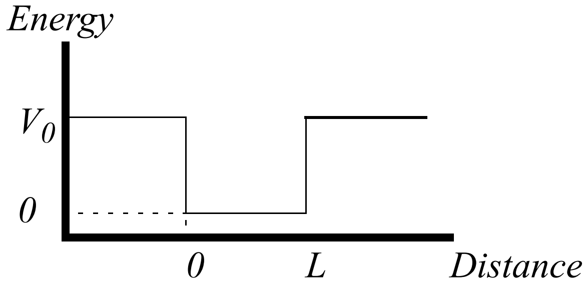
Semiconductors

Potential Well

- The simple approximation for a bound electron is a 1-dimentional well of potential energy $V(x)$ with width L and depth E.



$$V(x) = V_0 \qquad x \le 0$$
$$V(x) = 0 \qquad 0 < x < L$$
$$V(x) = V_0 \qquad L \le x$$

- Consider electrons with total energy $E < V_0$.
- The kinetic energy is $E - V(x)$ and is positive only inside the well ($0 < x < L$), so a classical electron cannot go outside the well.
- Since the wave must be 0 at the boundaries of the well the wavelength must have an integral division of $2L$:

$$\lambda = \frac{2L}{n} \qquad \Psi_n(x) = A\sin\frac{n\pi x}{L}$$

Filling the Potential Well

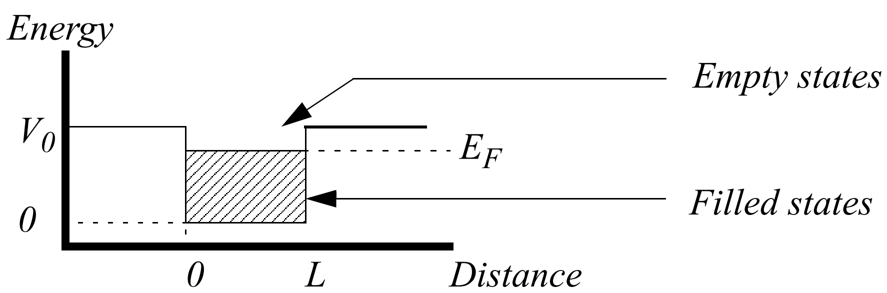
- The kinetic energy associated with a particular wave is:

$$K_n = \frac{p^2}{2m} = \frac{h^2}{2m\lambda^2} = \frac{n^2h^2}{8mL^2}$$

- The *Fermi energy* (E_F) is found for N_0 electrons filling the lowest energy states with two electrons per state:

$$E_F = \frac{N_0^2h^2}{32mL^2}$$

- Graphically:

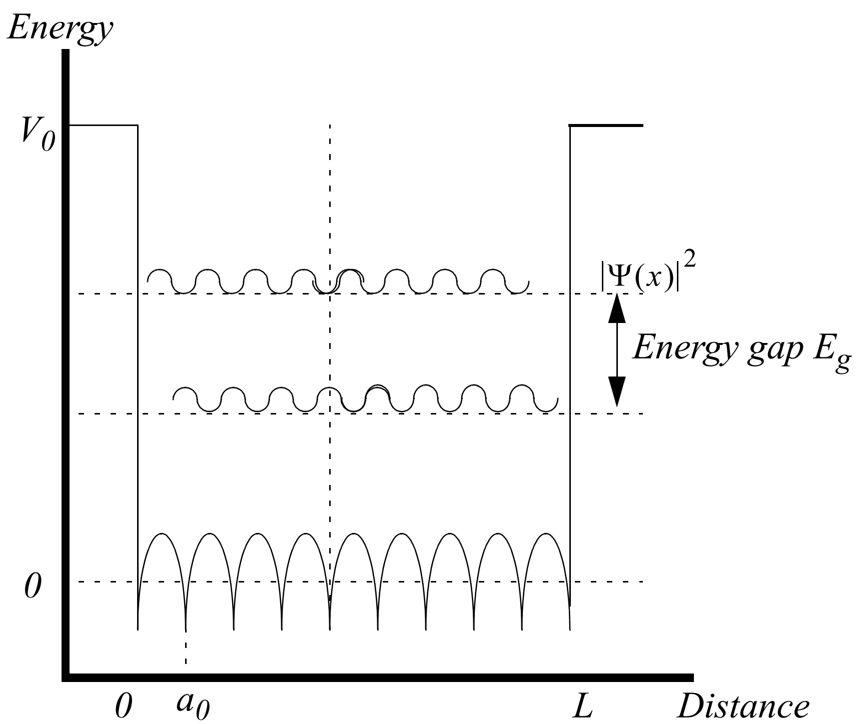


- The energy to remove one electron is V_0-E_F.
- The unit of potential in electronics: electron volt (eV) = 1.6 x 10^{-19} j
- In copper, approximately:

  N_0 = 4 x 10^7, L = 2.5 x 10^{-10} m, E_F = 1.5 eV.

Periodic Potential Well

- Crystals have positive nuclei at regular intervals a_0.



- Energy levels are filled until the period of the wave matches the periodic potential, $\lambda = 2a_0$.
- Waves that line up with the electron at the positive nuclei have a lower energy than waves that line up with the electrons away from the positive nuclei.
- There are no waves between those two, so an energy gap appears.
- No electrons can have energies in the gap.

Thermal Distribution

- Unit of temperature: kelvin (K)
- Electron energies in a material are a function of temperature (T)

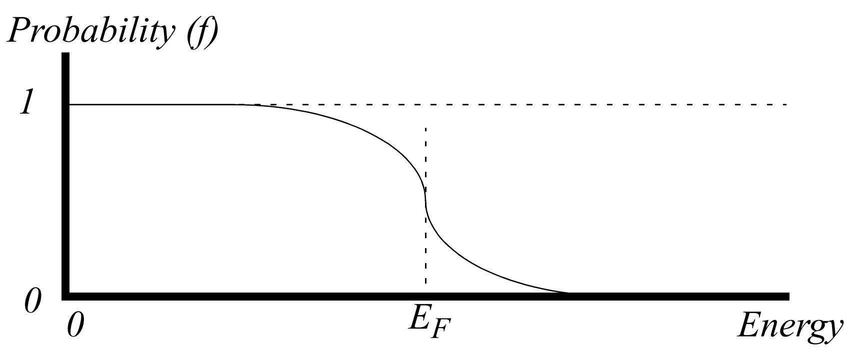
$$f(E) = \frac{1}{e^{(E - E_F)/kT} + 1}$$

Boltzman's constant: $k = 1.38 \times 10^{-23}$ j/K = 8.62×10^{-5} eV/K

At room temperature, $kT = 0.025$ eV.

