



Carrier Transport and Excess Carrier Phenomena

Carrier Drift

An electric field applied to a semiconductor will produce a force on electrons and holes so that they will experience a net acceleration and net movement, provided that there are available energy states in the conduction and valence bands. This net drift of charge gives rise to a *drift current*.

Drift Current Density (Holes)

If we have a positive volume charge density ρ moving at an average drift velocity v_{dr} , the drift current density is given by

$$J_{drf} = \rho v_d \quad (1)$$

where J_{drf} is in units of C/cm²-s or amps/cm². If the volume charge density is due to positively charged holes, then

$$J_{p/dr} = (ep)v_{dp} \quad (2)$$

where $J_{p/dr}$ is the drift current density due to holes, v_{dp} is the average drift velocity of holes, p is the hole concentration.

Average drift velocity of holes is written by

$$v_{dp} = \mu_p E \quad (3)$$

where μ_p is the proportionality factor and is called the *hole mobility* expressed in cm²/V-s, E is the electric field. By combining (2) and (3), we can write the drift current density due to holes as

$$J_{p/dr} = (ep)v_{dp} = e\mu_p pE \quad (4)$$

The drift current due to holes is in the same direction as the applied electric field

Drift Current Density (Electrons)

The same discussion of drift applies to electrons. We can write

$$J_{n/dr} = \rho v_{dn} = (-en)v_{dn} \quad (5)$$

where $J_{n/dr}$ is the drift current density due to electrons and v_{dn} is the average drift velocity of electrons. The net charge density of electrons is negative $(-e)$.

The average drift velocity of an electron is also proportional to the electric field for small fields. However, since the electron is negatively charged, the net motion of the electron is opposite to the electric field direction. We can write:

$$v_{dn} = -\mu_n E \quad (6)$$

where μ_n is the *electron mobility* and is a positive quantity. Equation (5) can now be written as

$$J_{n/dr} = (-en)(-\mu_n E) = e\mu_n nE \quad (7)$$

The conventional drift current due to electrons is also in the same direction as the applied electric field even though the electron movement is in the opposite direction.

The total drift current density is the sum of individual current densities:

$$J_{dr} = e(\mu_n n + \mu_p p)E \quad (8)$$

Mobility Effects

The equation of motion of a positively charged hole in a presence of an electric field is

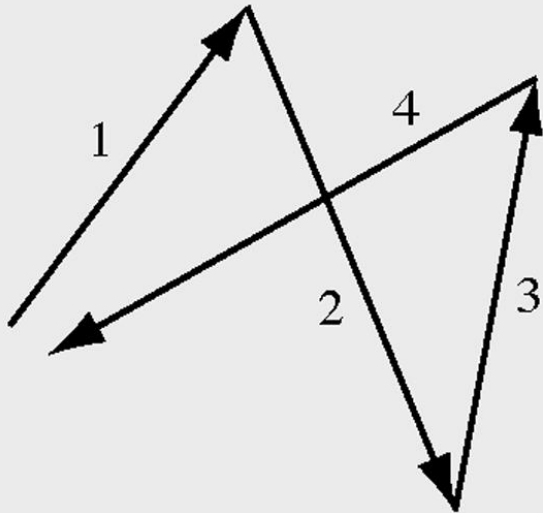
$$F = m_p^* a = m_p^* \frac{dv}{dt} = eE \quad (8)$$

where v is the velocity of the particle due to the electric field and does not include the random thermal velocity. If we assume that the effective mass and electric field are constants, then we may integrate (8) and obtain

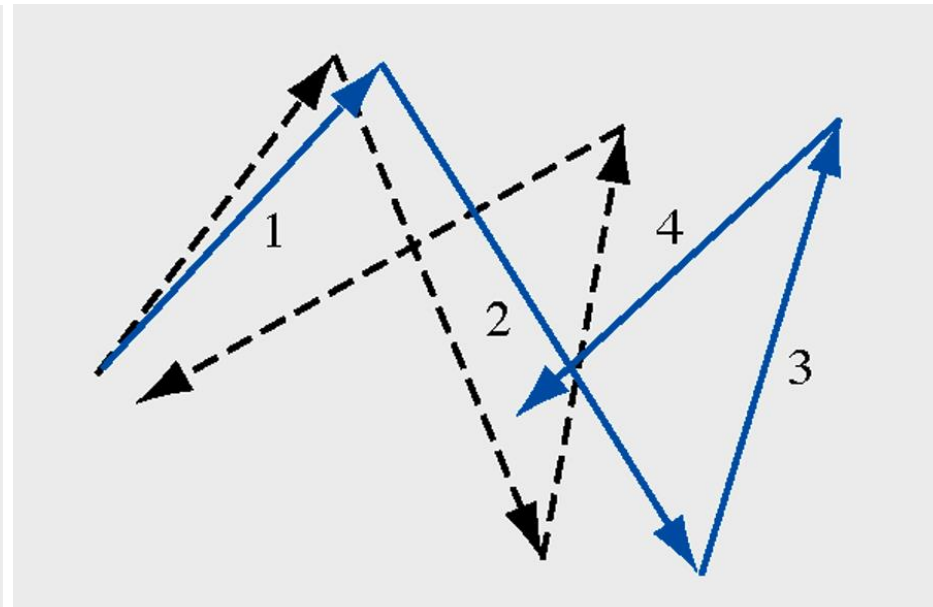
$$v = \frac{eEt}{m_p^*} \quad (9)$$

where we have assumed the initial drift velocity to be zero.

Scattering Effects



(a)



(b)

(a) Typical random behaviour of a hole or electron in a semiconductor with no applied electric field; (b) Behaviour of a hole in a semiconductor – dotted lines for $E=0$ and solid lines for $E>0$.

