5. Imperfections in Crystals – Generation and Recombination

Although the preceding derivation of the diode equation proceeded under the title "The forward-biased *pn*-junction", nothing in the assumptions and algebraic manipulations restricted the sign of the applied voltage.

If a negative bias is applied to the junction, the minority carrier concentrations at the junction edges will decrease with respect to thermal equilibrium and reverse the concentration gradient.

Setting a reverse voltage $V >> k_B T$ in the diode equation yields

$$J = -J_0$$

where

$$J_0 = q_e n_i^2 \left(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p} \right)$$

In this ideal case the diode current at large reverse bias voltage would be determined by the

- doping concentrations,
- diffusion constants and
- recombination lengths.

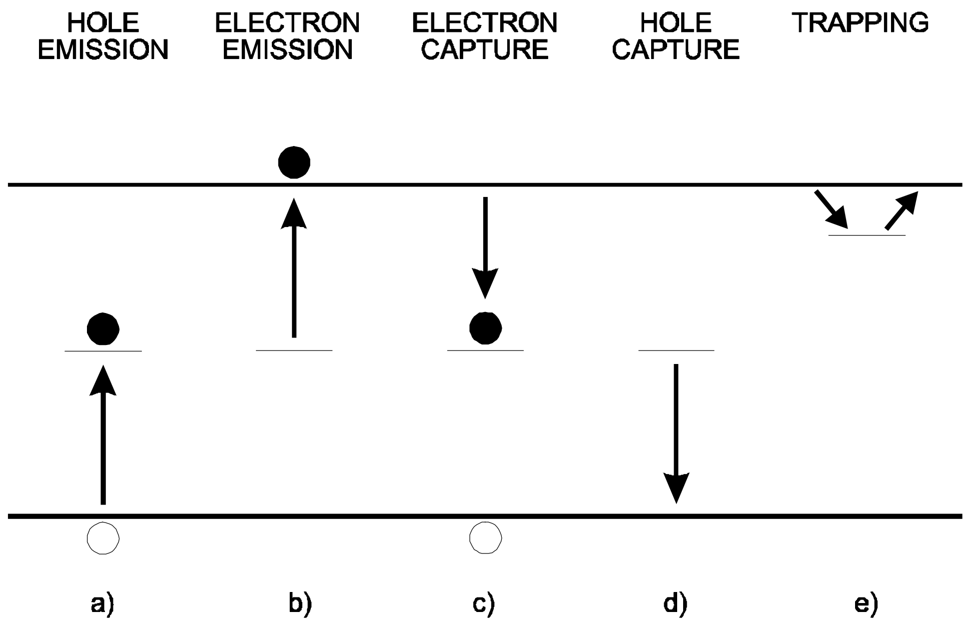
In reality, the measured currents are often orders of magnitude larger.

Whereas the diode equation predicts the saturation of the reverse diode current at voltages greater than order 100 mV (~ 4 $k_B T$), one frequently observes a monotonically increasing current, which increases linearly with depletion width.

This implies the presence of imperfections in the crystal that increase the reverse leakage current. For a uniform distribution of imperfections, the number of active sites will increase with the depletion volume.

Consider imperfections that introduce energy states into the forbidden gap.

These states can introduce the following processes, where the arrows represent electron transitions:



Hole Emission

The process of hole emission from a defect can also be viewed as promoting an electron from the valence band to the defect level, as shown in a).

Electron Emission

In a second step (b) this electron can proceed to the conduction band and contribute to current flow, generation current.

Electron Capture

Conversely, a defect state can capture an electron from the conduction band (c), which in turn can capture a hole (d). This “recombination” process reduces current flowing in the conduction band.

Trapping

Defect levels close to a band edge will capture charge and release it after some time, a process called “trapping” (e).

All of these processes are governed by Fermi statistics (or the Boltzmann approximation), as discussed previously.

Assume a concentration of centers N_t whose energy level E_t lies within the band gap.

The probability of a center being occupied is

$$f = \frac{1}{1 + e^{(E_t - E_F)/k_B T}}$$

so the concentration of vacant centers is

$$N_{t0} = N_t (1 - f)$$

a) Electron Capture

The rate of electron capture is proportional to the concentration of unoccupied centers

$$\frac{dN_{nc}}{dt} = v_{th} \sigma_n n N_{t0} = v_{th} \sigma_n n N_t (1 - f)$$

where v_{th} is the thermal velocity of an electron (about 10^7 cm/s at 300K), σ_n is the capture cross section and n is the concentration of electrons in the conduction band.

The velocity enters because the capture centers are localized and an electron has to move near the center to be captured.

b) Electron Emission

The rate of electron emission is proportional to the concentration of occupied centers $N_{nc}=N_t f$. If the emission probability is e_n, the rate of electron emission is

$$\frac{dN_{ne}}{dt}=e_n N_t f$$

c) Hole Capture and Emission

The rates of hole capture and emission can be expressed analogously to electrons. The rate of hole capture

$$\frac{dN_{pc}}{dt}=v_{th}\sigma_p p N_t f$$

since hole capture corresponds to the transition of an electron from the center to the valence band, this process is proportional to the concentration of centers occupied by electrons $N_t f$.

The rate of hole emission is proportional to the concentration of centers not occupied by electrons $N_t(1 - f)$.

$$\frac{dN_{pe}}{dt}=e_p N_t (1-f)$$

d) Emission Probabilities

In equilibrium, the rates of the two processes that move electrons to and from the conduction band, capture and emission, must be equal.

This seemingly trivial statement reflects a more profound principle of statistical mechanics, that of detailed balance, which states that under equilibrium conditions every process and its reverse must proceed at exactly equal rates.

