Semiconductor Physics

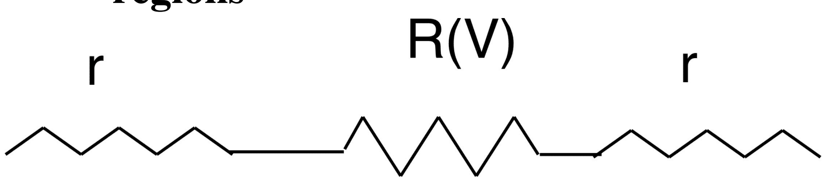
Lecture 6

Recap pn junction and the depletion region

Driven by the need to have no gradient in the fermi level free carriers migrate across the pn junction leaving a region with few free carriers (depletion region)

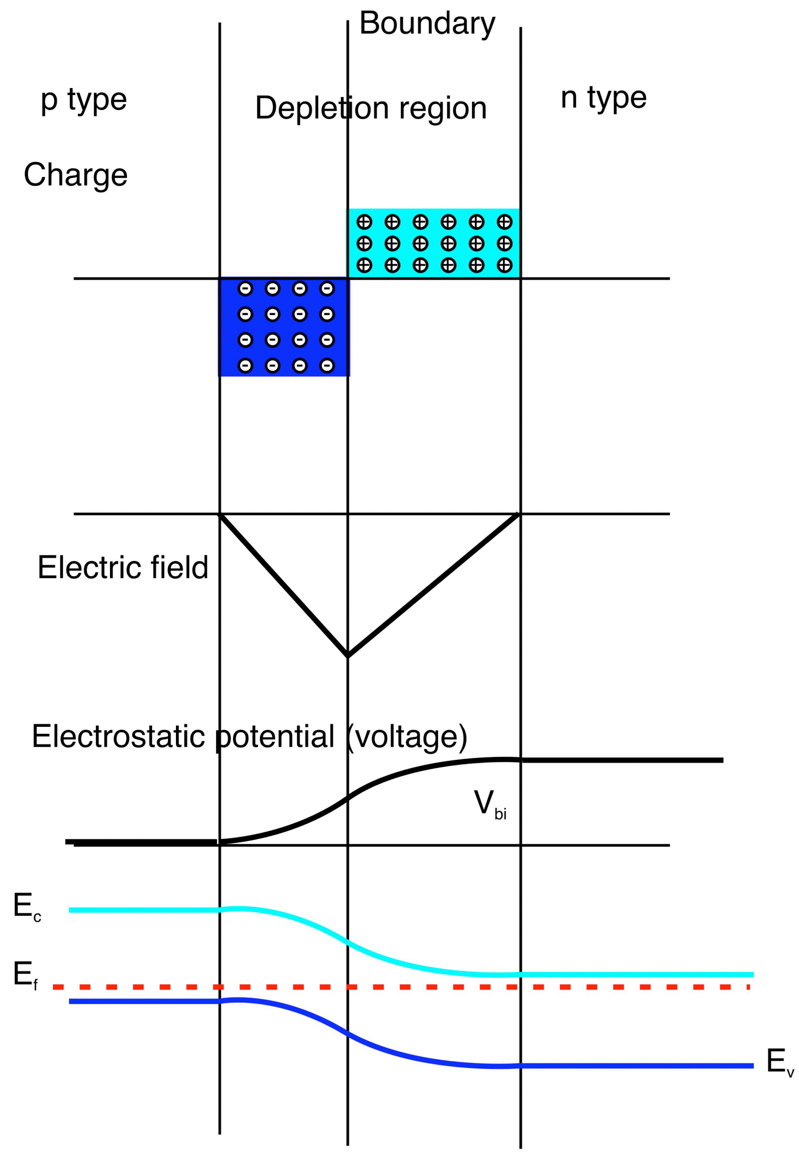
Have uncompensated changed acceptor and donor ions leading to an eletrostatic potential V_{bi} (n side positive with respect to the p side) which bend the bands to produce a flat fermi level

Absence of carriers in the depletion region means that the pn junction can be regarded as a high resistance region sandwiched between two low resistance regions



