Course: Basic Electronics (EC21101)

Course Instructor: Prof. Kapil Debnath

Lecture 3: pn junction

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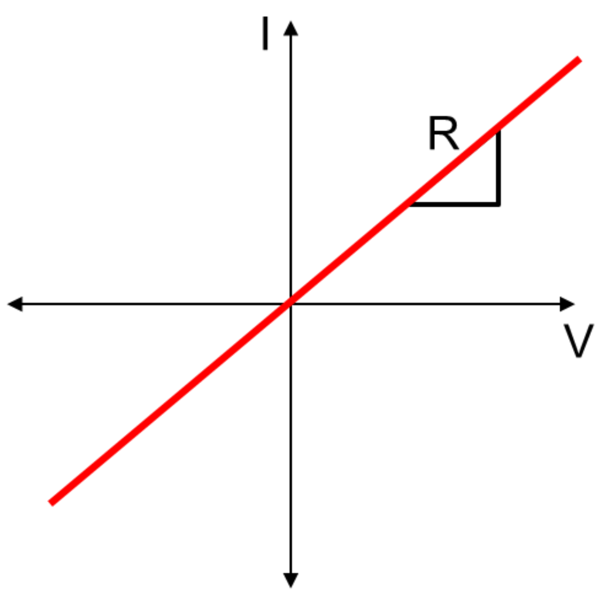
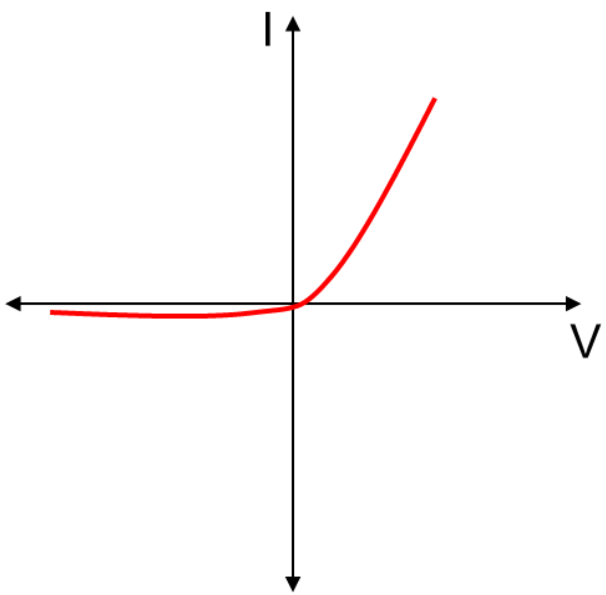
Current-voltage behaviour of semiconductors

When a piece of semiconductor, whether intrinsic or extrinsic, is used in a electrical circuit will behave just like a resistance and follow ohms law, i.e. as voltage increases current will also increase. So we can not expect a new functionality from an undoped or doped piece of semiconductor.
However, when two or more different types of semiconductors (p-type and n-type) are joined together, we observe novel functionalities. A pn-junction is essentially realized by joining a p-type semiconductor with an n-type semiconductor. When voltage is applied to such a junction, a unique current-voltage relationship emerges.



Behaviour of a single type semiconductor

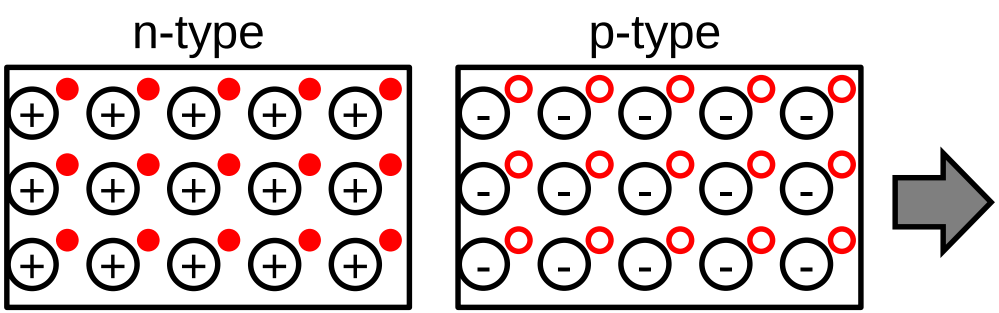


Behaviour of a pn junction

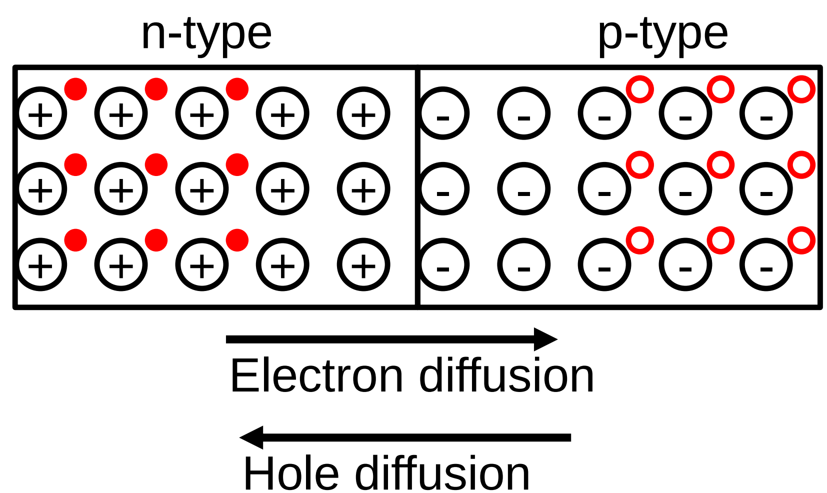
pn-junction at equilibrium

Depletion region:

When the n-type and p-type regions are separated, we have fixed carrier density on both sides. However, when they are joined together to form a junction, because there exists a density gradient across the junction, holes will initially diffuse to the n-side and electron will diffuse to the p-side. The holes on p-side will disappear because of the electrons which are diffused from the n-side and electrons will disappear because of the holes which are diffused from the p-side. Because of these diffusion of charge carriers, the net charge of the ions on n-side will become positive and net change of the ions on p-side will become negative. However, this process can not continue forever, because after a certain period of time, the negative charged regions that is formed on the p-side of the junction will repel any electron that tries to cross the junction and similarly for holes, the positively charged region will repel the holes. As a result a fixed region around the junction will be formed which is depleted of mobile charge carriers. This region is called depletion region or space-charge region.