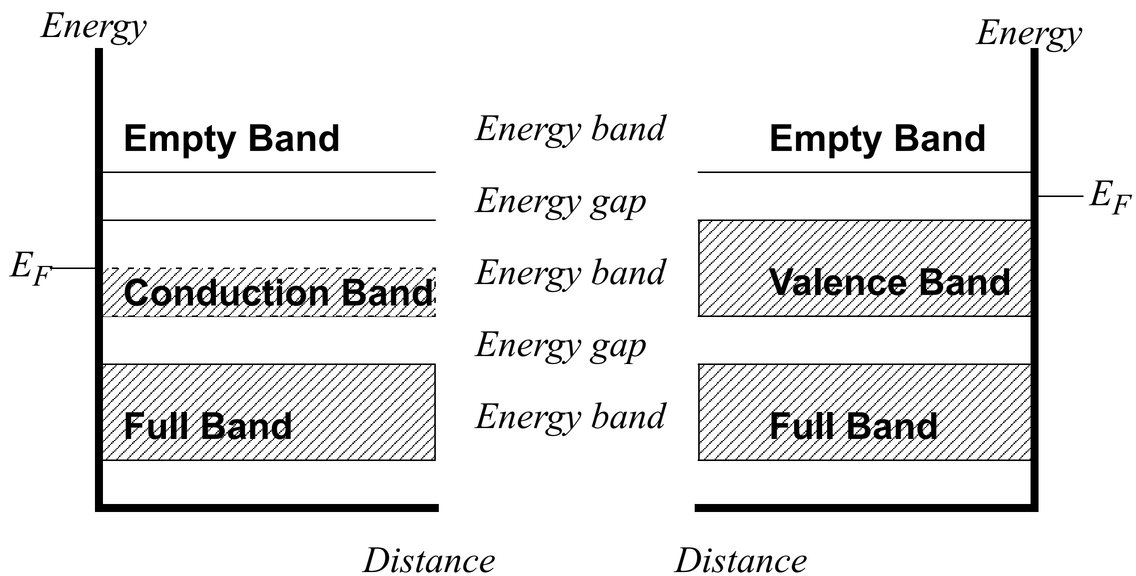
- At any temperature there can be some electrons in states with energies greater than E_F as long as those states are not in an energy gap.

- The Fermi-Dirac probability for an electron to be at an energy in excess of E_F decreases as the energy increases.



Energy Bands

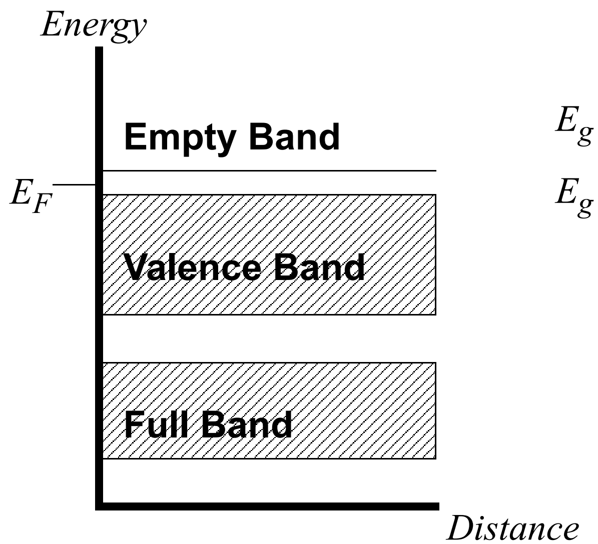
- Real materials have many bands separated by energy gaps
- There are two cases, with the Fermi energy in a band or a gap



- If the Fermi energy is in an energy band, the band is called a conduction band, and the material is a **conductor**.
- If the Fermi energy is in an energy gap, the highest band is called a valence band, and the material is an **insulator**.

Semiconductor Bands

- Semiconductors are insulators with small gaps between the valence band and empty band.



E_g = 1.1 eV in Silicon (Si)

E_g = 0.7 eV in Germanium (Ge)