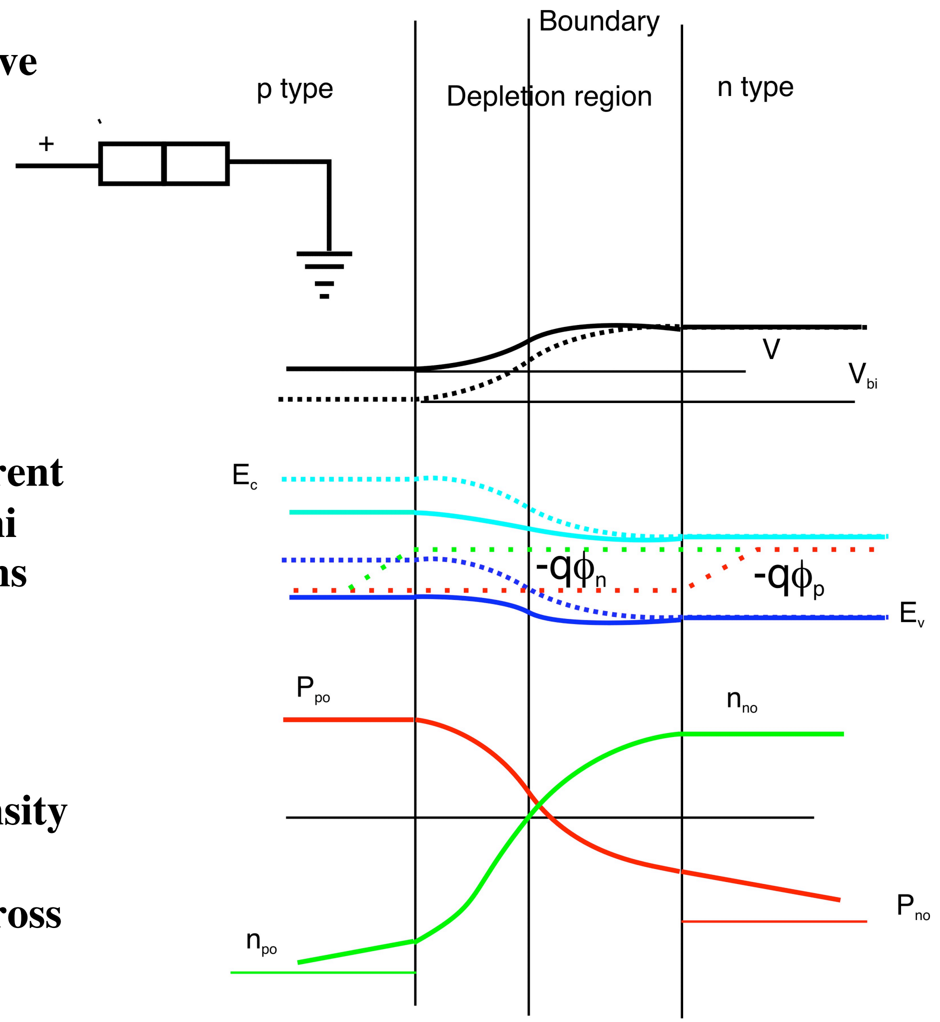
Resistance is a function of the magnitude and sign of the applied voltage

We will now consider the effect of applying a voltage



Applied voltage forward bias

If a the p end of the junction is made positive relative to the equilibrium state the junction is said to be forward biased



Step between energy levels is reduced

No longer have a flat Fermi level since current is now flowing replace with quasi Fermi levels $-q\Phi_p$, $-q\Phi_n$ for holes and electrons

Bulk of gradient close boundary since resistance is highest here

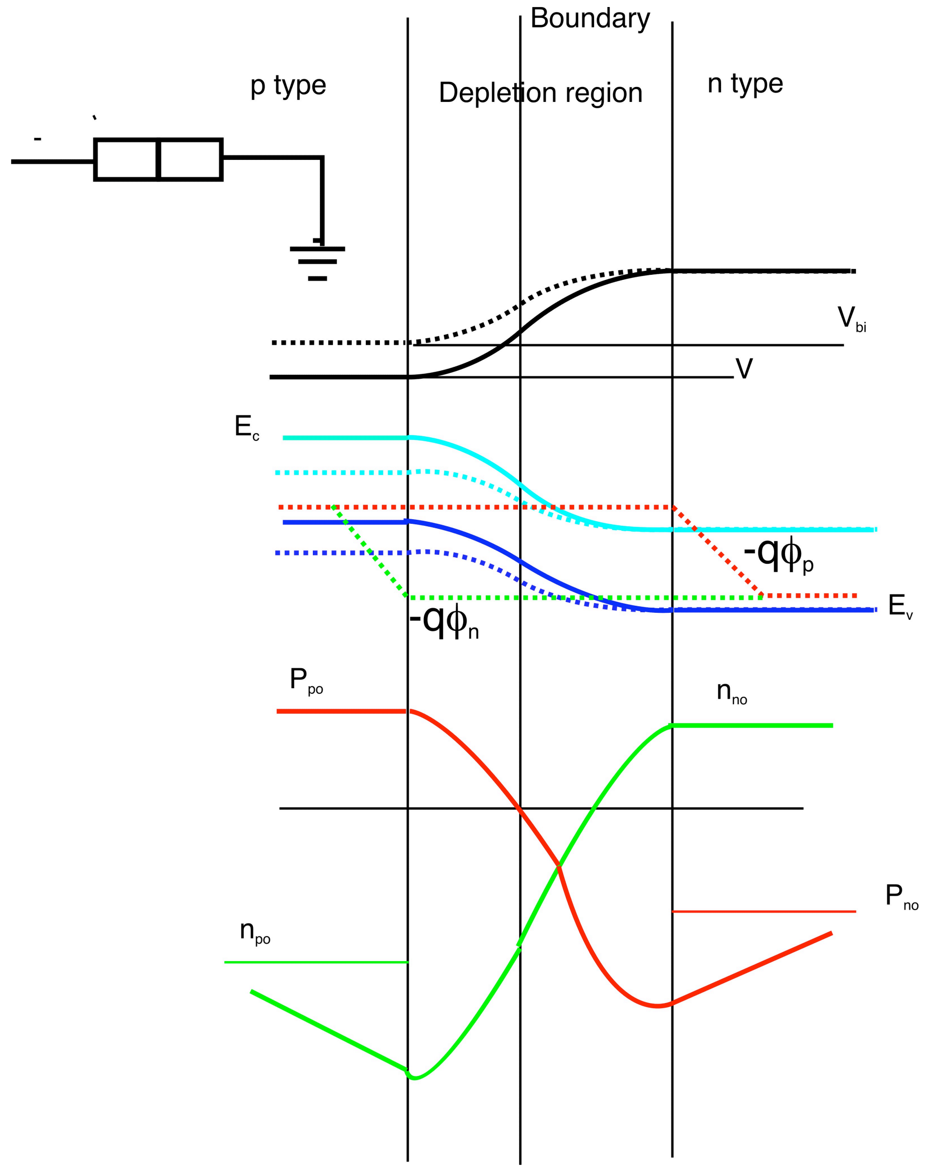
Have a situation where the free carrier density in the depletion region is increased (lowering its resistance) and carriers cross the boundary

