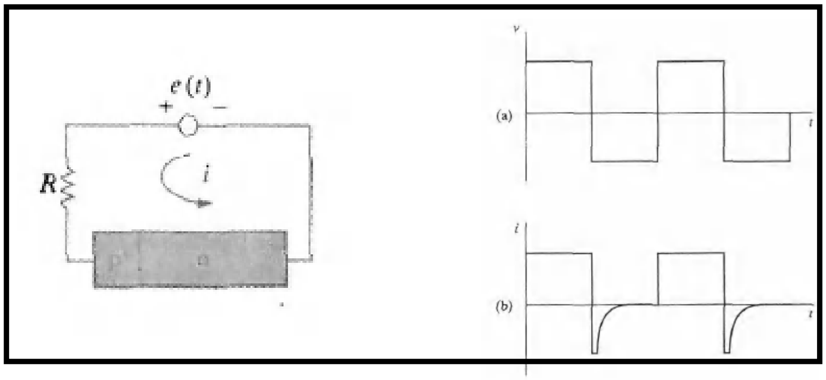
Reverse Recovery Transient:

In most switching applications a diode is switched from forward conduction to a reverse-biased state, and vice versa. The resulting stored charge transient is somewhat more complicated than for a simple turn-off transient. Let us assume a p+-n junction is driven by a square wave generator that periodically switches from $+E$ to $-E$ volt.



If E is much larger than the small forward voltage of the junction, the source voltage appears almost entirely across the resistor, and the current is $i = I_f \approx E/R$. After the generator voltage is reversed, the current must initially reverse approximately to $i = I_r = -E/R$. The reason for this unusually large reverse current through the diode is that the stored charge (and hence the junction voltage) cannot be changed instantaneously. When diode was forward biased, huge number of minority careers (h for n-sde, e for p-side) is diffused. At the moment diode is reverse biased, the excess minority careers start to flow in opposite directions and after small time Δt the reverse saturation current is obtained. So, reverse recovery time is the diode current needs to reach the value of reverse saturation current.

Capacitance of p-n Junctions

There are basically two types of capacitance associated with a junction: (1) the *junction capacitance* due to the dipole in the depletion region and (2) the *charge storage capacitance* arising from the lagging behind of voltage as current. Both of these capacitances are important, and they must be considered in designing p-n junction devices for use with time-varying signals. The junction capacitance (1) is dominant under reverse-bias conditions, and the charge storage capacitance (2) is dominant when the junction is forward biased. In many applications of p-n junctions, the capacitance is a limiting factor in the usefulness of the device; on the other hand, there are important applications in which the capacitance discussed here can be useful in circuit applications and in providing important information about the structure of the p-n junction.

The junction capacitance of a diode is easy to visualize from the charge distribution in the depletion region. The uncompensated acceptor ions on the p side provide a negative charge, and an equal positive charge results from the ionized donors on the n side of the transition region. The capacitance of the resulting dipole is slightly more difficult to calculate than is the usual parallel plate capacitance, but we can obtain it in a few steps.

$$\mathbf{C} = \left|\frac{\mathbf{dQ}}{\mathbf{dV}}\right|$$

The charge *Q* on each side of the transition region varies nonlinearly with the applied voltage.

The depletion width

$$\mathbf{W} = \left[\frac{2\varepsilon V_0}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2} \qquad \textbf{for equilibrium}$$

$$= \left[\frac{2\varepsilon(V_0 - V)}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2} \qquad \textbf{with external bias}$$

$$|Q| = qAx_{n0}N_d = qAx_{p0}N_a$$

$$x_{n0} = \frac{N_a}{N_a + N_d}W \qquad \& \qquad x_{p0} = \frac{N_d}{N_a + N_d}W$$

$$|Q| = qA\frac{N_a N_d}{N_a + N_d}W = A\left[2q\varepsilon(V_0 - V)\frac{N_a N_d}{N_a + N_d}\right]^{1/2}$$

Since the voltage that varies the charge in the transition region is the barrier height (V_0 — V),

$$C = \left|\frac{dQ}{d(V_0 - V)}\right| = \frac{A}{2}\left[\frac{2q\varepsilon}{(V_0 - V)}\frac{N_a N_d}{N_a + N_d}\right]^{1/2} = \varepsilon A\left[\frac{q}{2\varepsilon(V_0 - V)}\frac{N_a N_d}{N_a + N_d}\right]^{1/2} = \frac{\varepsilon A}{W}$$

An abrupt Si p-n junction ($A = 10^{-4}\ \text{cm}^2$) has the following properties at 300 K:

p side	n side
$N_a = 10^{17}\ \text{cm}^{-3}$	$N_d = 10^{15}$
$\tau_n = 0.1\ \mu\text{s}$	$\tau_p = 10\ \mu\text{s}$
$\mu_p = 200\ \text{cm}^2/\text{V-s}$	$\mu_n = 1300$
$\mu_n = 700$	$\mu_p = 450$

The junction is forward biased by 0.5 V. What is the forward current? What is the current at a reverse bias of −0.5 V?