Mobility Versus Scattering

If we use the mean time between collisions τ_{cp} for a hole in place of the time t in equation (9), then the mean velocity just prior to a collision or scattering event is

$$v_d = \left(\frac{e \tau_{cp}}{m_p^*} \right) E \quad (10)$$

The hole mobility is given by

$$\mu_p = \frac{v_{dp}}{E} = \frac{e \tau_{cp}}{m_p^*} \quad (11)$$

The same analysis applies to electrons; thus we can write the electron mobility as

$$\mu_n = \frac{e \tau_{cn}}{m_n^*} \quad (12)$$

where τ_{cn} is the mean time between collisions for an electron

Lattice Scattering

There are two collision or scattering mechanisms that dominate in a semiconductor:

phonon or lattice scattering,
ionized impurity scattering.

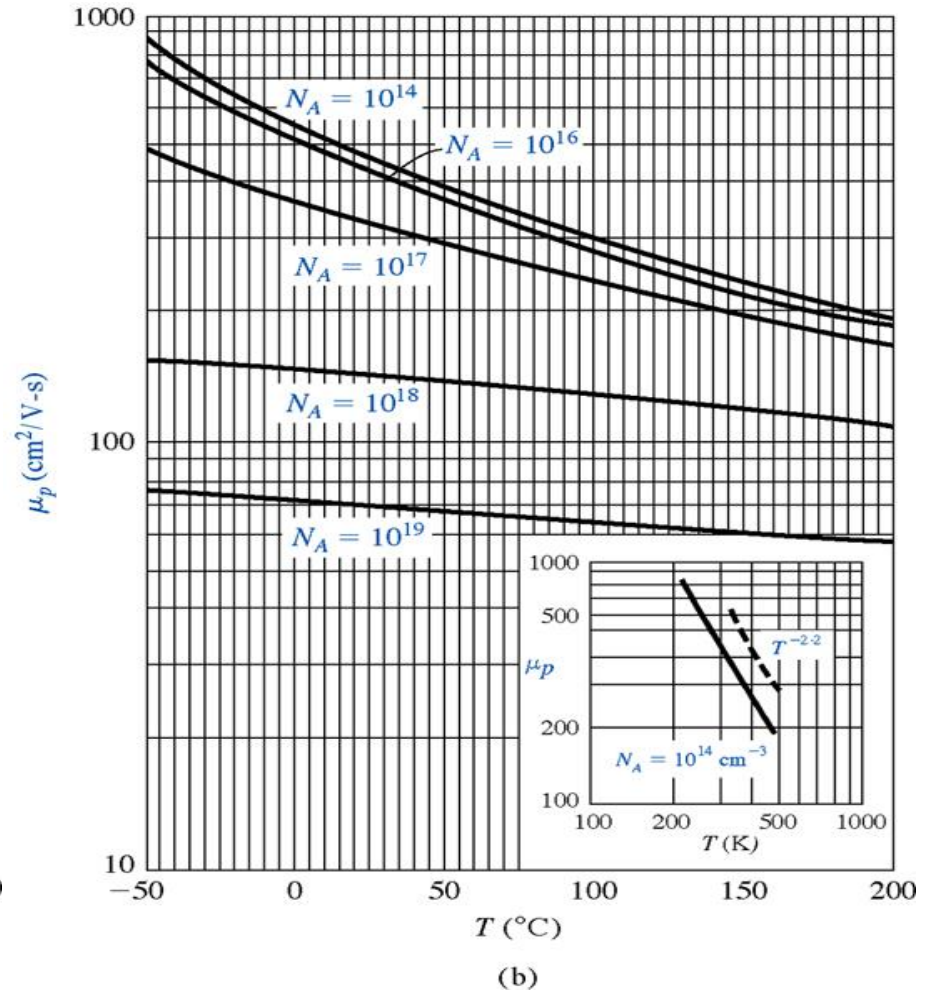
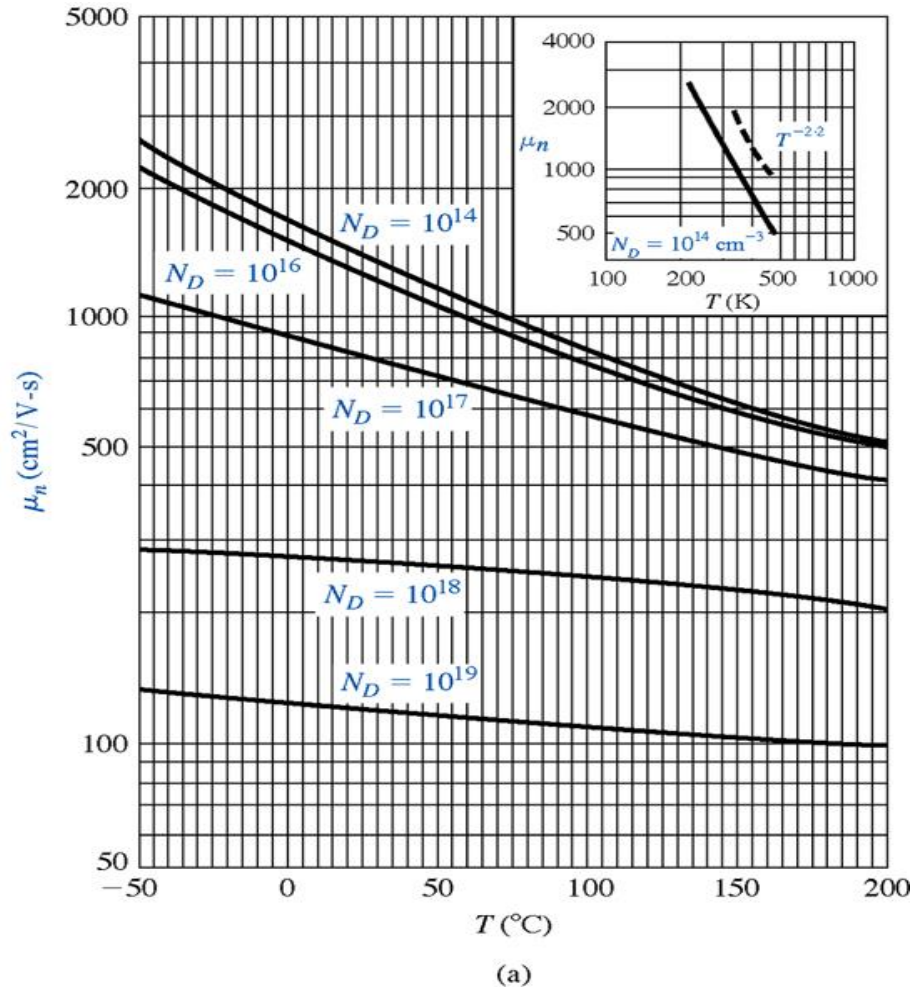
Lattice scattering is related to the thermal motion of atoms. If we denote μ_L as the mobility that would be observed if only lattice scattering existed, then the scattering theory states that to first order

