Announcements

- Homework 10 is due next Wednesday, April 19.
- Homework 11 is due next Monday, April 24.

Last time

- Band theory of solids

Today’s class

- Semiconductors

in-class quiz (5 min)

For a semiconductor, let's say the bandgap *Eg* is 1 eV. Let's assume Fermi energy is near the middle of the gap. At room temperature, what is the fraction of electrons near the bottom of the conduction band?

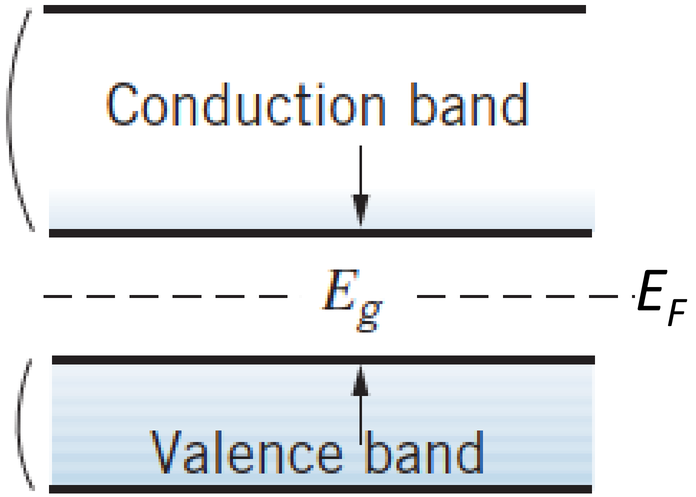
A. 0

B. 10^{-20}

C. 10^{-9}

D. 0.5

E. 1



in-class quiz (5 min)

$E - E_f = \frac{1}{2} E_g = 0.5\,eV$

$kT = 0.025\,eV$

$$f(E) = \frac{1}{e^{(E-E_f)/kT} + 1} = \frac{1}{e^{20} + 1} = e^{-20} = 10^{-9}$$

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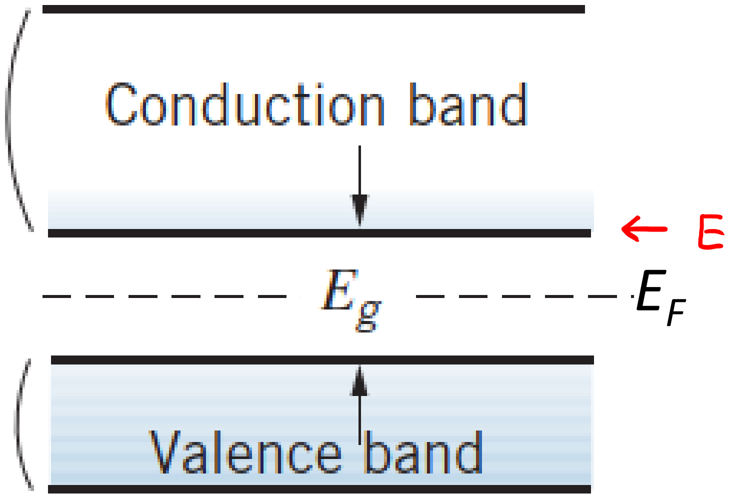


Electrons and holes

Conduction band:

charge carrier: electrons

move easily – lots of empty states to move into

Valence band:

