Lecture 7
PN Junctions

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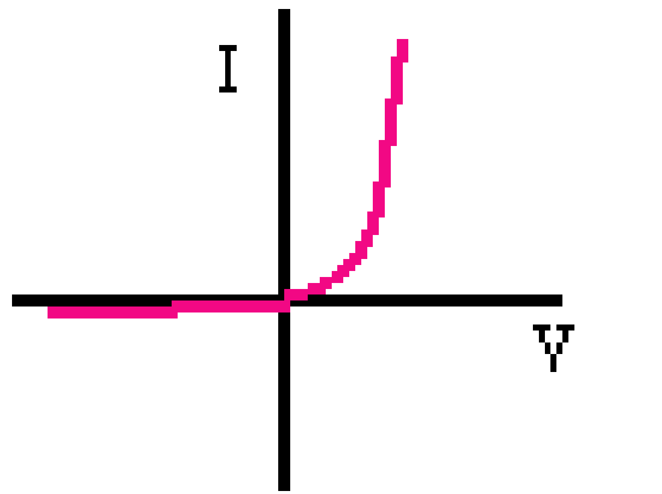
Active Circuit Elements

- Why are they desirable?
  - Much greater flexibility in circuit applications.
  - What's possible/impossible? Can you make it from a single device, or do you need to combine several into one unit? If you could have a device that does anything, what would it be?
- How are they made?
  - Exploit physical properties of the natural world
  - Enhance/alter what's available naturally

Reading: Sedra & Smith 3.3, Streetman Ch 5

PN Junction Diode

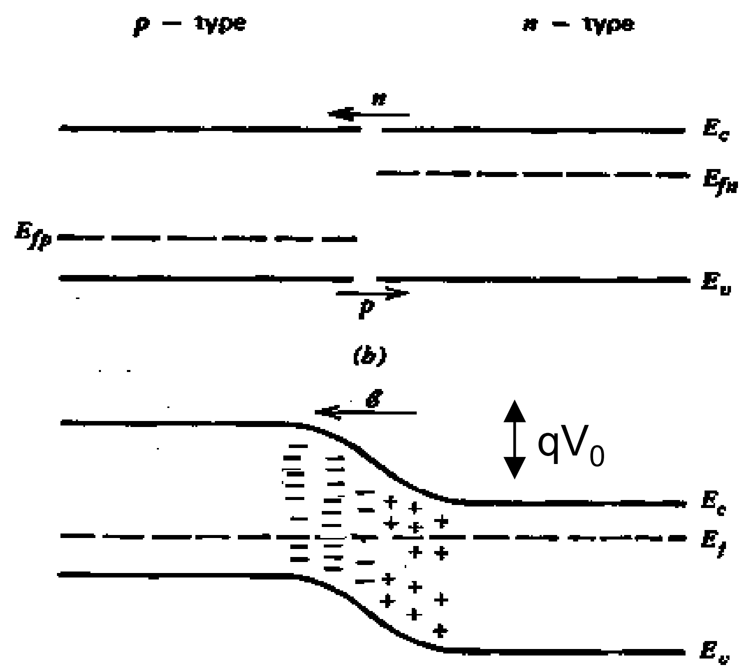


$$I = I_0\left(e^{qV/kT} - 1\right)$$

Subtracting 1 becomes negligible for higher applied V. I>>I0

$$\frac{kT}{q} \approx 26mV \ \ at\ room\ temp$$

Band Diagram



- P-type material is brought into contact with n-type material. The Fermi levels *must* be at equilibrium.
- Band Bending: The conduction and valence bands "bend" to bring the Fermi levels into contact.

What happens when p-type meets n-type?

- Holes diffuse from the p-type into the n-type, electrons diffuse from the n-type into the p-type, creating a diffusion current. The diffusion equation is given by

$$J_n = qD_n \frac{dn}{dx} \qquad D_n = \text{diffusion constant}$$

- Once the holes [electrons] cross into the n-type [p-type] region, they recombine with the electrons [holes].
- This recombination “strips” the n-type [p-type] of its electrons near the boundary, creating an electric field due to excess charge.
- The region “stripped” of carriers is called the space-charge region, or depletion region.
- V_0 is the contact potential that exists due to the electric field. $E(x) = -\frac{dV}{dx}$
- Some carriers are generated and make their way into the depletion region where they are whisked away by the electric field, creating a drift current.

