ECE 440
Lecture 32 : Minority and Majority Carrier Currents

Class Outline:

- Qualitative Current Flow in a P-N Junction
- Carrier Injection
- Reverse Bias

Key Questions

- What happens when we put a forward bias across a p-n junction?
- What type of currents are most important?
- How can I calculate the total current in the system?
- What happens when I apply reverse bias across the junction?

Qualitative Current Flow in a P-N Junction

How should the **diffusion current** behave?

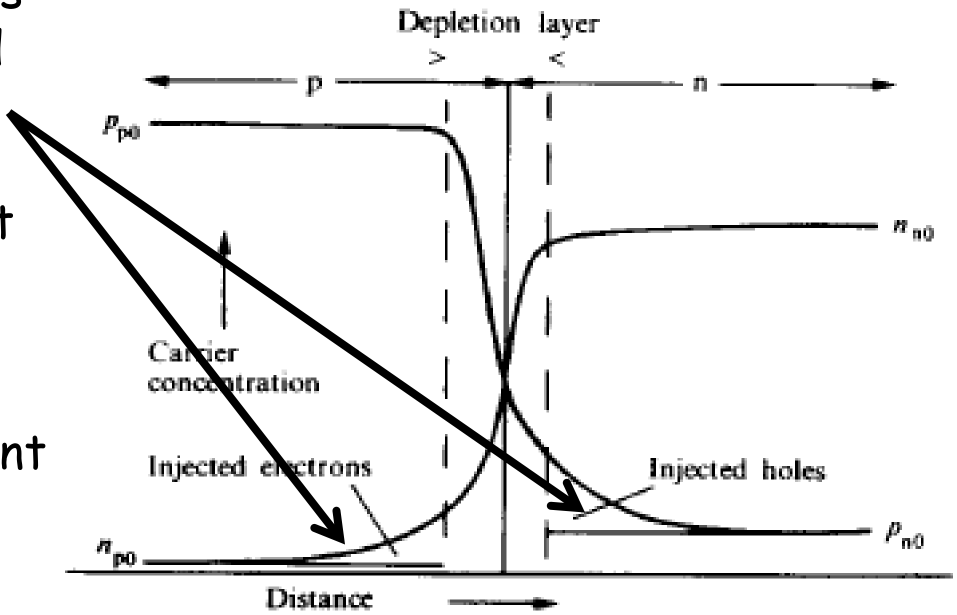
- The diffusion current is majority carriers on the n-side surmounting the barrier and crossing over to the p-side.

- Some high energy electrons can surmount the barrier at equilibrium.

- Under forward bias, both electrons and holes begin to diffuse creating a significant current.

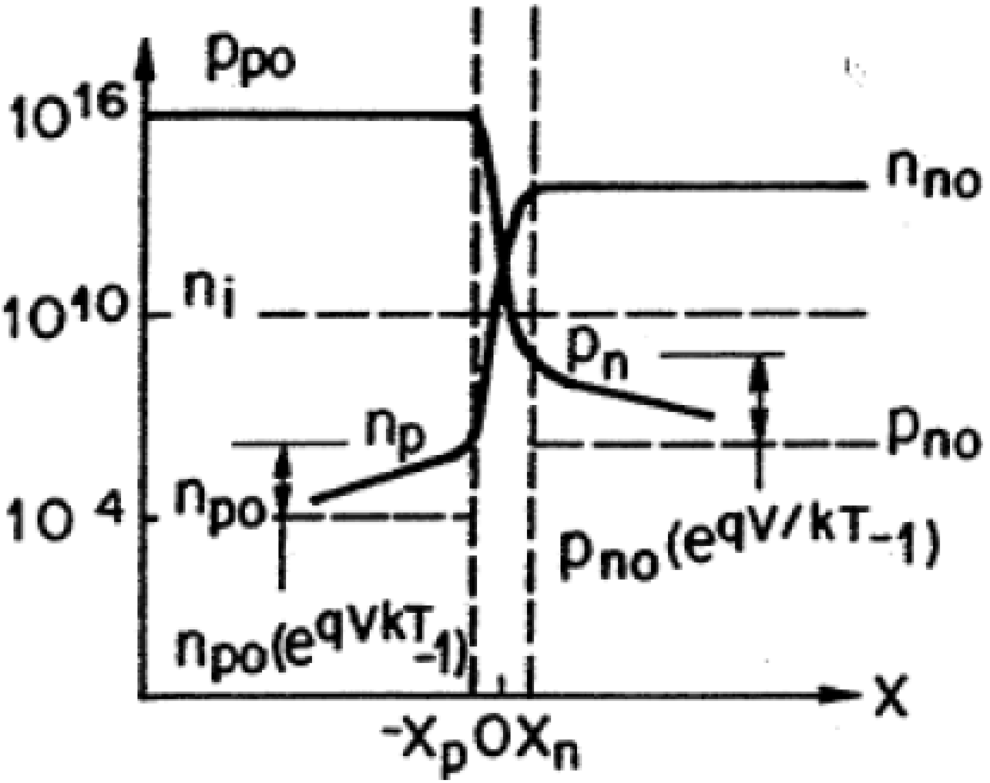
- Under reverse bias, the barrier to diffusion is raised and very few carriers can diffuse from one region to another.

