VE320 RC

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6.24

Outline

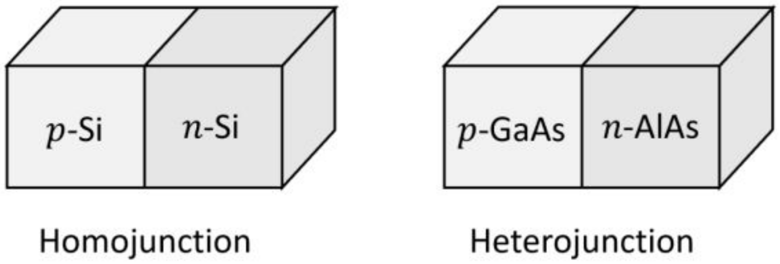
- PN Junction

Basic Structure

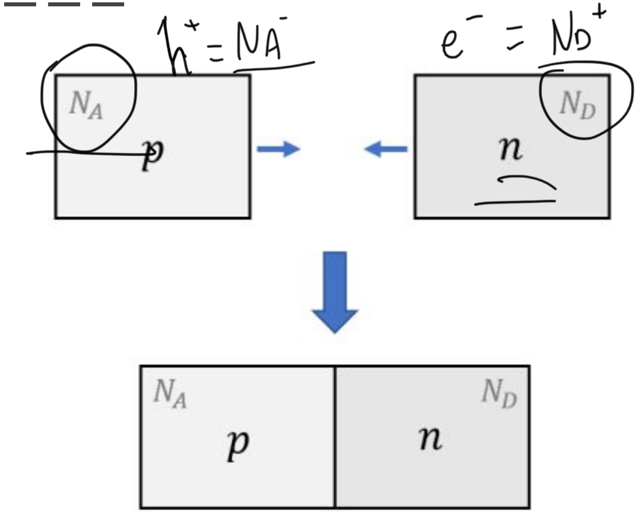
A p-n junction is a metallurgical and electrical junction formed between a p-type and an n-type semiconductor material.

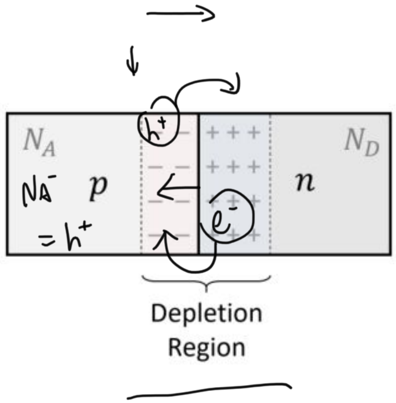
p-n Homojunction: p-type and n-type regions formed of the same semiconductor material

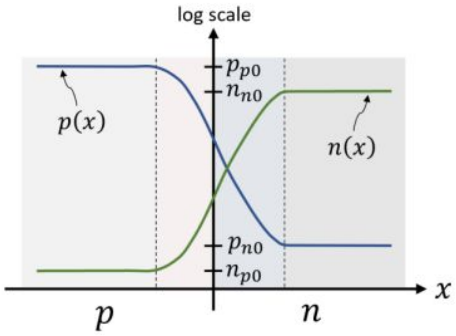
p-n Heterojunction: p-type and n-type regions formed of different semiconductor materials