Equilibrium motion of carriers

$$J_n(x) = q\mu_n n(x)E(x) + qD_n \frac{dn(x)}{dx}$$

$$J_p(x) = q\mu_p p(x)E(x) + qD_p \frac{dp(x)}{dx}$$

Drift *Diffusion*

The diffusion current is determined by the number of carriers able to overcome the potential.

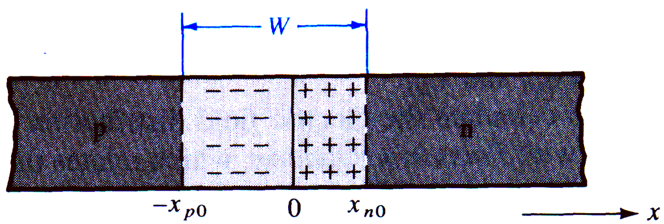
The drift current is determined by the generation of minority carriers which then feel the field and get whisked across.

This generation rate is determined by the temperature.

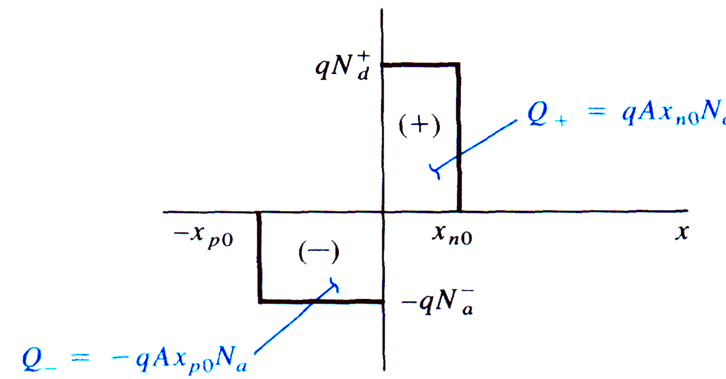
$$\text{At equilibrium, the two components are equal} \Rightarrow \frac{D}{\mu} = \frac{kT}{q} \quad \textit{Einstein's relation}$$

Space Charge at a junction

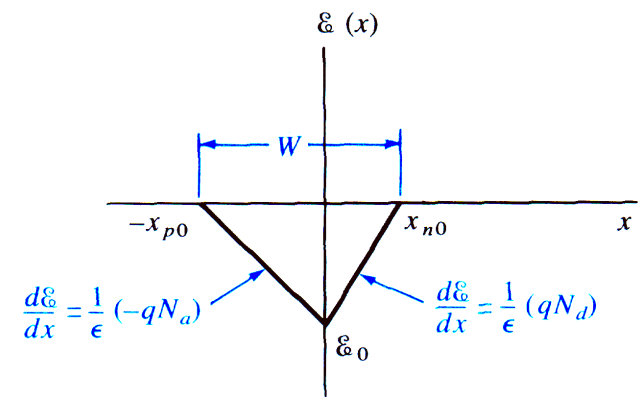
(a)



(b)



(c)