Thus, for electrons and holes, respectively,

$$v_{th}\sigma_n n N_t (1-f) = e_n N_t f$$
$$v_{th}\sigma_p p N_t f = e_p N_t (1-f)$$

From this, the emission probability for electrons

$$e_n = v_{th}\sigma_n n \frac{1-f}{f}$$

Since the concentration of electrons in the conduction band

$$n = n_i e^{(E_F - E_i)/k_B T} = N_c e^{-(E_c - E_F)/k_B T}$$

and

$$f = \frac{1}{1+e^{(E_t - E_F)/k_B T}} \quad \Rightarrow \quad \frac{1-f}{f} = \frac{1}{f} - 1 = e^{(E_t - E_F)/k_B T}$$

the emission probability

$$e_n = v_{th}\sigma_n n_i e^{(E_t - E_i)/k_B T} = v_{th}\sigma_n N_c e^{(E_c - E_i)/k_B T}$$

Similarly, the emission probability of holes

$$e_p = v_{th}\sigma_p n_i e^{(E_i - E_t)/k_B T} = v_{th}\sigma_n N_v e^{(E_t - E_v)/k_B T}$$

As intuitively expected, the emission probability grows exponentially as the energy level of the center approaches the band edge.

5.1 Recombination

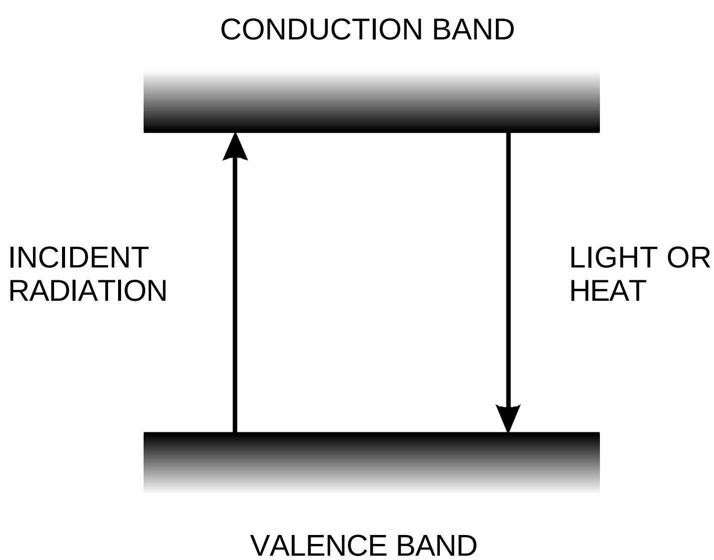
Recombination is important in detectors since it incurs a loss of signal charge.

a) Band-to-Band Recombination

Incident radiation excites electrons from the valence to the conduction band, forming an electron-hole pair.

The simplest recombination mechanism would be for electrons in the conduction band to recombine with holes in the valence band.

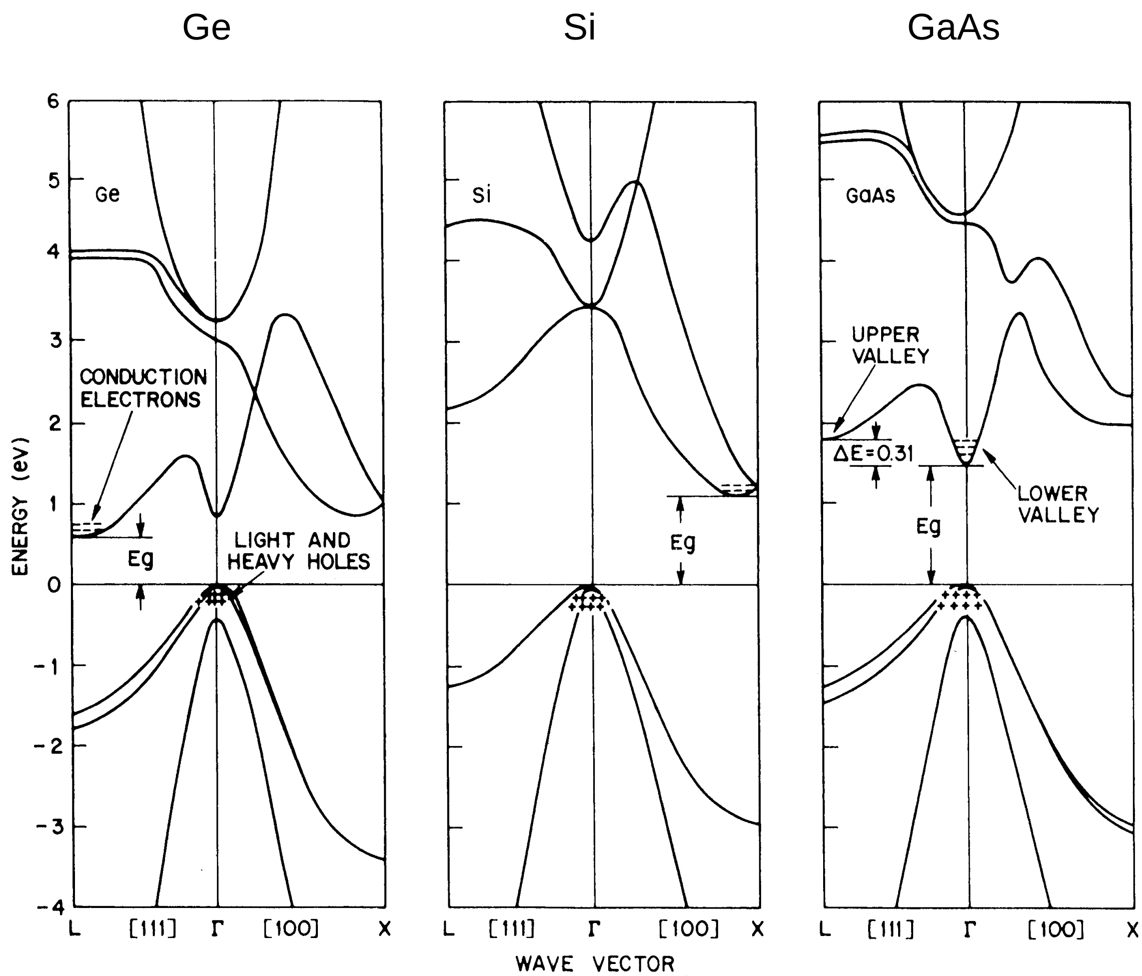
The energy released in the recombination could be emitted as light or converted into heat.