- Diffusion current is usually negligible for reverse bias.

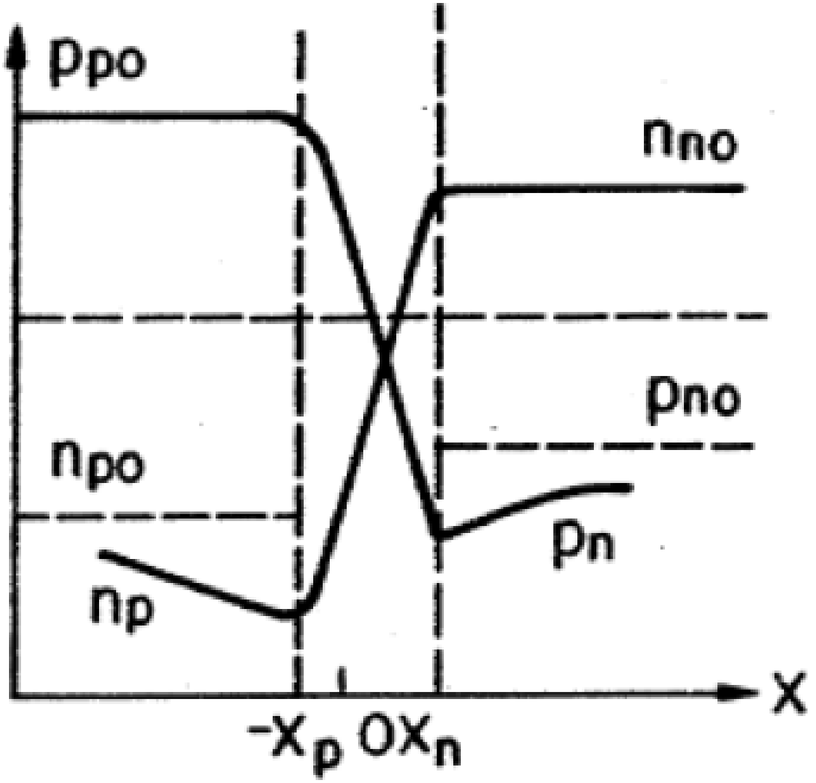


Qualitative Current Flow in a P-N Junction

Taking a closer look at the **forward and reverse bias carrier concentrations**…



Forward Bias



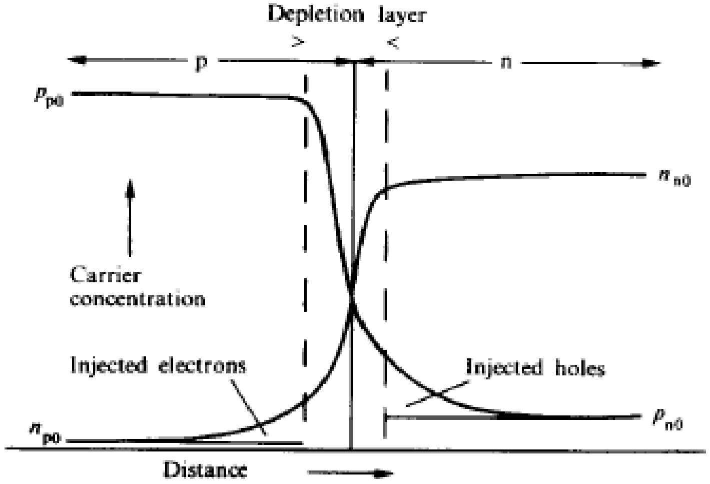
Reverse Bias

Physics of Semiconductor Devices, S.M. Sze, Wiley-Interscience

Qualitative Current Flow in a P-N Junction

Where there is diffusion, there is also **drift current**…

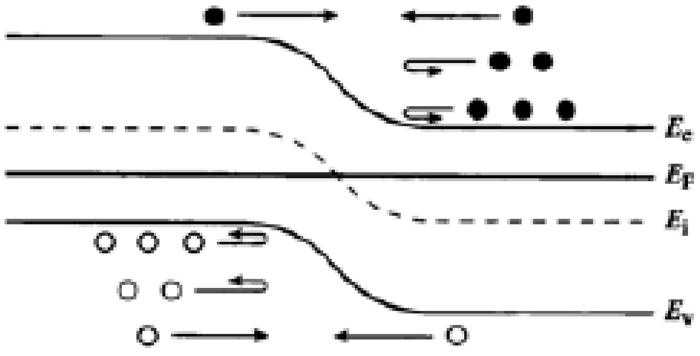
- The drift current is relatively insensitive to the height of the potential barrier.
- The drift current is not limited by how fast carriers are swept down the barrier but instead it is **limited by how often** they are swept down the barrier.
- Minority carriers wander too close to the space charge region and are swept across.
- This leads to a drift current.
- But there are not many carriers available to be swept across so this leads to a small current.
- Every minority carrier that participates will be swept across regardless of the size of the barrier.
- Minority carriers are generated by thermal excitation of EHPs.