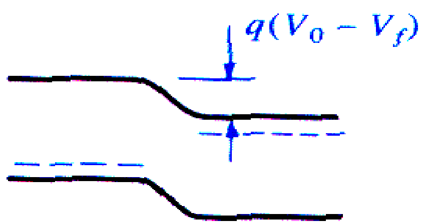


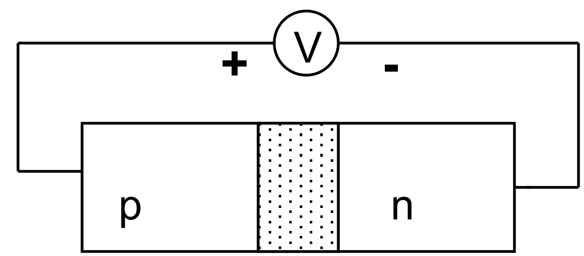
$$qx_{p0}AN_a = qx_{n0}AN_d$$

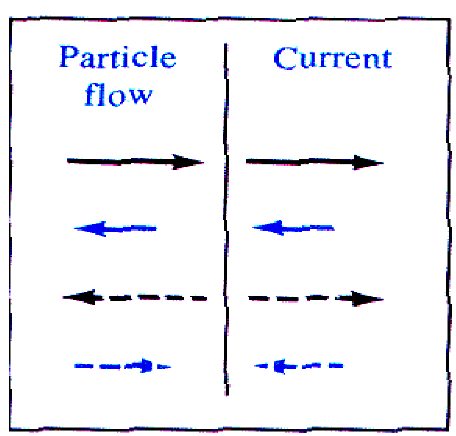
$$\frac{x_{n0}}{x_{p0}} = \frac{N_a}{N_d}$$

$$W_{dep} = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)V_0}$$

Forward Bias



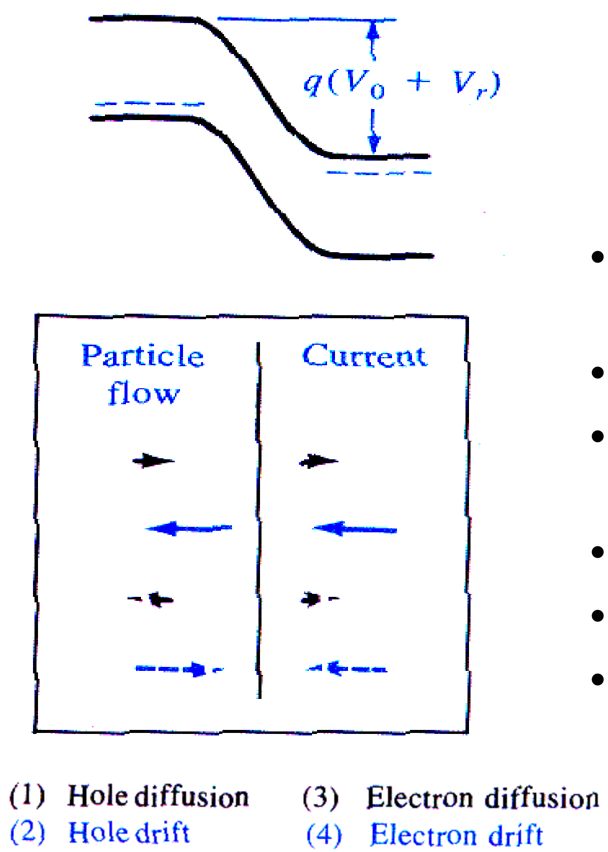


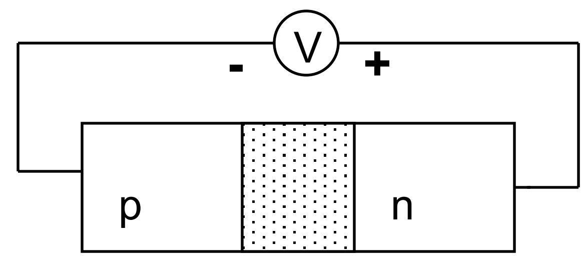


(1) Hole diffusion (3) Electron diffusion
(2) Hole drift (4) Electron drift

- Forward bias: apply a positive voltage to the p-type, negative to n-type.
- Decrease the built-in potential, lower the barrier height.
- Increase the number of carriers able to diffuse across the barrier
- Diffusion current increases
- Drift current remains the same
- Current flows from p to n