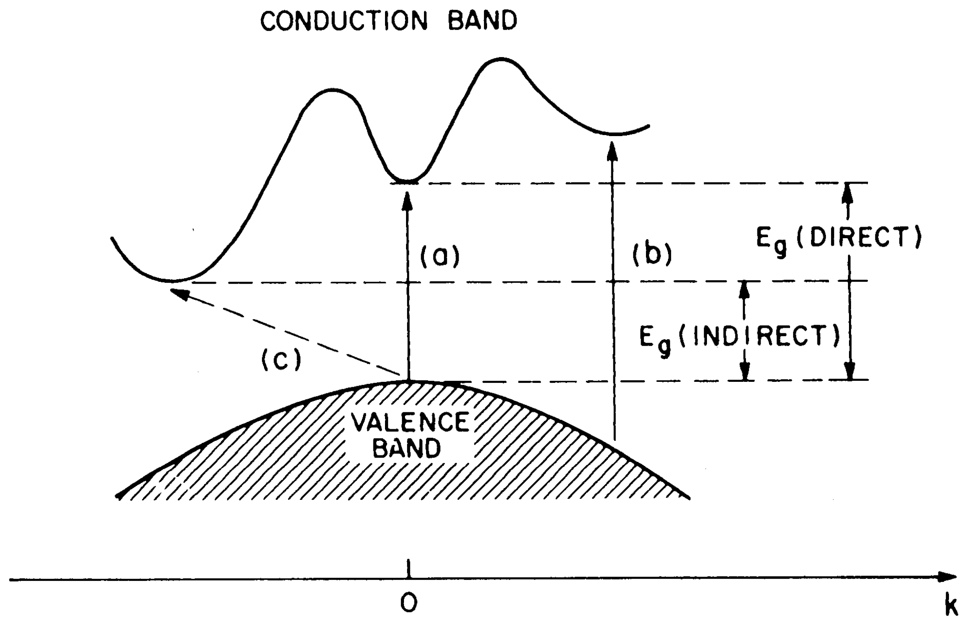
Direct transitions from the conduction to the valence band in Si or Ge are extremely improbable.

Si and Ge are “indirect bandgap” semiconductors, i.e. the minimum of the conduction band and the maximum of the valence band are offset in wavevector k, i.e. momentum.

Band Structure in Ge, Si and GaAs vs. Wavevector and Orientation



(from Sze, after Chelikowsky and Cohen)



(from Sze)

Direct transitions are possible, but only at larger bandgaps with exponentially lower population densities.

Indirect transitions can be facilitated by intermediate states that provide “stepping stones” for electrons and holes traversing the forbidden band.

b) Recombination via Intermediate States

Consider a steady flux of radiation, for example light, leading to a uniform generation rate per unit volume G_L.

To determine the effectiveness of centers as recombination sites, the charge due to the radiation will not be removed by an external circuit, but allowed to decay by recombination alone.

In the steady state the rate at which electrons enter the conduction band must equal the rate at which they leave it.

$$\frac{dn_n}{dt} = G_L - \left(\frac{dN_{nc}}{dt} - \frac{dN_{ne}}{dt} \right) = 0$$

Similarly, for the holes

$$\frac{dn_p}{dt} = G_L - \left(\frac{dN_{pc}}{dt} - \frac{dN_{pe}}{dt} \right) = 0$$

Incident radiation takes the system out of thermal equilibrium, so none of the equilibrium carrier concentrations are valid, nor is the occupancy determined by the Fermi distribution.

Instead, the concentrations n and p and the fractional occupancy f depend on the radiation flux G_L.

By equating G_L from the two expressions above

$$\left(\frac{dN_{pc}}{dt}-\frac{dN_{pe}}{dt}\right)=\left(\frac{dN_{nc}}{dt}-\frac{dN_{ne}}{dt}\right)$$

$$v_{th}\sigma_p pN_t f - e_p N_t (1-f) = v_{th}\sigma_n nN_t (1-f) - e_n N_t f$$

and inserting the emission probabilities calculated above one can extract the steady state fractional occupancy

$$f = \frac{\sigma_n n + \sigma_p n_i e^{(E_i - E_t)/k_B T}}{\sigma_n (n + n_i e^{(E_t - E_i)/k_B T}) + \sigma_p (p + n_i e^{(E_i - E_t)/k_B T})}$$

This occupancy depends implicitly on the generation flux G_L , which determines n and p.

Electrons are continuously captured and emitted by the center, and so are holes.

If an electron and a hole recombine, this leads to a deficit in the emission rates of both electrons and holes.

In the steady-state the emission deficit for electrons and holes must be equal, so the net rate of recombination is the capture rate minus the emission rate

$$\frac{dN_R}{dt}=\left(\frac{dN_{nc}}{dt}-\frac{dN_{ne}}{dt}\right)=\left(\frac{dN_{pc}}{dt}-\frac{dN_{pe}}{dt}\right)$$

This is the same expression as above, so one can determine the recombination rate by inserting the steady state fractional occupancy into either side of the above expression.

$$\frac{dN_R}{dt} = \frac{\sigma_p \sigma_n v_{th} N_t (pn - n_i^2)}{\sigma_n (n + n_i e^{(E_t - E_i)/k_B T}) + \sigma_p (p + n_i e^{(E_i - E_t)/k_B T})}$$

To simplify the equation and facilitate its interpretation, assume (somewhat arbitrarily) that the capture cross sections σ_n and σ_p are equal. Then

$$\frac{dN_R}{dt} = \sigma v_{th} N_t \frac{pn - n_i^2}{n + p + 2n_i (e^{(E_t - E_i)/k_B T} + e^{-(E_t - E_i)/k_B T})}$$

From this expression one can see that the driving force of the the recombination process is the excess carrier concentration pn beyond the equilibrium concentration n_i^2.

The third term in the denominator describes the relative occupancies of electrons and holes.

A center close to the conduction band will have a higher occupancy of electrons than holes, so the recombination rate is limited by the hole population.