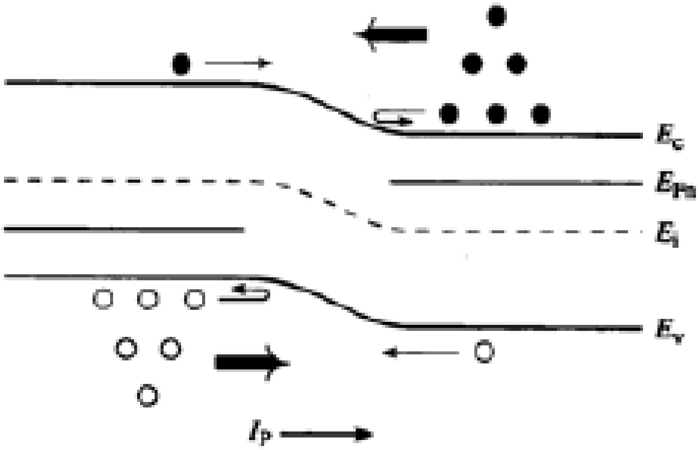
- **EHPs generated within L_P or L_N of the SCR will participate**.
- Referred to as **generation current**.

Qualitative Current Flow in a P-N Junction

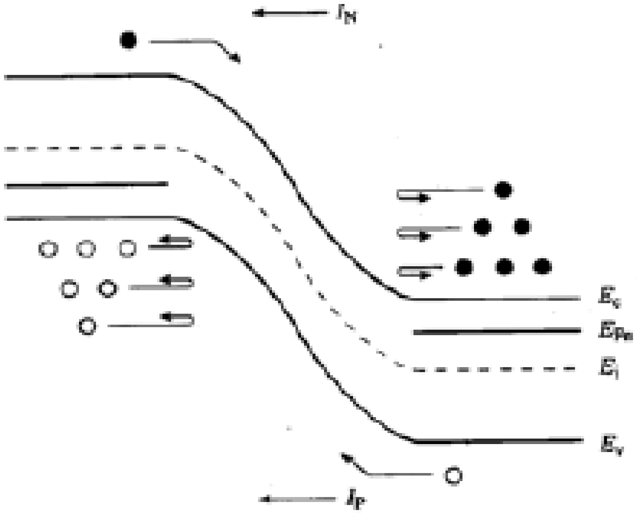
Summarizing the **total current** in the p-n junction…



Equilibrium:
- No current flows



Forward Bias:
- Large diffusion current from p to n



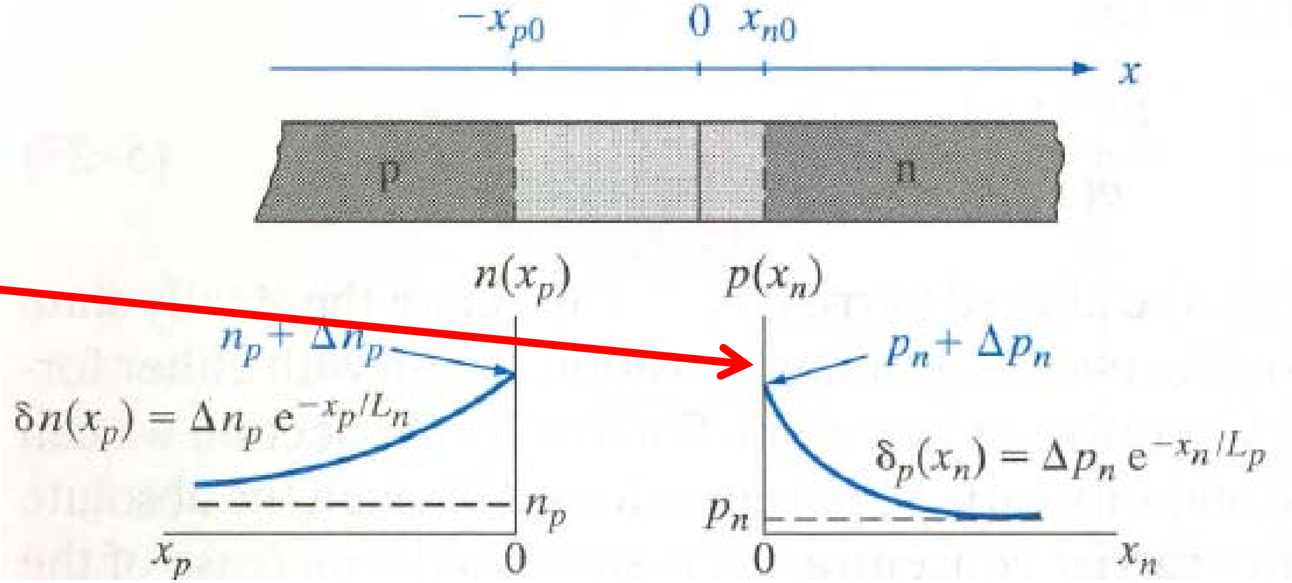
Reverse Bias:
- Both drift and diffusion currents are very small.
- Only current that flows is from the generation process..
- This current is bias independent.