$$\mu_L \propto T^{-3/2} \quad (13)$$

Experimental temperature dependencies of mobility demonstrate proportionality to T^n .



Mobility versus Temperature



Ionized Impurity Scattering

The impurities in semiconductor are ionized at room temperature so that a coulomb interaction exists between the electrons or holes and the ionized impurities.

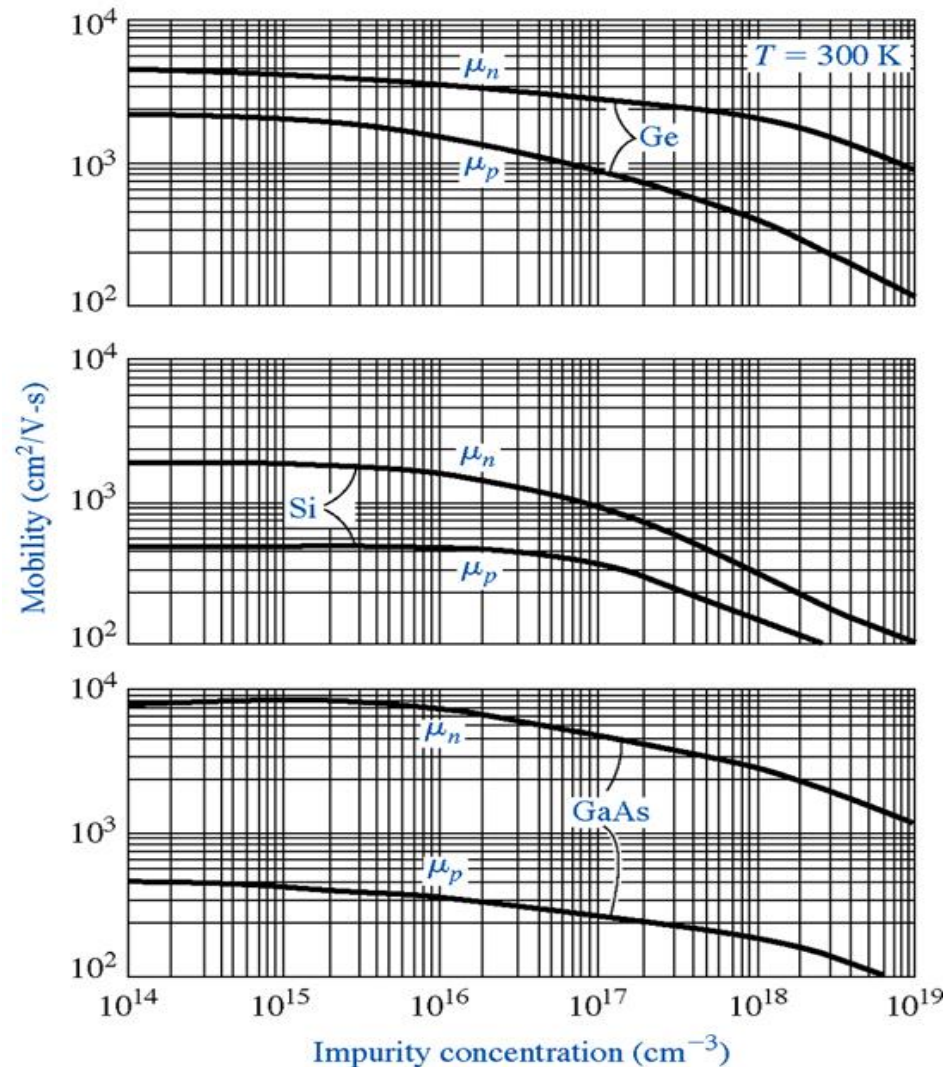
If we denote μ_I as the mobility that would be observed if only ionized impurity scattering existed, then to first order we have

$$\mu_I \propto \frac{T^{+3/2}}{N_I} \quad (14)$$

where $N_I = N_d^+ + N_a^-$ is the total ionized impurity concentration in the semiconductor.



Electron and Hole Mobilities versus Impurities Concentrations



Mobility versus Two Scattering Effects

If τ_L is the mean time between collisions due to lattice scattering, then dt/τ_L is the probability of a lattice scattering event occurring in a differential time dt .

Likewise, if τ_I is the mean time between the collisions due to ionized impurity scattering, then dt/τ_I is the probability of an ionized impurity scattering event occurring in the differential time dt . If these two scattering processes are independent, then the total probability of a scattering event occurring in the differential time dt is

$$\frac{dt}{\tau} = \frac{dt}{\tau_I} + \frac{dt}{\tau_L} \quad (15)$$

where τ is the mean time between any scattering event.