Conversely, a center close to the valence band will have a excess of holes, so the population of electrons limits the recombination rate.

The recombination rate is maximum when $E_t = E_i$, i.e. when the energy of the recombination center is at mid-gap.

A special case of recombination is minority carrier injection.

Consider holes injected into an *n*-type region, as in a forward biased diode.

In this case

$$n_n >> p_n$$

Furthermore, since efficient recombination centers are far from the band-edge, the Boltzmann approximation holds, so the equilibrium electron concentration

$$n_n >> n_i e^{(E_t - E_i)/k_B T}$$

Then the above expression for the recombination rate simplifies to

$$\frac{dN_R}{dt} = \frac{\sigma_p \sigma_n v_{th} N_t (n_n p_n - n_i^2)}{\sigma_n n_n} = \sigma_p v_{th} N_t (p_n - p_{n0})$$

Expressed as a lifetime

$$\frac{dN_R}{dt} = \frac{p - p_{n0}}{\tau_p}$$

so the lifetime

$$\tau_p = \frac{1}{\sigma_p v_{th} N_t}$$

The lifetime of the holes in the *n*-bulk is independent of the concentration of the electrons.

This is due to an abundance of electrons, so as soon as a hole is captured, an electron is available for immediate recombination. Hence, the hole concentration is the rate-limiting parameter.

Conversely, if electrons are injected into n-type material where they are majority carriers, their lifetime will be significantly greater, since few holes are available for recombination.

Minority carrier injection is the worst case with respect to recombination, so “minority carrier lifetime” is a figure of merit used to characterize the presence of defects in semiconductors.

Recombination is important whenever the carrier concentration deviates from thermal equilibrium

$$pn > n_i^2$$

This occurs

a) with incident radiation

b) in a forward biased diode

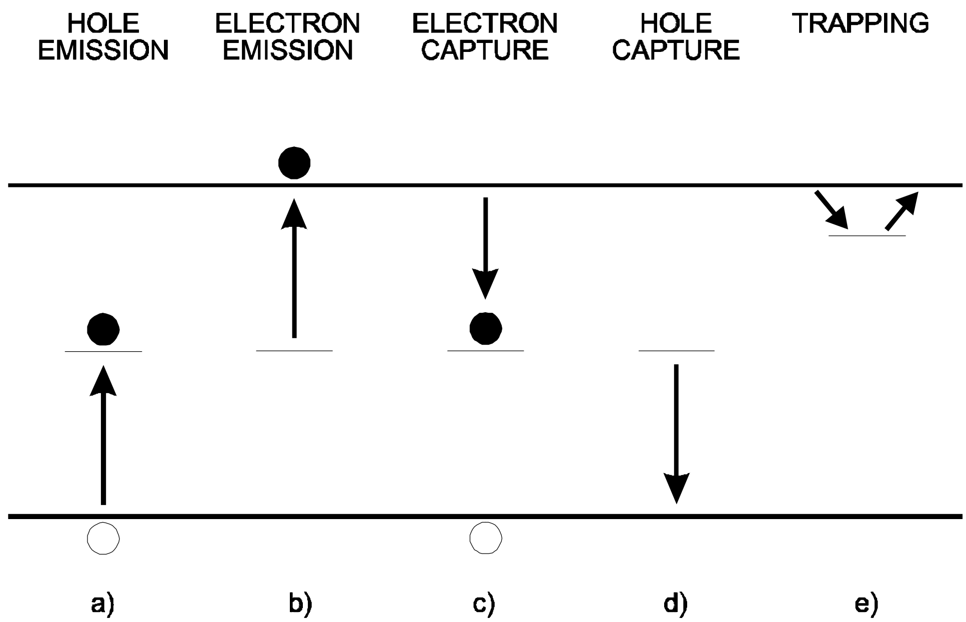
5.2 Carrier Generation

a) Generation in the depletion region

In a diode operated with reverse bias, e.g. a radiation detector, with

$$V_R >> \frac{k_B T}{q_e}$$

all of the free carriers are swept from the depletion region, so there are no free carriers available for capture and recombination.



In this configuration only emission processes are important.

Emission, in the absence of capture, can only proceed by alternating hole and electron emission, i.e. generation of electron-hole pairs.

The rate of generation of electron-hole pairs can be determined from the previously derived expression for the difference between capture and emission rates

$$\frac{dN_c}{dt} - \frac{dN_e}{dt} = \frac{\sigma_p \sigma_n v_{th} N_t (pn - n_i^2)}{\sigma_n (n + n_i e^{(E_t - E_i)/k_B T}) + \sigma_p (p + n_i e^{(E_i - E_t)/k_B T})}$$

Since $dN_c/dt = 0$ and $p \ll n_i$, $n \ll n_i$

$$\frac{dN_e}{dt} = \frac{\sigma_p \sigma_n v_{th} N_t n_i}{\sigma_n e^{(E_t - E_i)/k_B T} + \sigma_p e^{(E_i - E_t)/k_B T}}$$

This is often written as

$$\frac{dN_e}{dt} \equiv \frac{n_i}{2\tau_g}$$

where τ_g is called the generation lifetime.

Again consider the simplification of equal cross sections $\sigma_p = \sigma_n = \sigma$. Then the generation rate becomes

$$\frac{dN_e}{dt} = \frac{\sigma v_{th} N_t n_i}{e^{(E_i - E_t)/k_B T} + e^{-(E_i - E_t)/k_B T}}$$

which again shows that only states near the intrinsic Fermi level E_i, i.e. mid-gap states, contribute significantly to the generation rate

Intuitively, this is easy to see in the “stepping stone” picture. Since the emission probabilities for electrons and holes increase exponentially with the separation from their respective band edges, the probability for sequential hole and electron emission is maximum at mid-gap.

The emission rate of carriers leads to an electrical current, the generation current, which increases with the density of centers.

