ECE 340
Lecture 23 : Qualitative Current Flow in a P-N Junction

Class Outline:

- Qualitative Current Flow in a P-N Junction

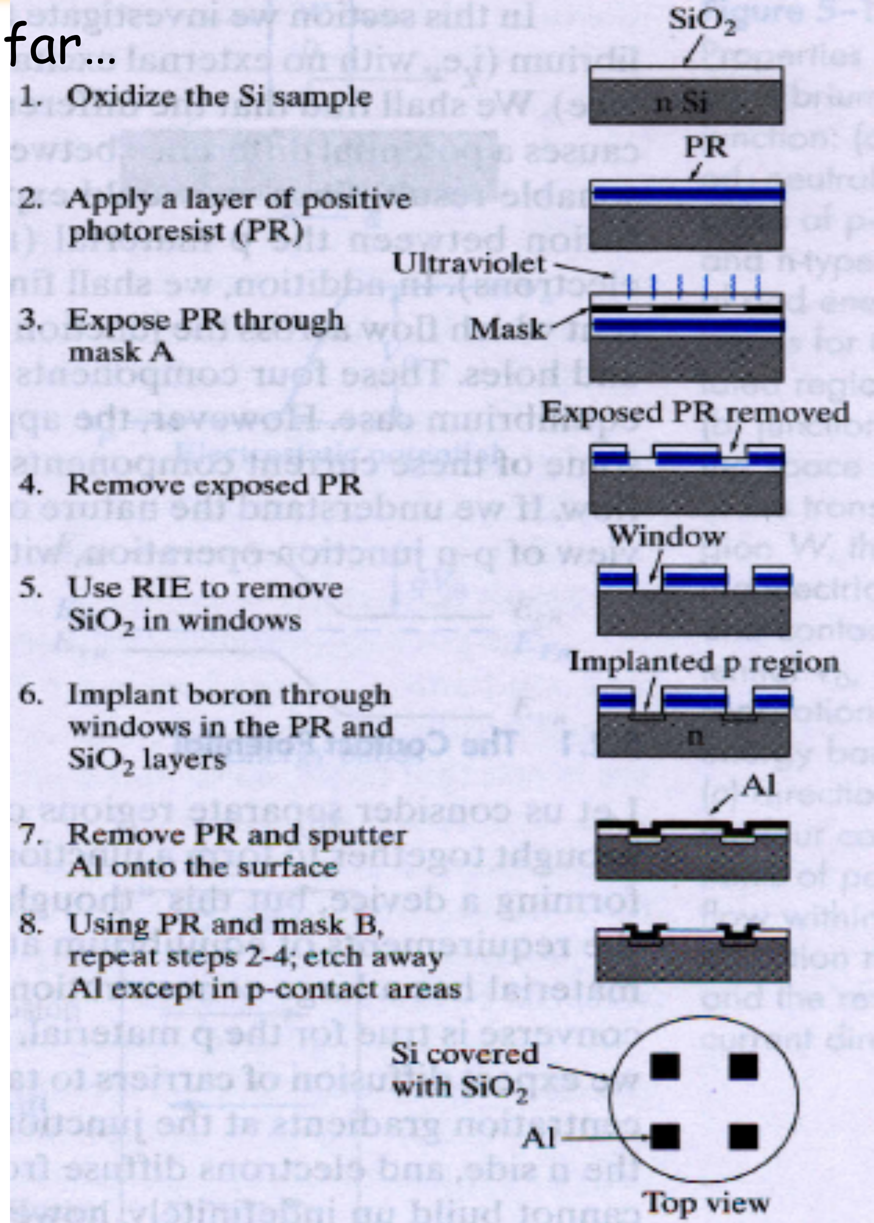
Key Questions

- What happens to a p-n junction under a forward bias?
- What happens to a p-n junction under a reverse bias?
- What physical processes are in play?
- What can I safely ignore when I apply a bias?

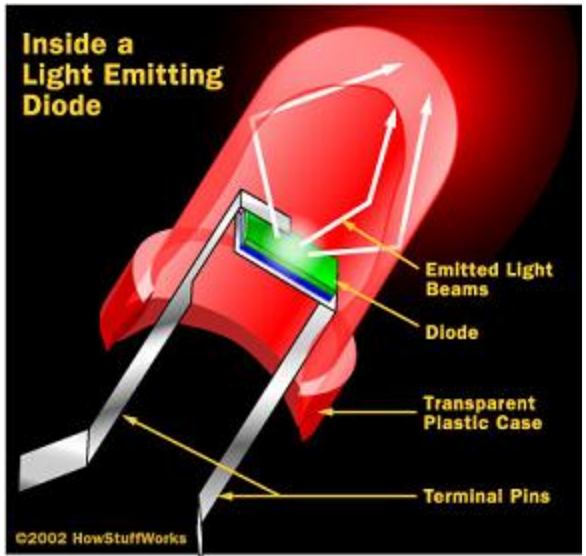
Qualitative Current Flow in a P-N Junction