Each region is charge neutral



pn-junction at equilibrium

Built in potential:

From our previous discussion, we have

Drift current: $J_{drfit} = (\mu_n ne + \mu_p pe)E$ *and diffusion current:* $J_{diffusion} = \left(D_n \frac{dn}{dx} - D_p \frac{dp}{dx}\right) e$

Under equilibrium, at the pn junction:

Drift current of electrons = Diffusion current of electrons

Drift current of holes = Diffusion current of holes

For holes:

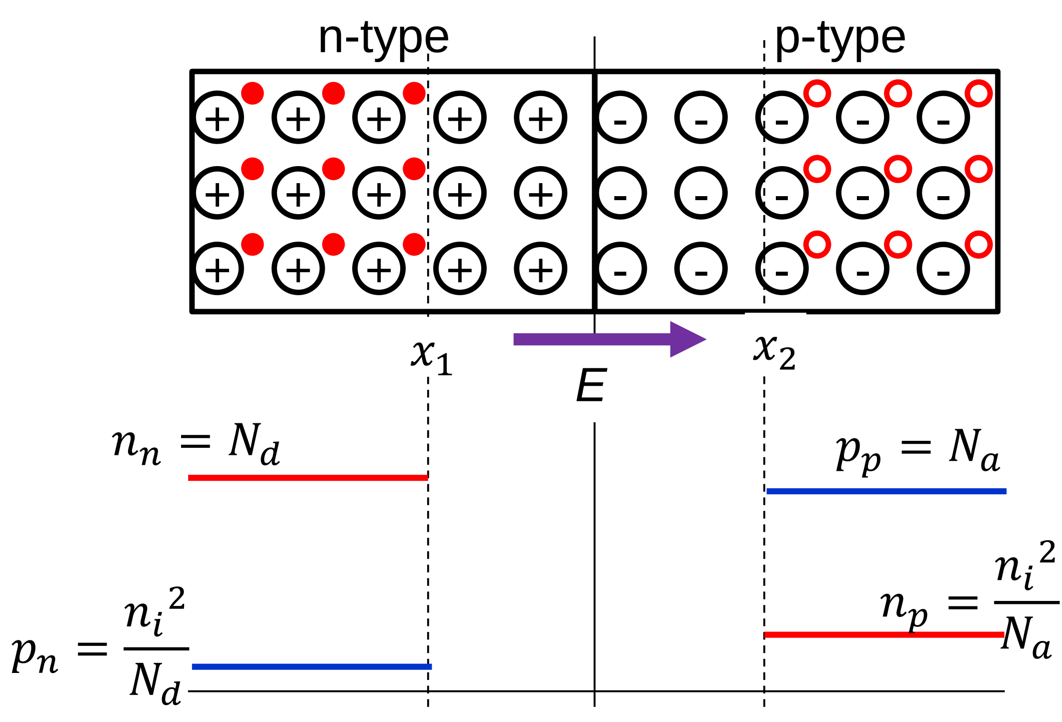
$$\mu_p peE = D_p \frac{dp}{dx} e$$

After rearranging, we can write:

$$\frac{D_p}{\mu_p} \frac{dp}{p} = E dx$$

By integrating on both side over the depletion region, we get

$$\frac{D_p}{\mu_p} \int_{p_n}^{p_p} \frac{dp}{p} = \int_{x_1}^{x_2} E dx$$



pn-junction at equilibrium

Built in potential:

$$\frac{D_p}{\mu_p}\int_{p_n}^{p_p}\frac{dp}{p} = \int_{x_1}^{x_2} E dx$$

$$\Rightarrow \frac{D_p}{\mu_p} ln\left(\frac{p_p}{p_n}\right) = V(x_1) - V(x_2)^{*}$$

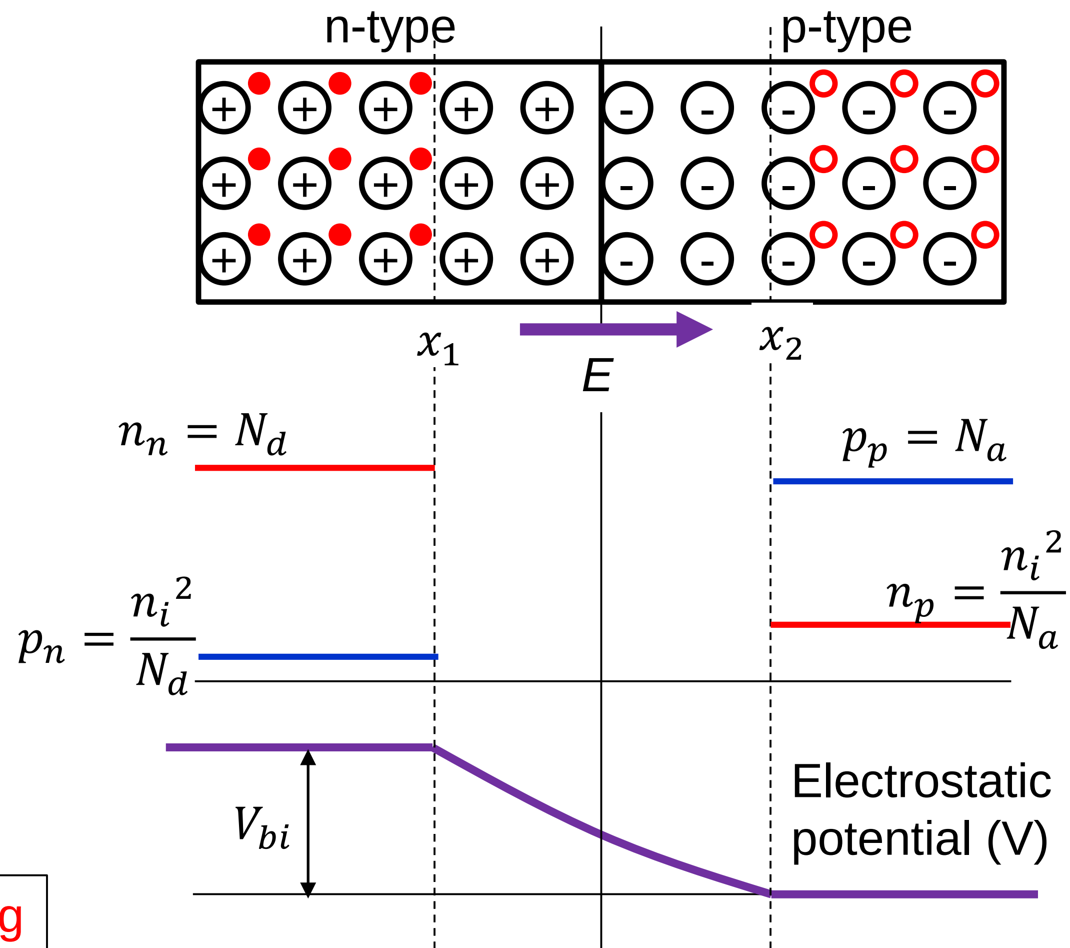
$$\Rightarrow V_{bi} = V_T ln\left(\frac{N_a N_d}{{n_i}^2}\right)$$

V_{bi} is known as the built-in voltage.

For N_d=N_a=$10^{16}/cm^3$, at 300K,

$$V_{bi} = 0.72mV$$

Find the expression for V_{bi} considering electrons



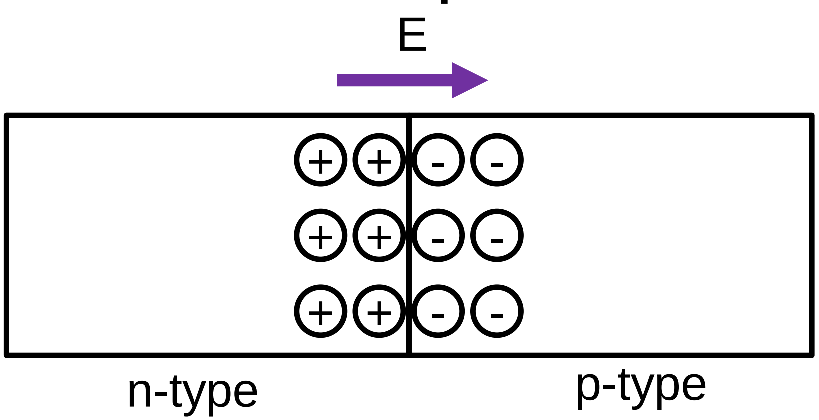
Remember, this voltage (V_{bi}) can not be measured by any external device, such as a voltmeter