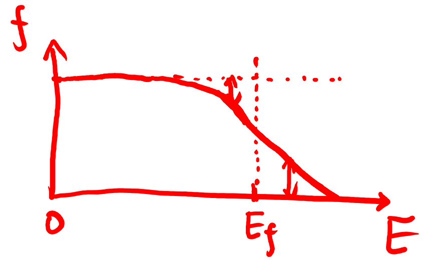
charge carrier: electrons

harder to move – most states are occupied

apparent motion of “vacancies” or “holes” in the opposite direction

effectively charge carrier: positively-charged holes

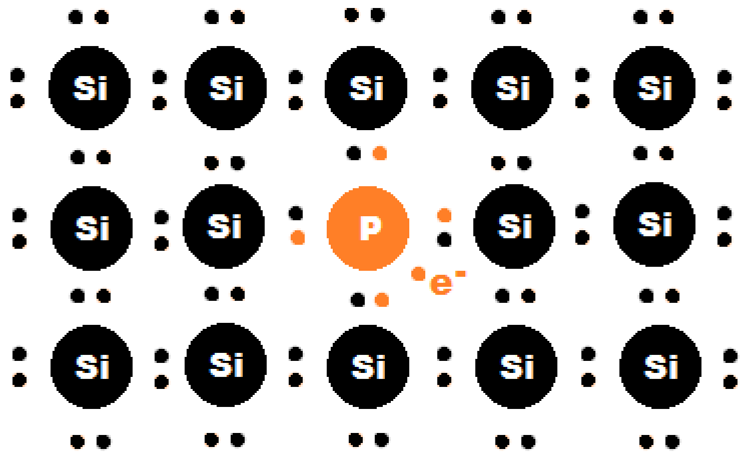
Intrinsic semiconductors



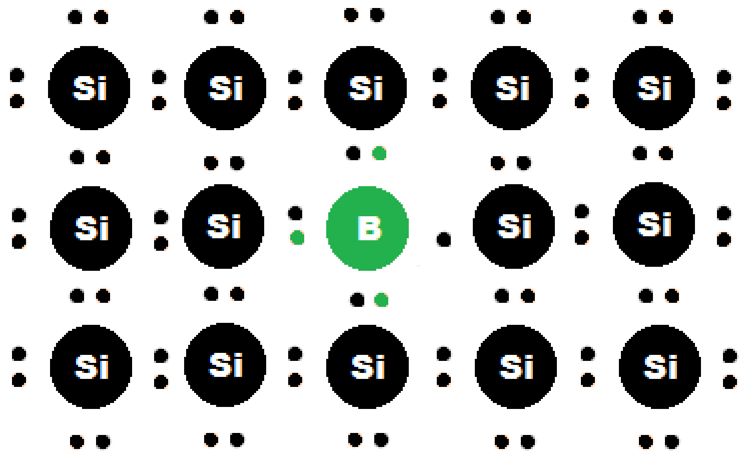
- # of electrons in the conduction band vs. # of holes in the valence band? equal
- Where is Fermi energy with respect to the band gap? middle
- Which one contributes more to conduction – electrons or holes? electrons
- Fraction of electrons (or holes) contributes to conduction? 10^{-9}