Carrier Injection

We have insight into the **carrier concentration behavior under bias conditions**…

$$\frac{p(x_{n0})}{p_n} = e^{qV/kT}$$

Under forward bias: the equation suggests a greatly increased hole concentration at the edge of the n-side.



Conversely, the hole concentration under reverse bias is much smaller than the equilibrium value.

Exponential increase in hole concentration at x_{n0} with forward bias is an example of **minority carrier injection**.

Carrier Injection

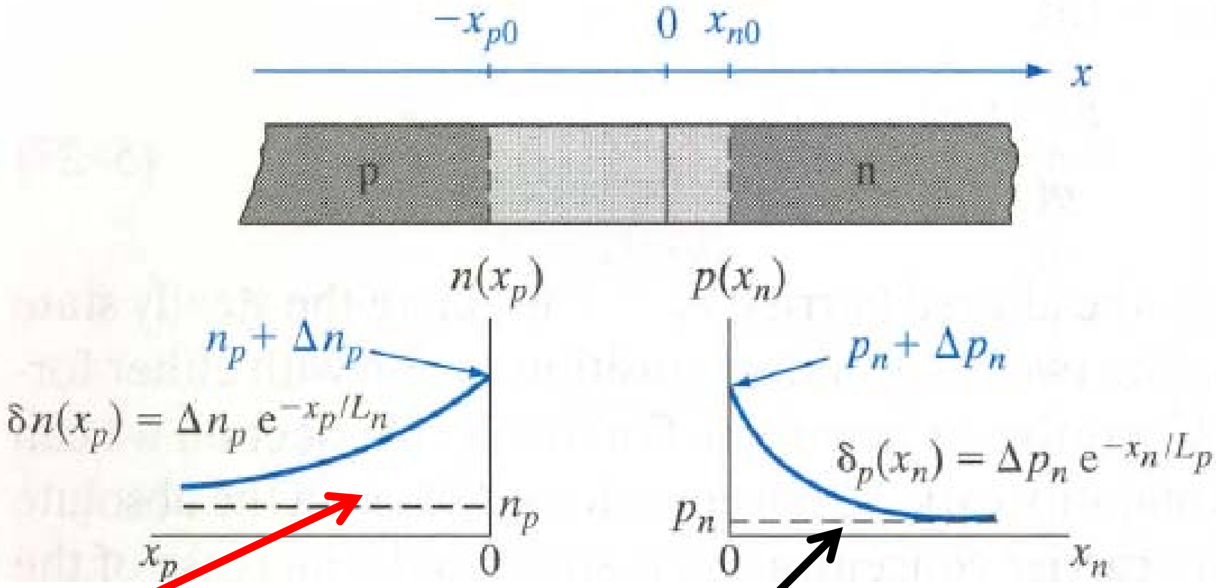
We can determine the **excess electrons and holes**…

Subtract the equilibrium concentrations…

$$\frac{p_p}{p_n} = e^{qV_0/kT}$$

From the concentrations under bias…

$$\frac{p(x_{n0})}{p_n} = e^{qV/kT}$$



$$\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1)$$

$$\Delta n_p = n(-x_{p0}) - n_p = n_p(e^{qV/kT} - 1)$$

- Should produce a distribution of excess holes in the n material.
- As the holes diffuse, the recombine so the solution is identical to the **diffusion equation**.