What do we know about **p-n junctions** so far…

We know how to make them: →



We can make interesting things out of them…

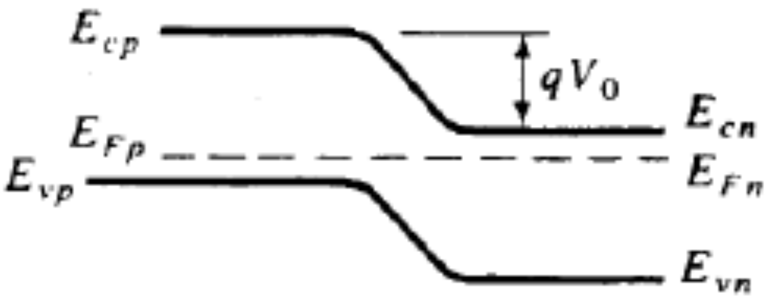


LED

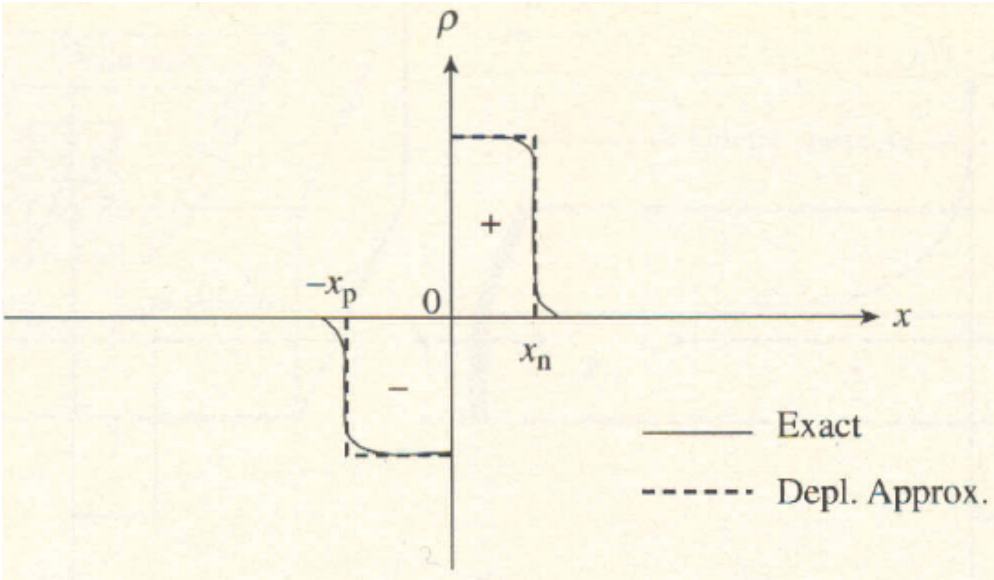
Photocells

Qualitative Current Flow in a P-N Junction

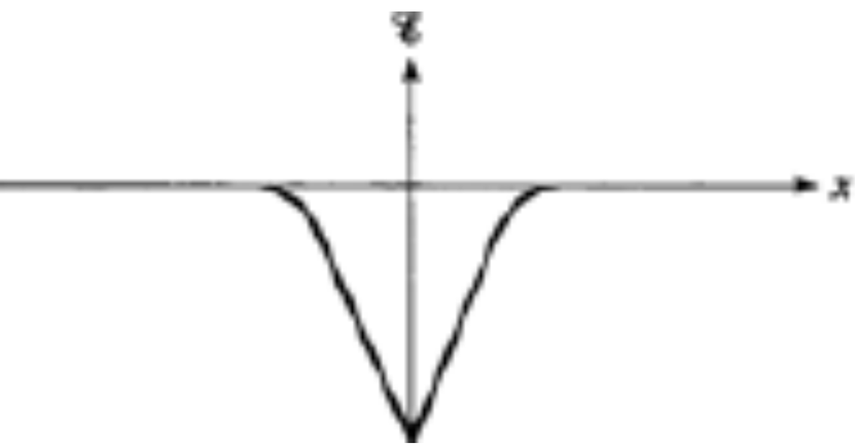
We understand the electrostatics:



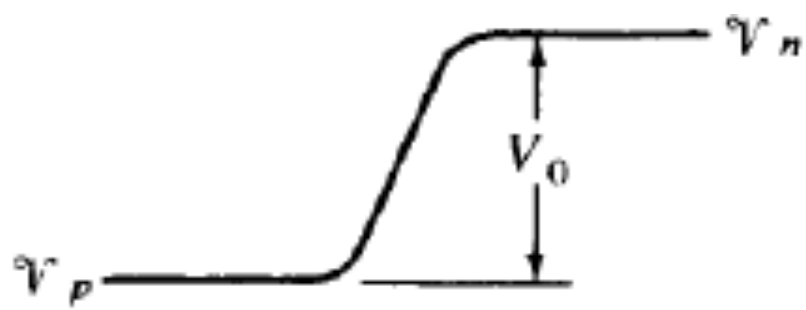
Energy bands



Charge Density



Electric Field



Electrostatic potential

Qualitative Current Flow in a P-N Junction

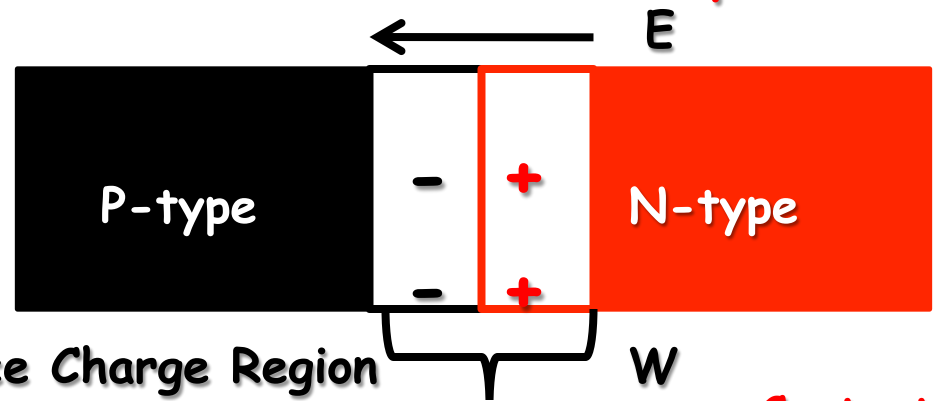
We have a tentative game plan for solving p-n junction problems…

Plan for finding the **charge density**, **electric field**, and **potential**:

1. Find the **built-in potential, V_0**.
2. Use the **depletion approximation** to find the **charge density**.
   - Gives an easy solution to the Poisson equation.
   - Depletion layer widths are still unknown.
3. Integrate the **charge density** to find the **electric field**.
   - Be sure to use the appropriate boundary conditions $E(-x_p) = E(x_n) = 0$.
4. Integrate the **electric field** to find the **potential**.
   - Boundary conditions are $V(-x_p) = 0$ and $V(x_n) = V_0$.
5. Solve for the **depletion layer widths** ($-x_p$ and x_n).
   - Use the fact that for $E(x)$ to be continuous at $x = 0$, $N_A x_p = N_D x_n$.

Qualitative Current Flow in a P-N Junction

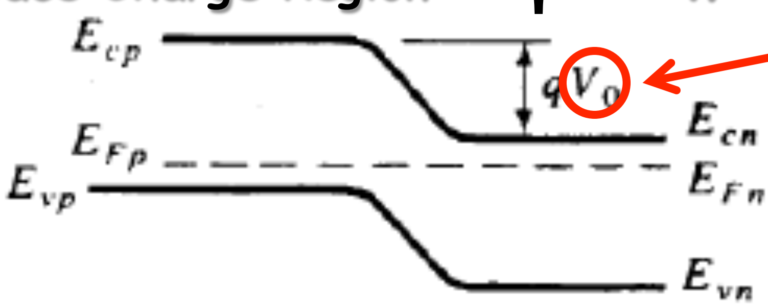
We know that currents flow in **equilibrium**…



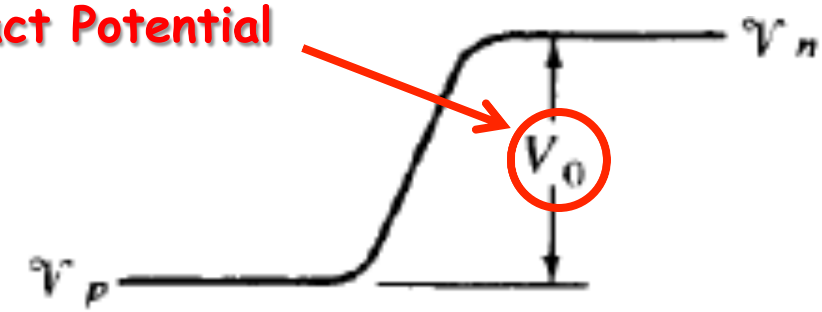
Space Charge Region

$$J_p(\text{drift}) + J_p(\text{diff.}) = 0$$
$$J_n(\text{drift}) + J_n(\text{diff.}) = 0$$