Comparing (15) with the definitions of mobility (11) or (12), we can write

$$\frac{1}{\mu} = \frac{1}{\mu_I} + \frac{1}{\mu_L} \quad (16)$$

Conductivity and Resistivity

The drift current density, given by (8), can be written as

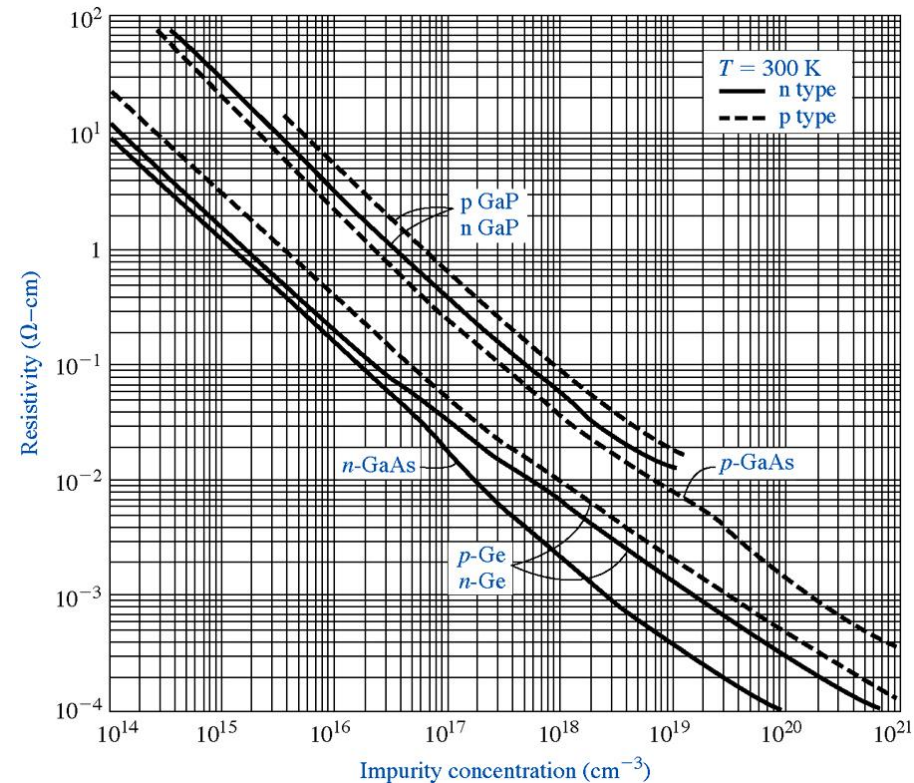
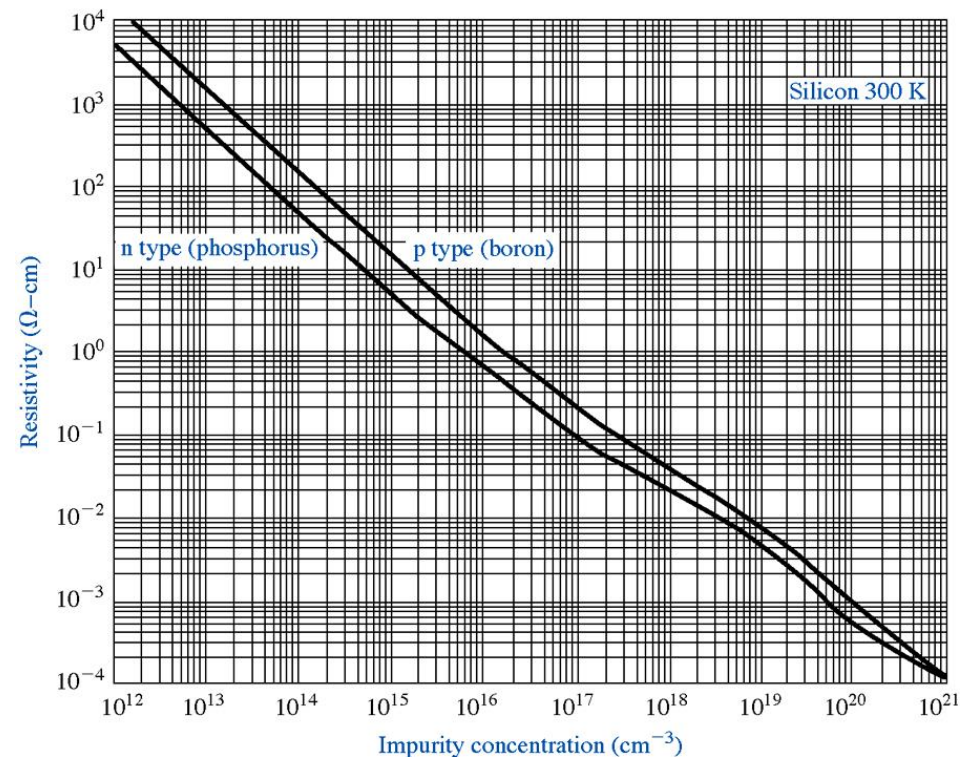
$$J_{drf} = e(\mu_n n + \mu_p p)E = \sigma E \quad (17)$$

where σ is the *conductivity* of the semiconductor material. The conductivity is given in units of $(\Omega\text{-cm})^{-1}$ and is a function of the electron and hole concentrations and mobilities.

The reciprocal of conductivity is *resistivity*, which is denoted by ρ and is given in units of ohm-cm:

$$\rho = \frac{1}{\sigma} = \frac{1}{e(\mu_n n + \mu_p p)} \quad (18)$$

Resistivity versus Impurity Concentration



(a) silicon; (b) germanium, gallium arsenide and gallium phosphide.