If the emission centers are distributed uniformly throughout the depletion width W, the generation current density

$$J_{gen} = q_e \frac{dN_e}{dt} W = q_e W \frac{\sigma v_{th} N_t n_i}{e^{(E_i - E_t)/k_B T} + e^{-(E_i - E_t)/k_B T}}$$

b) Generation in the neutral region

In the neutral region the absence of a significant electric field means that any excess carriers due to generation move only by diffusion,

Charges generated near the transition to the depletion region can reach the influence of the electric field and will be swept to the opposite electrode.

This additional contribution to the reverse diode current is called the diffusion current.

The starting point of the calculation is the steady-state diffusion equation for minority carriers. Consider electrons generated in the p-region.

$$D_n \frac{d^2 n_p}{dx^2} - \frac{n_p - n_{p0}}{\tau_n} = 0$$

Far from the space charge region the carrier concentration attains the thermal equilibrium value

$$n_p(\infty) = n_{p0}$$

At the edge of the depletion region all carriers will be swept away by the electric field, so

$$n_p(0) = 0$$

The solution of the diffusion equation for these boundary conditions is

$$n_p(x) = n_{p0}(1 - e^{-x/L_n})$$

where

$$L_n \equiv \sqrt{D_n \tau_n}$$

is the diffusion length of electrons in the p-region.

This gives rise to an electrical current

$$J_{diff,n} = -q_e \left(-D_n \left. \frac{dn_p}{dx} \right|_{x=0} \right) = q_e D_n \frac{n_{p0}}{L_n} = q_e \frac{D_n}{L_n} \frac{n_i^2}{N_A}$$

Similarly, for holes in the n-region

$$J_{diff,p} = q_e D_p \frac{p_{n0}}{L_p} = q_e \frac{D_p}{L_p} \frac{n_i^2}{N_D}$$

The diffusion current increases with the square of the intrinsic carrier concentration, in contrast to the generation current in the depletion zone, which increases linearly with n_i.

The generation rate in a neutral region depleted of minority carriers can be drastically different from the depletion region.

For simplicity, assume that the diffusion lifetime is equal to the generation lifetime.

Then the ratio of the two generation currents

$$\frac{J_{diff,n}}{J_{gen}} = \frac{\frac{n_{p0}}{\tau} L_n}{\frac{n_i}{2\tau} W} = 2\frac{n_{p0}}{n_i}\frac{L_n}{W} = 2\frac{n_i}{N_A}\frac{L_n}{W}$$

In an *n*-bulk Si radiation detector with a thin *p*-electrode, the diffusion length is limited by the electrode thickness, i.e. ~ 1 μm.

For $n_i \approx 10^{10}$, $N_A \approx 10^{15}$ and $W \approx$ 300 μm

$$\frac{J_{diff,n}}{J_{gen}} \approx 3 \cdot 10^{-8}$$

In high quality radiation detectors the generation current dominates.

By contrast, in a symmetrical Ge small signal rectifier diode with $L_n \approx$ 100 μm, $W \approx$ 1 μm, $n_i \approx 10^{13}$, and $N_A \approx 10^{15}$

$$\frac{J_{diff,n}}{J_{gen}} \approx 2$$

At higher temperatures the exponential increase in n_i can increase the diffusion current so much that the generation current is negligible.

5.3 The origin of recombination and generation centers

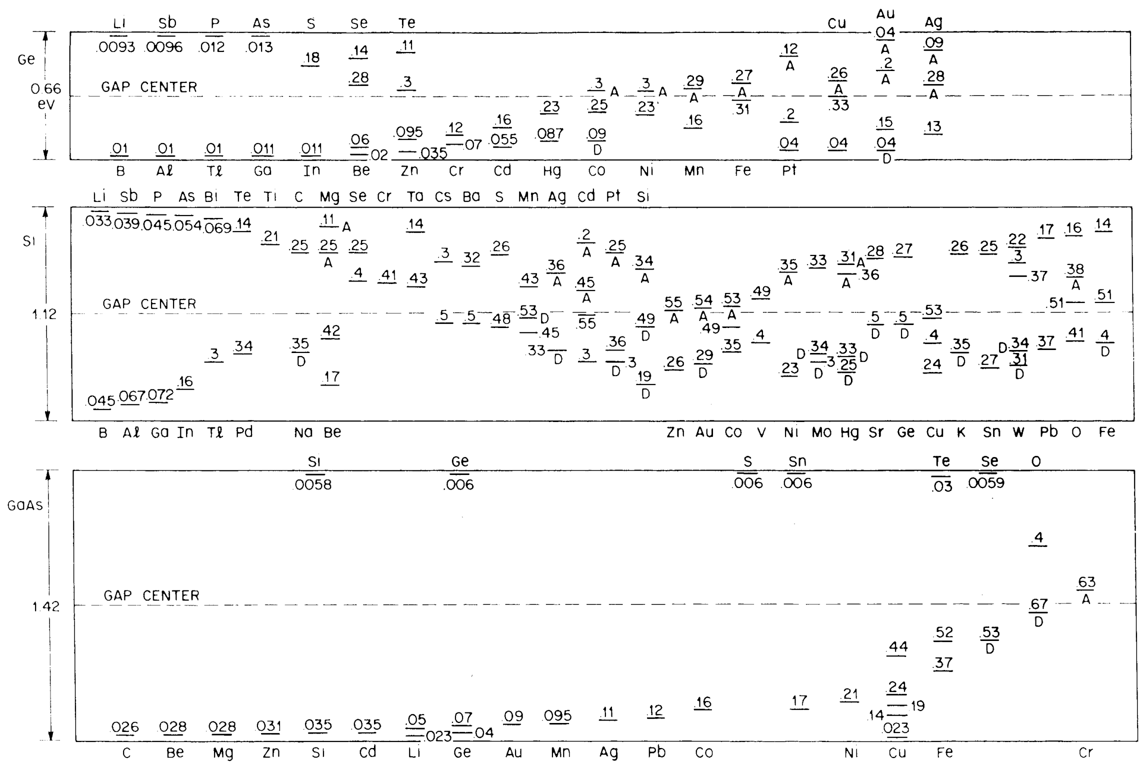
Recombination and generation centers can be introduced by

a) impurity atoms

b) structural imperfections

c) radiation damage (displacement of atoms from lattice sites)

Impurity levels in Ge, Si, and GaAs



(from Sze)

Mn, Cd, Zn, Au, Co, V and Fe are effective “lifetime killers” in Si.
Au is commonly introduced intentionally in devices where short liftetimes are desirable (fast switching diodes, transistors).