Contact Potential



Energy bands



Electrostatic potential

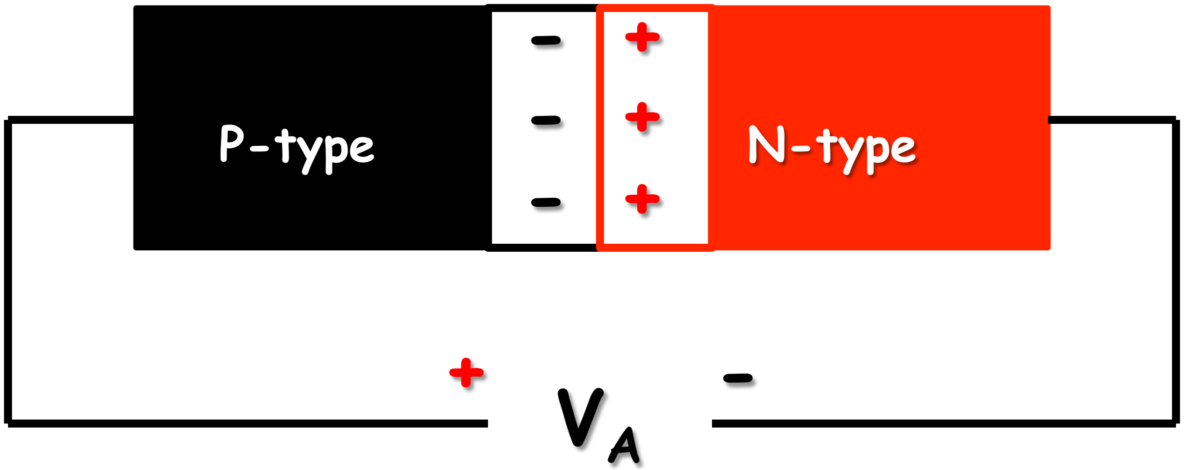
φ_p (diff)	φ_p (diff)	φ_n (diff)	φ_n (drift)
J_p (diff)	J_p (diff)	J_n (diff)	J_n (drift)

Dashed Arrows = Particle Flow

Solid Arrows = Resulting Currents

Qualitative Current Flow in a P-N Junction

Now apply a bias. What do we know?



Things we know or will assume:

•We are assuming that the contacts to the p-n junction are ohmic.

•We are assuming that there is no voltage drop in the bulk of the p and n regions (low level injection).

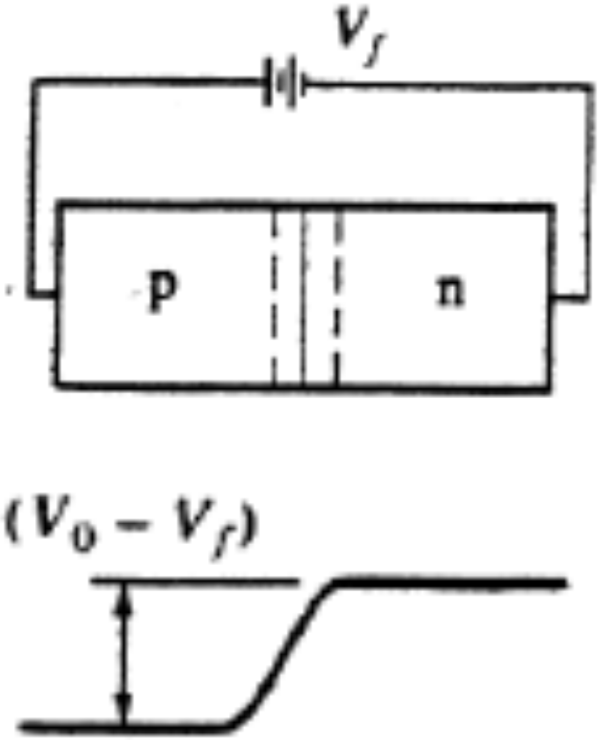
•We assume that all of the voltage is dropped across the space charge region.

•We assume that $V_A < V_0$ otherwise we cannot assume low level injection.

Qualitative Current Flow in a P-N Junction

So what will happen to the **potential**…

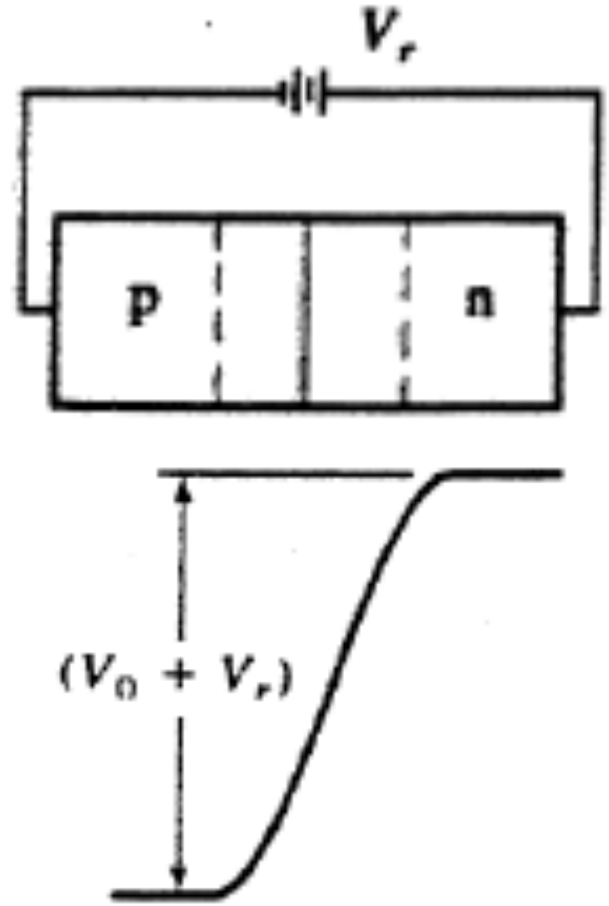
Forward Bias ($V = V_F$):



- The potential barrier is lowered for a forward bias.

- The potential barrier is raised for a reverse bias.

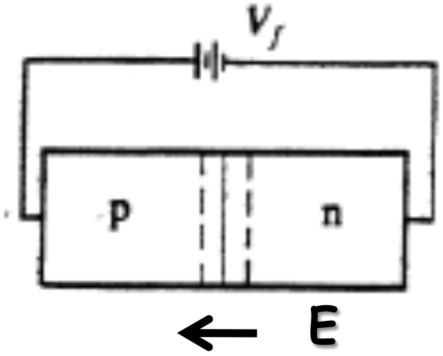
Reverse Bias ($V = -V_R$):



Qualitative Current Flow in a P-N Junction

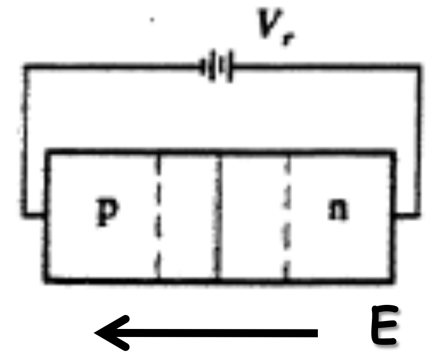
What will happen to the **electric field and space charge region**?