Ohm's Law

If we have a bar of semiconductor material with a voltage V applied that produces a current I , then we can write

$$J = \frac{I}{A} \qquad E = \frac{V}{L} \qquad (19a,b)$$

where A is the area of the facet of the bar, and L is the length. We can now rewrite the equation (17) as

$$\frac{I}{A} = \sigma \left(\frac{V}{L} \right) \qquad (20a)$$

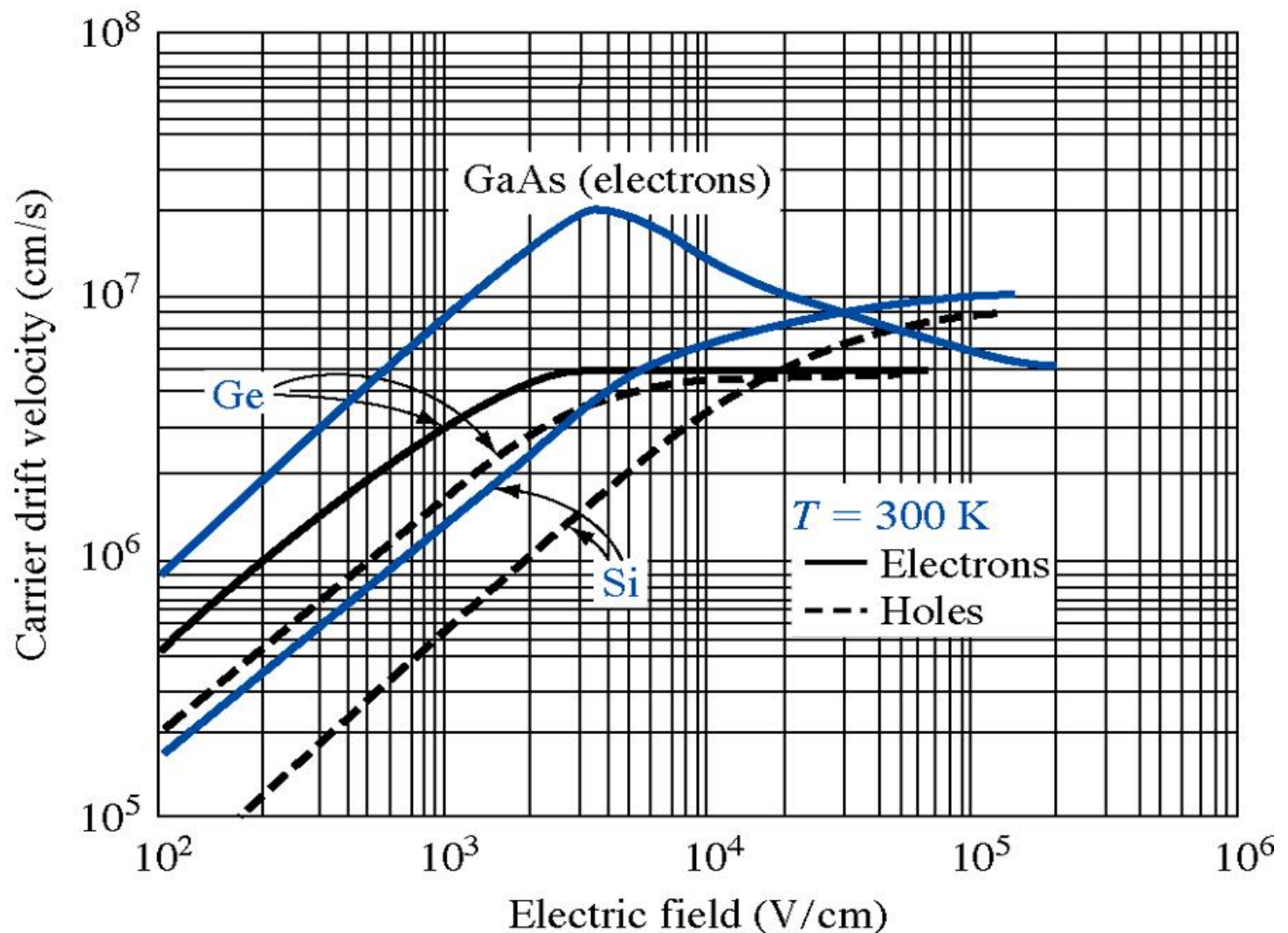
or

$$V = \left(\frac{L}{\sigma A} \right) I = \left(\frac{\rho L}{A} \right) I = IR \qquad (20b)$$

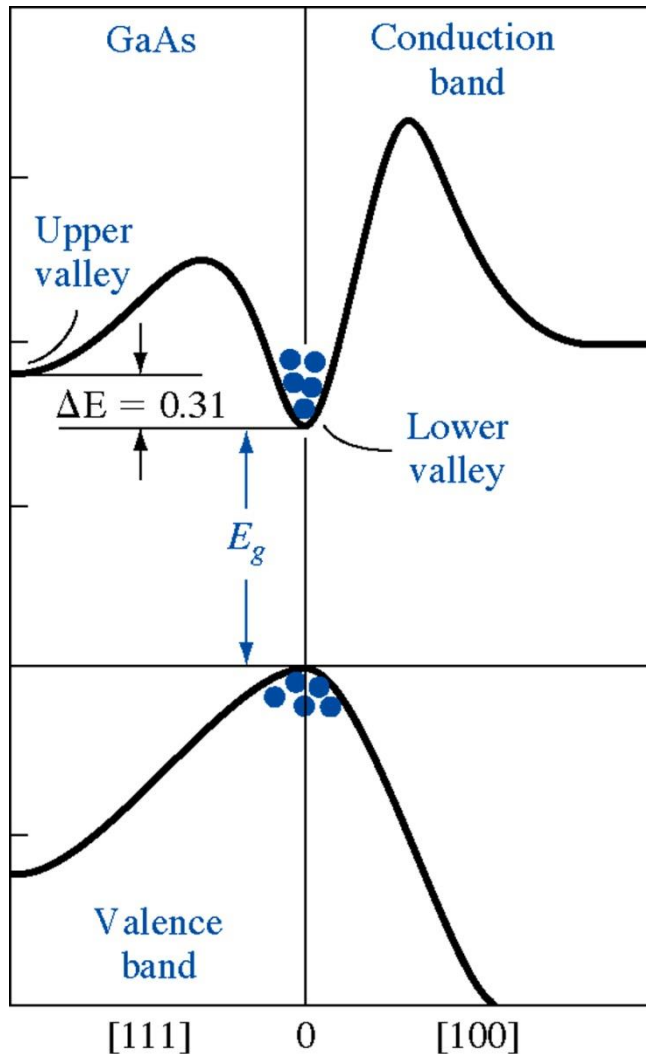
Equation (20b) is Ohm's law for a semiconductor. The resistance is a function of resistivity, or conductivity, as well as the geometry of the semiconductor.