All three defect mechanisms can create states distributed throughout the band-gap

Since only mid-gap states can contribute significantly to generation and recombination, in a continuum of states statistics automatically select the states near mid-gap.

GaAs appears favorable, since relatively few impurity states are near mid-gap.

However, a structural defect tends to dominate:

The “anti-site” defect, where a Ga atom occupies an As site (or vice versa), introduces a mid-gap state that effectively pins the Fermi level at mid-gap.

This is why GaAs commonly appears intrinsic, or “semi-insulating”, so that large depletion widths can be obtained with small reverse bias voltages.

Unfortunately, recombination is also high, although acceptable for thin (~10^2 μm) detectors.

6. The Diode Equation Revisited

a) Reverse Current

Both the generation and diffusion currents invariably override the ideal reverse saturation current

$$J_0 = q_e n_i^2 \left(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p} \right) << J_{diff} + J_{gen} \,,$$

so the diode equation becomes

$$J = J_R (e^{q_e V / k_B T} - 1)$$

where the reverse current J_R for voltages > $3k_B T/q_e$ is the sum of the diffusion and generation currents

$$J_R = q_e n_i^2 \left(\frac{1}{N_A} \sqrt{\frac{D_n}{\tau_n}} + \frac{1}{N_D} \sqrt{\frac{D_p}{\tau_p}} \right) + q_e \frac{n_i}{2\tau_g} W$$

Whether the generation or diffusion current dominate can be determined from the temperature coefficient. Since the diffusion current scales with n_i^2,

$$\frac{dJ_R}{dT} = J_R \frac{E_g}{k_B T^2}$$

whereas the generation current scales with n_i, so that

$$\frac{dJ_R}{dT} = J_R \frac{E_g}{2k_B T^2}$$

In practice, a plot of log J_R vs. $1/k_B T$ will yield a slope of $-E_g$ for diffusion and $-E_g/2$ for generation dominated operation.
At sufficiently high temperatures diffusion will always dominate.

b) Forward Current

Recombination in the depletion region also affects the forward diode characteristic.

Experimental results can generally be described by introducing an "ideality factor" n

$$J = J_R (e^{q_e V / n k_B T} - 1)$$

where $n = 2$ when the recombination current dominates and $n = 1$ when the current is dominated by diffusion in the neutral regions.

At very low currents the generation currents dominate.

Since these currents are opposite to the forward injection current, one observes a change of sign in the current flow at low voltage.

c) Comments

In radiation detectors the reverse current is of primary interest, as it is a source of shot noise.

Nevertheless, the forward current-voltage characteristic can provide useful diagnostic information.

Since recombination and generation are both maximized for mid-gap states, one commonly observes that devices with large generation currents also exhibit high recombination rates.

This has promoted a tendency to characterize both phenomena by one parameter, the minority carrier lifetime.

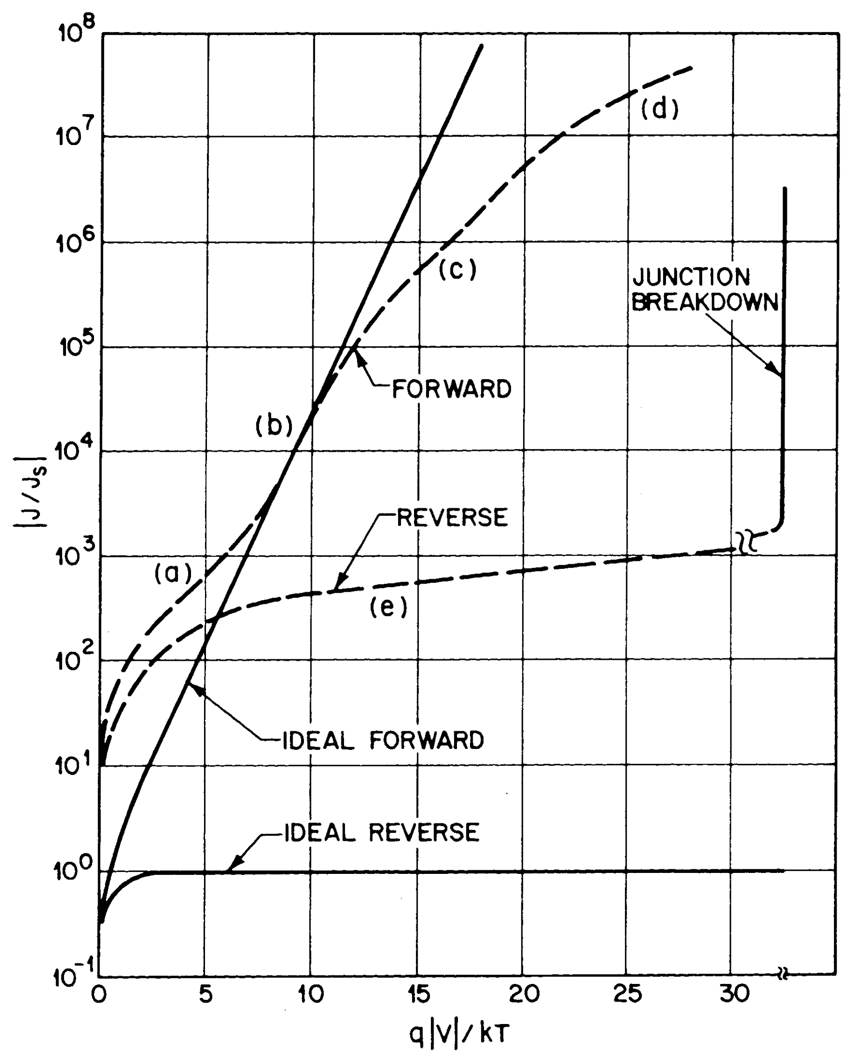
Generation and recombination are two distinct phenomena.