Applied voltage reverse bias

If a the p end of the junction is made negative relative to the equilibrium state the junction is said to be forward biased

Step between energy levels is increased

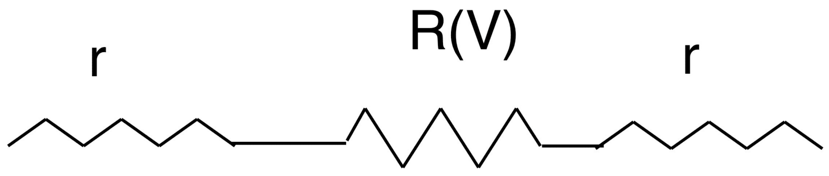
Have a situation where the free carrier density in the depletion region is decrease (increasing its resistance)



Shockley equation

Want to calculate current voltage relationship

Assume that all of the potential gradients are supported by the depletion layer and that outside of this region the semiconductor is neutral



Assume that the relationships between the quasi-Fermi level and the carrier density are the same as for the thermal equilibrium case (departures from equilibrium are small)

Low injection conditions apply. The injected minority carrier concentrations are small compared with the majority

No generation of carriers in the depletion layer

Shockley equation II

In thermal equilibrium the electron and hole concentrations are

$$n = n_i e^{\left(\frac{E_f - E_i}{kT}\right)} \equiv n_i e^{\left(\frac{q(\psi - \phi)}{kT}\right)} \qquad \psi \equiv \frac{-E_i}{q} \text{ and } \phi \equiv \frac{-E_f}{q}$$

$$p = n_i e^{\left(\frac{E_i - E_f}{kT}\right)} \equiv n_i e^{\left(\frac{q(\phi - \psi)}{kT}\right)}$$

Change made from energies to potentials so that we can handle the applied voltage
Applied voltage means that Φ is replaced by Φ_p, Φ_n quasi Fermi levels

$$n \equiv n_i e^{\left(\frac{q(\psi - \phi n)}{kT}\right)} \text{ and } \phi_n = \psi - \frac{kT}{q} ln\left(\frac{n}{n_i}\right)$$

$$p \equiv n_i e^{\left(\frac{q(\phi p - \psi)}{kT}\right)} \text{ and } \phi_p = \psi + \frac{kT}{q} ln\left(\frac{p}{n_i}\right)$$

$$pn = n_i^2 e^{\frac{q(\phi p - \phi n)}{kT}} \qquad pn \neq n_i^2$$

If $\Phi_p > \Phi_n$ then $pn > n_i^2$ forward bias , $\Phi_p < \Phi_n$ $pn < n_i^2$ reverse bias

Current density

The current density is the sum of the currents produced by the electric field (gradient of the potential) and the diffusion current produced by the concentration gradient.

$$J_n = q\mu_n(n\xi + \frac{kT}{q}\nabla n) = q\mu_n n(-\nabla\psi) + q\mu_n\frac{kT}{q}[\frac{qn}{kT}(\nabla\psi - \nabla\phi_n)]$$

Which reduces to

$$J_n = -q\mu_n n\nabla\phi_n \quad J_p = -q\mu_p p\nabla\phi_p$$

Thus the current density is simply proportional to the spatial gradients of the quasi Fermi levels

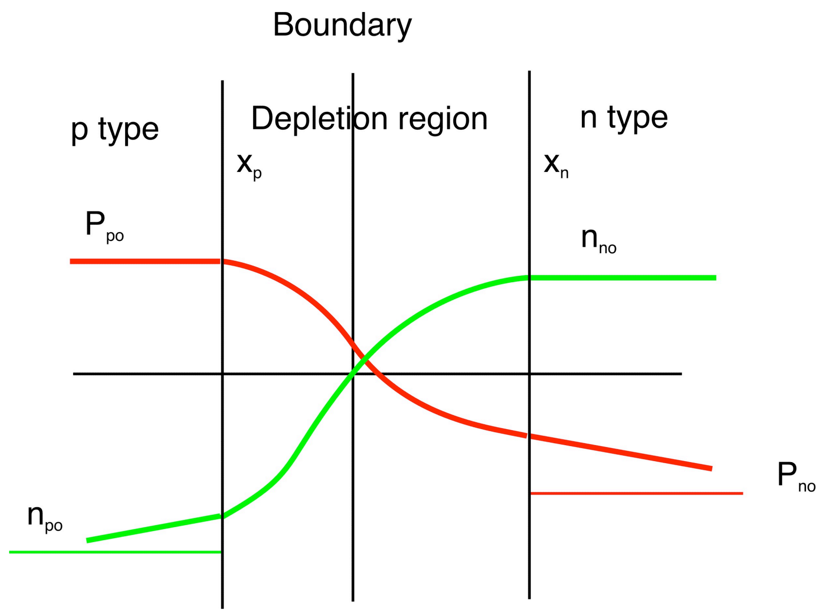
$$n \equiv n_i e^{\left(\frac{q(\psi-\phi n)}{kT}\right)} \text{ and } \phi_n = \psi - \frac{kT}{q} ln(\frac{n}{n_i})$$