Impurity semiconductors

Doping at 1 in 10^6 or 10^7 can dominate conduction >> intrinsic 10^9

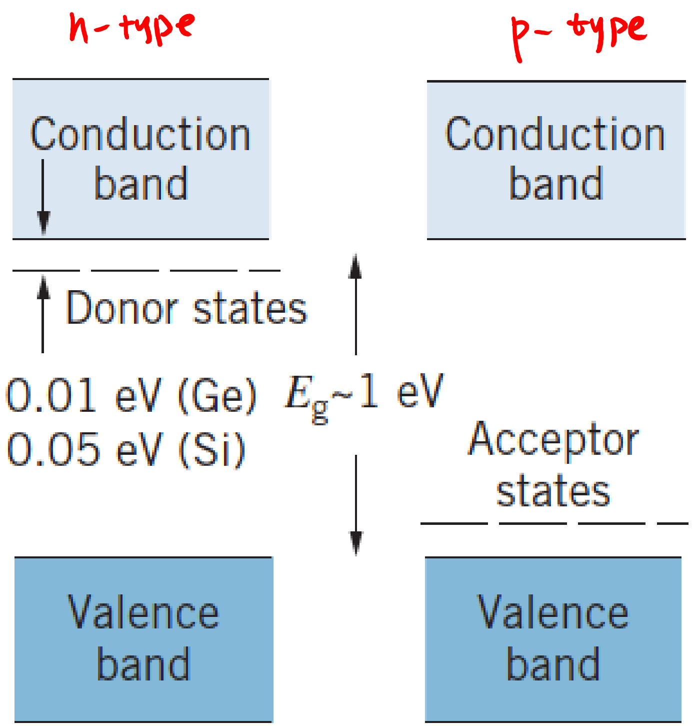


n-type
Doping with Group V elements
Donor impurities



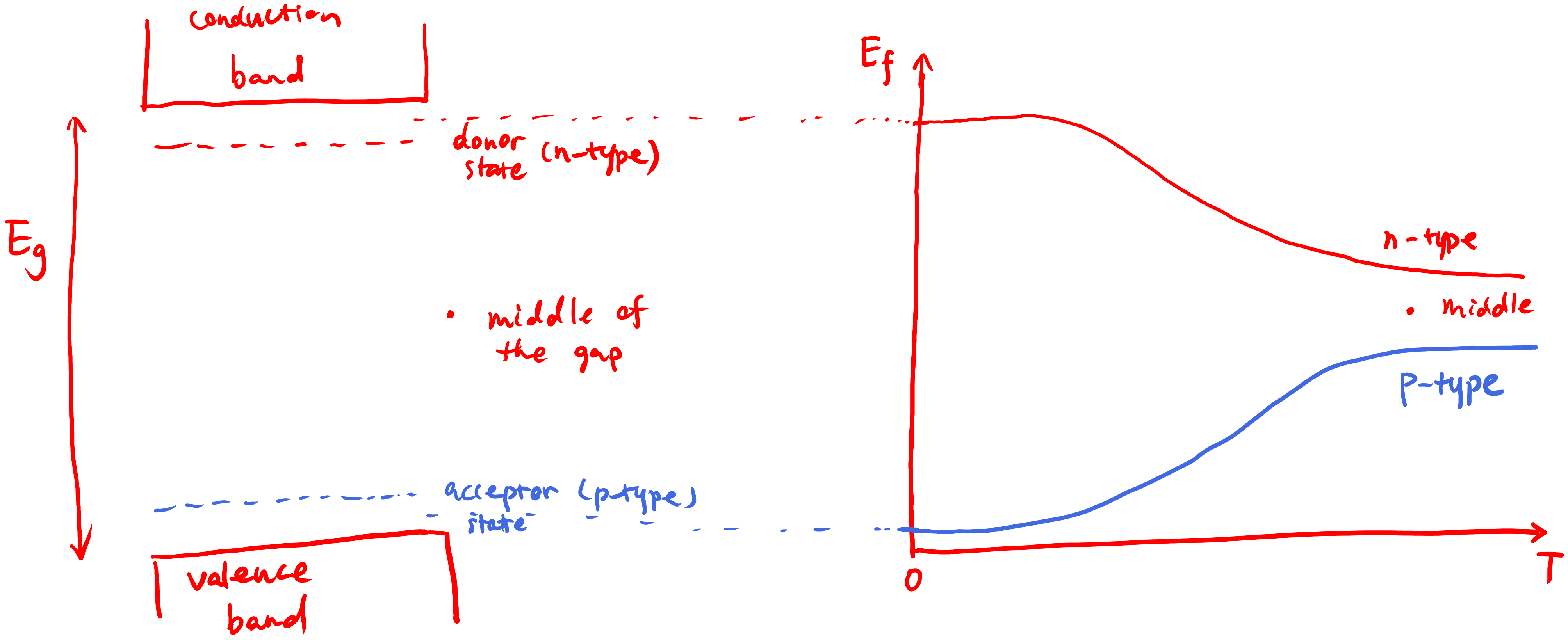
p-type
Doping with Group III elements
Acceptor impurities

Energy levels in semiconductors



Doping introduces a new energy level within the bandgap.
Electron donor impurities create states near the conduction band.
Electron acceptor impurities create states near the valence band.