*Remember: $V_{AB} = -\int_A^B E dx$

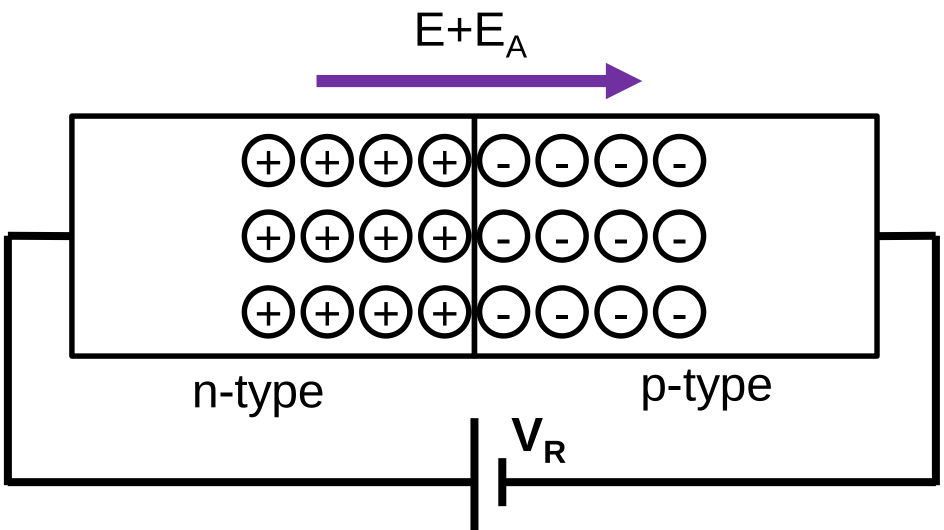
pn-junction in reverse bias

So far our discussion has been about a pn junction which is not connected to any voltage source. Now we will take up a case where the n-side of the junction is connected to the positive terminal of a voltage source and the p-side of the junction is connected to the negative terminal of the same voltage source (V_R). This applied voltage introduces an electric field, E_A, which is in the same direction as the electric field under thermal equilibrium. As a result the electric field in the depletion region increases. Accordingly the electrons on n-side moves to the positive terminal of the voltage source and the holes on p-side moves to the negative terminal of the voltage source. As a result the width of the depletion region also increases. Moreover, this electric field holds back electron on the n-side and holes on the p-side. Therefore, essentially there is no current flows through the junction. This is known as ***reverse biasing***. [*In reality, however, a very small amount of current flows through the junction due to the minority carriers in each region (electrons in p-side and holes in n-side), known as reverse saturation current. For silicon this current is of the order of 10^{-9}A*].

Under equilibrium



Under reverse bias



pn-junction in reverse bias

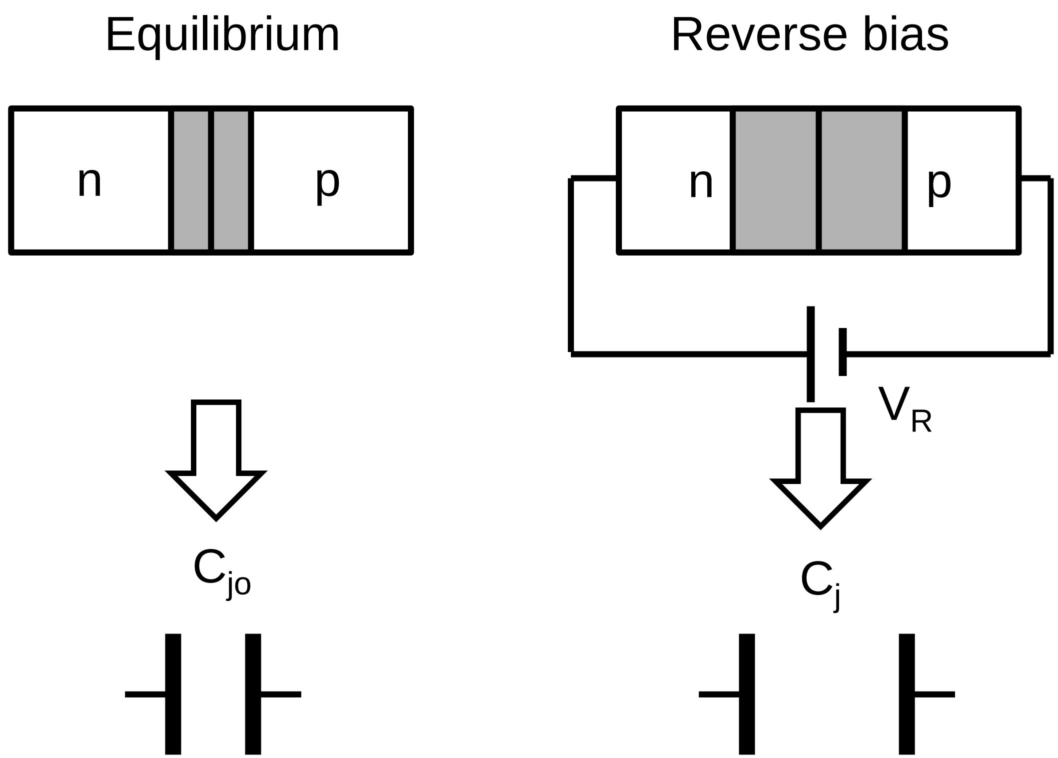
Junction capacitance:

One of the observation that we can make about a pn-junction in reverse bias is that as we increase the reverse bias, the depletion width increases. In side the depletion region, the change carrier concentration is zero (except few thermally generated electron holes). Outside the depletion region, we have a large number of charge carriers. So we can approximate this as a parallel plate capacitor, where the width of the depletion region is the separation between the two parallel plates. This capacitance is known as junction capacitance.

The junction capacitance can be varied by controlling the reverse bias voltage across the pn junction. This type of variable capacitor is called a varactor diode. The capacitance is expressed as:

$$C_j = C_{jo}\left(1+\frac{V_R}{V_{bi}}\right)^{-1/2}$$

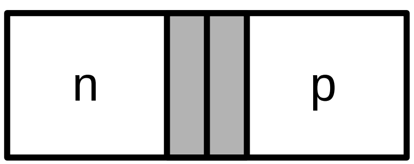
Where C_{jo} *is the capacitance at equilibrium, i.e. when no voltage is applied.*



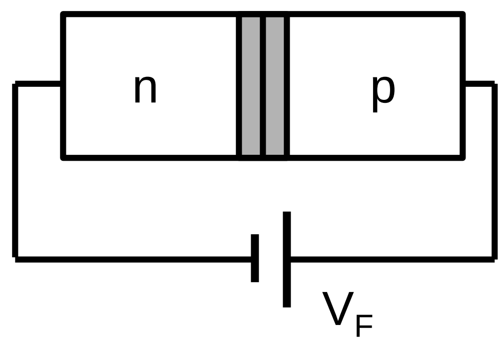
pn-junction in forward bias

When the positive terminal of the voltage source is connected to the p-side of the n-junction and negative side to the n-side, this configuration is called forward biasing*. The applied electric field will now oppose the electric field existed at equilibrium, as a result the potential barrier at the junction will be lowered. This will disturb the equilibrium initially established between the drift current and the diffusion current. Since the electric field at the junction is reduced due to the applied voltage, the diffusion current will start to dominate over the drift current. Hence, for forward bias, the holes will cross the junction from p-side to n-side, where they constitute an injected minority current. Similarly, the electrons will cross the junction in the reverse direction and become a minority injected current into the p-side. As the conventional current direction is opposite to the direction of electron flow, we will have a resultant current crossing the junction p-side to n-side.*