Since the carrier density varies by many orders of magnitude across the depletion layer and yet J_n is roughly constant it follows that Φ_n has a very small gradient across the depletion layer

Carrier densities

The voltage across the junction is V= Φ_p -Φ_n

$$pn = n_i^2 e^{\frac{q(\phi_p - \phi_n)}{kT}}$$



At the p side of the depletion layer (x=x_p)

$$n_p = \frac{n_i^2}{p_p} e^{\frac{qV}{kT}} = n_{po} e^{\frac{qV}{kT}}$$

$$p_p = \frac{n_i^2}{n_n} e^{\frac{qV}{kT}} = p_{no} e^{\frac{qV}{kT}}$$

For holes at x=x_n

I.E. excess of minority carriers at the edges of depletion layer for forward bias and depletion for reverse bias wrt equilibrium concentration

Continuity equations

For a steady state the change in carrier concentration with time is zero and the continuity equations become consider the case in the neutral region of the n type material

$$0 = n_p \mu_n \frac{\partial \xi}{\partial x} + \mu_n \xi \frac{\partial n_p}{\partial x} + D_n \frac{\partial^2 n_p}{\partial x^2} - U$$

$$0 = -p_n \mu_p \frac{\partial \xi}{\partial x} - \mu_p \xi \frac{\partial p_n}{\partial x} + D_p \frac{\partial^2 p_n}{\partial x^2} - U$$

If we assume approximate charge neutrality so that $n_n - n_{no} \approx p_n - p_{no}$ then the spatial variations of p and n are the same. We can then eliminate the term in the electric field gradient to obtain

$$0 = -\frac{(n_n - p_n)}{\left(\frac{n_n}{\mu_p} + \frac{p_n}{\mu_n}\right)} \xi \frac{\partial p_n}{\partial x} + D_a \frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{no}}{\tau_a}$$

Continuity equations II

$$0 = -\frac{(n_n - p_n)}{(\frac{n_n}{\mu_p} + \frac{p_n}{\mu_n})}\xi\frac{\partial p_n}{\partial x} + D_a\frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{no}}{\tau_a}$$

Where

$$D_a = \frac{n_n + p_n}{\frac{n_n}{D_n} + \frac{p_n}{D_p}} \text{ ambipolar diffusion coefficient}$$

And

$$\tau_a = \frac{(p_n - p_{no})}{U} = \frac{(n_n - n_{no})}{U} \text{ the ambipolar lifetime}$$

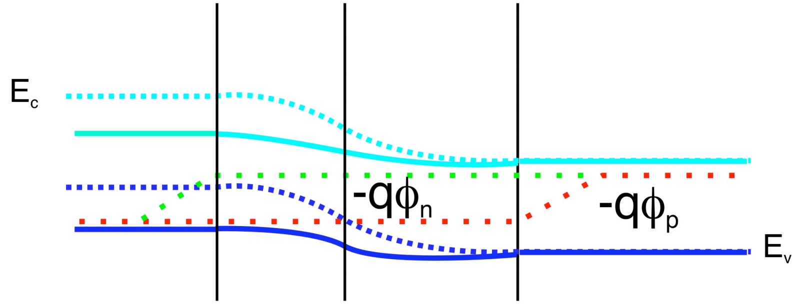
Continuity equations III

For low injection conditions n is much greater than p and approximately equal to n_{no}

$$0 = -\frac{(n_n - p_n)}{(\frac{n_n}{\mu_p} + \frac{p_n}{\mu_n})}\xi\frac{\partial p_n}{\partial x} + D_a\frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{no}}{\tau_a}$$

Becomes

$$0 = -\mu_p\xi\frac{\partial p_n}{\partial x} + D_p\frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{no}}{\tau_p}$$