- Their temperature dependences differ.
- It is not at all assured that a state is equally effective at generation as it is at recombination.

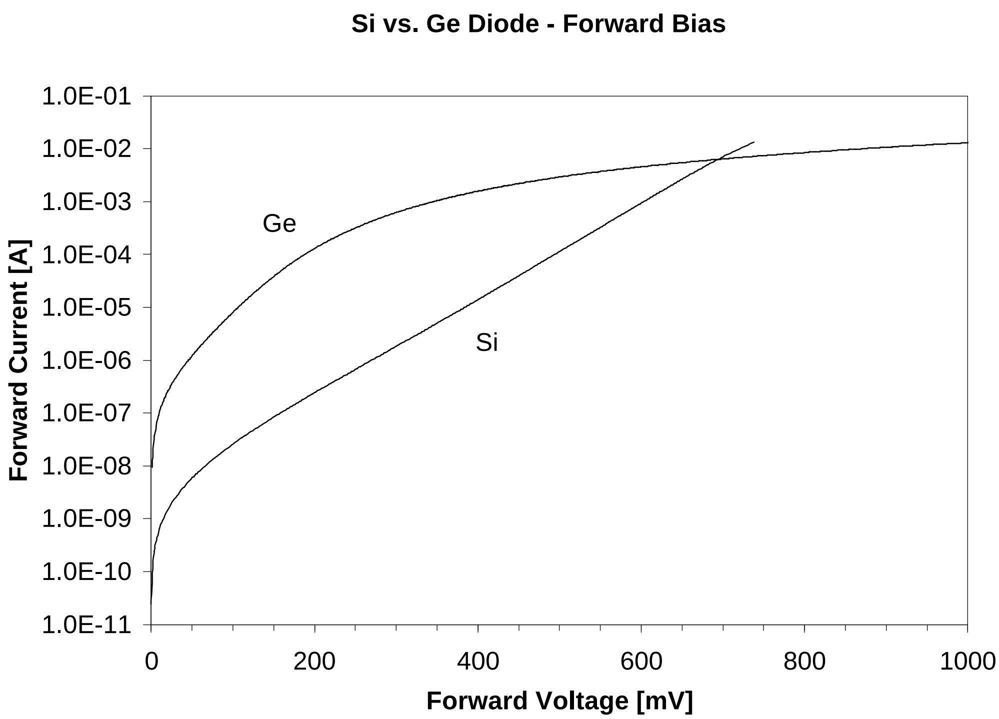
The characteristics of practical diodes are summarized in the figure below. The following phenomena are observed in the forward current:

a) generation- recombination in the depletion region
b) diffusion current (as just calculated for the ideal diode)
c) high-injection region where the injected carrier concentration affects the potentials in the neutral regions
d) voltage drop due to bulk series resistance

The reverse current is increased by generation-diffusion from the neutral region at low currents and then by generation currents in the depletion zone.



Some of these effects can be recognized in the measured data for common Ge and Si diodes shown previously.



Defects due to Radiation Damage

An incident particle or photon capable of imparting an energy of about 20 eV to a silicon atom can dislodge it from its lattice site.

Displacement damage creates defect clusters.

For example, a 1 MeV neutron transfers about 60 to 70 keV to the Si recoil atom, which in turn displaces roughly 1000 additional atoms in a region of about 0.1 μm size.

Displacement damage is proportional to non-ionizing energy loss, which is not proportional to the total energy absorbed, but depends on the particle type and energy.

X-rays do not cause direct displacement damage, since momentum conservation sets a threshold energy of 250 keV for photons.

^{60}Co γ rays cause displacement damage primarily through Compton electrons and are about three orders of magnitude less damaging per photon than a 1 MeV neutron.

Relative displacement damage for various particles and energies:

Particle	**proton**	**proton**	**neutron**	**electron**	**electron**
Energy	1 GeV	50 MeV	1 MeV	1 MeV	1 GeV
Relative Damage	1	2	2	0.01	0.1

Displacement damage manifests itself in three important ways:

- formation of mid-gap states, which facilitate the transition of electrons from the valence to the conduction band. In depletion regions this leads to a generation current, i.e. an increase in the current of reverse-biased pn-diodes. In forward biased junctions or non-depleted regions mid-gap states facilitate recombination, i.e. charge loss.

- states close to the band edges facilitate trapping, where charge is captured and released after a certain time.

- a change in doping characteristics (donor or acceptor density).

1. Increase in reverse bias current

The bias current after irradiation has been shown to be

$$I_R = I_0 + \alpha \cdot \Phi \cdot Ad$$

where I_0 is the bias current before irradiation, α is a damage coefficient dependent on particle type and fluence, Φ is the particle fluence, and the product of detector area and thickness Ad is the detector volume.

For 650 MeV protons $\alpha \approx 3 \cdot 10^{-17}$ A/cm

1 MeV neutrons $\alpha \approx 2 \cdot 10^{-17}$ A/cm.
(characteristic of the albedo emanating from a calorimeter)

The parametrization used is quite general, as it merely assumes a spatially uniform formation of electrically active defects in the detector volume, without depending on the details of energy levels or states.

The coefficients given above apply to room temperature operation. The reverse bias current of silicon detectors depends strongly on temperature.

Even after rather low fluences the generation current dominates, so the reverse bias current

$$I_R(T) \propto v_{th} n_i \propto v_{th} \sqrt{N_c N_v}\, e^{-E/2k_B T} \propto T^2 e^{-E/2k_B T}$$

The effective activation energy E= 1.2 eV for radiation damaged samples, whereas unirradiated samples usually exhibit E= 1.15 eV.

The ratio of currents at two temperatures T_1 and T_2 is

$$\frac{I_R(T_2)}{I_R(T_1)} = \left(\frac{T_2}{T_1} \right)^2 \exp\left[-\frac{E}{2k_B} \left(\frac{T_1 - T_2}{T_1 T_2} \right) \right]$$

Cooling to 0 °C typically reduces the reverse bias current to 1/6 of its value at room temperature.