Reverse Bias

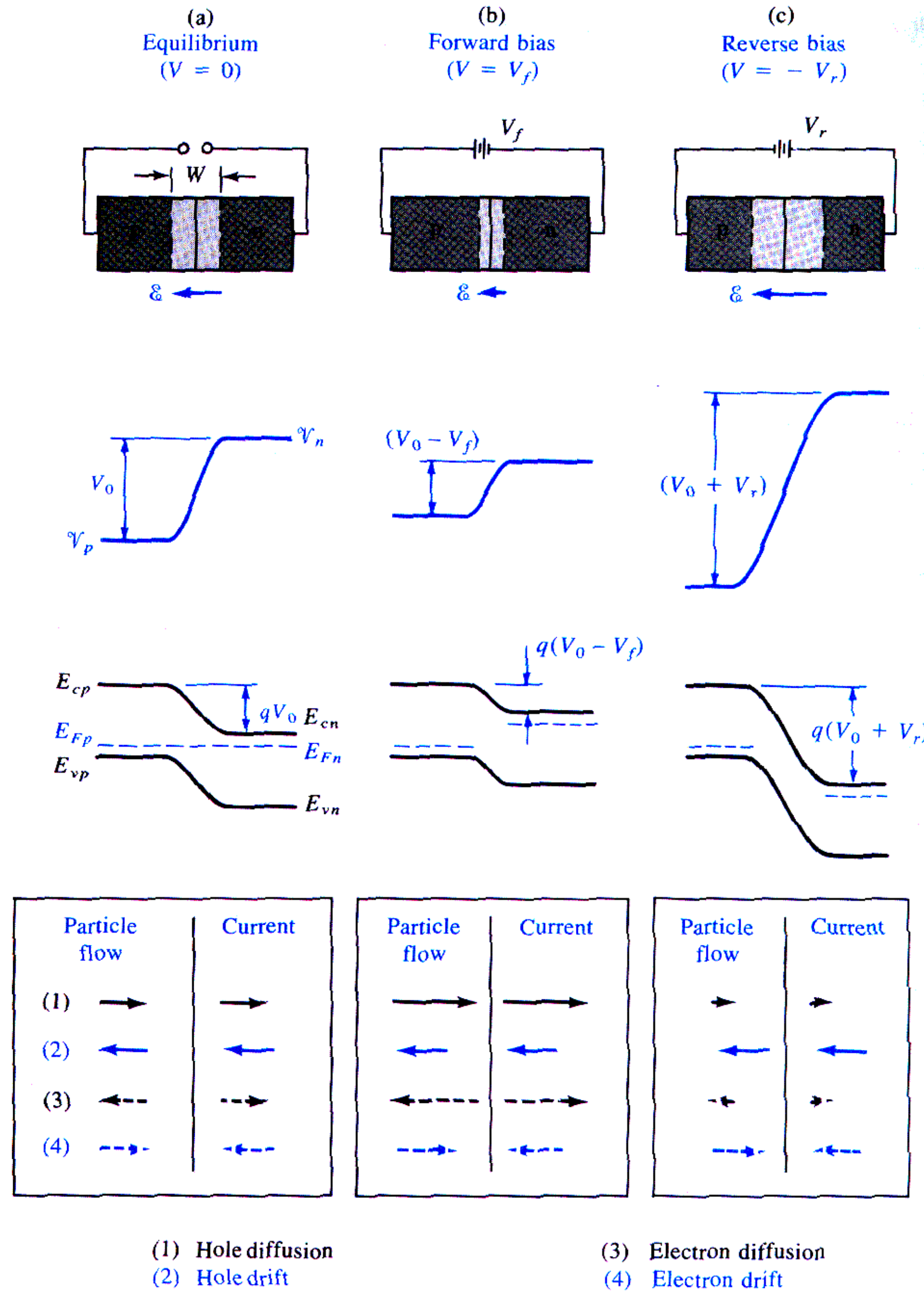




- Reverse bias: apply a negative voltage to the p-type, positive to n-type.
- Increase the built-in potential, lower the barrier height.
- Decrease the number of carriers able to diffuse across the barrier.
- Diffusion current decreases.
- Drift current remains the same.
- Almost no current flows. Reverse leakage current, I_0, is the drift current, flowing from n to p.

Review of Biasing

- Applying a bias adds or subtracts to the built-in potential.
- This changes the diffusion current, making it harder or easier for the carriers to diffuse across.
- The drift current is essentially constant, as it is dependent on temperature.



