic semiconductor containing excess carriers. Then $n = n_i + \delta n$ and $p = n_i + \delta n$. Also assume that $n' = p' = n_i$.

Equation (6.105) now becomes

$$R = \frac{2n_i\delta n + (\delta n)^2}{(2n_i + \delta n)(\tau_{p0} + \tau_{n0})}$$

If we also assume very low injection, so that $\delta n \ll 2n_i$, then we can write

$$R = \frac{\delta n}{\tau_{p0} + \tau_{n0}} = \frac{\delta n}{\tau}$$

where τ is the excess carrier lifetime. We see that $\tau = \tau_{p0} + \tau_{n0}$ in the intrinsic material.

6.6 SURFACE EFFECTS

- In all previous discussions, we have implicitly assumed the semiconductors were infinite in extent
- The abrupt termination of the periodic potential at the surface results in a distribution of allowed energy states within the bandgap
- We may argue that since the density of traps at the surface is larger than in the bulk, the excess minority carrier lifetime at the surface will be smaller than the corresponding lifetime in the bulk material

We may write a similar expression for the recombination rate of excess carriers at the surface as

$$R_s = \frac{\delta p_s}{\tau_{p0s}}$$

Surface States

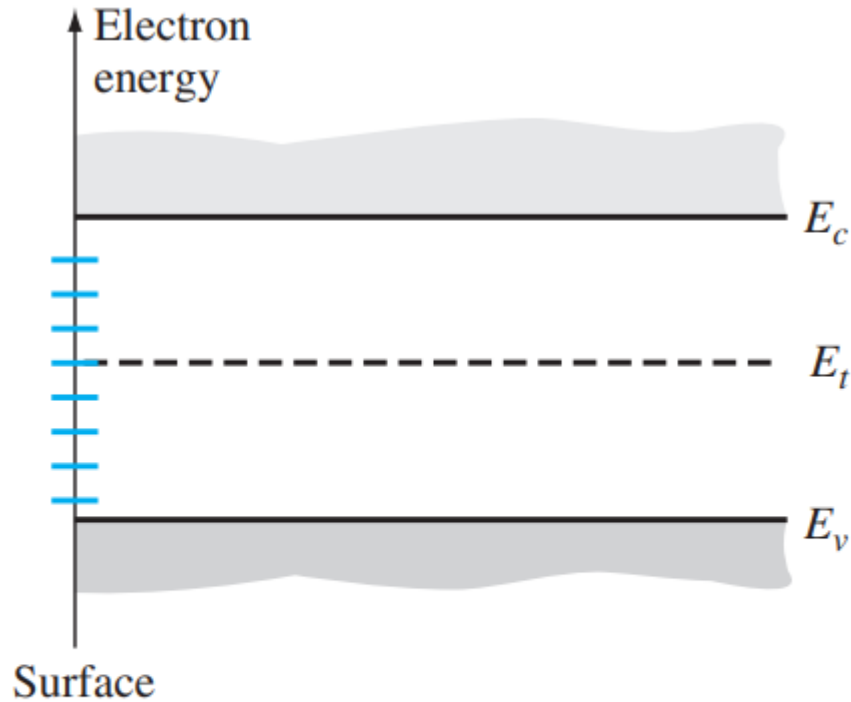


Figure 6.17 | Distribution of surface states within the forbidden bandgap.

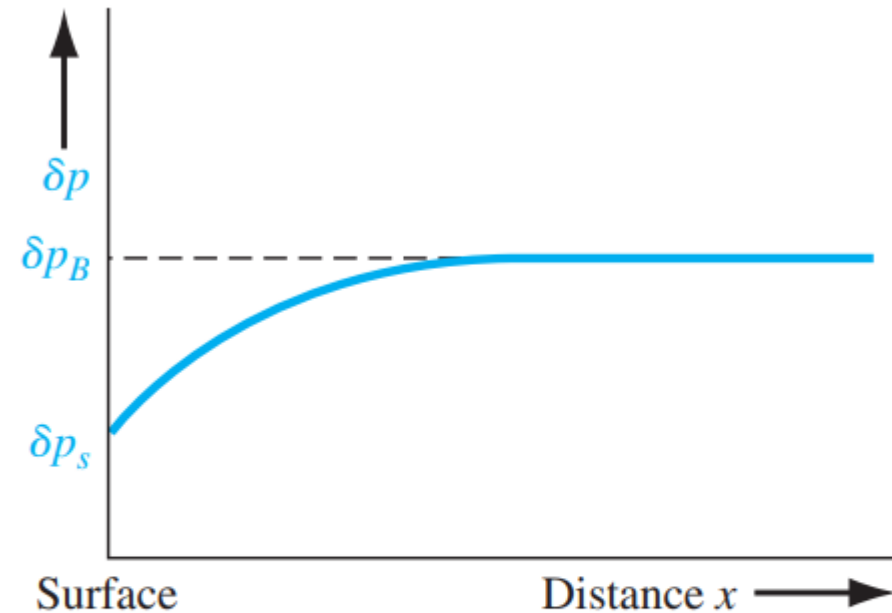


Figure 6.18 | Steady-state excess hole concentration versus distance from a semiconductor surface.

EXAMPLE 6.9

Objective: Determine the steady-state excess carrier concentration as a function of distance from the surface of a semiconductor.

Consider Figure 6.18, in which the surface is at $x = 0$. Assume that in the n-type semiconductor $\delta p_B = 10^{14} \text{ cm}^{-3}$ and $\tau_{p0} = 10^{-6} \text{ s}$ in the bulk, and $\tau_{p0s} = 10^{-7} \text{ s}$ at the surface. Assume zero applied electric field and let $D_p = 10 \text{ cm}^2/\text{s}$.