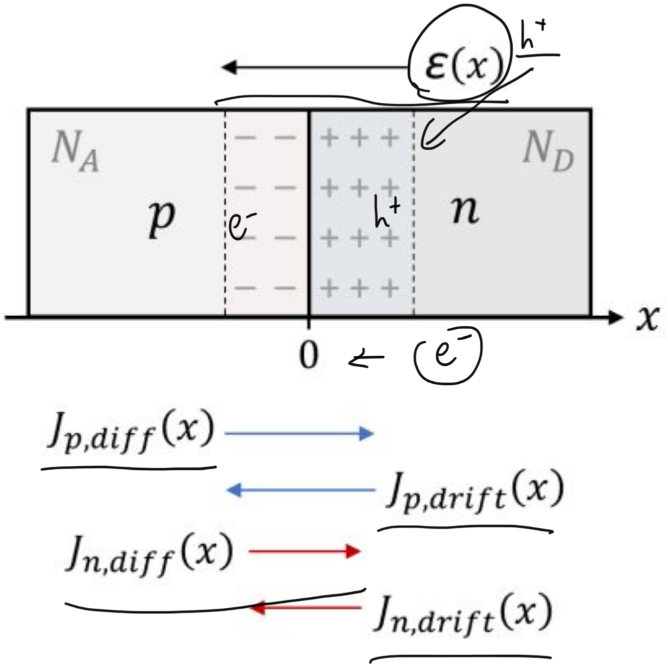
Basic Structure



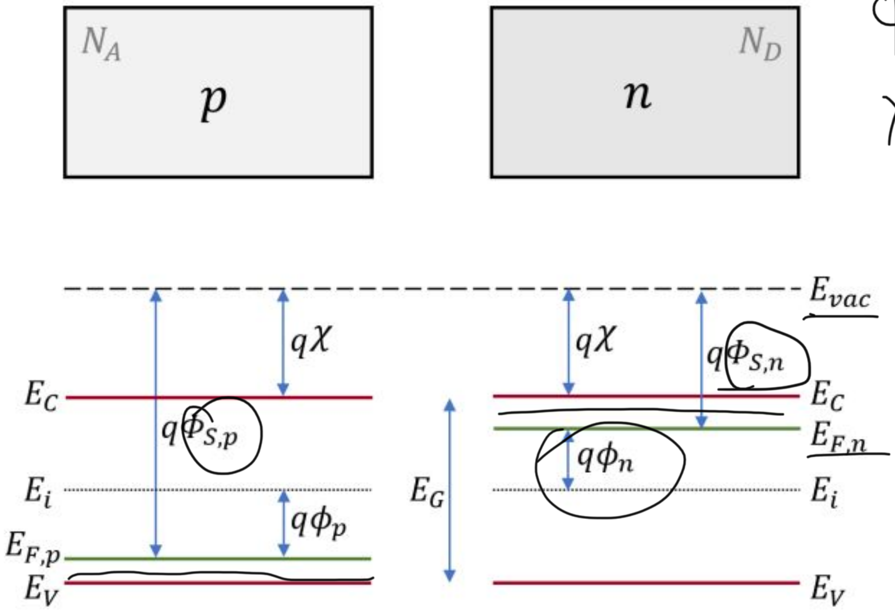




Thermal Equilibrium Conditions



Energy Perspective



ϕ = Work functions

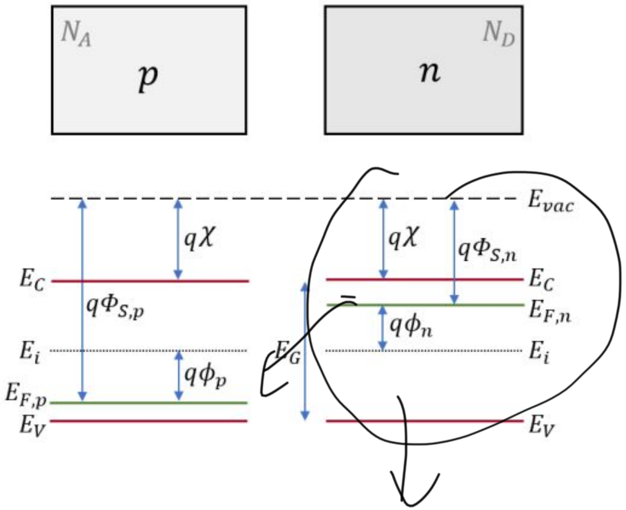
χ = Electron affinity

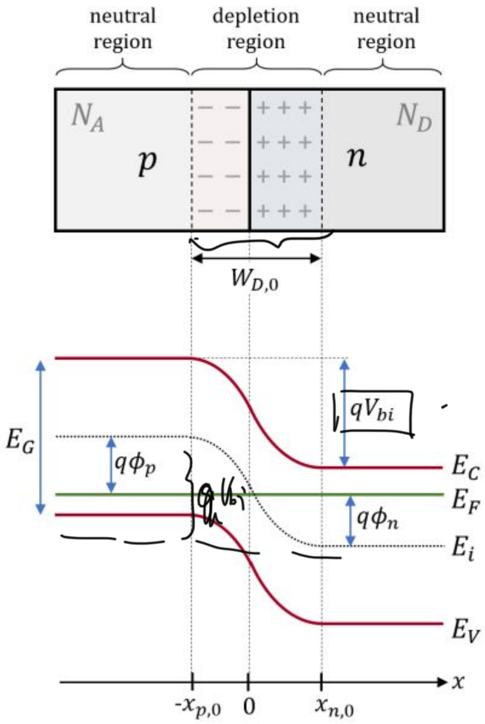
$$q\phi_n = kT \ln\left(\frac{N_D}{n_i}\right), \quad q\phi_p = kT \ln\left(\frac{N_A}{n_i}\right)$$

$$n = N_C \exp\left[\frac{-(E_C - E_{F,n})}{kT}\right]$$ (N_C = conduction band density of states)

$$p = N_V \exp\left[\frac{-(E_{F,p} - E_V)}{kT}\right]$$ (N_V = valence band density of states)

Energy Perspective





χ ≡ electron affinity

$\Phi_{S,p}$ ≡ semiconductor work function in *p*-material

$\Phi_{S,n}$ ≡ semiconductor work function in *n*-material

$W_{D,0}$ ≡ total depletion width under zero bias

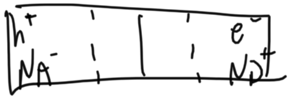
$x_{p,0}$ ≡ depletion width in *p*-material under zero bias