Equilibrium



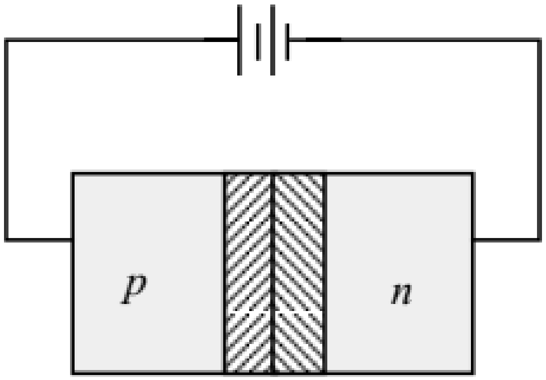
Forward bias

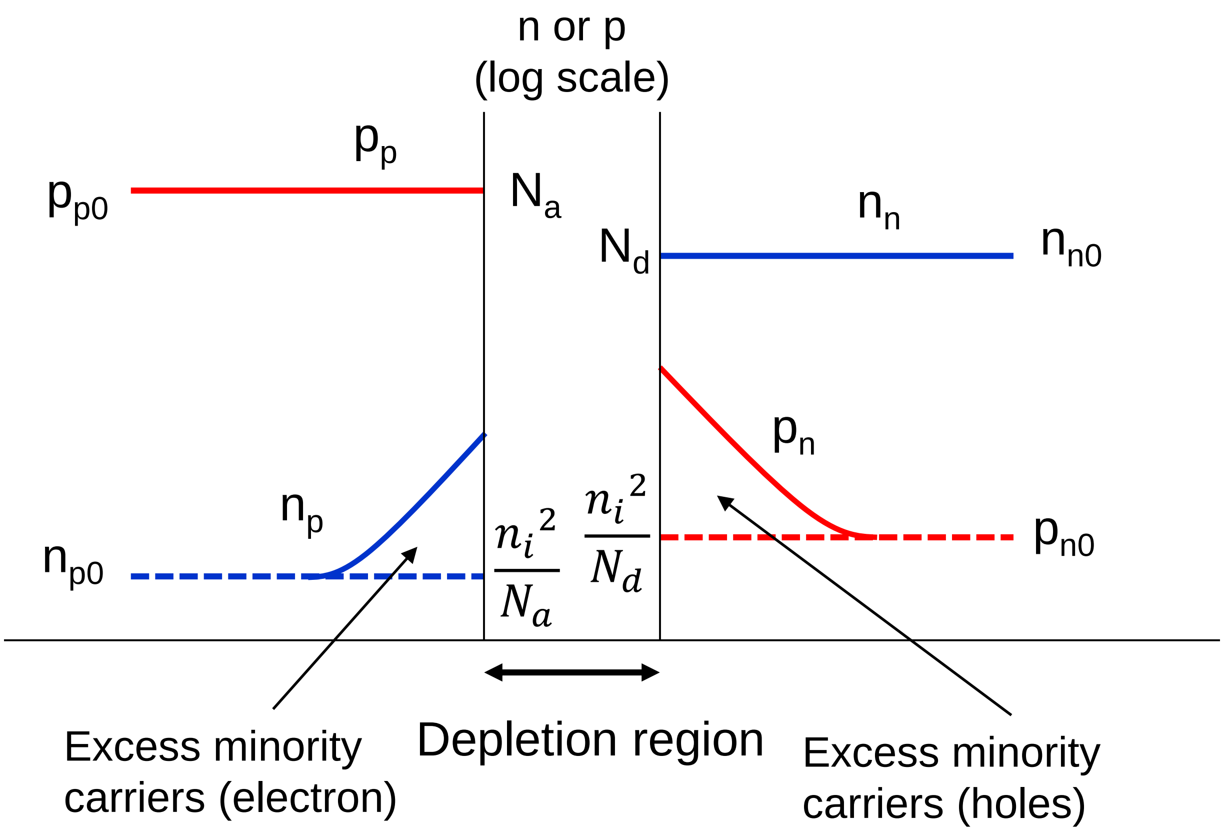


At the junction $J_{drift} = J_{diffusion}$ $J_{drift} < J_{diffusion}$

pn-junction in forward bias

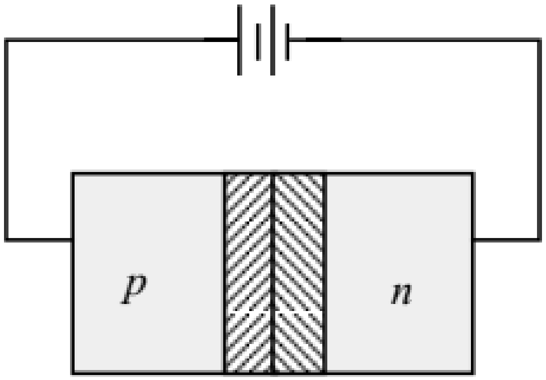
Charge carrier distribution in a pn junction:

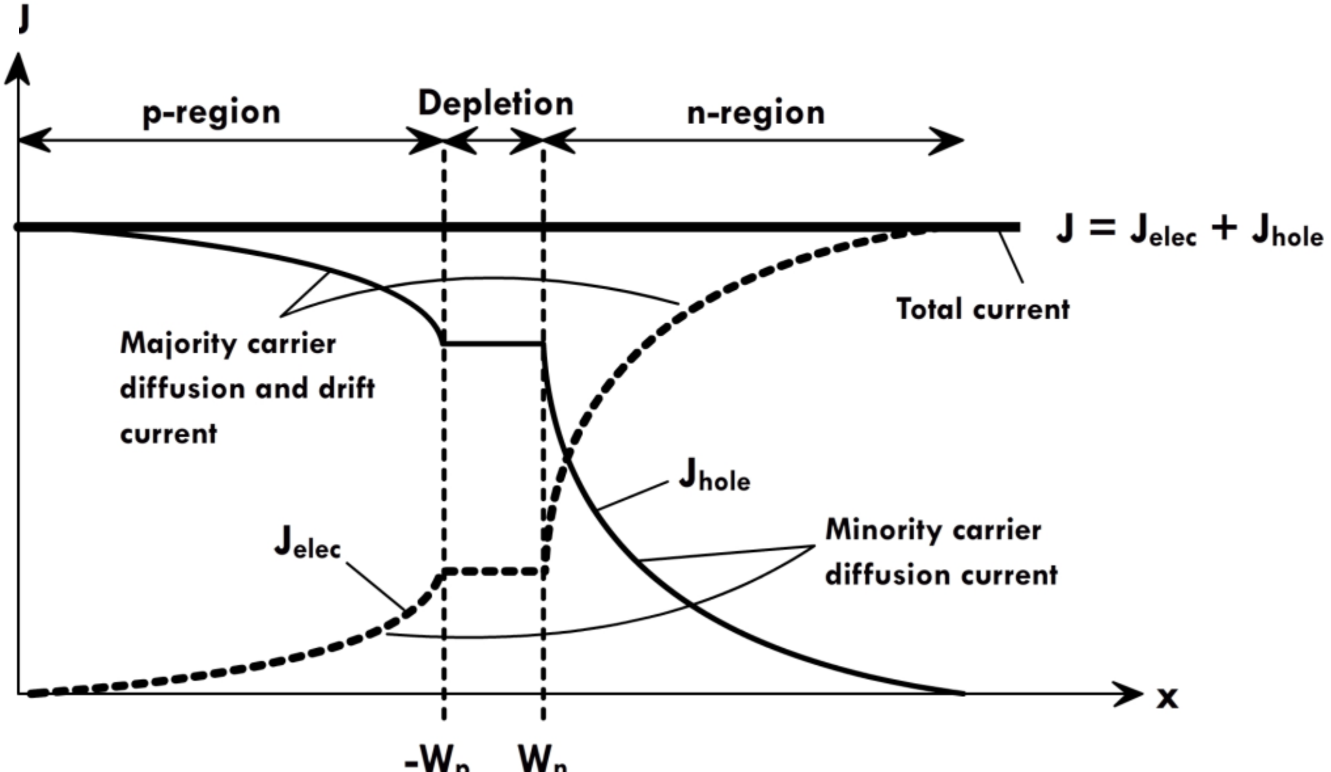




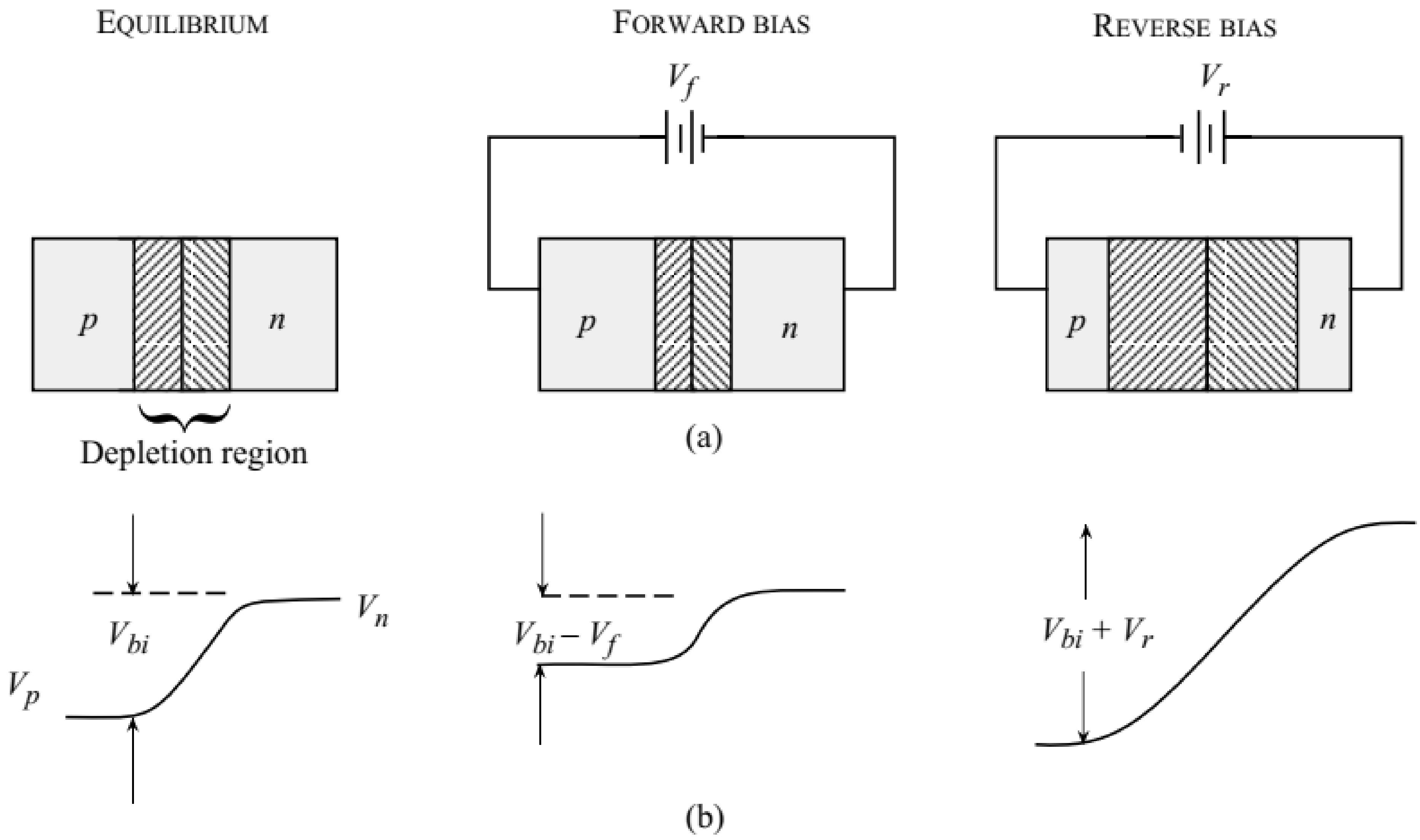
pn-junction in forward bias

Current components in a pn junction:

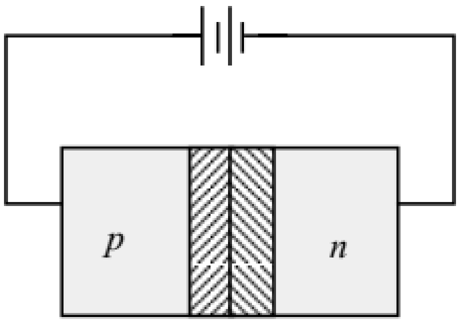




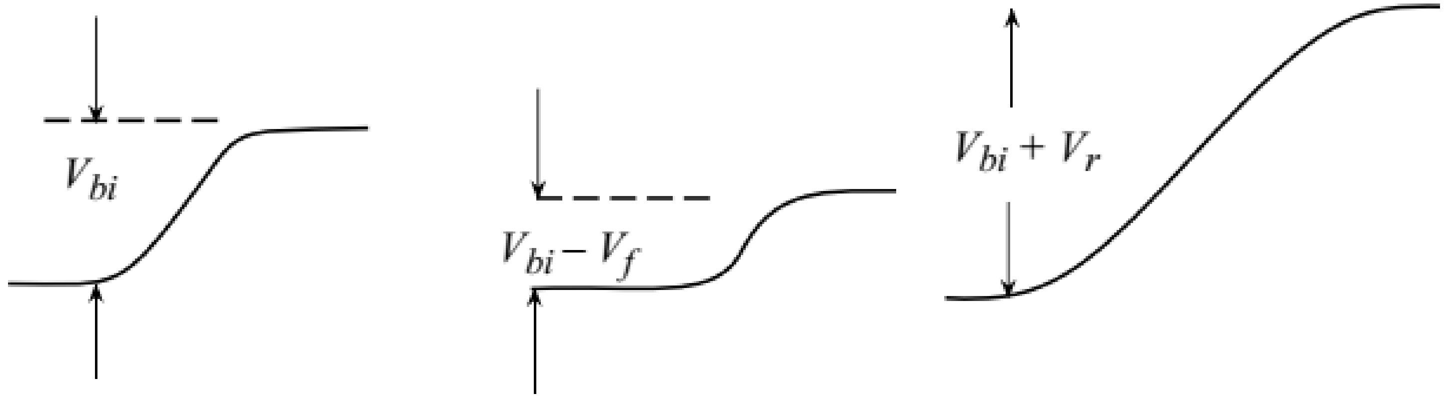
pn junction under various bias condition