- Thermal excitation can move some electrons at room temperature

$$f(0.55eV) = \frac{1}{e^{(0.55eV)/(0.025eV)} + 1} \cong 10^{-9}$$

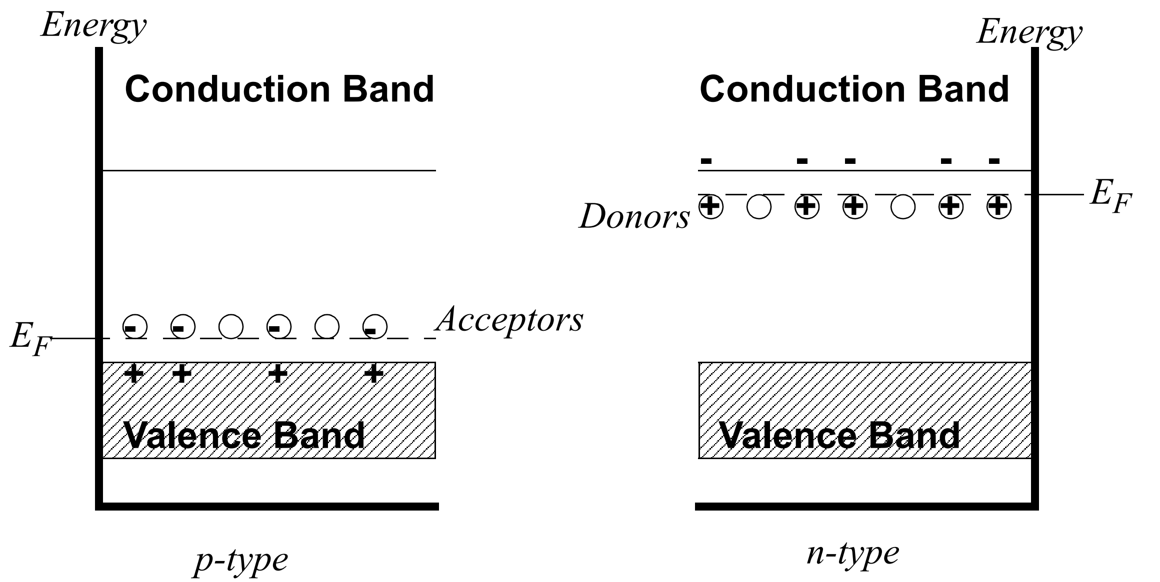
- Electrons that move up into the empty band can form a current
- The *holes* that are left by the excited electrons can also conduct current as positive charges.

Doping

- Addition of impurities can create additional states within an energy gap.
- Typically add 10^{-7} to 10^{-10} as a fraction of impurity to silicon

- Addition of P, As or An add an additional electron: n-type
- Addition of B, In add an additional hole: p-type

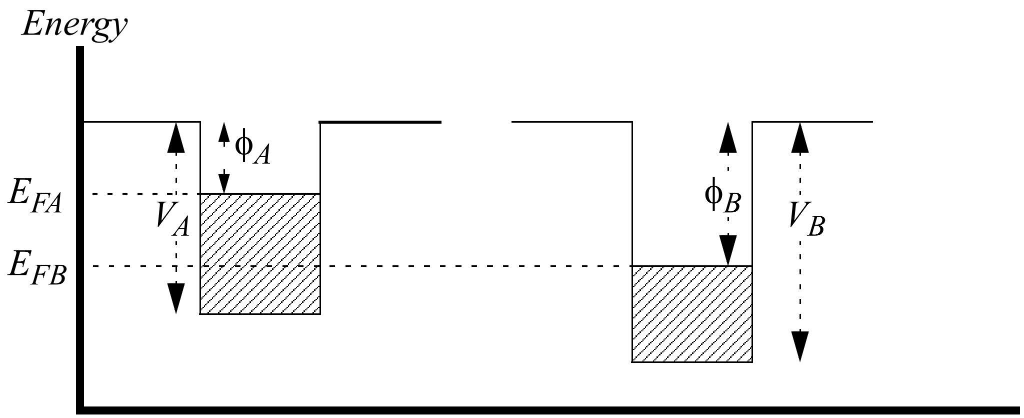
- E_F can be controlled to form a very small gap