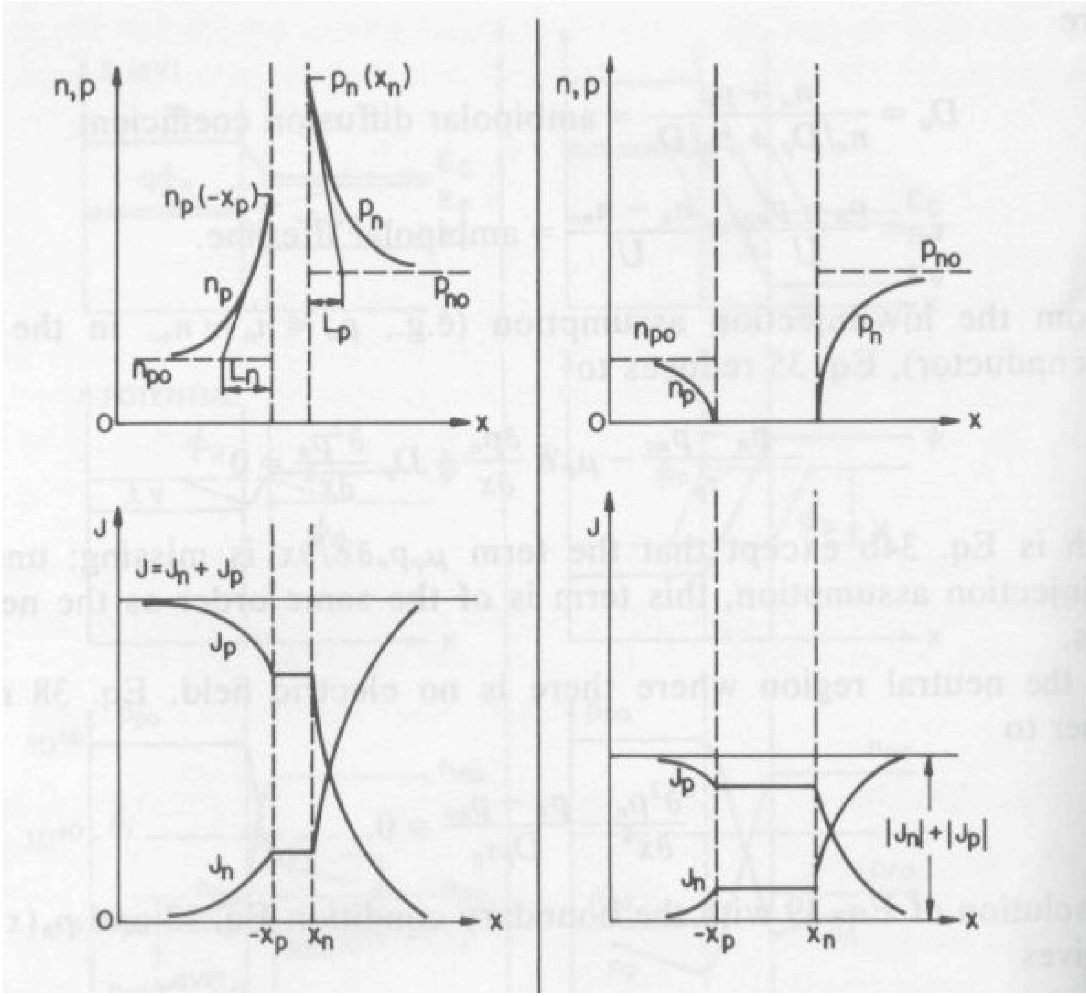
Once we are far enough away from the junction there is no electric field

$$0 = D_p\frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{no}}{\tau_p}$$

With the boundary condition that $p_n(\infty)=p_{no}$ the solution is

$$p_n - p_{no} = p_{no}(e^{\frac{qV}{kT}} - 1)e^{\frac{-(x-x_n)}{L_p}} \text{ where } L_p = sqrtD_p\tau_p$$

Current densities



$$p_n - p_{no} = p_{no}(e^{\frac{qV}{kT}} - 1)e^{\frac{-(x-x_n)}{L_p}} \text{ where } L_p = sqrtD_p\tau_p$$

Shockley equation

$$p_n - p_{no} = p_{no}(e^{\frac{qV}{kT}} - 1)e^{\frac{-(x-x_n)}{L_p}} \text{ where } L_p = sqrtD_p\tau_p$$

Total current density is the sum of the hole current density at $x=x_n$ and the electron current density at $x=-x_p$

$$J_p = -qD_p\frac{\partial p_n}{\partial x}\Big|_{x_n} = \frac{qD_p p_{no}}{L_p}(e^{\frac{qV}{kT}} - 1)$$

$$J_n = -qD_n\frac{\partial n_n}{\partial x}\Big|_{-x_p} = \frac{qD_n n_{po}}{L_n}(e^{\frac{qV}{kT}} - 1)$$

$$J = J_p + J_n = J_s(e^{\frac{qV}{kT}} - 1) \text{ where } J_s \equiv \frac{qD_p p_{no}}{L_p} + \frac{qD_n n_{po}}{L_n}$$