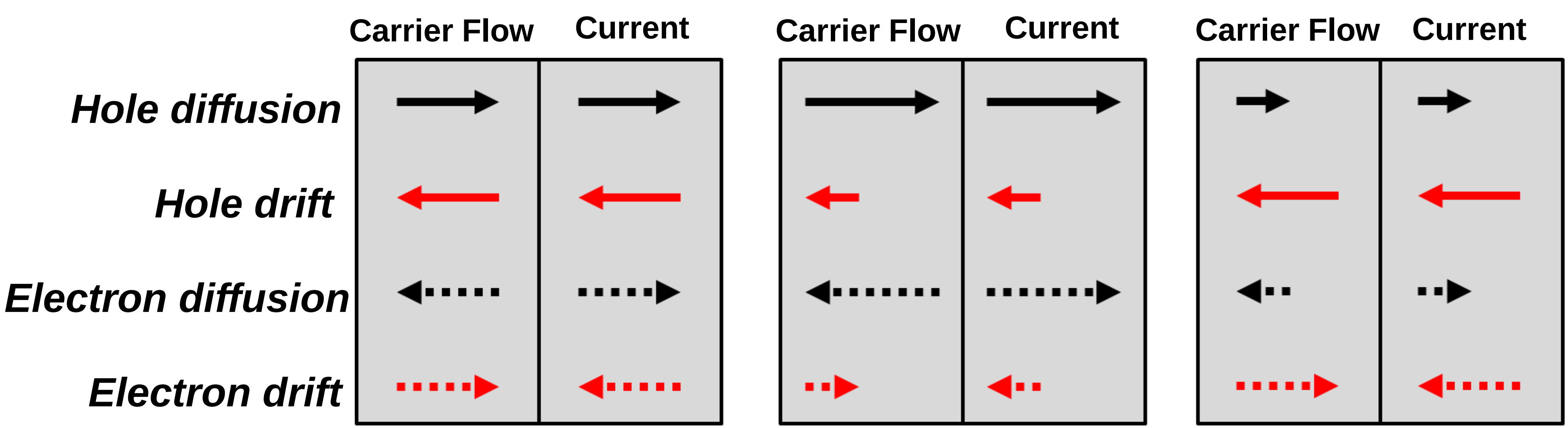


Various currents under different biasing condition



Equilibrium **Forward** **Reverse**



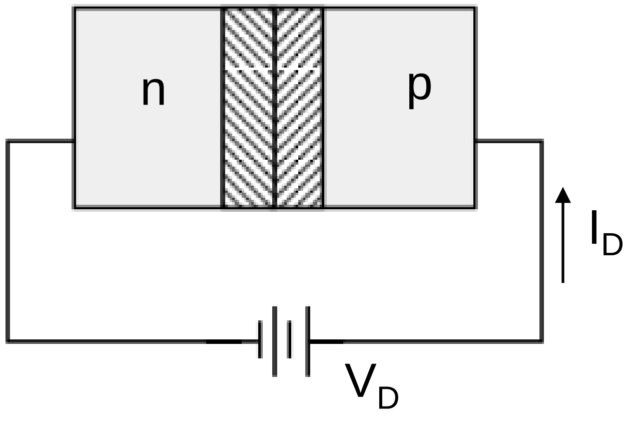


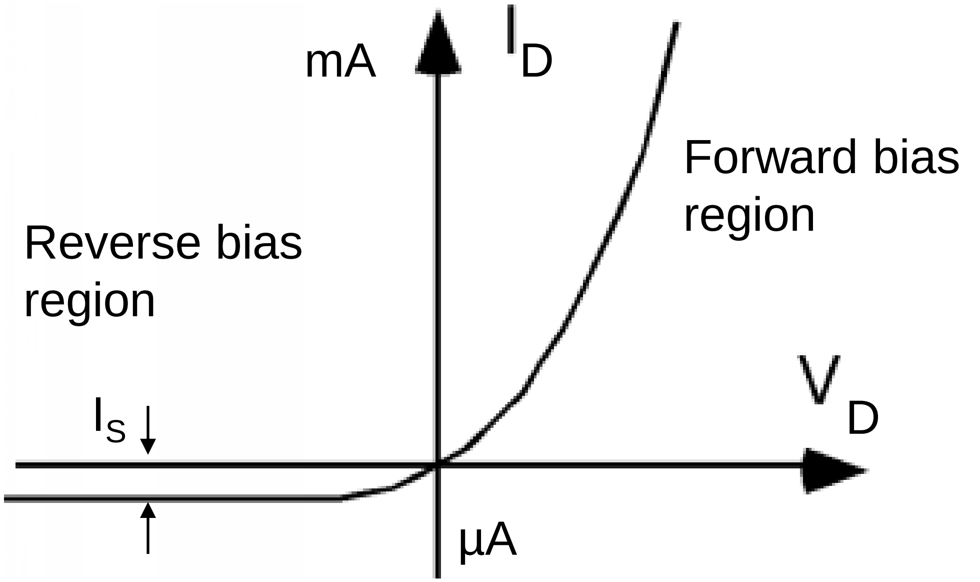
Current-voltage characteristics

The theoretical relationship between the applied voltage and current through a pn-junction is given as:

$$I_D = I_S\left[e^{\left(\frac{V_D}{\eta V_T}\right)} - 1\right]$$

Where V_D is the applied voltage, I_D is the current, I_s is known as reverse saturation current, V_T is volt-equivalent of temperature, i.e. kT/e, and η is known as ideality factor which varies between $1 \leq \eta \leq 2$. for silicon $\eta \approx 2$ and for germanium $\eta \approx 1$.
When V_D is zero, the junction is in equilibrium condition and no current flow through the circuit.
When V is negative, the junction is in reverse bias and I_D=-I_S,
When V_D is positive, the junction is in forward bias and the current grows exponentially as V_D increases.

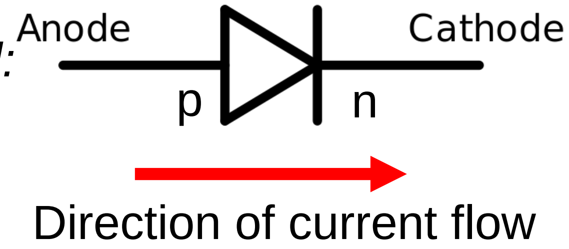




Current-voltage characteristics

The I-V characteristic of a pn-junction depends strongly on the polarity of the applied voltage. pn-junction, with such nonlinear rectifying current characteristic is called a pn junction diode.

Diode symbol:



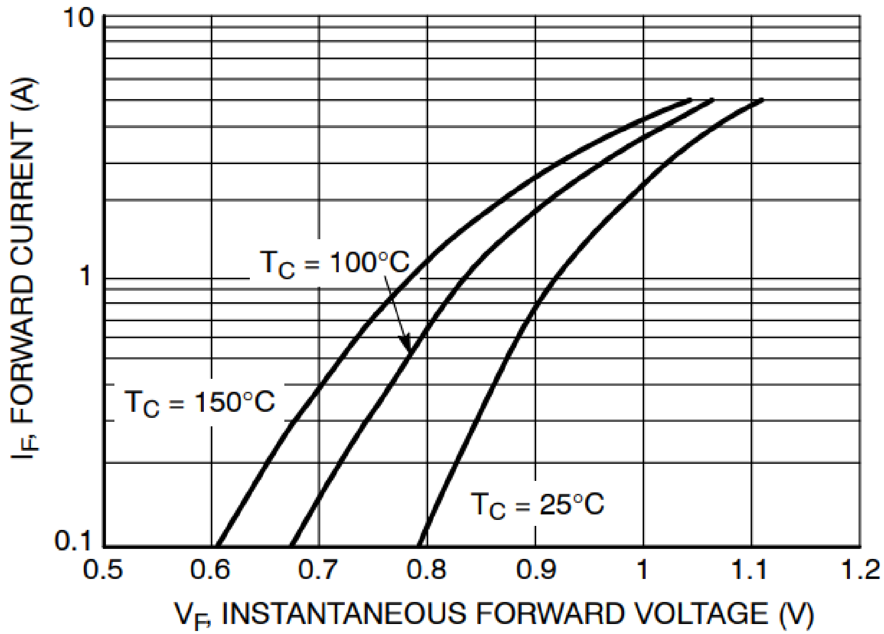


Figure 1. Typical Forward Voltage

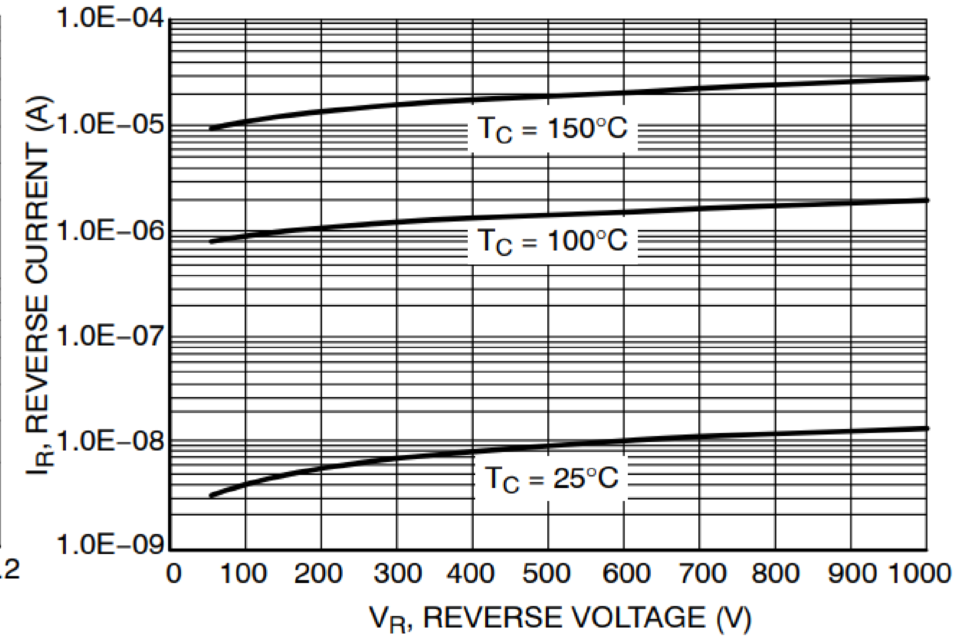


Figure 2. Typical Reverse Current

Current-voltage characteristics

Effect of material on IV characteristics of a pn junction:

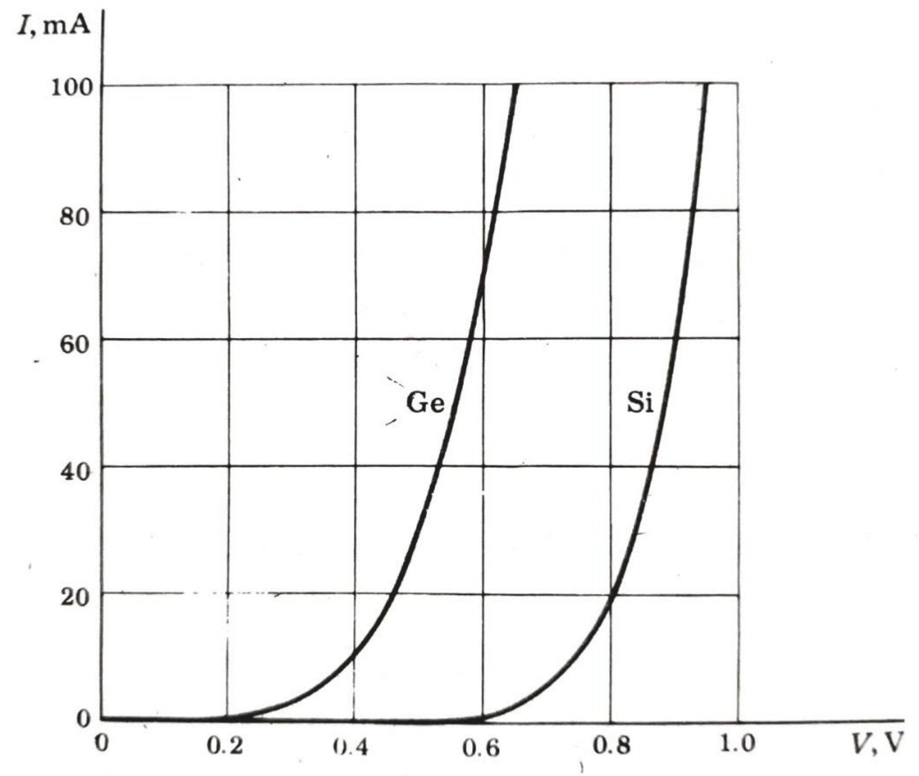
The IV characteristics of both silicon and germanium has similar current ratings. However one can notice that the current in a germanium diode sharply increases after about 0.2V, whereas for silicon this voltage is about 0.6V. This voltage has various names: cutin, offset, break-point, or threshold voltage and denoted by V_γ. There are two factors that decides the cuitin voltage. One is the reverse saturation current, I_S and another one is the ideality factor η.

For germanium, η is close to 1 and for silicon η is close to 2.

I_s is expressed as:

$$I_S = Ae\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right){n_i}^2$$

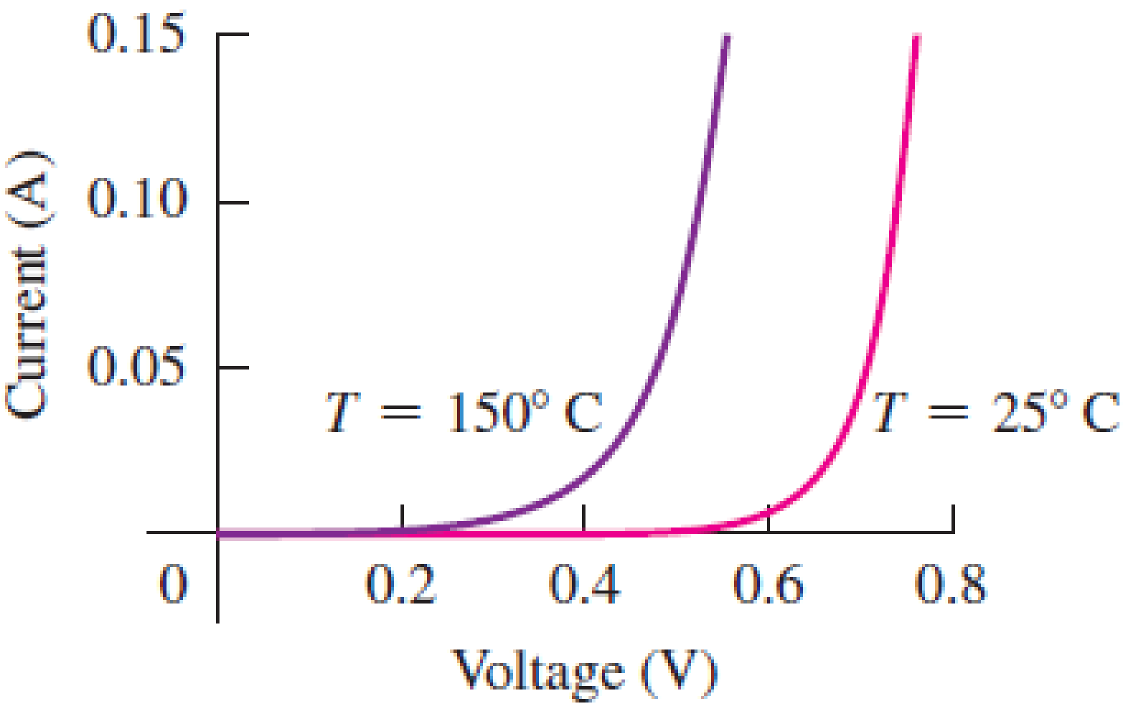
Where, A is the cross sectional area of the diode, Lp and Ln are the diffusion length of holes and electrons respectively. For silicon ni is about $10^{10}/cm^3$, whereas for germanium, ni is about $10^{13}/cm^3$. As a result germanium has a reverse saturation current 1000 times larger than silicon.