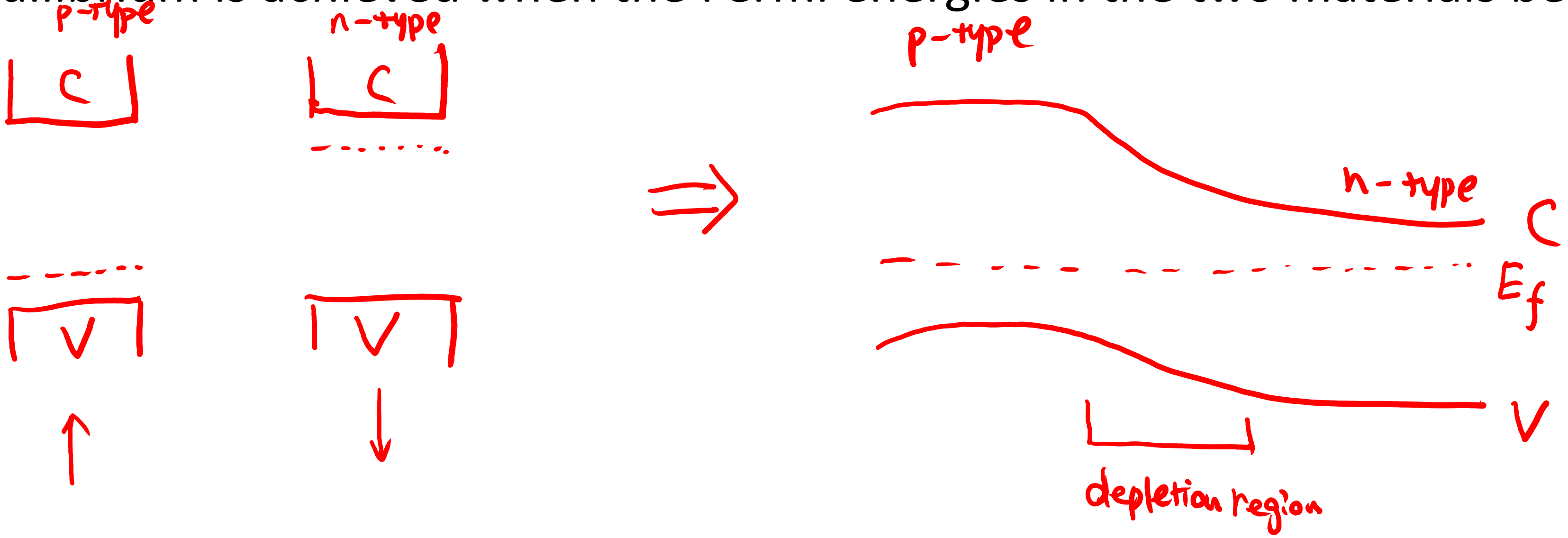
Fermi energy in semiconductors

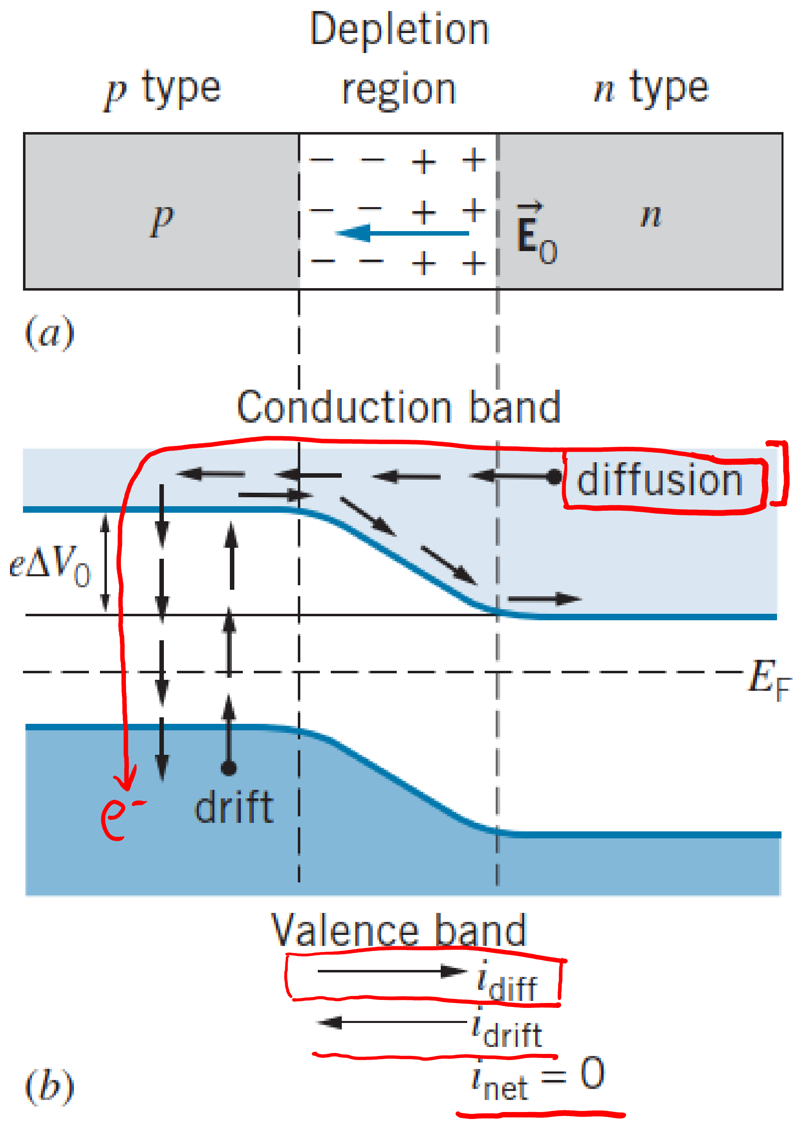


The p-n junction

Electrons flow from the n-type into the p-type material

Equilibrium is achieved when the Fermi energies in the two materials become identical





e^-s enter into p-type, building up ⊖ charge