Forward Bias ($V = V_F$):



$$W = \left[\frac{2\epsilon V_0}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2} = \left[\frac{2\epsilon V_0}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)\right]^{1/2}$$

Reverse Bias ($V = -V_R$):



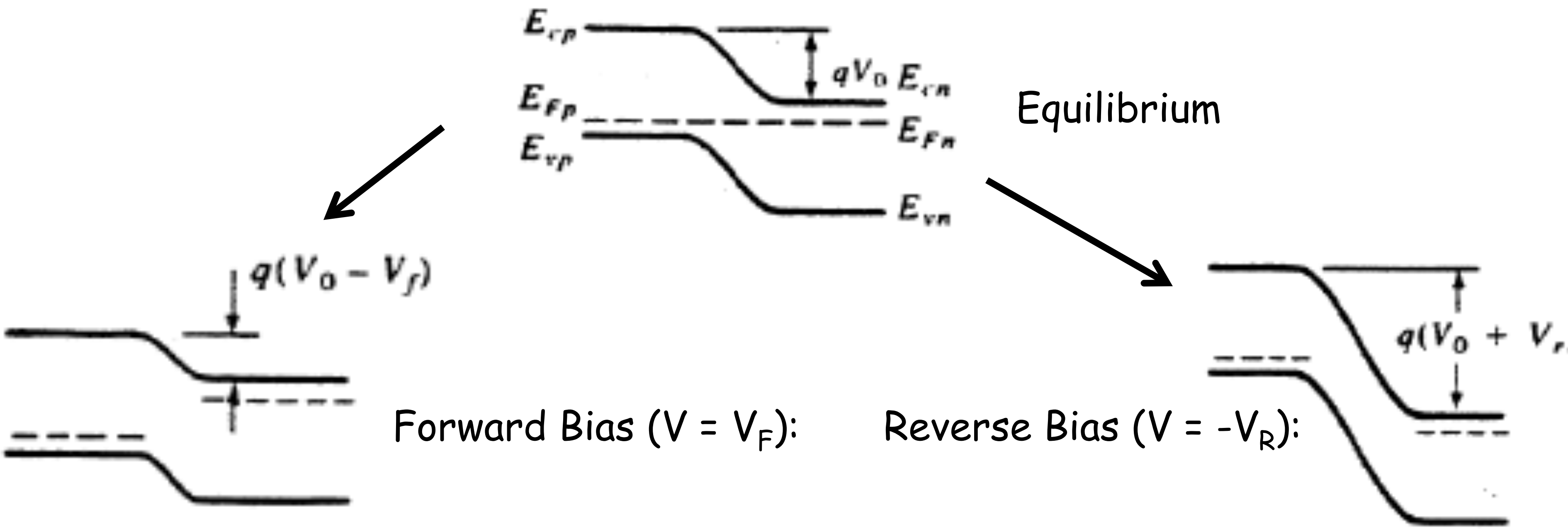
When we apply a bias we are changing the electric field which will change the space charge region as we still need the proper number of positive and negative charges.

- Apply a **positive bias** and we will **decrease the electric field** because the bias potential will oppose it. We also expect a **smaller space charge region** because of the smaller field with reduced uncompensated charge.

- Apply a **negative charge** and we will **increase the electric field** as the bias potential is now in the same direction as the field. We expect a **larger space charge region** because we now have more uncompensated charge to balance.

Qualitative Current Flow in a P-N Junction

What happens to the **energy bands**?



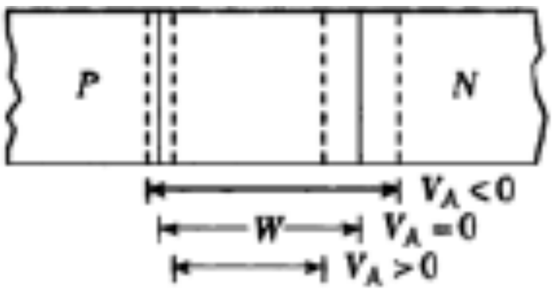
•We can already anticipate the change in the energy bands as a **forward bias** will bring the **bands closer** to one another.

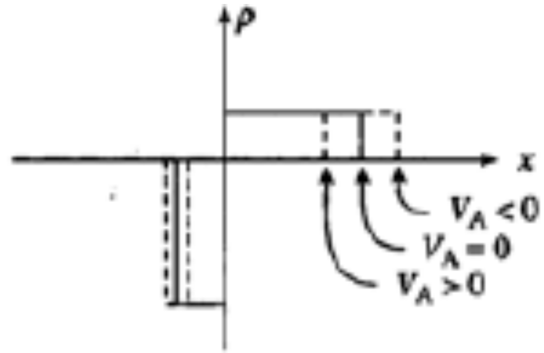
•Naturally, if we then apply a **reverse bias** the energy bands, the bands will **separate farther apart**.

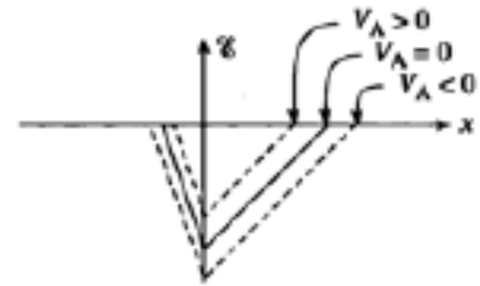
•The bias also separates the Fermi levels with **E_{FN} > E_{FP} by V_f for forward bias and E_{FN} < E_{FP} by V_r for reverse bias**.

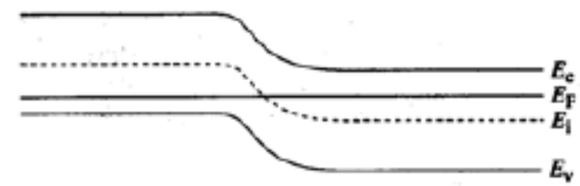
Qualitative Current Flow in a P-N Junction