Quantitative Analysis of Current Flow

Consider the holes that can now diffuse across to the n-type region.

$$p_n(x_n) = p_{n0} e^{qV/kT}$$

$$p_n(x) = \left[p_{n0} + (p_n(x_n) - p_{n0}\right] e^{-\frac{(x-x_n)}{L_p}}$$

$$J_p = q\frac{D_p}{L_p} p_{n0}\left(e^{qV/kT} - 1\right) e^{-(x-x_n)/L_P}$$

$$L_p = diffusion\ length$$

But with the applied voltage, the electrons that get consumed by the holes are replenished from the circuit, at a constant rate determined by the vale at x_n, simplifying this to…

Analysis Continued

$$J_p = q\frac{D_p}{L_p} p_{n0}\left(e^{qV/kT} - 1\right)$$

Smilarly, for the electrons in the p-type, one obtains

$$J_n = q\frac{D_n}{L_n} n_{p0}\left(e^{qV/kT} - 1\right)$$

A bit of manipulation gives us

$$I = Aqn_i^2\left(\frac{D_p}{L_p N_d} + \frac{D_n}{L_n N_a}\right)\left(e^{qV/kT} - 1\right)$$

$$I_0 = Aqn_i^2\left(\frac{D_p}{L_p N_d} + \frac{D_n}{L_n N_a}\right)$$

- Reverse saturation current, the drift current, depends directly on the area of the junction.
- Also depends on n_i, which is dependent on temperature.

Capacitance

The junction acts as a parallel plate capacitor. Charge builds up on both sides.

$$C_j = \frac{\varepsilon_s A}{W_{dep}} \qquad W_{dep} = \sqrt{\left(\frac{2\varepsilon_s}{q}\right)\left(\frac{1}{N_a}+\frac{1}{N_d}\right)(V+V_0)}$$

This expression is accurate for reverse bias, but not very good for forward bias. $V+V_0$ is the total voltage across the junction under reverse bias conditions.