$x_{n,0}$ ≡ depletion width in *n*-material under zero bias

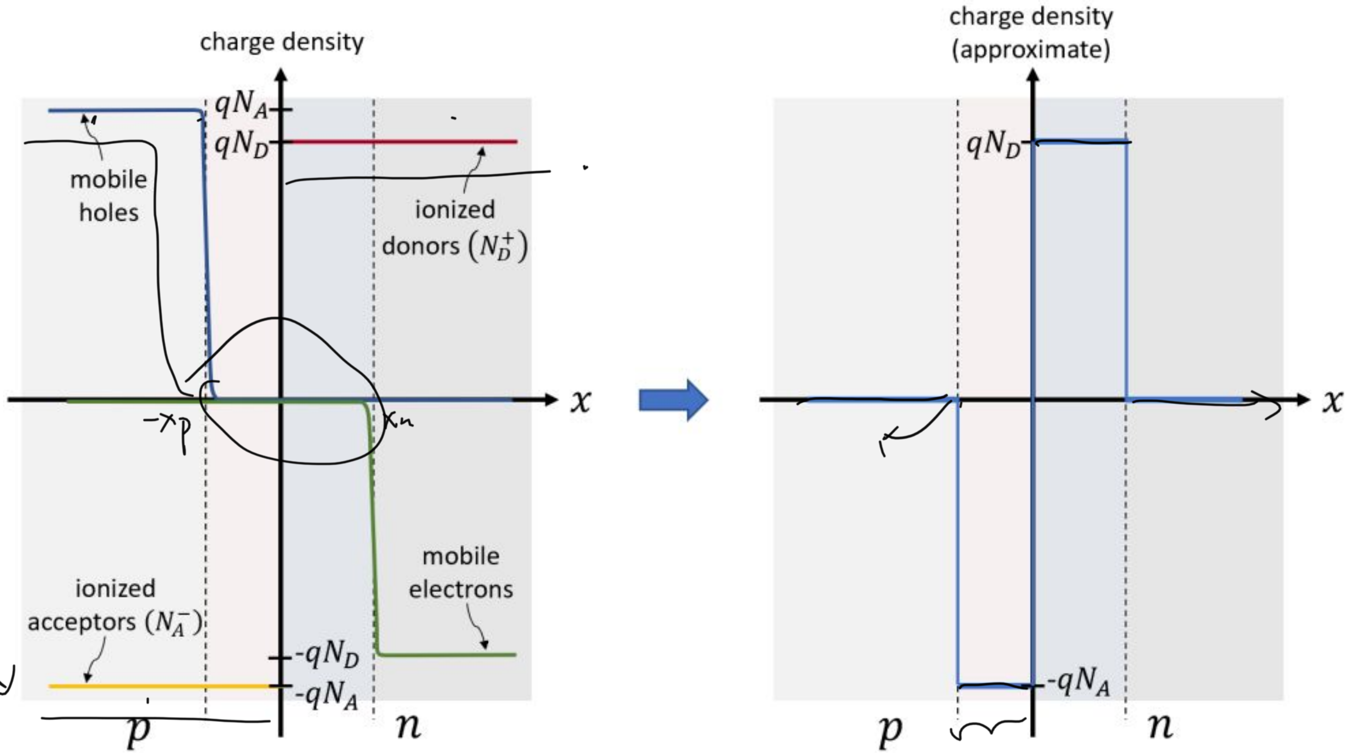
V_{bi} ≡ built-in voltage

$$qV_{bi} = q\phi_p + q\phi_n$$

$$V_{bi} = \phi_p + \phi_n = \frac{kT}{q}\ln\frac{N_A}{n_i} + \frac{kT}{q}\ln\frac{N_D}{n_i} = \frac{kT}{q}\ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)$$