After irradiation the leakage current initially decreases with time. Pronounced short term and long term annealing components are observed and precise fits to the annealing curve require a sum of exponentials.

In practice, the variation of leakage current with temperature is very reproducible from device to device, even after substantial doping changes due to radiation damage. The leakage current can be used for dosimetry and diodes are offered commercially specifically for this purpose.

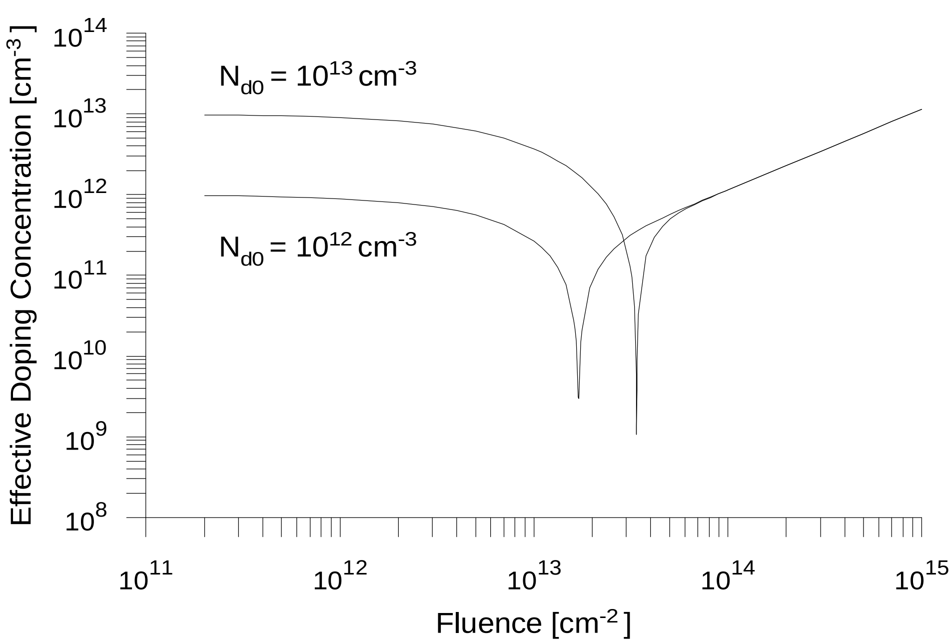
2. Changes in Effective Doping

The processes leading to a change in effective doping are extremely complex and poorly understood, so the results are only summarized briefly.

It has been observed by many groups that the doping of n-type silicon initially decreases, becomes intrinsic (i.e. undoped) and then turns p-like, with the doping density increasing with fluence.

> This phenomenon is consistent with the notion that acceptor sites are formed by the irradiation, although this does not mean that mobile holes are created. Instead, the electrons captured by the acceptor states build up a space charge that requires an external field for signal charges to move.

Initially, the effective doping level $N_d - N_a$ decreases as new acceptor states neutralize original donor states. At some fluence the two balance, creating "intrinsic" material, and beyond this fluence the acceptor states dominate.



Type inversion from n- to p-type silicon typically occurs at a fluence of about 10^{13} cm^{-2}.

Very high resistivity silicon (ρ >10 kΩcm or $N_d < 4 \cdot 10^{11}$ cm^{-3}) is often highly compensated, $N_{eff} = N_d - N_a$ with $N_d \sim N_a >> N_{eff}$, so that minute changes to either donors or acceptors can alter the net doping concentration significantly. Moderate resistivity n-type material (ρ = 1 to 5 kΩcm) used in large area tracking detectors is usually dominated by donors.

In addition to acceptor formation, there is evidence for a concurrent process of donor removal.

After defect states are formed by irradiation, their electronic activity changes with time.

A multitude of processes contribute, some leading to beneficial annealing, i.e. a reduction in acceptor-like states, and some increasing the acceptor concentration.

The most deleterious is the increase in effective acceptor concentration, called “anti-annealing”

The relative effect of anti-annealing increases strongly with

- fluence and
- temperature.

Effect of anti-annealing on doping level and depletion voltage:

Fluence [cm^{-2}]	10^{13}	10^{13}	10^{13}	10^{14}	10^{14}	10^{14}
Temperature [°C]	0	20	40	0	20	40
$N_a(t=100\text{h})/N_a(0)$	1.00	1.02	1.39	1.01	1.21	4.71
$V_{depl}(t=100\text{h})/V_{depl}(0)$	1.00	1.04	1.92	1.02	1.46	22.2

Anti-annealing is a concern because of its effect on detector depletion voltage, i.e. the voltage required to collect charge from the complete thickness of the silicon detector. Since this voltage increases with the square of the doping concentration, antiannealing of 20 to 40% can easily exceed the safe operating range, especially at high fluences.

Clearly, low temperature operation is beneficial. Nevertheless, even a low temperature system will require maintenance at room temperature and warm up periods must be controlled very carefully.

3. Charge loss due to trapping

Data on charge collection efficiency are still rather sketchy. The primary mechanism is expected to be trapping of signal charge at defect sites, i.e. a decrease in carrier lifetime τ.

Since the loss in signal charge is proportional to $exp(-t_c/\tau)$, reducing the collection time t_c mitigates the effect.

Since either the operating voltage is increased or depletion widths are reduced at damage levels where charge trapping is appreciable, fields tend to be higher and collection times decrease automatically with radiation damage, provided the detector can sustain the higher fields.

The lifetime can be described by

$$1/\tau = \gamma \Phi ,$$

where for holes $\gamma_p = 2.7 \cdot 10^{-7}$ cm^{2}s and for electrons $\gamma_e = 1.2 \cdot 10^{-6}$ cm^{2}s for $\Phi > 10^{13}$ cm^{-2} of 1 MeV equivalent neutrons.

For a fluence $\Phi = 5 \cdot 10^{13}$ cm^{-2}s^{-1}, a 400 μm thick detector with a depletion voltage of 130V operated at a bias voltage of 200V would show a decrease in signal charge of 12%.