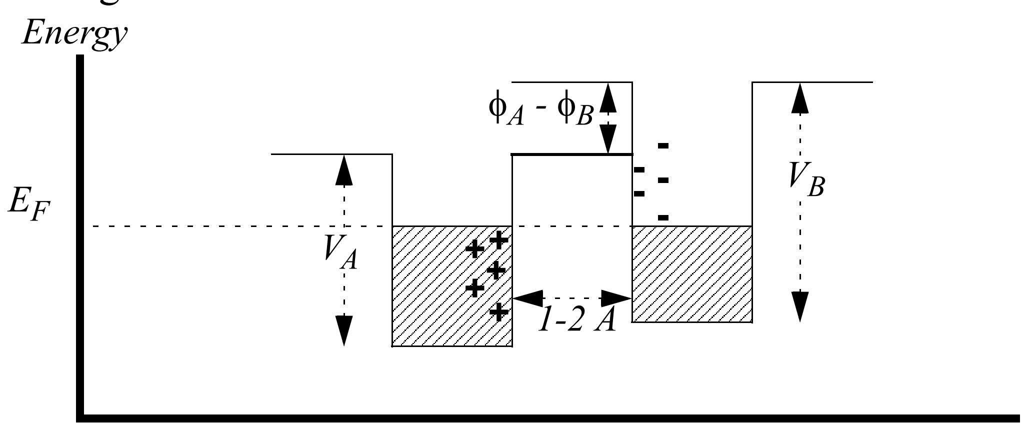
Junctions

Metal-Metal Junction

- Each metal has its own Fermi energy and potential, separately they are neutral.

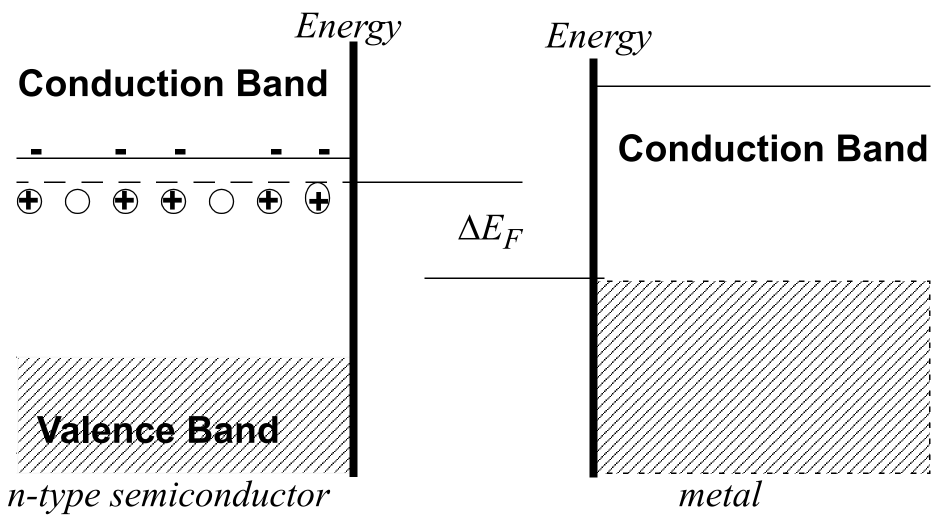


- If placed in contact electrons will move from A to B until the energy levels are equal, but the metals become charged.

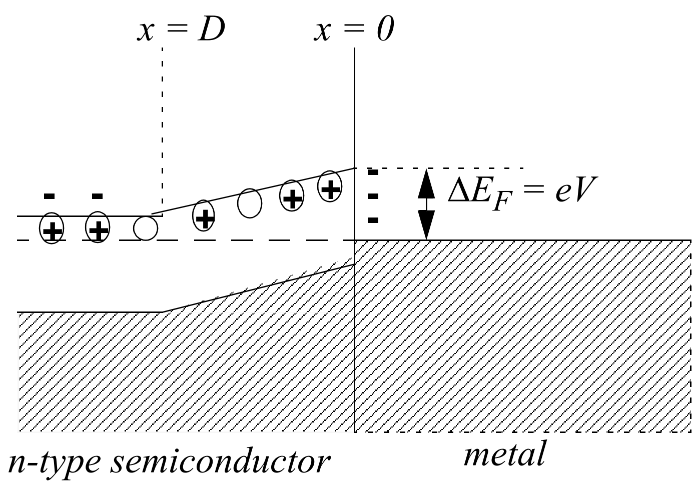


Metal-Semiconductor Junction

- The two materials begin with different Fermi energies and potentials:



- Once the materials are in contact electrons flow from the semiconductor into the metal:



Forward Current

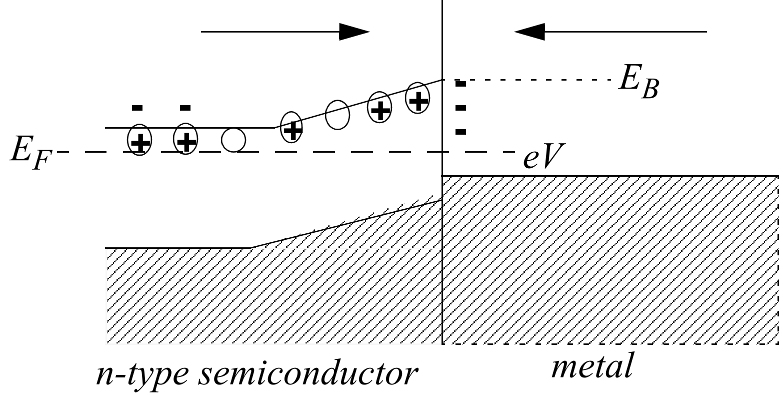
- Thermal electrons will flow in both directions if $E_e > E_B$:

$$f(E) = \frac{1}{e^{(E - E_F)/kT} + 1} \cong e^{-(E - E_F)/kT}$$

$$j = j_0 e^{-(E_B - E_F)/kT}$$

- Currents are equal and opposite so there is no net current
- With an external potential applied:

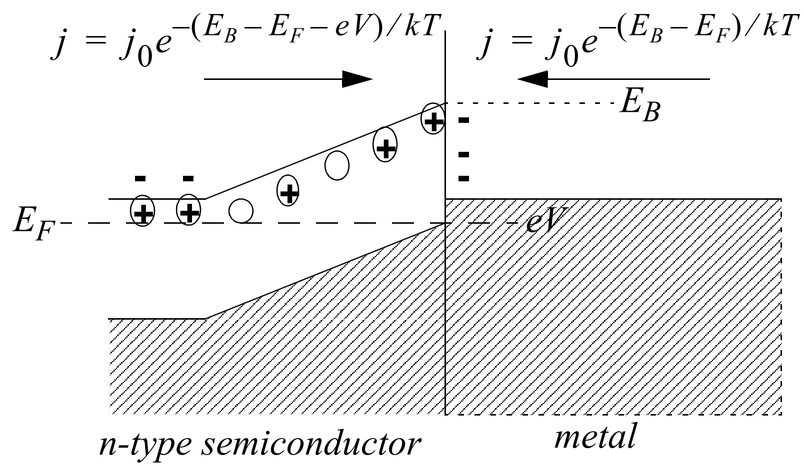
$$j = j_0 e^{-(E_B - E_F - eV)/kT} \qquad j = j_0 e^{-(E_B - E_F)/kT}$$



- Net current flows from metal to semiconductor
- This is ***forward biased***, eV is positive.

Reverse Current

- With the potential reversed, eV is negative



- The electrons in the metal see a constant barrier
- The electrons in the semiconductor see a variable barrier
- Net current density:

$$j = j_0 e^{-(E_B - E_F - eV)/kT} - j_0 e^{-(E_B - E_F)/kT} = j_0 e^{-(E_B - E_F)/kT}(e^{eV/kT} - 1)$$