Current-voltage characteristics

Effect of temperature:

Since both I_S and V_T depends on temperature, the IV relationship in a diode also changes with temperature.



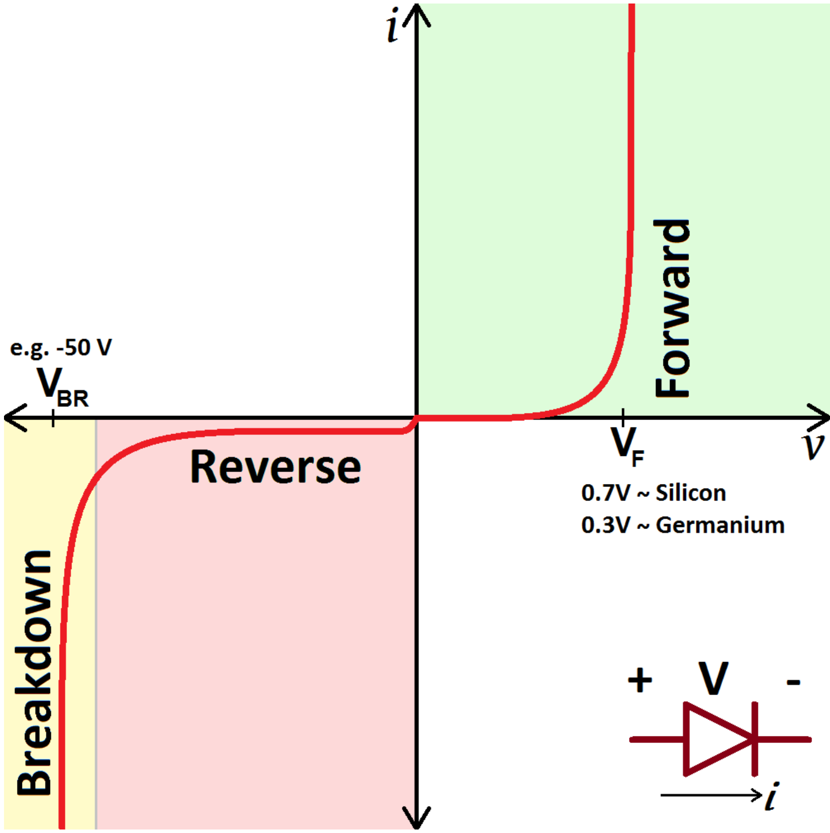
Reverse Bias diodes

Breakdown voltage:

From the ideal diode equation, we saw that under reverse bias the current essentially remains as I_S. However, in a real diode when the reverse bias voltage is increased, the electric field in the depletion region (space charge region) also increases. The electric field may become large enough that covalent bonds within the depletion region are broken and electron hole pairs are created. These newly generated electrons are swept into the n-region and holes are swept into the p-region. Thus generating a large reverse bias current. This phenomenon is known as breakdown.

The voltage at which the breakdown occurs depends on fabrication parameters, such as doping concentration, size etc. Typically this breakdown voltage lies in the range of 50-200V. Except for few applications, diodes are operated under the breakdown voltage, which is termed as peak inverse voltage or PIV. Beyond the PIV, the diode current suddenly increases and can cause damage to the device, unless the current is controlled by the external circuit.

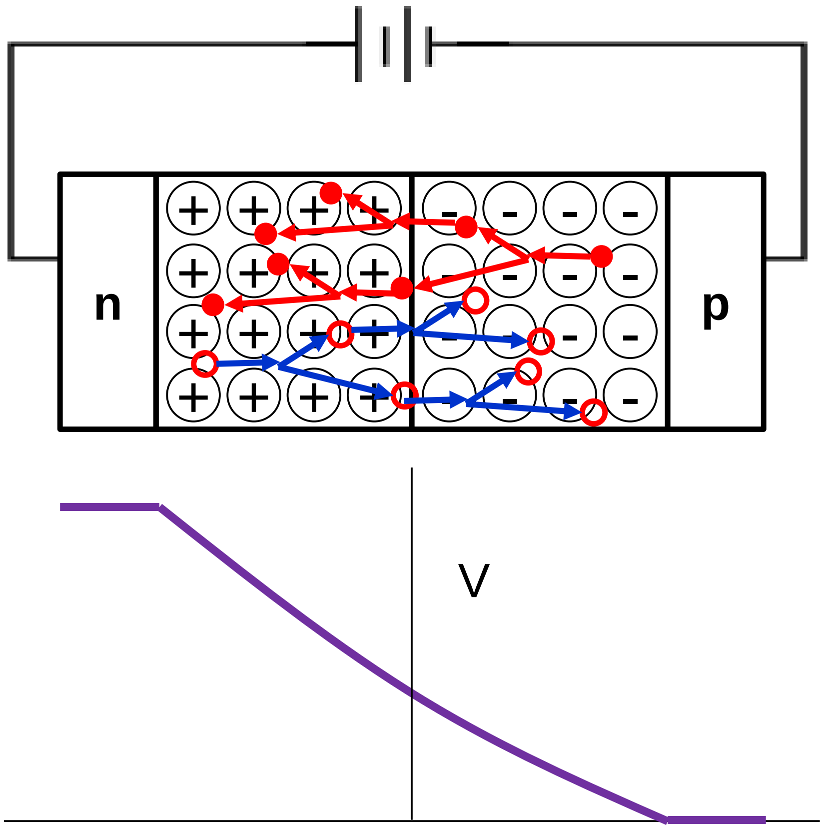
There are two mechanisms by which breakdown happens: a) Avalanche breakdown, b) Zener breakdown.



Reverse Bias diodes

Avalanche breakdown:

Avalanche breakdown occurs when carriers crossing the space charge region gain sufficient kinetic energy from the high electric field to be able to beak the covalent bonds during a collision process. The generated electron-hole pairs can themselves be involved in a collision process generating additional electron-hole pairs, thus resulting in a avalanche process.



Reverse Bias diodes

Zener breakdown:

Zener breakdown is a result of tunnelling of carriers across the junction under reverse bias. This breakdown occurs in pn-junctions with very high carrier concentration. For high carrier concentrations, since the junction width is very small, the carriers may simply tunnel through the space-charge region from one-side to another.

The Zener breakdown may occur at voltages below 5V. Zener diodes are designed and fabricated to provide a specified breakdown voltage, called as Zener breakdown voltage (V_Z). The IV curve of a Zener diode is shown below. It can be noticed that the slope of the IV curve beyond breakdown is quite large, so the incremental resistance is very small typically of the order of few ohms. In electronic circuits Zener diodes are used as a constant-voltage reference.

Zener diode symbol