Let's summarize the electrostatic changes with applied bias…

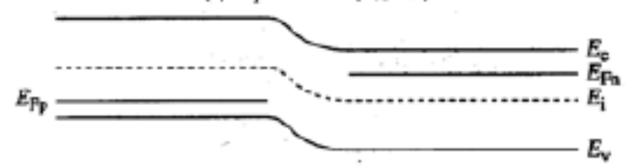




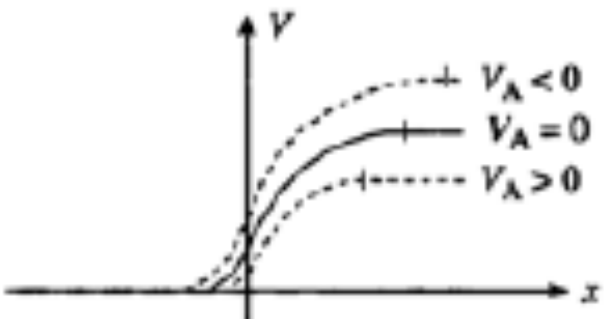


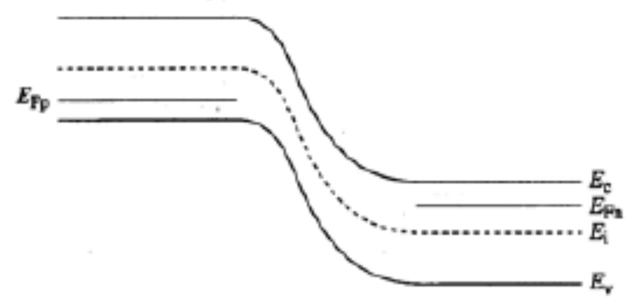


(a) Equilibrium ($V_A = 0$)



(b) Forward bias ($V_A > 0$)





(c) Reverse bias ($V_A < 0$)

Qualitative Current Flow in a P-N Junction

How should the **diffusion current** behave?

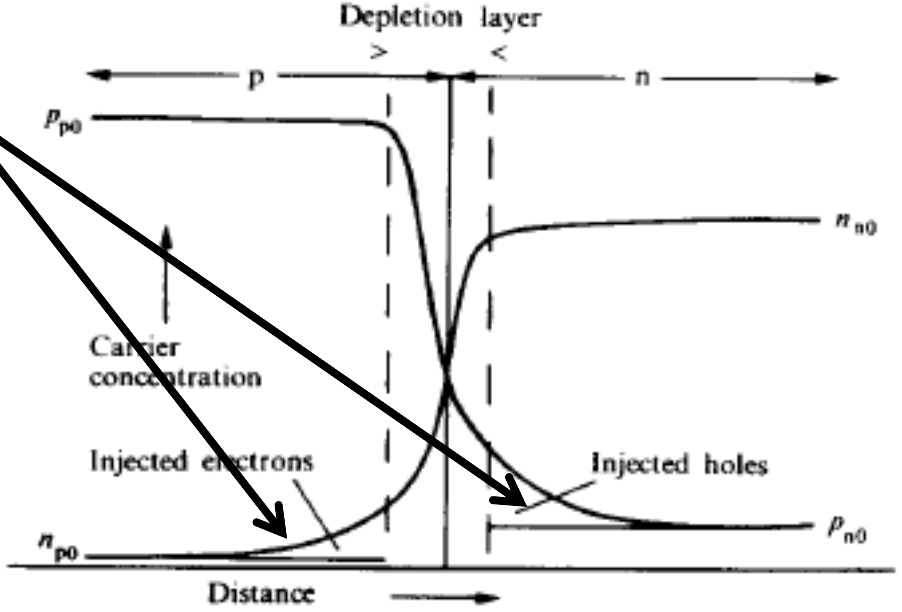
•The diffusion current is majority carriers on the n-side surmounting the barrier and crossing over to the p-side.

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

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

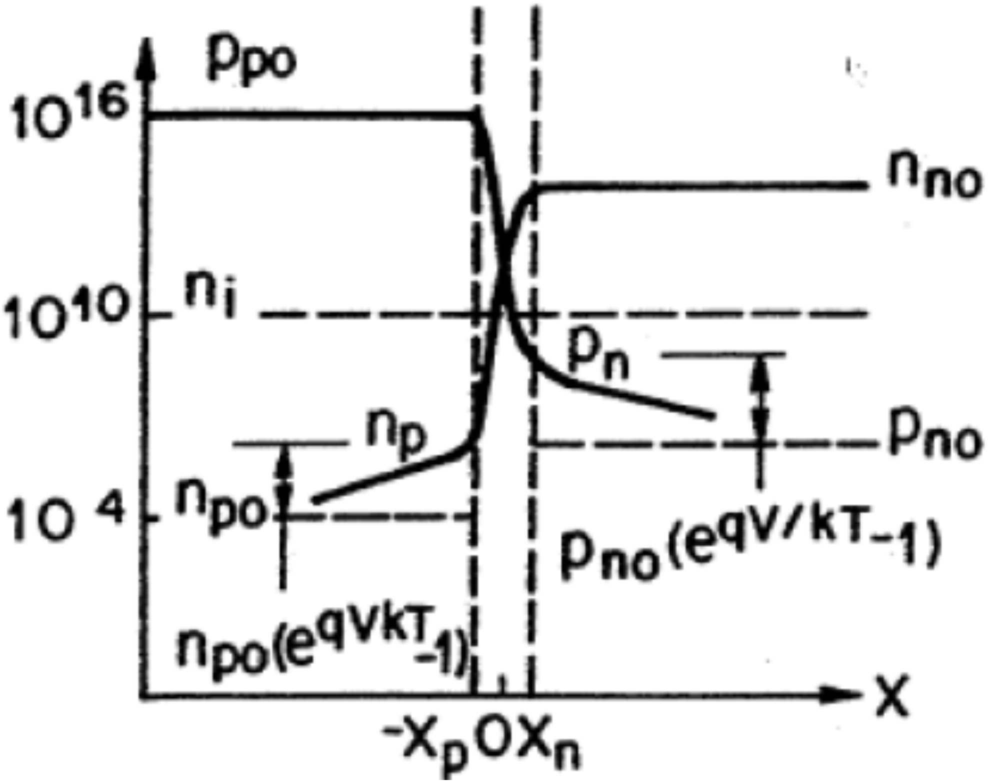
•Under reverse bias, the barrier to diffusion is raised and very few carriers can diffuse from one region to another.

•Diffusion current is usually negligible for reverse bias.

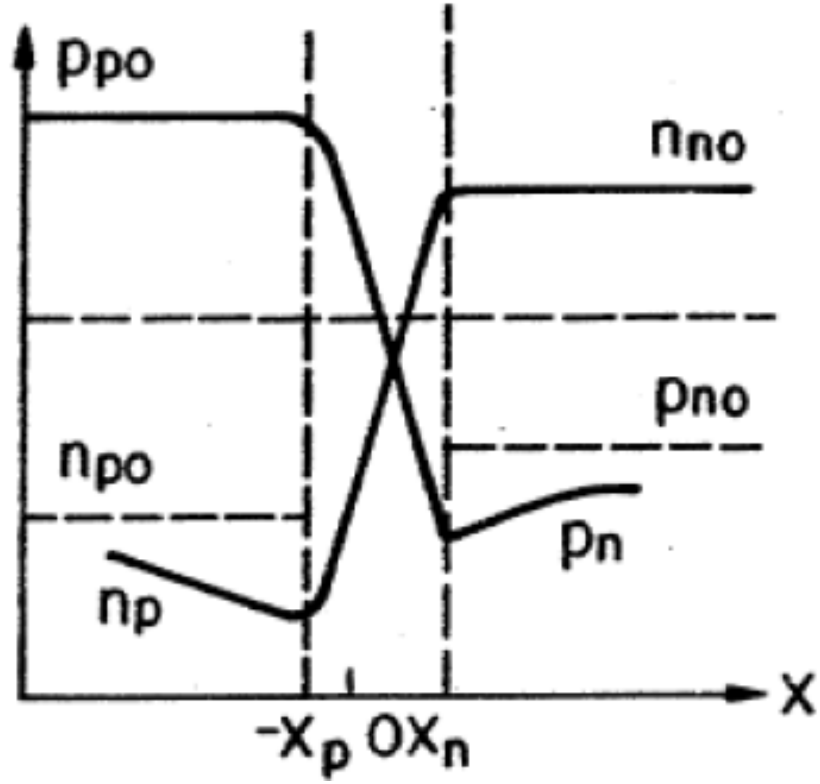


Qualitative Current Flow in a P-N Junction

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.