Carrier Injection

So we can write down the solution to the **diffusion equation** on either side of the junction…

Excess electrons on p-side: $\delta n(x_p) = \Delta n_p e^{-x_p/L_n} = n_p(e^{qV/kT} - 1)e^{-x_p/L_n}$

Excess holes on n-side: $\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n(e^{qV/kT} - 1)e^{-x_n/L_p}$

Now we understand the hole diffusion current at any point…

$$I_p(x_n) = -qAD_p \frac{d\delta p(x_n)}{dx_n} = qA\frac{D_p}{L_p}\Delta p_n e^{-x_n/L_p} = qA\frac{D_p}{L_p}\delta p(x_n)$$

Hole diffusion proportional to excess hole concentration. So what is the total current injected into the n-material?

$$I_p(x_n = 0) = \frac{qAD_p}{L_p}\Delta p_n = \frac{qAD_p}{L_p}p_n(e^{qV/kT} - 1)$$

$$I_n(x_p = 0) = -\frac{qAD_n}{L_n}\Delta n_p = -\frac{qAD_n}{L_n}n_p(e^{qV/kT} - 1)$$

Minus arises from current being directed opposite to x_p.

Carrier Injection

Take +x as the reference direction, what is the **total current**?

The total current must be the sum of the electron and hole contributions…

$$I = I_p(x_n = 0) - I_n(x_p = 0) = \frac{qAD_p}{L_p}\Delta p_n + \frac{qAD_n}{L_n}\Delta n_p$$

Which can be simplified to the **Diode Equation**…

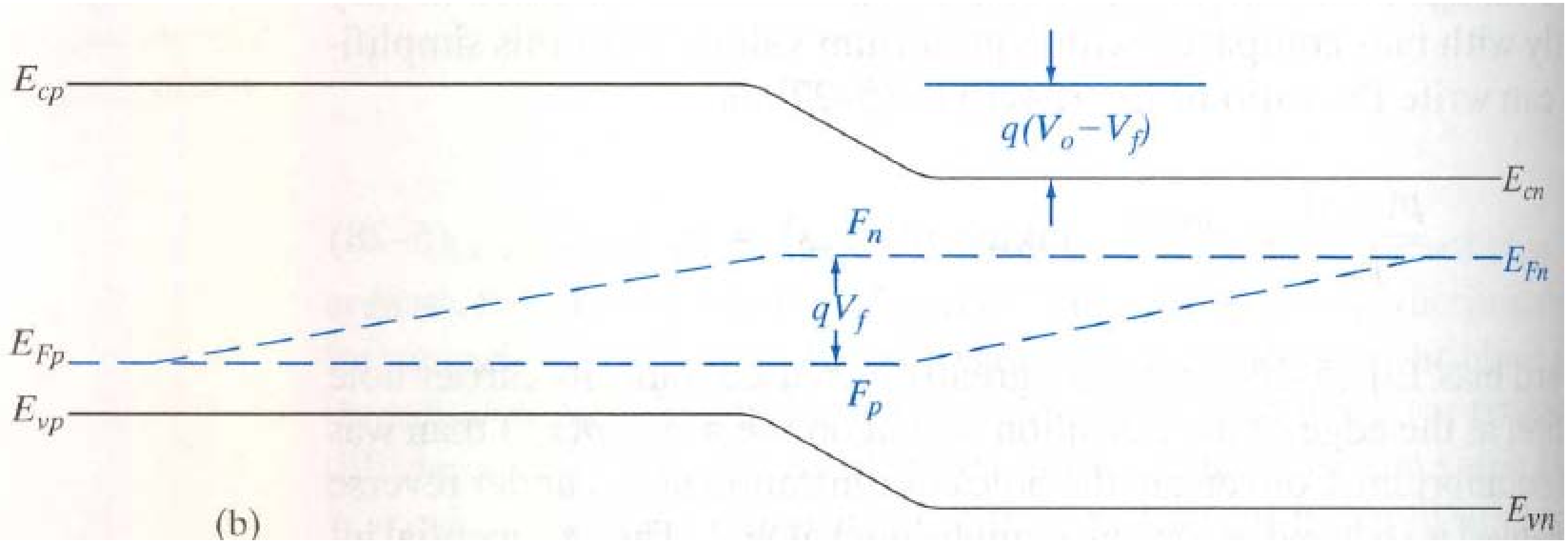
$$I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)$$

In arriving at this equation:

- We have made no assumptions as to the sign of the bias voltage.
- Bias may be either forward or reverse

