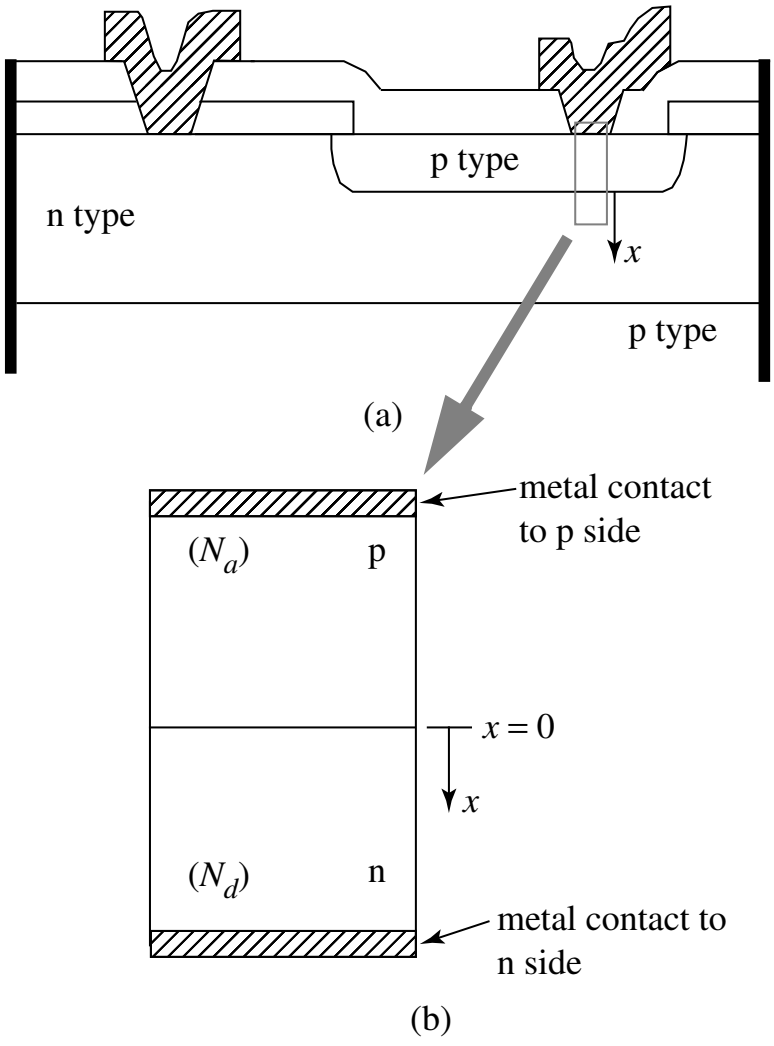
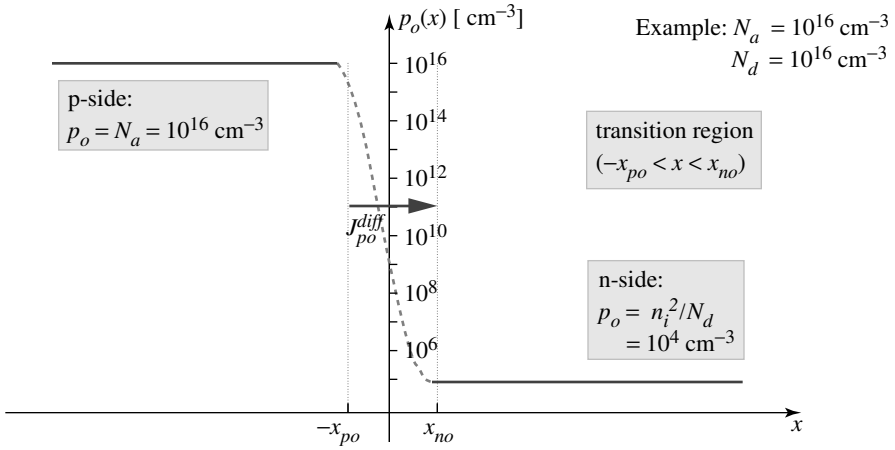
I. Introduction to PN Junctions