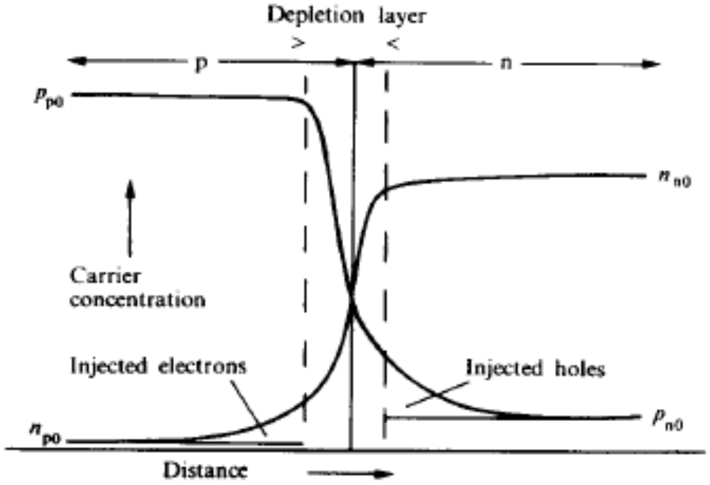
•Minority carriers wander too close to the space charge region and are swept across.

•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.

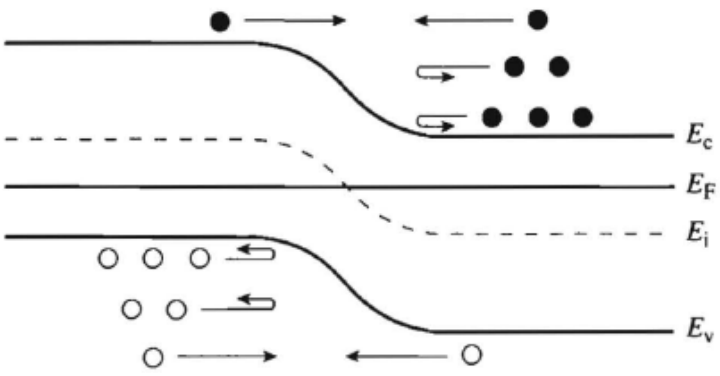


•EHPs generated within L_P or L_N of the SCR will participate.

•Referred to as **generation current**.

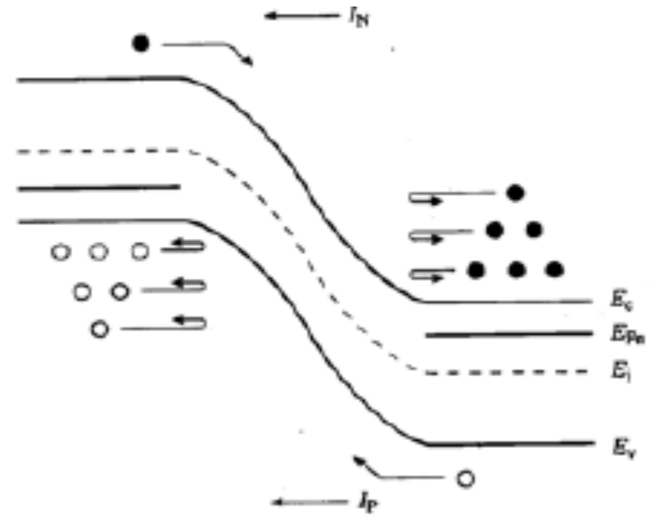
Qualitative Current Flow in a P-N Junction

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

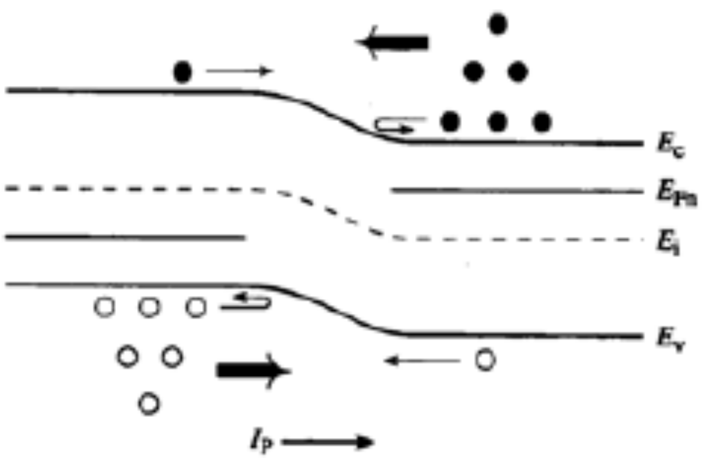


(a) Equilibrium ($V_A = 0$)