⇒ E_0, a net electric field in the depletion region. preventing further flow of e^-s.

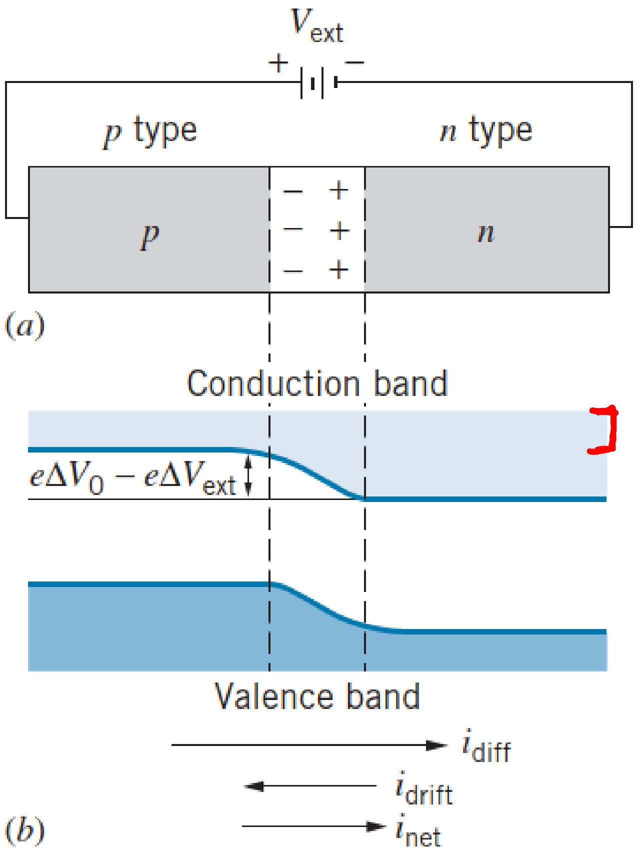
for e^- to go from n to p, it has to overcome the energy barrier imposed by $\vec{E_0}$, eV_0

Diffusion current: highest-energy e^-s can go from n to p.