Drift Velocity Saturation



Negative Differential Mobility



A differential mobility is the slope of the v_d versus E -field at a particular point on the curve.

Negative differential mobility produces a negative differential resistance.

Effective mass of the electron in the lower valley is $m_n^* = 0.067m_0$. The small effective mass leads to a large mobility. As E -field increases, the energy of the electron increases and the electron can be scattered into the upper valley, where the effective mass is $0.55m_0$. The larger effective mass yields a smaller mobility

Carrier Diffusion

Diffusion is the process whereby particles flow from a region of high concentration toward a region of low concentration. If the particles are electrically charged, the net flow of charge would result in a *diffusion current*.

Diffusion Current Density

The diffusion of electrons from a region of high concentration to a region of low concentration produces a flux of electrons. We can write the electron diffusion current density for the one-dimensional case in the form

$$J_{nx/dif} = eD_n \frac{dn}{dx} \quad (21)$$

where D_n is called the *electron diffusion coefficient*, has units of cm^2/s , and is a positive quantity. If the electron density gradient becomes negative, the electron diffusion current density will be in the negative x direction.

The diffusion of holes, from a region of high concentration to a region of low concentration produces a flux of holes in the negative x direction. Since holes are positively charged particles, the conventional diffusion current density is also in the negative x direction. The hole diffusion current density is given by

$$J_{px/dif} = -eD_p \frac{dp}{dx} \quad (22)$$

D_p is called the *hole diffusion coefficient*, has units of cm^2/s , and is a positive quantity.

Total Current Density

There are four possible independent current mechanisms in a semiconductor. These components are electron drift and diffusion currents and hole drift and diffusion currents. The total current density is the sum of these four components

$$J = en\mu_n E_x + ep\mu_p E_x + eD_n \frac{dn}{dx} - eD_p \frac{dp}{dx} \quad (23)$$

This equation can be generalized to three dimensions as

$$J = en\mu_n E + ep\mu_p E + eD_n \nabla n - eD_p \nabla p \quad (24)$$

The Einstein Relation

The diffusion coefficient and mobility are not independent parameters. The relation between the mobility and diffusion coefficient is given by *Einstein relation*:

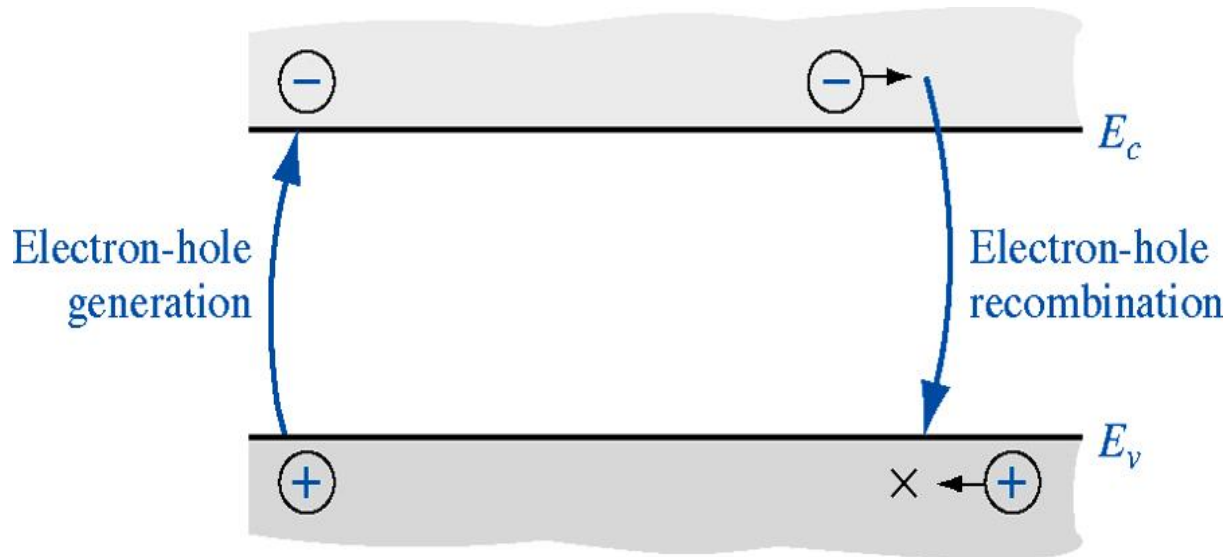
$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{e} \quad (1)$$

Carrier Generation and Recombination

Generation – the process whereby electrons and holes (carriers) are created.

Recombination – the process whereby electrons and holes (carriers) are annihilated.

Thermal Generation and Recombination Rates



The net carrier concentrations are independent of time in thermal equilibrium, the rate at which electrons and holes are generated and the rate at which they recombine must be equal.

Let G_{n0} and G_{p0} be thermal-generation rates of electrons and holes. For the direct band-to-band generation, the electrons and holes are created in pairs, so

$$G_{n0} = G_{p0} \quad (2)$$

Let R_{n0} and R_{p0} be the recombination rates of electrons and holes. In direct band-to-band recombination, electrons and holes recombine in pairs, so

$$R_{n0} = R_{p0} \quad (3)$$

$$G_{n0} = G_{p0} = R_{n0} = R_{p0} \quad (4)$$

Excess Carrier Generation

Electrons in the valence band may be excited into the conduction band when high-energy photons are incident on a semiconductor. When this happens, a hole is also created in valence band; thus electron-hole pair is generated. The additional electrons and holes are called *excess electrons* and *excess holes*.