A. IC structure

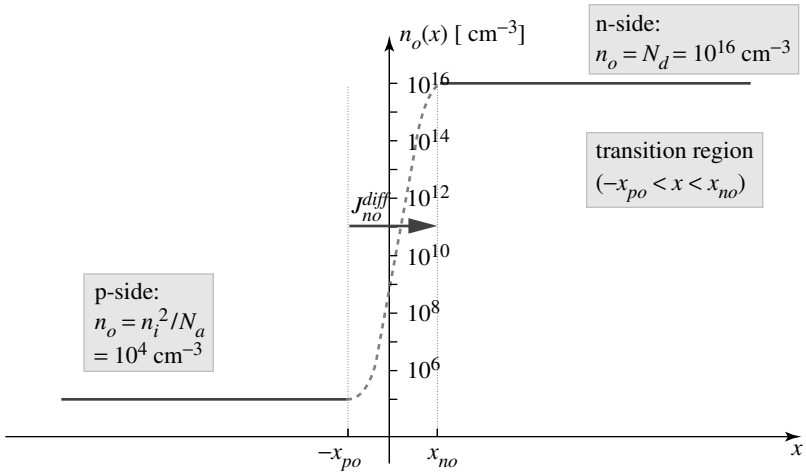


B. Diffusion Currents in Thermal Equilibrium

- Huge gradients in hole and electron concentration --> assume a transition region between - x_{po} and + x_{no}
- Note: we don't know how wide the transition region is (yet)
- Thermal equilibrium: no hole current, no electron current ... no voltage applied between metal interconnects (could short them together)



(a)



(b)

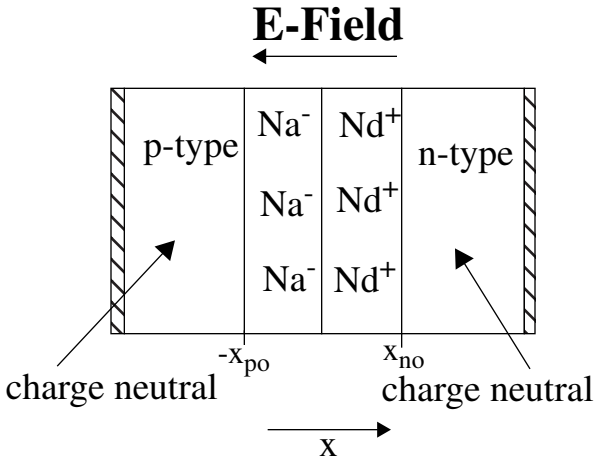
C. Drift and Diffusion in the Transition Region

- $J_{no} = 0$ and $J_{po} = 0$ since we are in thermal equilibrium
- This fact implies that a negative electric field in the transition region is needed
- Where do + and - charges come from?
- The roll-off in electron concentration between $x = 0$ and x_{no} means that

$$\rho_o(x) = q\,(-n_o(x) + N_d) > 0$$

since $n_o(x) < N_d$ on the n-side of the transition region.

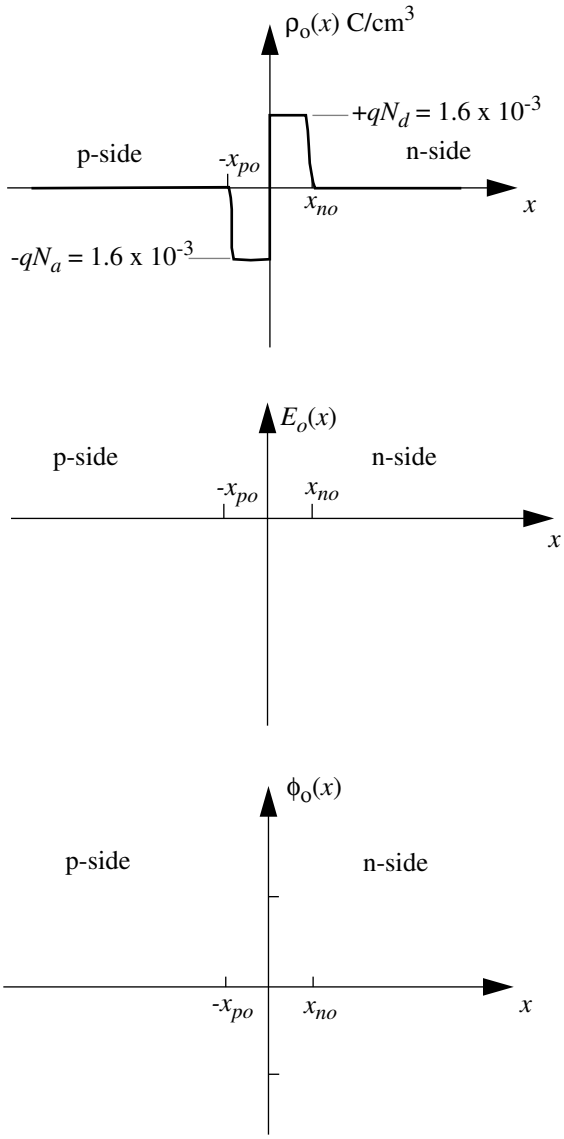
- On the p-side, the charge density is negative, since the hole concentration rolls off between $x = -x_{po}$ and $x = 0$.



E-Field causes Drift Current

D. Qualitative Electrostatics in Thermal Equilibrium

- From the charge density, we can find the electric field and the potential.