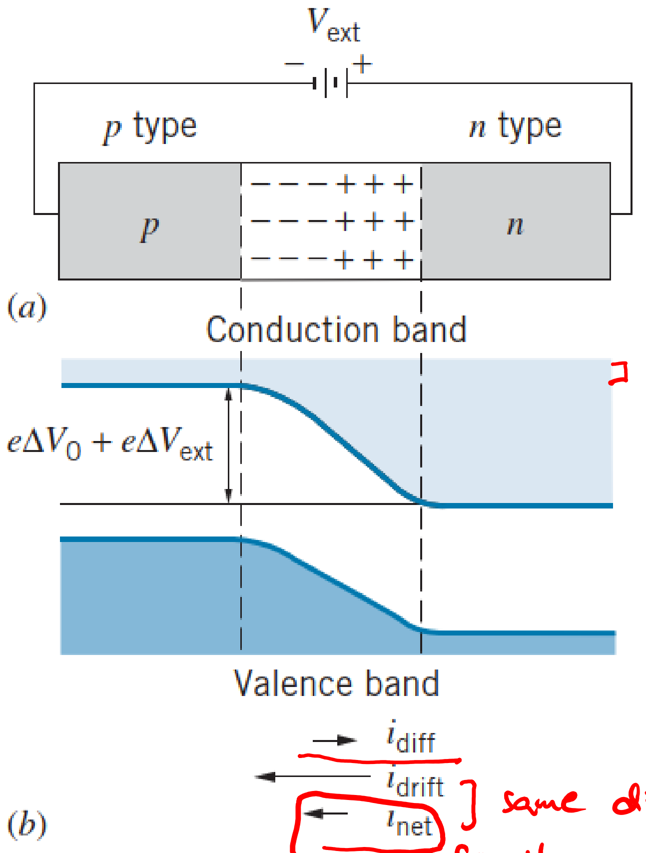
Drift/thermal current: e^-s jumps from valence band in p to conduction band

Applying bias on the p-n junction

Forward bias



Reverse bias



] fewer e^-

] same direction

small

forward bias:
① pull e^- from p. put into n
② depletion region narrower. ΔE↓
③ more e^- can contribute to diffusion current, i diff ↑
④ i drift unchanged

At equilibrium, diffusion current is proportional to the number of electrons above the energy E_c

E_c is the energy level at the bottom of conduction band in the p-type region

$$f(E) = \frac{1}{e^{(E-E_f)/kT}+1}$$ fraction of occupied states

At equilibrium, $i_{drift} = i_{diffusion}$. Both diffusion and drift current are proportional to N_1 (→ # of electrons)