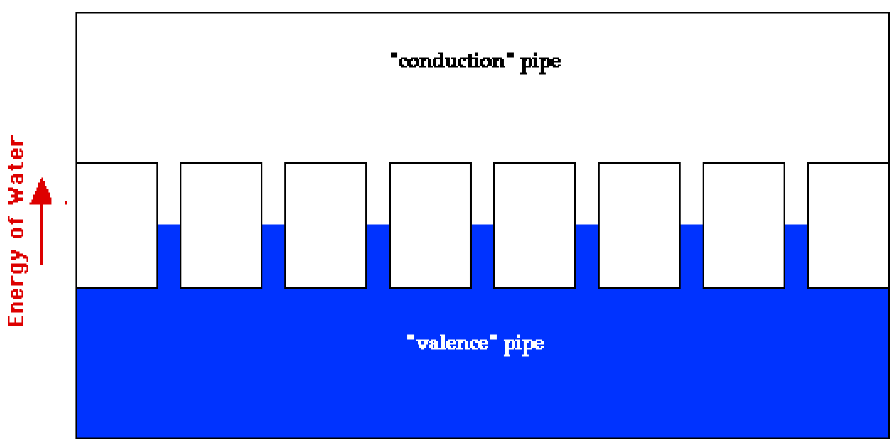
We can also write this as

$$C_j = \frac{C_{j0}}{\left(1+\frac{V_R}{V_0}\right)}$$

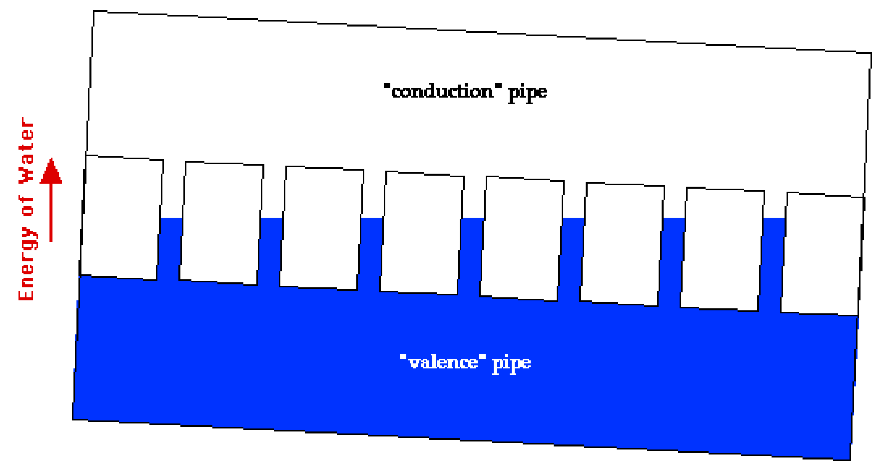
Notice we can use a diode as a varactor! (Voltage controlled capacitor.)

Two pipe/fluid model

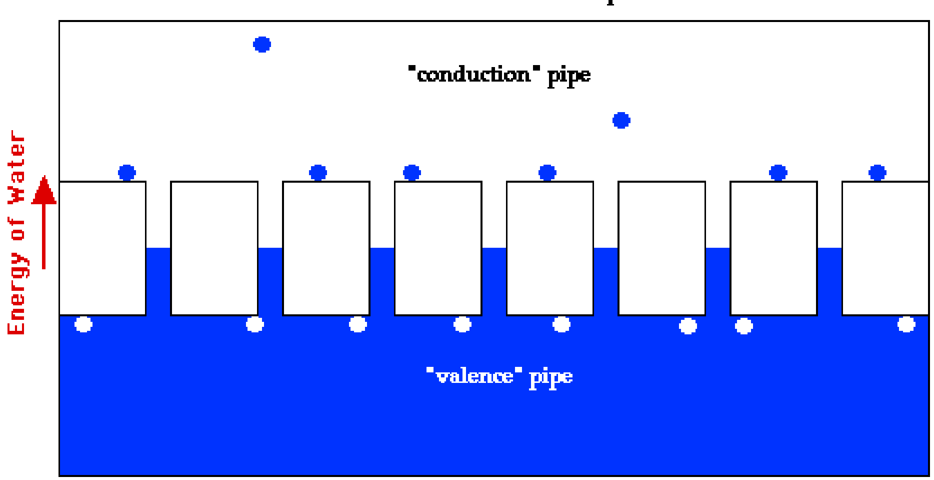
Insulator at equilibrium – i.e. there is no applied external potential



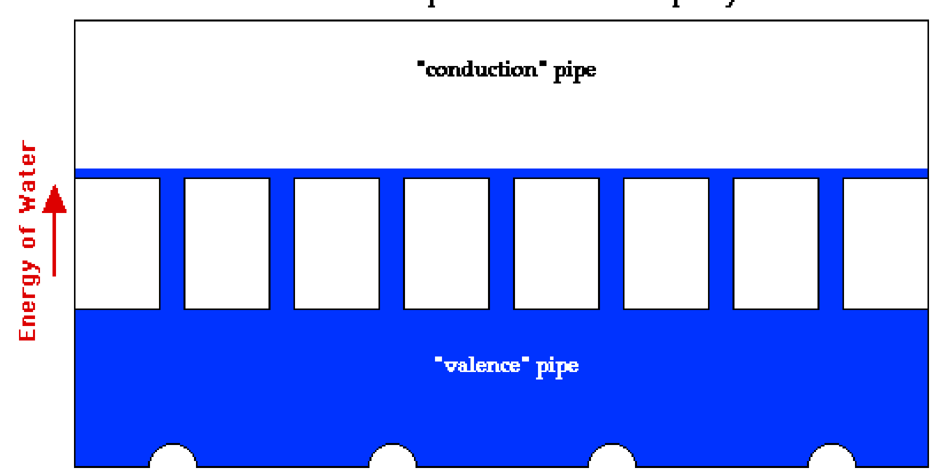
Insulator with an applied external potential – no current flow possible