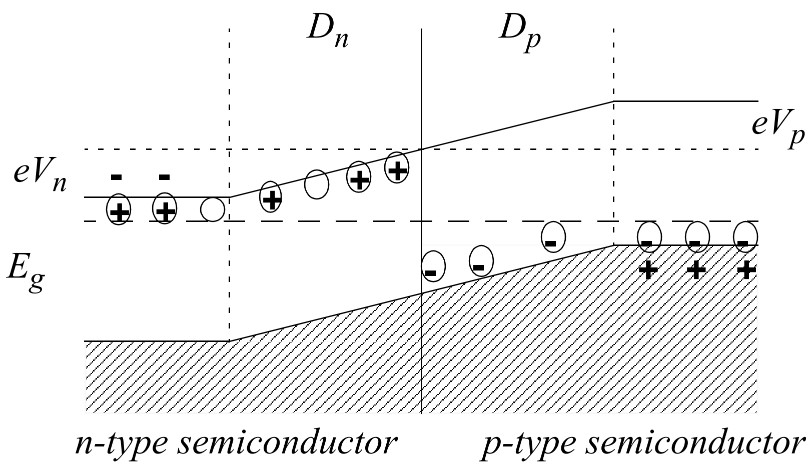
- For a junction with area A

$$I = j_0 A e^{-E_B - E_F/kT}(e^{eV/kT} - 1) = I_0(e^{eV/kT} - 1)$$

- Net current has an exponential dependence on applied voltage and temperature.

p-n Junction

- n-type has ionized positive donors but no free electrons
- p-type has ionized acceptors but no free holes
- Fermi energies are matched



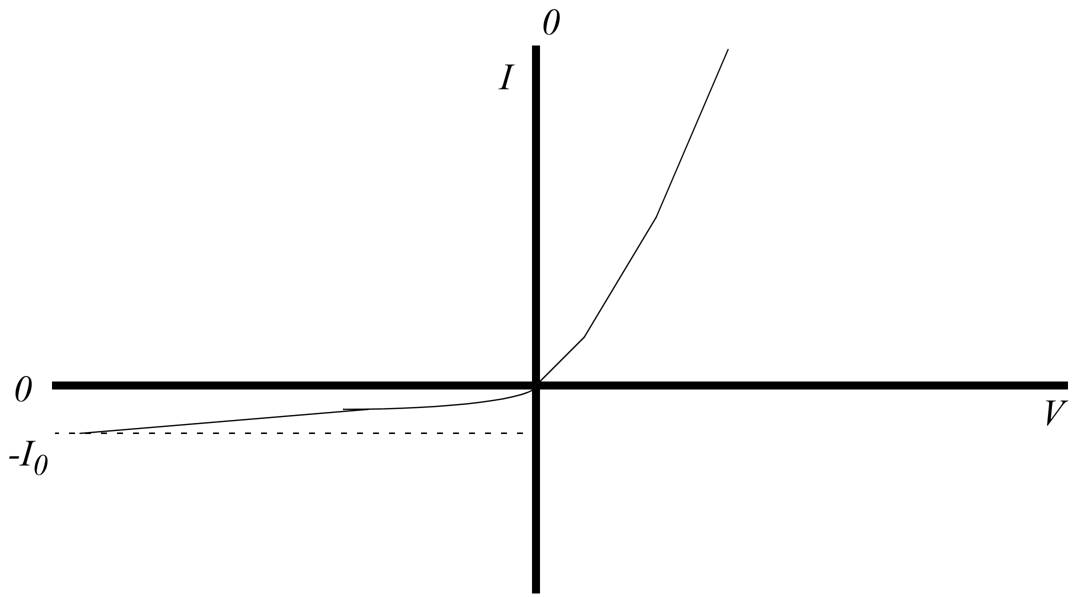
- N is the number density of donor atoms
- ε_r is the dielectric of the semiconductor

$$D_n = \sqrt{\frac{2\varepsilon_r\varepsilon_0 V_n}{N_n e}} \qquad D_p = \sqrt{\frac{2\varepsilon_r\varepsilon_0 V_p}{N_p e}}$$

VI Curve

Current-Voltage Curve:

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



- At room temperature, $kT/e = 2.58 \times 10^{-2}$ V

$$I = I_0(e^{eV/kT} - 1) = I_0(e^{V/0.0258\dot{V}} - 1)$$

- Typically, $I_0 = 0.1$ nA.
- Reverse current is very small, but with 1/40 V over 1 A can flow in the forward direction.