Relevant Parameters



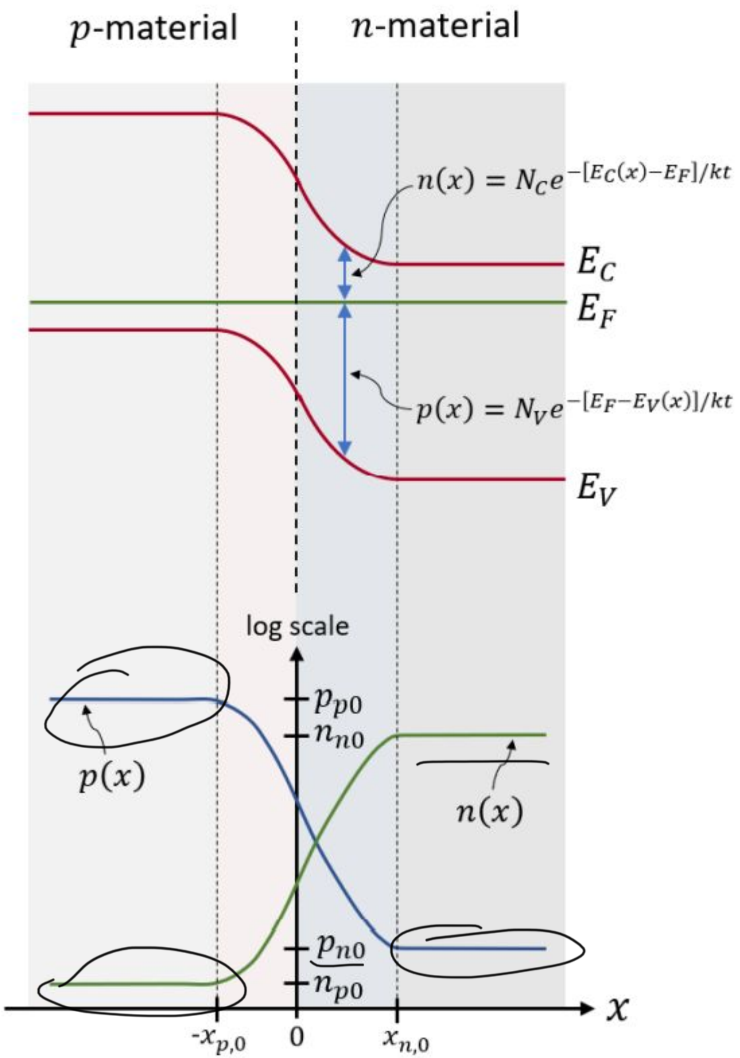
Relevant Parameters

p_{p0} = hole concentration in neutral p-material = N_A

n_{n0} = electron concentration in neutral n-material = N_D

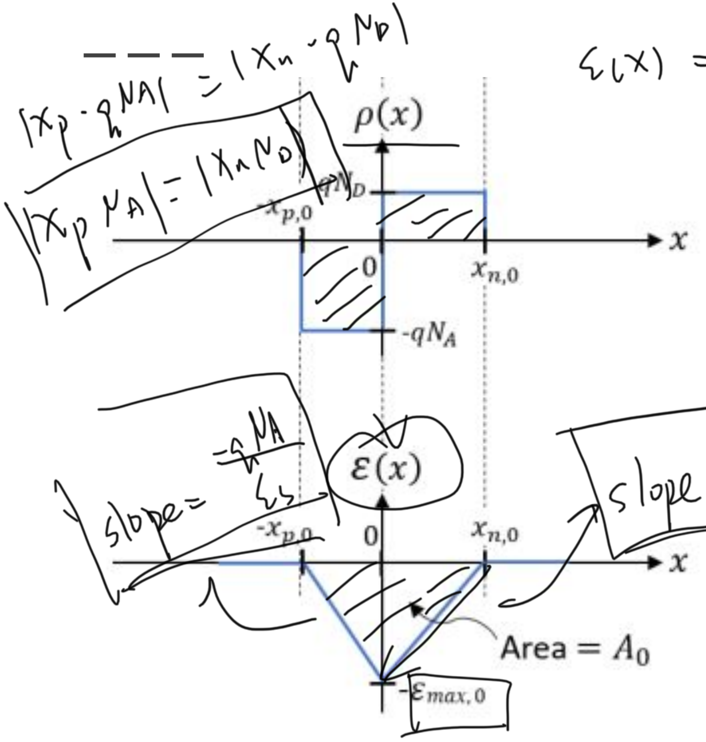
p_{n0} = hole concentration in neutral n-material = $\frac{n_i^2}{N_D}$

n_{p0} = electron concentration in neutral p-material = $\frac{n_i^2}{N_A}$



Relevant Parameters

$\leftarrow \mathcal{E}(x)$



$$\mathcal{E}(x) = \frac{-dV(x)}{dx}$$

$$\frac{d\mathcal{E}(x)}{dx} = \frac{-d^2V(x)}{dx^2} = \frac{\rho(x)}{\varepsilon_s}$$