More fluid Models



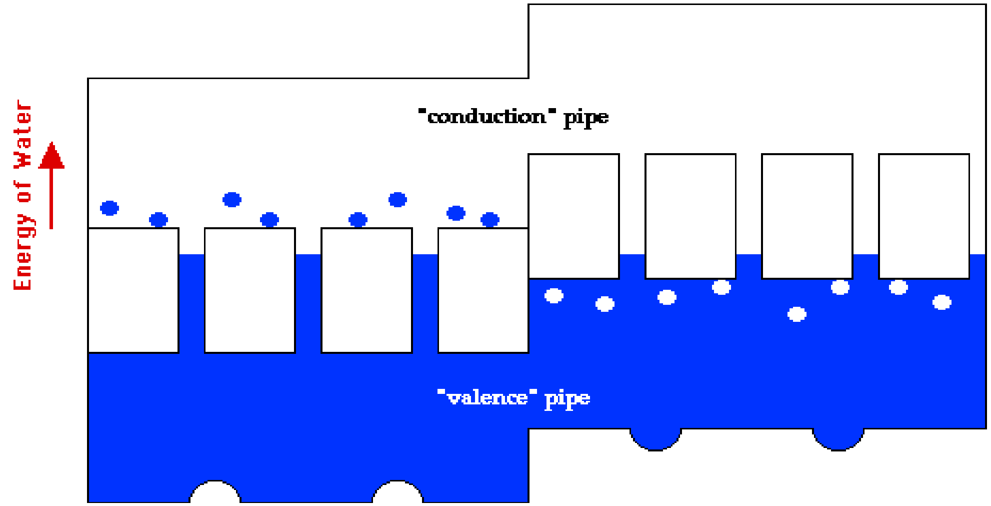
Thermal Excitation



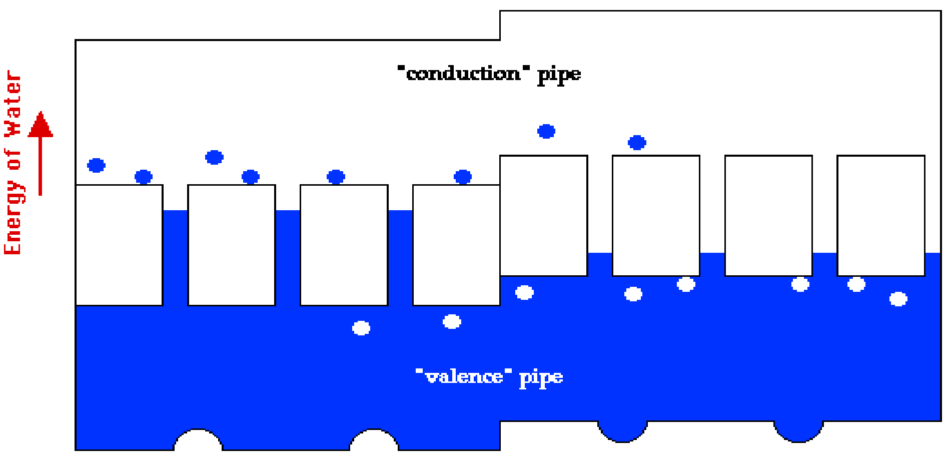
Chemical "Doping" (n-type)

And more!