- Need to relate carrier concentration to the potential

II. Carrier Concentration and Potential

A. Thermal equilibrium

- *Thermal equilibrium:* no external stimulus
- $J_p = 0$ and $J_n = 0$.

$$0 = qn_o\mu_n E + qD_n\frac{dn_o}{dx} = qn_o\mu_n\left(-\frac{d\phi}{dx}\right) + qD_n\frac{dn_o}{dx}$$

- **Einstein Relation: *D*/μ = *kT*/*q* or μ/*D* = *q*/*kT***

$$d\phi = \frac{D_n}{\mu_n}\left(\frac{dn_o}{n_o}\right) = \frac{kT}{q}\left(\frac{dn_o}{n_o}\right) = V_{th}\left(\frac{dn_o}{n_o}\right)$$

$$\frac{D_n}{\mu_n} = \frac{kT}{q} = V_{th} = 25mV$$

- V_{th} is called the *Thermal Voltage*.

B. Potential Reference - Electrons

- By integrating the equation relating potential to the electron concentration from a position x_o to position x, we find that:

$$\phi(x) - \phi(x_o) = V_{th} \ln\left(\frac{n_o(x)}{n_o(x_o)}\right)$$

- We can choose any reference.
- $\phi(x_o) = 0$ when $n(x_o) = n_i = 10^{10}$ cm^{-3} at room temperature.
- Using this reference, the potential in thermal equilibrium can be found, given the electron concentration:

$$\boxed{\phi = V_{th} \ln\left(\frac{n_o}{n_i}\right)}$$

C. 60mV Rule - Electrons

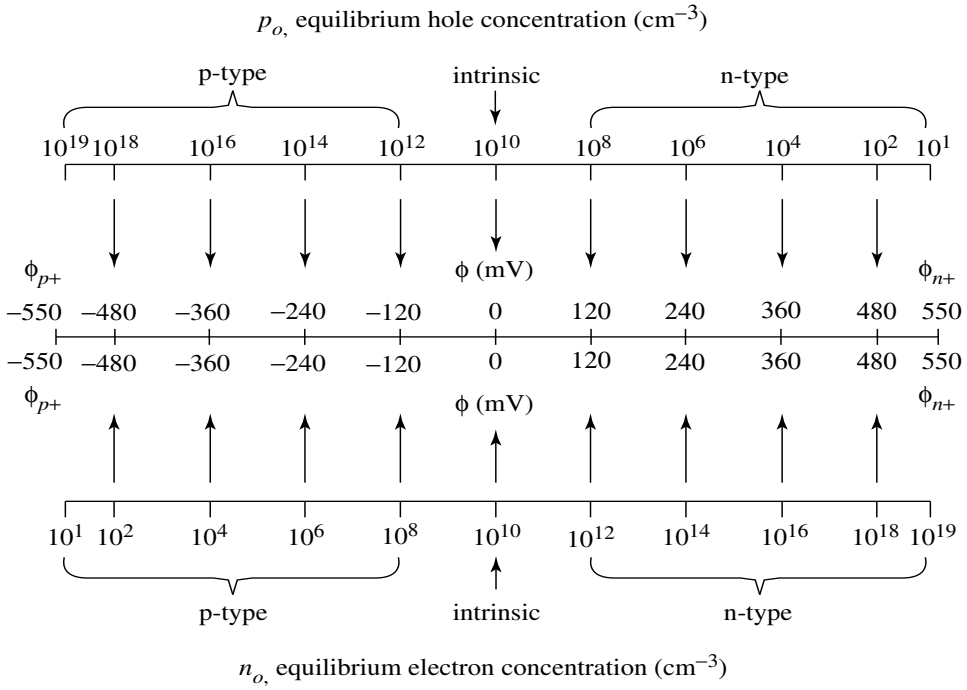
$$\phi = V_{th} \ln\left(\frac{n_o}{n_i}\right) = (26\text{mV}) \ln(10) \log\left(\frac{n_o}{10^{10}}\right) = (60\text{mV}) \log\frac{n_o}{10^{10}}$$

Donor concentrations from 10^{13} to 10^{19} cm^{-3} therefore correspond to potentials of (60 mV) x 3 = 180 mV to (60 mV) x 9 = 540 mV (at room temperature)

D. Potential Reference-Holes

- The hole concentration can also be related to the potential, by repeating the derivation starting with $J_p = 0$ or by substituting the equilibrium hole concentration $p_o = n_i^2 / n_o$

$$\phi = V_{th}\ln\left(\frac{n_i}{p_o}\right) = -V_{th}\ln\left(\frac{p_o}{n_i}\right)$$

E. 60 mV Rule - Holes

$$\phi = V_{th}\ln\left(\frac{n_i}{p_o}\right) = (-26\text{mV})\ln(10)\log\left(\frac{p_o}{10^{10}}\right) = (-60\text{mV})\log\left(\frac{p_o}{10^{10}}\right)$$