EXAMPLE 6.9

Objective: Determine the steady-state excess carrier concentration as a function of distance from the surface of a semiconductor.

Consider Figure 6.18, in which the surface is at $x = 0$. Assume that in the n-type semiconductor $\delta p_B = 10^{14} \text{ cm}^{-3}$ and $\tau_{p0} = 10^{-6} \text{ s}$ in the bulk, and $\tau_{p0s} = 10^{-7} \text{ s}$ at the surface. Assume zero applied electric field and let $D_p = 10 \text{ cm}^2/\text{s}$.

$$\frac{\delta p_B}{\tau_{p0}} = \frac{\delta p_s}{\tau_{p0s}} \quad \delta p_s = \delta p_B \left(\frac{\tau_{p0s}}{\tau_{p0}} \right) = (10^{14}) \left(\frac{10^{-7}}{10^{-6}} \right) = 10^{13} \text{ cm}^{-3}$$

根據條件

可以先求得

$$D_p \frac{d^2(\delta p)}{dx^2} + g' - \frac{\delta p}{\tau_{p0}} = 0 \quad g' = \frac{\delta p_B}{\tau_{p0}} = \frac{10^{14}}{10^{-6}} = 10^{20} \text{ cm}^{-3}\text{-s}^{-1}$$

通解

$$\delta p(x) = g' \tau_{p0} + A e^{x/L_p} + B e^{-x/L_p}$$

$$\delta p(x) = 10^{14} (1 - 0.9 e^{-x/L_p})$$

再利用邊界條件

$$\text{As } x \rightarrow +\infty, \delta p(x) = \delta p_B = g' \tau_{p0} = 10^{14} \text{ cm}^{-3}$$

$$\text{which implies that } A = 0. \text{ At } x = 0 \text{ 得到 } \delta p(0) = \delta p_s = 10^{14} + B = 10^{13} \text{ cm}^{-3}$$

Surface Recombination Velocity

$$-D_p \left[\hat{n} \cdot \frac{d(\delta p)}{dx} \right] \Big|_{surf} = s \delta p \Big|_{surf}$$

\hat{n} :outward vector normal to the surface

The parameter s is called the surface recombination velocity

- If the excess concentrations at the surface and in the bulk region were equal, then the gradient term would be zero and the surface recombination velocity would be zero

$$D_p \frac{d(\delta p)}{dx} \Big|_{surf} = s \delta p \Big|_{surf}$$

$$\delta p_{surf} = \delta p(0) = g' \tau_{p0} + B$$

$$\frac{d(\delta p)}{dx} \Big|_{surf} = \frac{d(\delta p)}{dx} \Big|_{x=0} = -\frac{B}{L_p}$$

$$B = \frac{-s g' \tau_{p0}}{(D_p/L_p) + s}$$

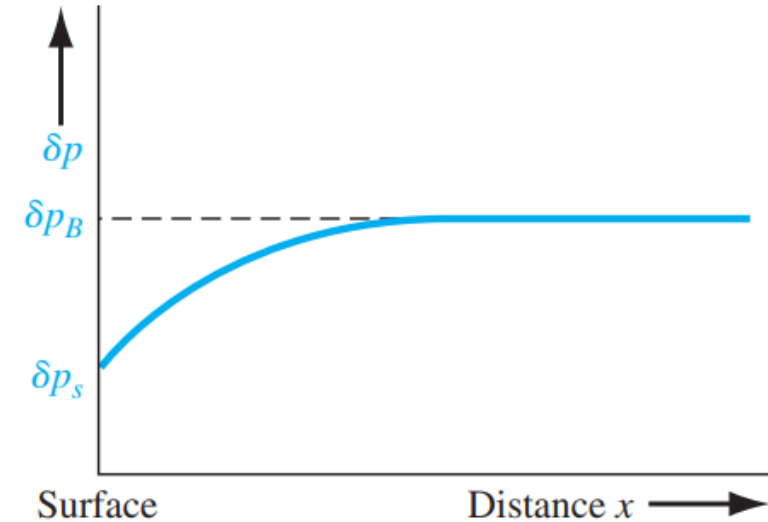


Figure 6.18 | Steady-state excess hole concentration versus distance from a semiconductor surface.

$$\delta p(x) = g' \tau_{p0} \left(1 - \frac{s L_p e^{-x/L_p}}{D_p + s L_p} \right)$$

EXAMPLE 6.10

Objective: Determine the value of surface recombination velocity corresponding to the parameters given in Example 6.9.

From Example 6.9, we have that $g'\tau_{p0} = 10^{14} \text{ cm}^{-3}$, $D_p = 10 \text{ cm}^2/\text{s}$, $L_p = 31.6 \text{ }\mu\text{m}$, and $\delta p(0) = 10^{13} \text{ cm}^{-3}$.

EXAMPLE 6.10

Objective: Determine the value of surface recombination velocity corresponding to the parameters given in Example 6.9.

From Example 6.9, we have that $g'\tau_{p0} = 10^{14} \text{ cm}^{-3}$, $D_p = 10 \text{ cm}^2/\text{s}$, $L_p = 31.6 \text{ }\mu\text{m}$, and $\delta p(0) = 10^{13} \text{ cm}^{-3}$.

$$\delta p(0) = g'\tau_{p0} \left[1 - \frac{s}{(D_p/L_p) + s} \right]$$

Solving for the surface recombination velocity, we find that

$$s = \frac{D_p}{L_p} \left(\frac{g'\tau_{p0}}{\delta p(0)} - 1 \right)$$

$$s = \frac{10}{31.6 \times 10^{-4}} \left[\frac{10^{14}}{10^{13}} - 1 \right] = 2.85 \times 10^4 \text{ cm/s}$$