Let g_n' be the generation rate of excess electrons and g_p' be that of excess holes. For the direct band-to-band generation, the excess electrons and holes are also created in pairs, so

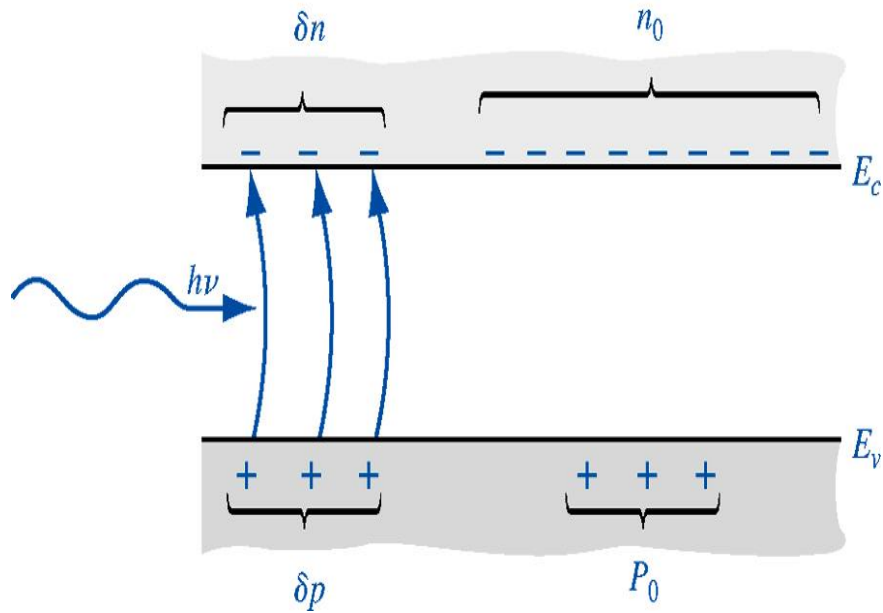
$$g_n' = g_p' \quad (5)$$

When excess electrons are created, the concentration of electrons in the conduction band and of holes in the valence band increase above their thermal equilibrium value

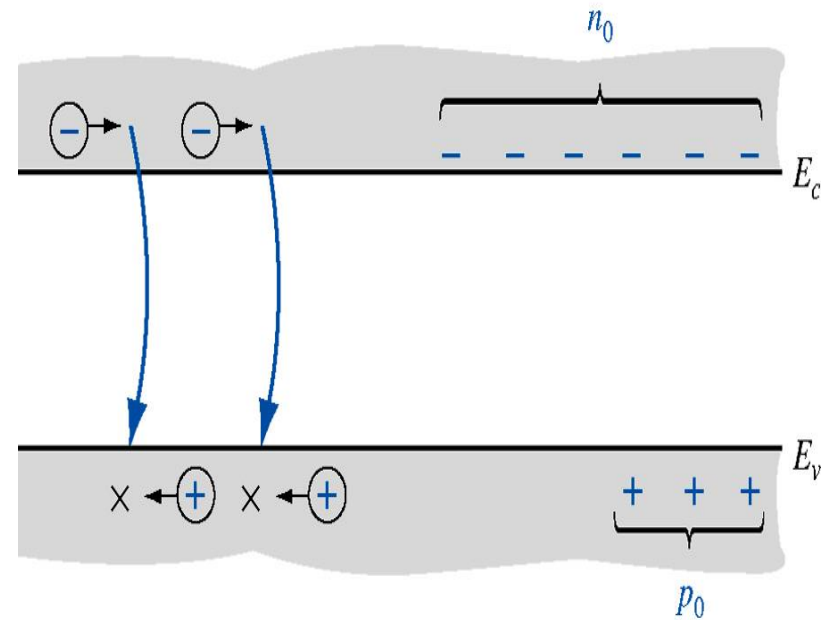
$$\begin{aligned} n &= n_0 + \delta n \\ p &= p_0 + \delta p \end{aligned} \quad (6a,b)$$

where n_0 and p_0 are the thermal-equilibrium concentrations, and δn and δp are the excess electron and hole concentrations, respectively.

Excess Carrier Generation and Recombination



Creation of excess electron and hole densities by photons



Recombination of excess carriers re-establishing thermal equilibrium

Excess Carrier Recombination

The recombination rate for excess electrons is denoted by R_n' and for excess holes by R_p' . The excess electrons and holes recombine in pairs, so recombination rates must be equal

$$R_n' = R_p' \quad (7)$$

In the direct band-to-band recombination, the recombination occurs spontaneously; thus 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.

The net rate of change in the electron concentration can be written as

$$\frac{dn(t)}{dt} = \alpha_r [n_i^2 - n(t)p(t)] \quad (8)$$

where

$$n(t) = n_0 + \delta n(t) \quad (9a,b)$$

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

Excess Electrons and Holes

Since excess electrons and holes are created and recombine in pairs, $\delta n(t) = \delta p(t)$. The thermal-equilibrium parameters, n_0 and p_0 , being independent of time, equation (8) becomes

$$\begin{aligned} \frac{d(\delta n(t))}{dt} &= \alpha_r \left[n_i^2 - (n_0 + \delta n(t))(p_0 + \delta p(t)) \right] = \\ &= -\alpha_r \delta n(t) [(n_0 + p_0) + \delta n(t)] \end{aligned} \quad (10)$$

Equation (10) can easily be solved if we impose the condition of *low-level injection*. Low-level injection puts limits on the magnitude of the excess carrier concentration compared with the thermal-equilibrium carrier concentrations. Low-level injection means that the excess carrier concentration becomes much less than the thermal-equilibrium majority carrier concentrations.