$$N_1 = n e^{-(E_c-E_f)/kT}$$. n is a proportionality factor

With bias, the number of electrons above the energy $E_c\text{-}e\Delta V_{ext}$

$$N_2 = n e^{-(E_c - e\Delta V_{ext} - E_f)/kT}$$

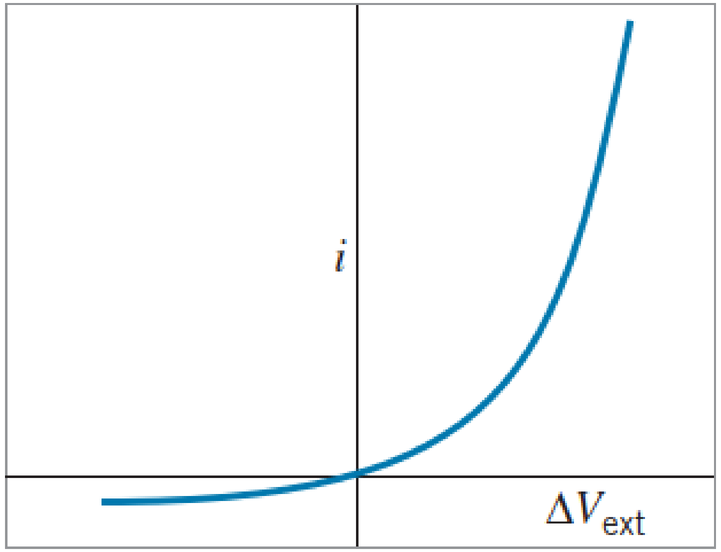
$i_{diffusion} \propto N_2$, $i_{drift} \propto N_1$

$$i_{net} \propto N_2 - N_1 = n e^{-(E_c - e\Delta V_{ext} - E_f)/kT} - n e^{-(E_c - E_f)/kT} = n e^{-(E_c-E_f)/kT}\left(e^{e\Delta V_{ext}/kT} - 1\right)$$

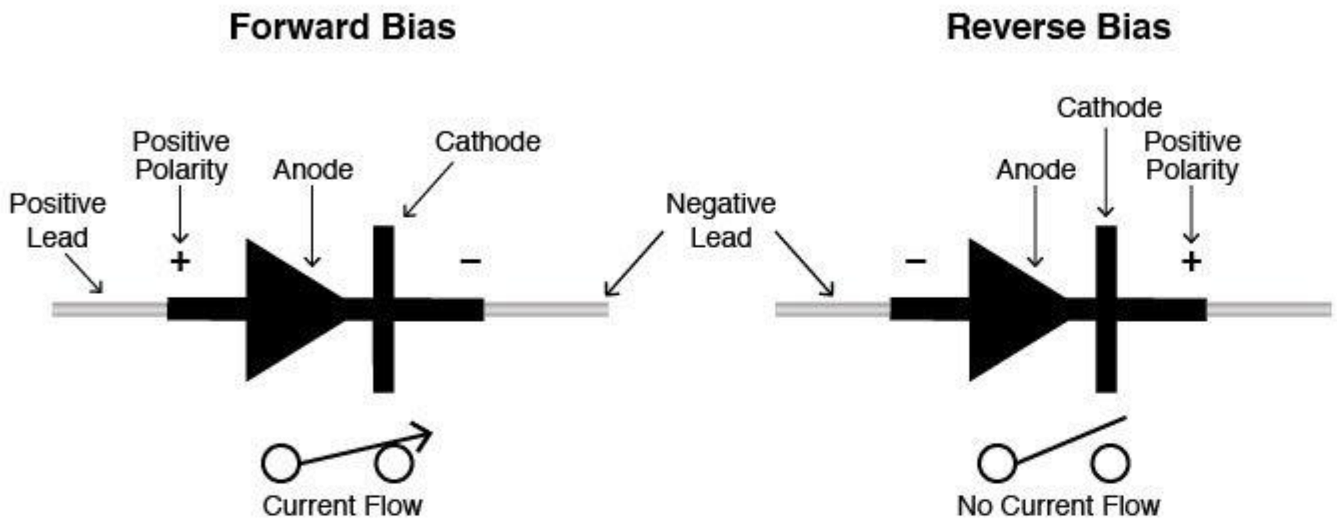
$$= i_0\left(e^{e\Delta V_{ext}/kT} - 1\right)$$

Diode

$$i = i_0(e^{e\Delta V_{ext}/kT} - 1)$$



Diode



Forward Bias
Reverse Bias
Positive Polarity
Anode
Cathode
Positive Lead
+
−
Negative Lead
Cathode
Anode
Positive Polarity
−
+
Current Flow
No Current Flow