Carrier Injection

But remember the **Fermi levels**…



We are out of equilibrium, so we need to use the quasi-Fermi levels to calculate the carrier concentrations…

$$pn = n_i^2 e^{(F_n - F_p)/kT} = n_i^2 e^{(qV/kT)}$$

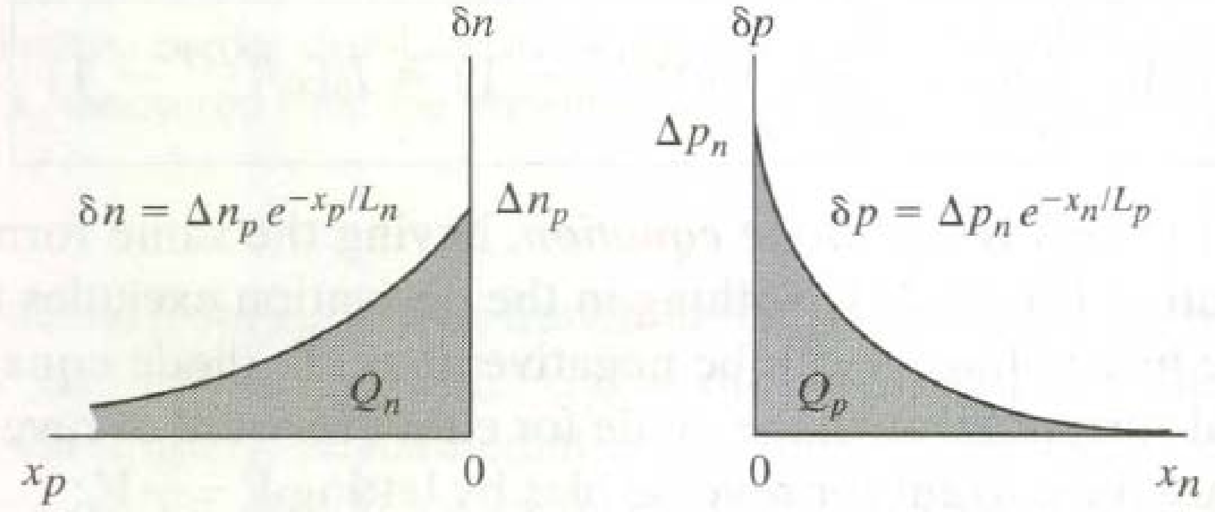
- Minority carrier concentration usually varies the most and the majority carrier quasi-Fermi level is close to the original Fermi level.
- Outside the space charge region the quasi-Fermi levels vary linearly and then merge with the bulk Fermi levels.

Carrier Injection

Is there another way to **calculate the current**?

- Assume the current supplies the excess carriers in the distributions.

- I_p must supply enough holes per second to maintain the steady-state.



We can determine the total positive charge stored in the excess carrier distribution…

$$Q_p = qA\int_0^\infty \delta p(x_n)dx_n = qA\Delta p_n \int_0^\infty e^{-x_n/L_p}dx_n = qAL_p\Delta p_n$$

Charge that recombines must then be resupplied… $D_p/L_p = L_p/\tau_p$

$$\boxed{I_p(x_n = 0) = \frac{Q_p}{\tau_p} = qA\frac{L_p}{\tau_p}\Delta p_n = qA\frac{D_p}{L_p}\Delta p_n}$$

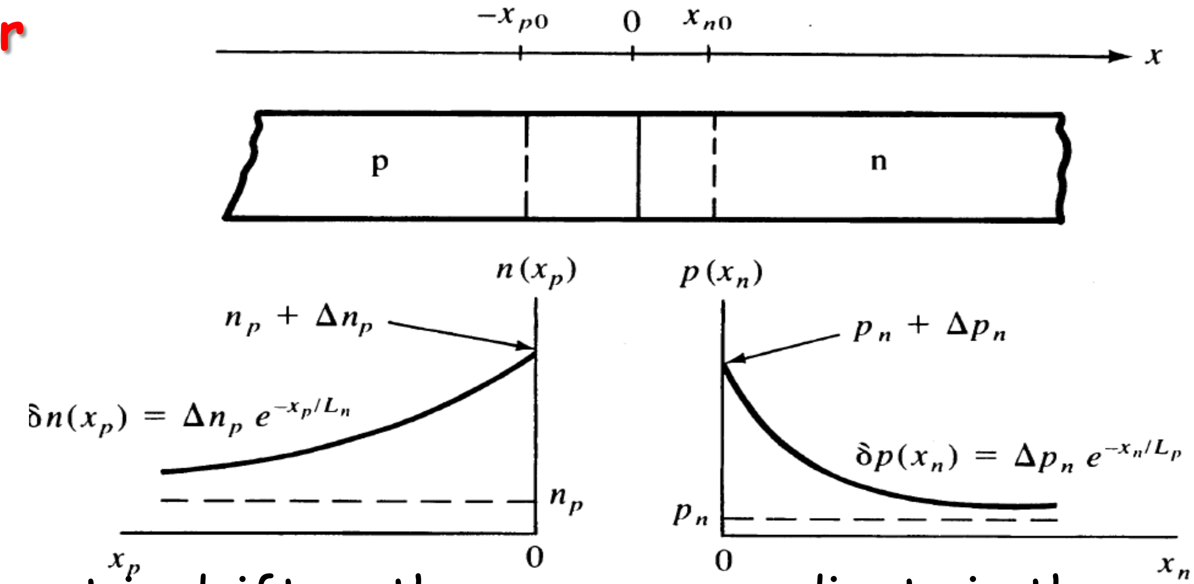
- Solve for negative charge to get τ_n.