If we consider a *p*-type material ($p_0 \gg n_0$) under low-level injection ($\delta n(t) \ll p_0$), then equation (10) becomes

$$\frac{d(\delta n(t))}{dt} = -\alpha_r p_0 \delta n(t) \quad (11)$$

Excess Minority Carrier Lifetime

The solution to the equation (11) is an exponential decay from the initial concentration, or

$$\delta n(t) = \delta n(0)e^{-\alpha_r p_0 t} = \delta n(0)e^{-t/\tau_{n0}} \quad (12)$$

where $\tau_{n0} = (\alpha_r p_0)^{-1}$ and is a constant for the low-level injection. Equation (12) describes the decay of excess minority carrier electrons so that τ_{n0} is often referred to as the *excess minority-carrier lifetime*.

Recombination Rates

The recombination rate of excess minority-carrier electrons can be written, using equation (11), as

$$R_n' = \frac{-d(\delta n(t))}{dt} = +\alpha_r p_0 \delta n(t) = \frac{\delta n(t)}{\tau_{n0}} \quad (13)$$

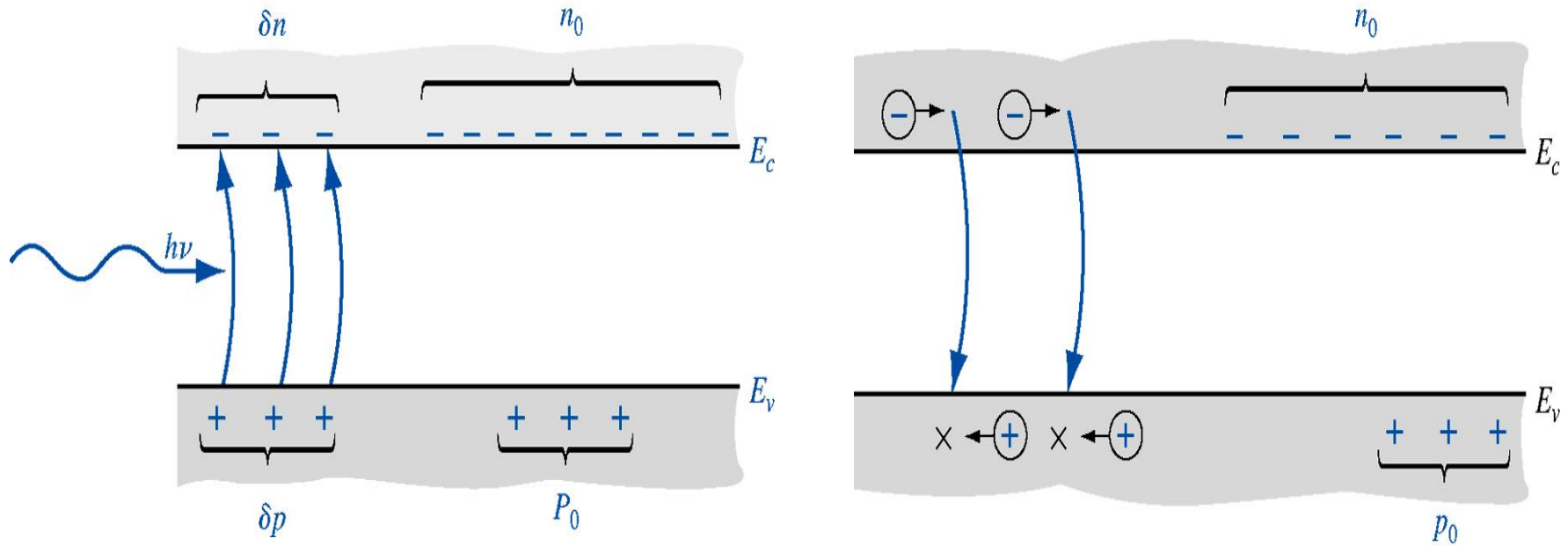
For the direct band-to-band recombination, the excess majority-carrier holes recombine at the same rate, so that for the p -type material:

$$R_n' = R_p' = \frac{\delta n(t)}{\tau_{n0}} \quad (14)$$

In the case of an n -type material ($n_0 \gg p_0$) under low-level injection ($\delta n(t) \ll n_0$), the decay of minority carrier holes occurs with a time constant $\tau_{p0} = (\alpha_r n_0)^{-1}$, where τ_{p0} is also referred to as the excess minority-carrier lifetime. The recombination rate of the majority-carrier electrons will be the same as that of the minority-carrier holes, so we have

$$R_n' = R_p' = \frac{\delta n(t)}{\tau_{p0}} \quad (15)$$

Band-to-Band Generation and Recombination



Recombination- Generation Centres

Lattice defects or impurity atoms result in allowed electronic states within the bandgap and serve as “stepping stones” in the recombination-generation process.

Recombination: an electron is trapped in a trapping centre, and then a hole is trapped; or a hole is trapped and then an electron is trapped; or an electron is trapped and then the electron falls into an empty state.

Generation: an electron is elevated from the valence band into the trap creating a free hole and then the electron is elevated into the conduction band creating a free electron.

This is a predominate process in silicon.

Auger Recombination

Auger recombination is a recombination between an electron and hole, accompanied by the transfer of energy to another free hole. Similarly, a recombination between an electron and hole can result in the transfer of energy to a free electron. The third particle will eventually lose its energy to the lattice in the form of heat.

The process involving two holes and an electron would occur predominantly in heavily doped p -type materials, and the process involving two electrons and a hole would occur predominantly in a heavily doped n -type material.

Momentum Considerations

When electrons and holes recombine, energy is released. The form of the energy that is released depends on whether the semiconductor is a direct or indirect bandgap material.

During any electron-hole interaction, both energy and momentum must be conserved.

Direct bandgap semiconductor – recombination with no change in momentum – emission of a photon

Indirect bandgap semiconductor- a change in momentum is required interaction with the crystal lattice – absorption of heat in the lattice with only a small amount of photon emission