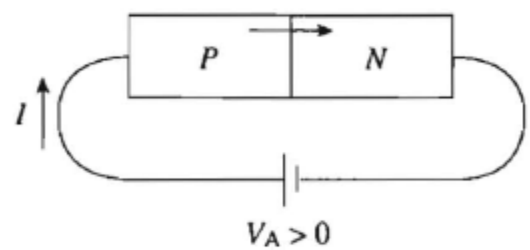
Equilibrium:
- No current flows



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



Forward Bias:
- Large diffusion current from p to n



Qualitative Current Flow in a P-N Junction

Take a closer look at the **forward bias** regime…

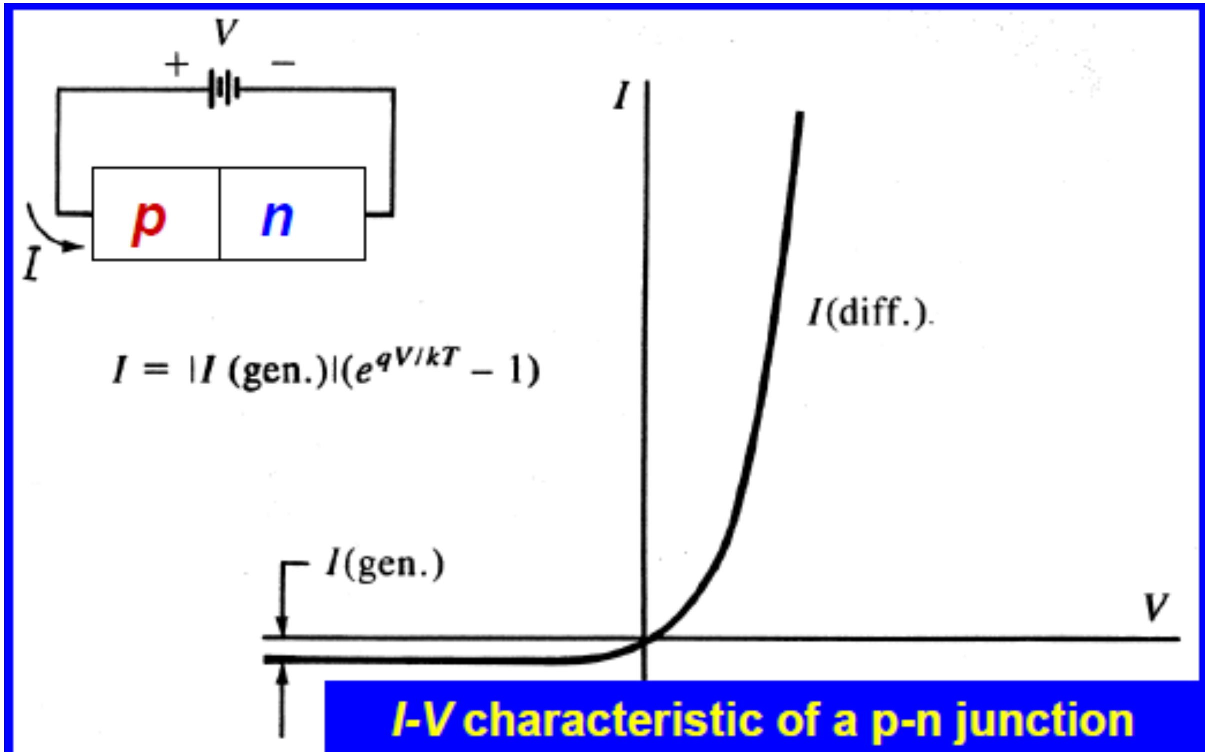
Forward bias increases the probability of diffusion across the junction exponentially.

$$I = I_0(e^{qV/kT} - 1)$$

Total current is the diffusion current minus the absolute value of the generation current.

At V = 0, the generation and diffusion currents cancel.

End result is a rectifying type of behavior seen in MS contacts.

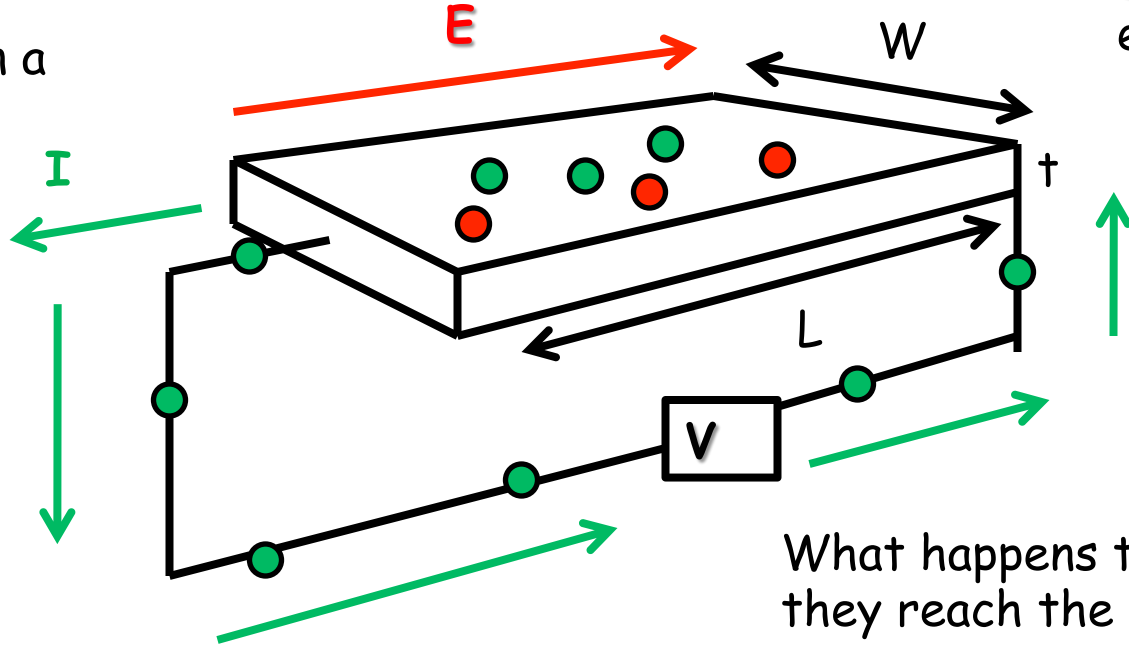


I-V characteristic of a p-n junction

Qualitative Current Flow in a P-N Junction

Let's try to visualize what is going on…

Carrier motion in a material:



Electrons are easy to visualize.

For this structure, we can use the dimensions to define the resistance:

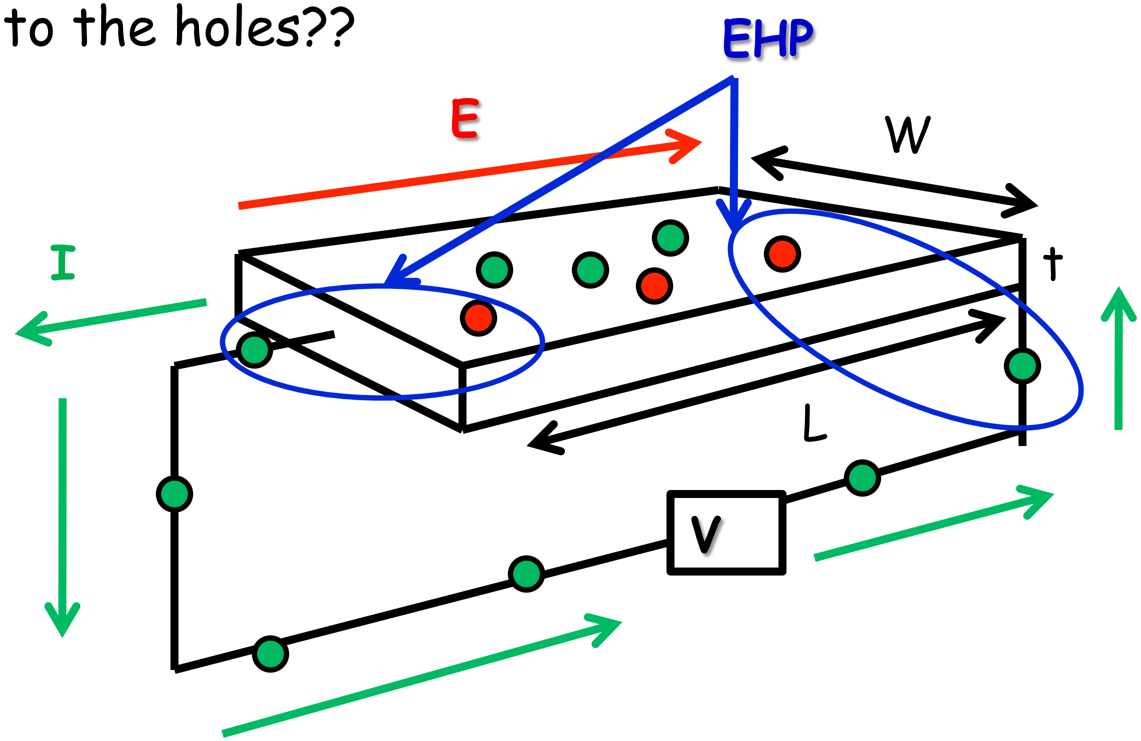
$$R = \frac{\rho L}{wt} = \frac{L}{\sigma wt}$$

What happens to **holes** when they reach the contact?