Charge Control Approximation

Carrier Injection

But is this current drift, or diffusion or both?

Near the junction the majority carrier concentration changes with the minority carrier concentration to keep the device charge neutral.



- In the bulk most of the current is drift as there are no gradients in the concentrations.

- As we approach the junction, carrier concentrations change and we get a combination of drift and diffusion. Drift will dominate for majority carriers.

- Note that the electric field in the neutral regions cannot be zero, as we assumed but since, we have a large majority carrier concentration, the field need not be large.

Reverse Bias

Most of the preceding analysis dealt with forward bias, what about the reverse bias case?

We can use the same equations and analysis to determine the reverse bias behavior…

Set $V = -V_r$ which biases the p-side negatively with respect to the n-side and examine the relationship for the excess hole concentration…

$$\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1)$$

$$\downarrow$$

$$\Delta p_n = p_n(e^{q(-V_r)/kT} - 1) \simeq -p_n \qquad V_r \gg k_bT/q$$

- For large reverse bias, the minority carrier concentration goes to zero.
- Minority carrier concentration equations still given by previously derived equations.
- Depletion of minortiy carriers extends one diffusion length on either side of the junctions.
- Referred to as **minority carrier extraction.**

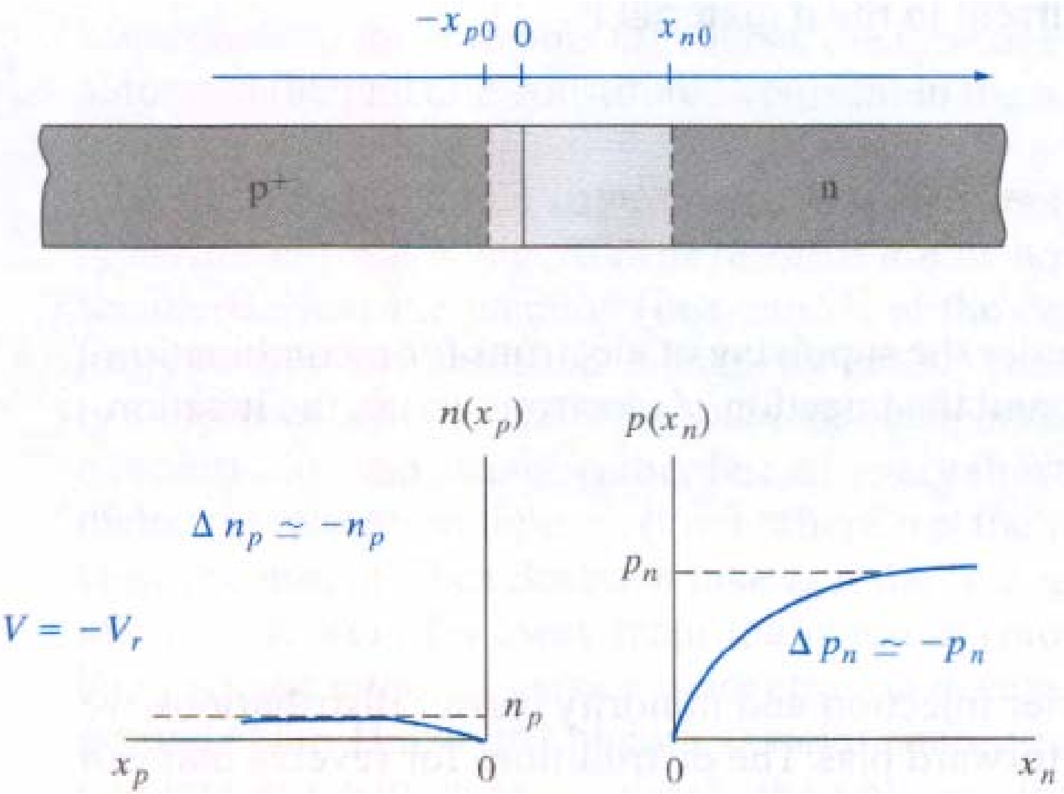
Reverse Bias

What is happening physically to the carriers…

- Carriers are being swept down the barrier at the junction to the other side.

- They are not being replaced by an opposing diffusion of carriers.