Shockley equation

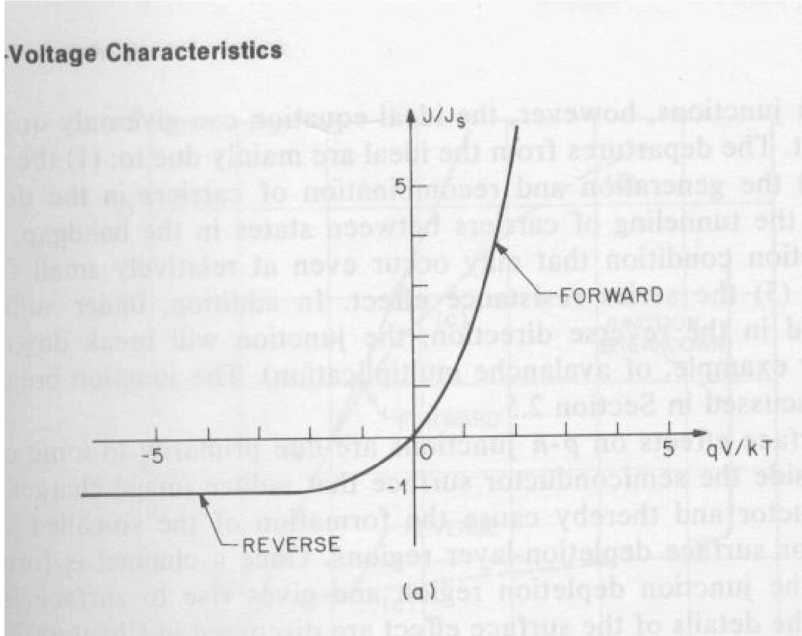
Current voltage characteristics

Notice ease with which current flows in forward bias

Difficulty in reverse

Max reverse current is

$$J_s = \frac{qD_p p_{no}}{L_p} = T^{\left(3+\frac{\gamma}{2}\right)} e^{-\frac{E_g}{kT}}$$



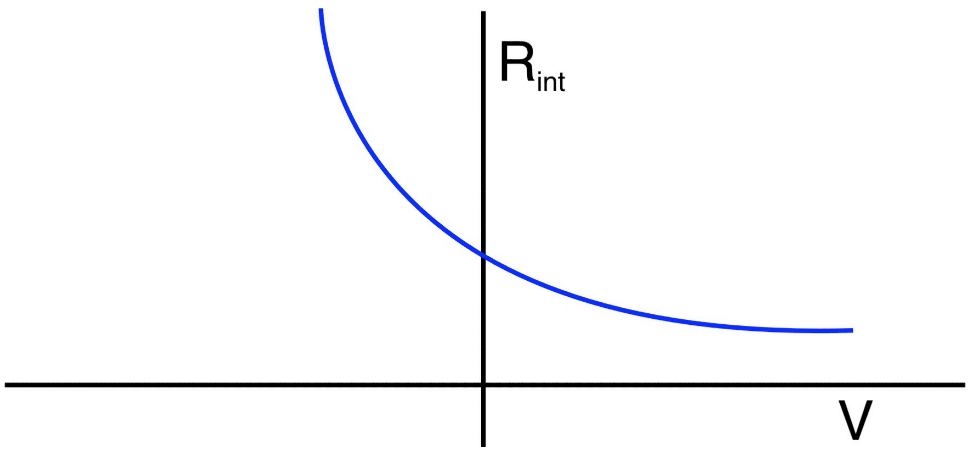
Instantaneous resistance

$$R_{int} = \frac{dV}{dI}$$

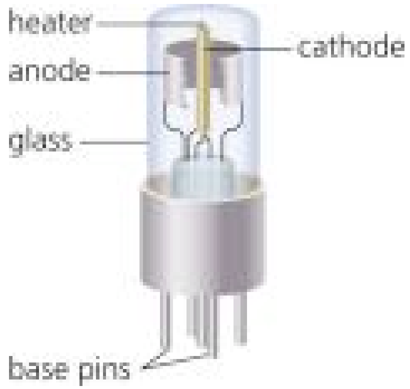
Is almost infinite in reverse bias

pn junction acts as a rectifier

Also known as a diode



Important breakthrough



Prior to solid state rectifiers

Rectifiers we based on
vacuum electronics

Thermionic diode or mercury
rectifiers

For industrial application
high heat output and
large and cumbersome

For example to power a train
takes ~1000 A DC at 1 kV

1 rectifier house every 10
miles

Now such equipment can be
put on the train

Power transmission at much
higher voltage more
effficent

Departures from the ideal case

The shockley equation is an idealised form but it incorporates some approximations which are not valid for real systems

It assumes carriers are not generated in the depletion region

For a reverse biased junction we have emission in the depletion region given by a rate

$$U \equiv \frac{-n_i}{\tau_e}$$

Current density is simply the integral of this over the width of the depletion layer

$$J_{gen} = qUW = \frac{qn_iW}{\tau_e}$$

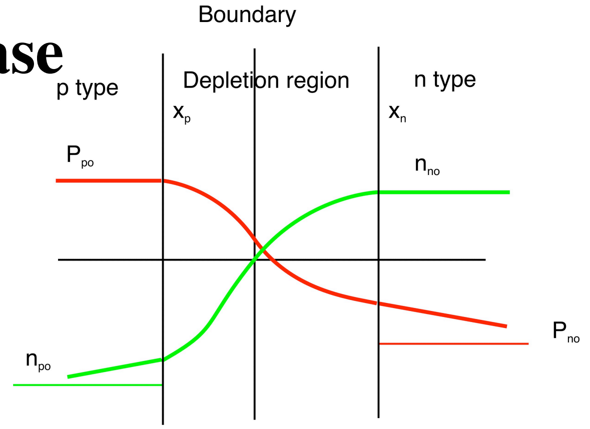
But the width increases as the square root of the applied voltage