- Carriers move in a group.
  - Electrons move against the electric field.
  - Holes move with the electric field.
- Convention makes the drift currents flow in the same direction.
- The contacts are considered ohmic
  - Perfect sources and sinks for carriers.
  - No tendency to inject either carrier.

Qualitative Current Flow in a P-N Junction

What happens to the holes??



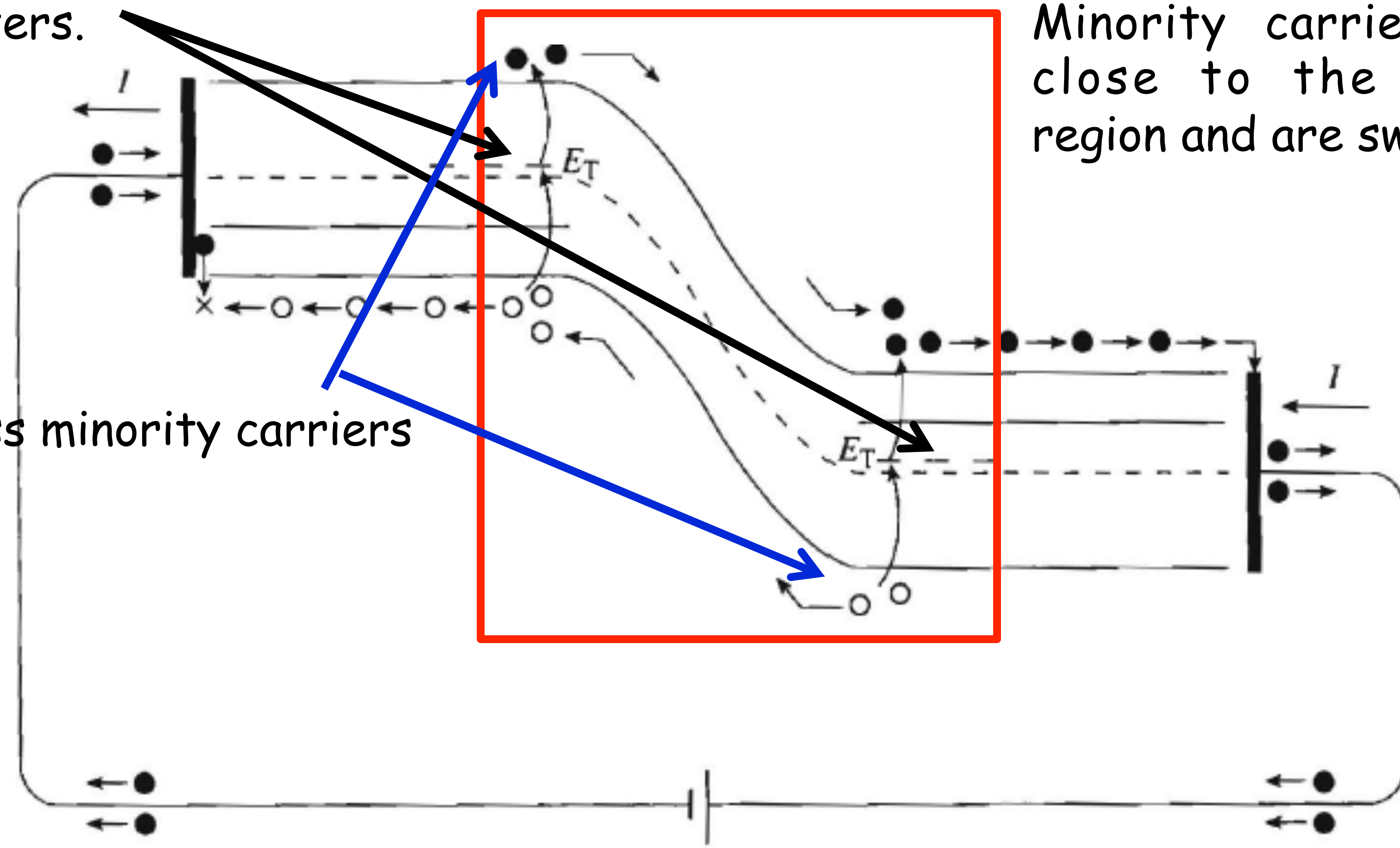
•As the hole reaches the end of the semiconductor, it recombines with an electron which must be supplied by the external circuit.
•As one hole disappears, another hole must appear at the entrance of the circuit to conserve charge neutrality.
•So, we have the generation of an electron-hole pair when an electron leaves the semiconductor sample.
  •The hole flows in while the electron flows out.

Qualitative Current Flow in a P-N Junction

Now look at the big picture of a p-n junction under bias…

R-G centers.

Minority carriers wander close to the depletion region and are swept away.



Excess minority carriers

•When electrons are swept across the junction they are replaced by an electron generated from an R-G center. Similar for holes.
•Excess minority carriers set up a local field pushing carriers to the contacts.

Qualitative Current Flow in a P-N Junction

Let's solve a simple problem…

The electrostatic potential in the depletion region of a p-n junction under equilibrium conditions is determined to be:

$$V(x) = \frac{V_{bi}}{2}\left[1 + \sin\left(\frac{\pi x}{W}\right)\right] \qquad -\frac{W}{2} \leq x \geq \frac{W}{2}$$

(a) Establish a relationship for and sketch the electric field in the depletion region.

(b) Establish a relationship for the charge density and sketch it.

(c) Invoke the depletion approximation, determine and sketch $N_D - N_A$ in the depletion region.

Qualitative Current Flow in a P-N Junction

Let's solve a hard problem…

A P-I-N diode is a three-region device with a middle region that is intrinsic and relatively narrow. Assuming that the p and n regions are uniformly doped and ND – N_A = 0 in the intrinsic region:

(a) Sketch the expected charge density, electric field, electrostatic potential and band diagram.

(b) What is the built-in voltage drop between the p and n regions? Justify it.

(c) Establish a quantitative relationship for the charge density, electric field, potential and the depletion widths.