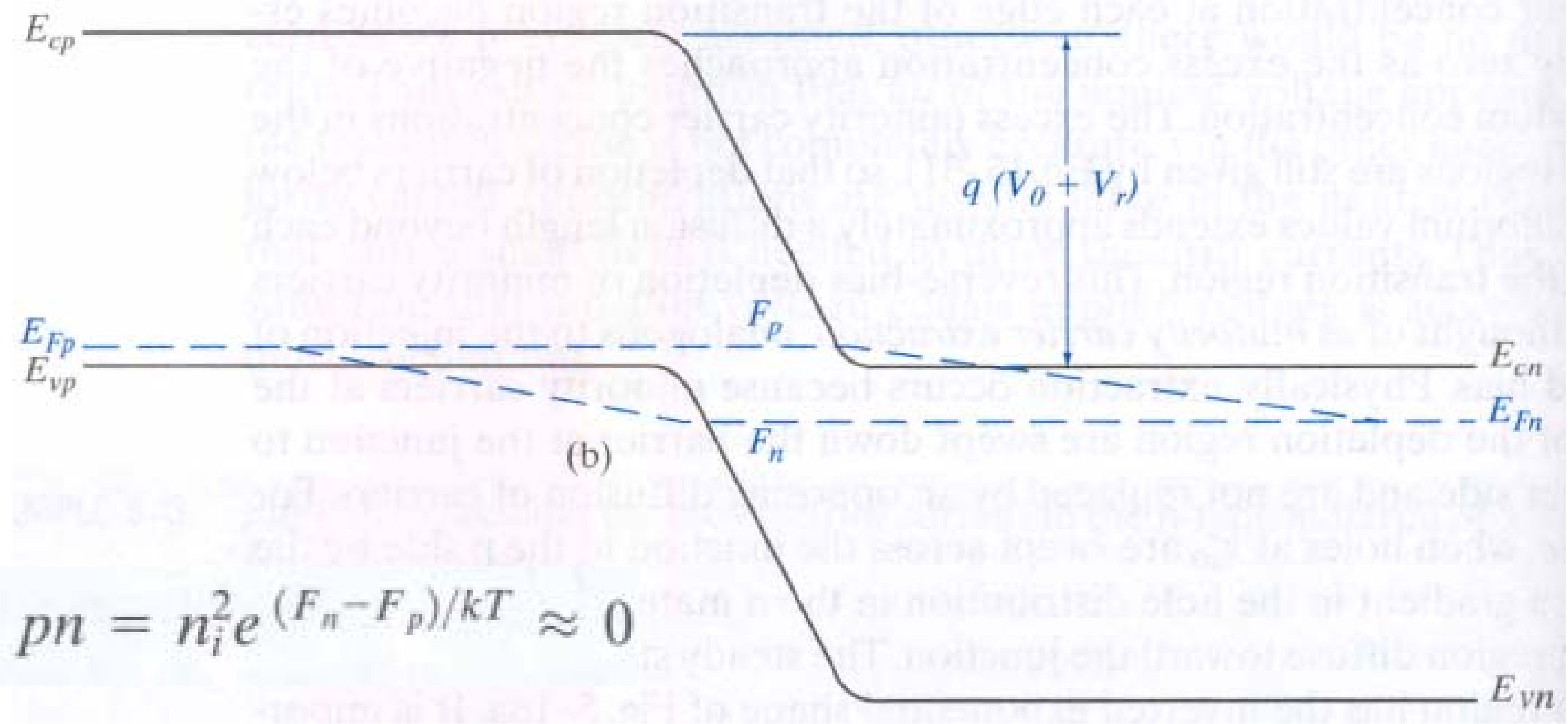
- Reverse bias saturation occurs because of drift of carriers down the barrier



But the rate of drift depends on the rate of minority carriers arrive by diffusion from the neutral material supplied by thermal generation.

Reverse Bias

And the quasi-Fermi levels move again…



$$pn = n_i^2 e^{(F_n - F_p)/kT} \approx 0$$

- Fn moves farther away from EC towards EV because in reverse bias we have fewer carriers than in equilibrium.
- **Quasi-Fermi levels here go inside the bands but we need to remember that Fp is a measure of the hole concentration and is correlated with EV and not EC.**
- This just tells us we have very few holes (smaller than in equilibrium).

Reverse Bias

Let's try a problem…

A pn junction photodiode is just a pn junction diode that has been specifically fabricated and encapsulated to permit light penetration into the vicinity of the metallurgical junction. Commercially available solar cells are in essence large-area pn junction photodiodes designed to minimize energy losses. The general form of the similar *I-V* characteristics exhibited by photodiodes is readily established by a straightforward modification of the ideal diode equation.

Consider a p+-n step junction diode where incident light is uniformly absorbed throughout the device producing a photogeneration rate of GL EHP per cm^{-3}-sec. Assume low-level injection prevails.

(a) What is the excess minority carrier concentration on the n-side a large distance from the junction.

(b) Derive an equation for the *I-V* characteristics under illumination.

(c) Sketch the general form of the *I-V* characteristics taking in turn $G_L = 0$, G_{L0}, $2G_{L0}$, and $4G_{L0}$.