$$J_{gen} \sim (V_{bi} + V^{\frac{1}{2}})$$

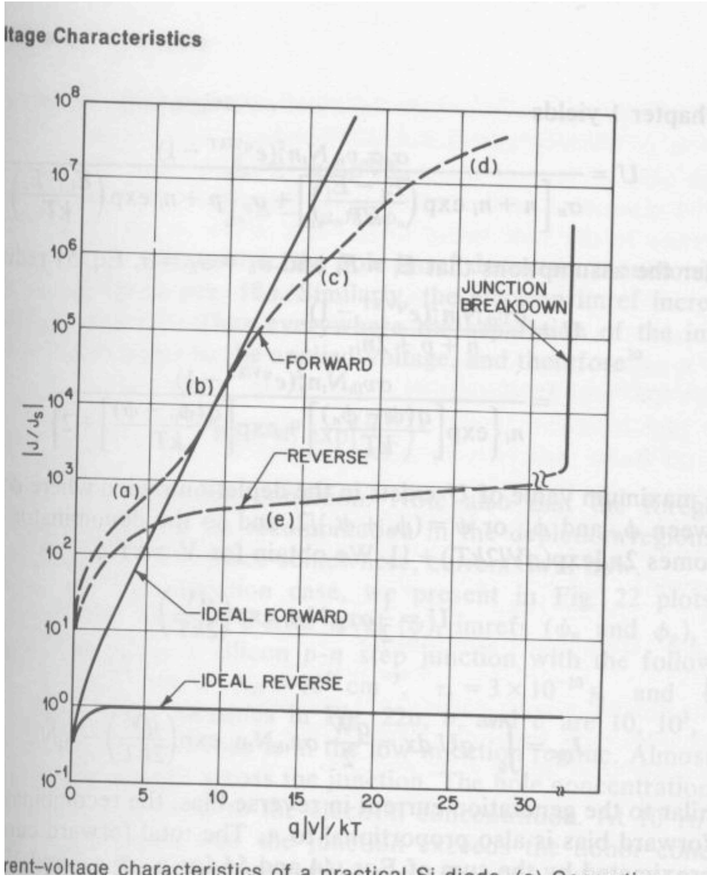
Total reverse current is for low n_i (for example Si second term is significant

$$J_r = q\sqrt{\frac{D_p}{\tau_p}}\frac{n_i^2}{N_D} + \frac{qn_iW}{\tau_e}$$

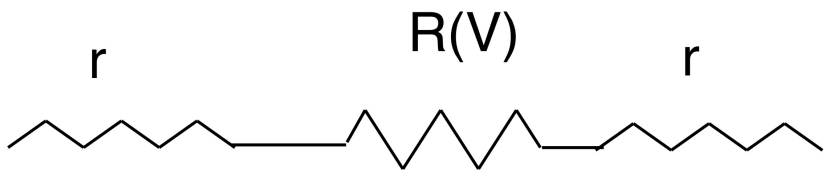
Departures from the ideal case



Also have recombination effects in forward bias case



And at very high currents the effects of the resistance of the neutral parts away from the junction and high injection where the number of injected carriers becomes comparable with the number of majority carriers overall behaviour looks like



Diffusion capacitance

We have met depletion capacitance associated with reversed biased junctions but in forward bias there is a significant capacitance from rearrangement of minority carriers.

Consider a small ac signal

$$V(t) = V_0 + V_1 e^{i\omega t} \quad J(t) = J_0 + J_1 e^{i\omega t}$$

$$\overline{p_n}(x,t) = P_{n1}(x) e^{i\omega t}$$

For small V_1

$$p_n = p_{no} e^{\left[\frac{q(V_0 + V_1 e^{i\omega t})}{kT}\right]} \approx p_{no} e^{\frac{qV_0}{kT}} + \frac{p_{no} q V_1}{kT} e^{\frac{qV_0}{kT}} e^{i\omega t}$$

Continuity equation becomes

$$i\omega \overline{p_n} = -\frac{\overline{p_n}}{\tau_p} + D_p \frac{\partial^2 \overline{p_n}}{\partial x^2}$$

Diffusion capacitance II

$$i\omega\overline{p_n} = -\frac{\overline{p_n}}{\tau_p} + D_p\frac{\partial^2\overline{p_n}}{\partial x^2} \qquad 0 = D_p\frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{no}}{\tau_p}$$

This is the same as the static case

$$\tau*_p = \frac{\tau_p}{1 + i\omega\tau_p}$$

Current is then

$$J_1 = \frac{qV_1}{kT}\left[\frac{qD_p p_{no}}{\frac{L_p}{\sqrt{1+i\omega\tau_p}}} + \frac{qD_n n_{po}}{\frac{L_n}{\sqrt{1+i\omega\tau_n}}}\right]e^{\left(\frac{qV_0}{kT}\right)}$$