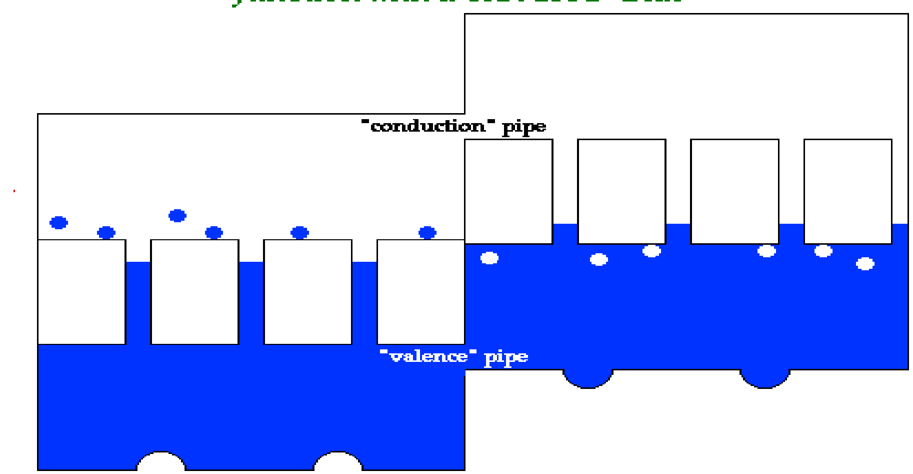
Junction at Equilibrium



Junction with a ***Forward*** Bias



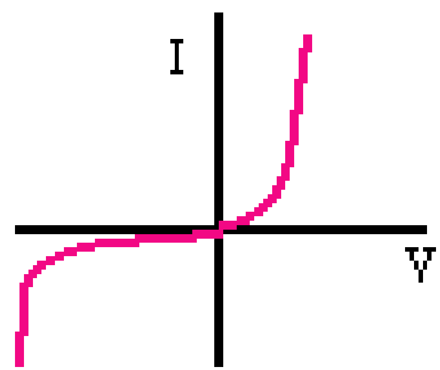
Junction with a ***Reverse*** Bias



Reverse Breakdown

- Zener Breakdown: The bands bend so much that carriers tunnel through the depletion region. This will occur in heavily doped junctions when the n-side conduction band appears opposite the p-side valence band.

- Avalanche Breakdown: carriers have enough energy to ionize an electron-hole-pair, creating more highly energetic carriers, which collide to form more EHPs, which creates…

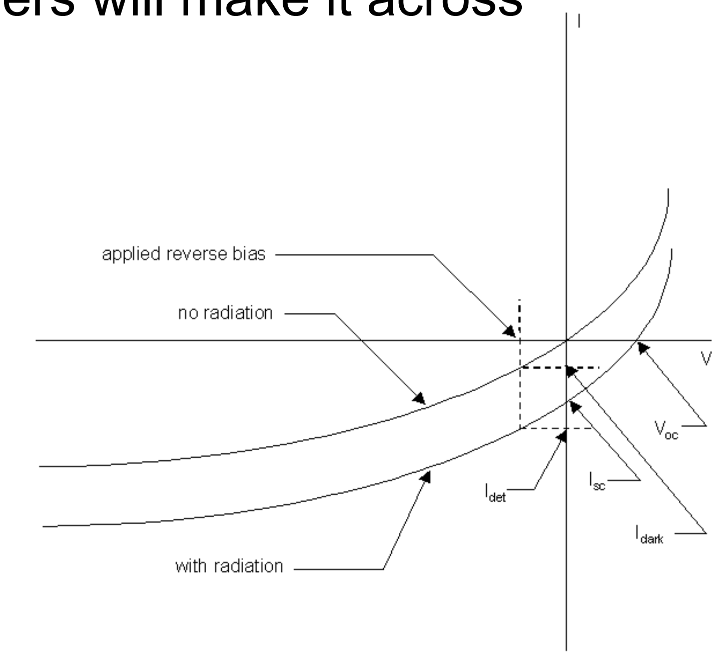


Photodiodes

- Diodes have an optical generation rate. Carriers are created by shining light with intensity greater than the bandgap.
- One wants large depletion widths and long diffusion lengths, as it is only in these areas that excited carriers will make it across the junction.
- Photodetector: operate in third quadrant.

Compromise between speed and junction width leads to a p-intrisic-n junction, where carriers will be rapidly swept across, and can quickly diffuse in the p and n regions.

- Solar Cell: operating in the fourth quadrant generates current, though small.



Light Emitting Diodes

- When electrons and holes combine, they release energy.
- This energy is often released as heat into the lattice, but in some materials, known as direct bandgap materials, they release light.
- Engineering LEDs can be difficult, but has been done over a wide range of wavelengths.
- This illustration describes the importance of the plastic bubble in directing the light so that it is more effectively seen.