what is the total depletion capacitance

what is the total depletion capacitance at −4 V?

$$I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)$$

$$p_n = \frac{n_i^2}{n_n} = \frac{(1.5 \times 10^{10})^2}{10^{15}} = 2.25 \times 10^5\ \text{cm}^{-3}$$

$$n_p = \frac{n_i^2}{p_p} = \frac{(1.5 \times 10^{10})^2}{10^{17}} = 2.25 \times 10^3\ \text{cm}^{-3}$$

For minority carriers,

$$D_p = \frac{kT}{q}\mu_p = 0.0259 \times 450 = 11.66\ \text{cm}^2/\text{s on the n side}$$

$$D_n = \frac{kT}{q}\mu_n = 0.0259 \times 700 = 18.13\ \text{cm}^2/\text{s on the p side}$$

Note: Consider the parameters for minority careers only (hole for n-side and electron for p side)

$$L_p = \sqrt{D_p\tau_p} = \sqrt{11.66 \times 10 \times 10^{-6}} = 1.08 \times 10^{-2}\ \text{cm}$$

$$L_n = \sqrt{D_n\tau_n} = \sqrt{18.13 \times 0.1 \times 10^{-6}} = 1.35 \times 10^{-3}\ \text{cm}$$

$$I_0 = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)$$

$$= 1.6 \times 10^{-19} \times 0.0001\left(\frac{11.66}{0.0108}2.25 \times 10^5 + \frac{18.13}{0.00135}2.25 \times 10^3\right) = 4.370 \times 10^{-15}\ \text{A}$$

$I = I_0(e^{0.5/0.0259} - 1) \approx \mathbf{1.058 \times 10^{-6}\ A}$ in forward bias.

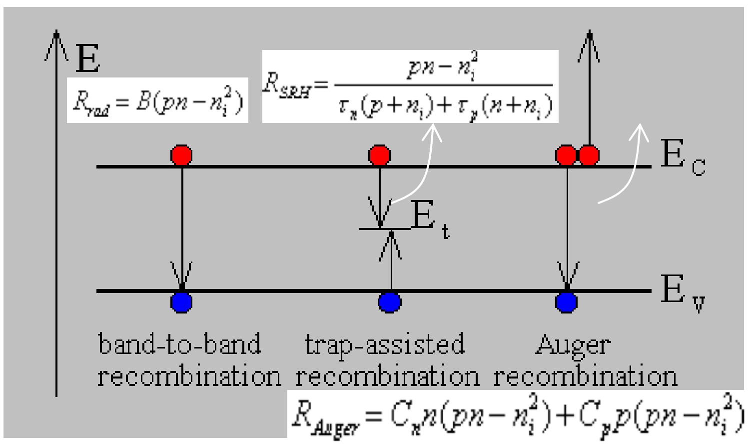
$I = -I_0 = \mathbf{-4.37 \times 10^{-15}\ A}$ in reverse bias.

$$C_j = \sqrt{\epsilon}A\left[\frac{q}{2(V_0 - V)}\frac{N_dN_a}{N_d - N_a}\right]^{1/2}$$

$$= \sqrt{(8.85 \times 10^{-14} \times 11.8)}(10^{-4})\left[\frac{1.6 \times 10^{-19}}{2(0.695 + 4)}\left(\frac{10^{15} \times 10^{17}}{10^{15} + 10^{17}}\right)\right]^{1/2} = \mathbf{4.198 \times 10^{-13}\ F}$$

Recombination in semiconductor:

Recombination of electrons and holes is a process by which both carriers annihilate each other: the electrons fall in one or multiple steps into the empty state which is associated with the hole. Both carriers eventually disappear in the process. The energy difference between the initial and final state of the electron is given off. This leads to one possible classification of the recombination processes: In the case of radiative recombination this energy is emitted in the form of a photon, in the case of non-radiative recombination it is passed on to one or more phonons and in Auger recombination it is given off in the form of kinetic energy to another electron. Another classification scheme considers the individual energy levels and particles involved. These different processes are further illustrated with the figure below.



Carrier recombination mechanisms in semiconductors with corresponding recombination rate

Band-to-band recombination occurs when an electron falls from its state in the conduction band into the empty state in the valence band which is associated with the hole. This band-to-band transition is typically also a radiative transition in direct bandgap semiconductors.

Trap-assisted recombination occurs when an electron falls into a "trap", an energy level within the bandgap caused by the presence of a foreign atom or a structural defect. Once the trap is filled it cannot accept another electron. The electron occupying the trap energy can in a second step fall into an empty state in the valence band, thereby completing the recombination process. One can envision this process either as a two-step transition of an electron from the conduction band to the valence band or also as the annihilation of the electron and hole which meet each other in the trap. We will refer to this process as Shockley-Read-Hall (SRH) recombination.

Auger recombination is a process in which an electron and a hole recombine in a band-to-band transition, but now the resulting energy is given off to another electron or hole. The involvement of a third particle affects the recombination rate so that we need to treat Auger recombination differently from band-to-band recombination.