Admittance (generalised conductance or inverse impedance

$$Y = J_1/V_1 = G_d + iwC_d$$

Diffusion capacitance III

For low frequencies when ϖτ<1

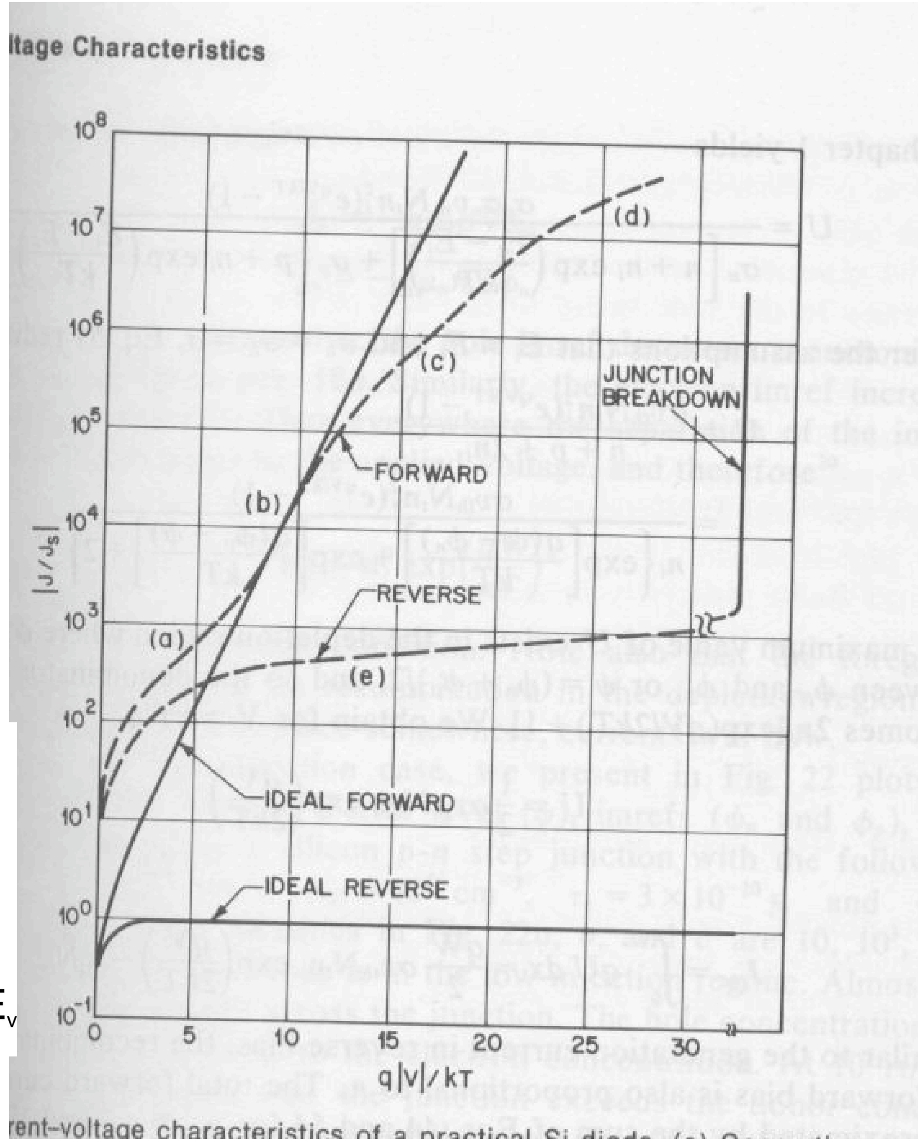
Conductance

$$G_{d0} = \frac{q}{kT}(\frac{qD_p p_{no}}{L_p} + \frac{qD_n n_{po}}{L_n})e^{(\frac{qV_0}{kT})}$$

Capacitance

$$C_{d0} = \frac{q}{kT}(\frac{qL_p p_{no}}{2} + \frac{qL_n n_{po}}{2})e^{(\frac{qV_0}{kT})}$$

Breakdown

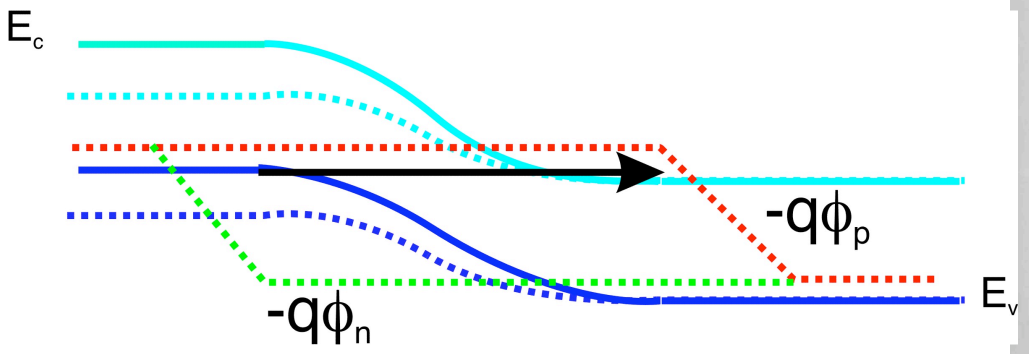


At extreme reverse bias the junction begins to conduct and is said to break down

3 Causes

Thermal instability where the heat dissipated by the reverse voltage excites more carriers causing a runaway current

Tunnelling



Avalanche multiplication