$\varepsilon_s = \varepsilon_0 \varepsilon_r$

$$\boxed{\frac{W \cdot \mathcal{E}_{max}}{2} = V_{bi}}$$

$$x_{n,0} = \left\{\frac{2\epsilon_s V_{bi}}{q}\left[\frac{N_A}{N_D(N_A+N_D)}\right]\right\}^{1/2}$$

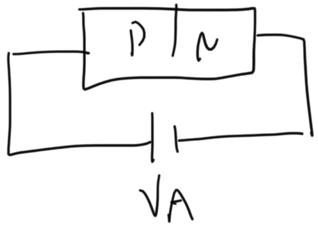
$$x_{p,0} = \left\{\frac{2\epsilon_s V_{bi}}{q}\left[\frac{N_D}{N_A(N_A+N_D)}\right]\right\}^{1/2}$$

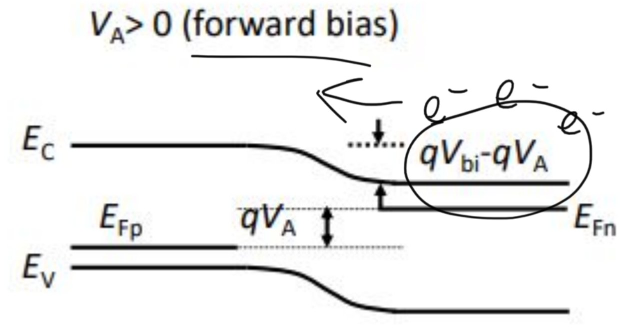
$$W_{D,0} = \left\{\frac{2\epsilon_s V_{bi}}{q}\left[\frac{1}{N_A}+\frac{1}{N_D}\right]\right\}^{1/2}$$

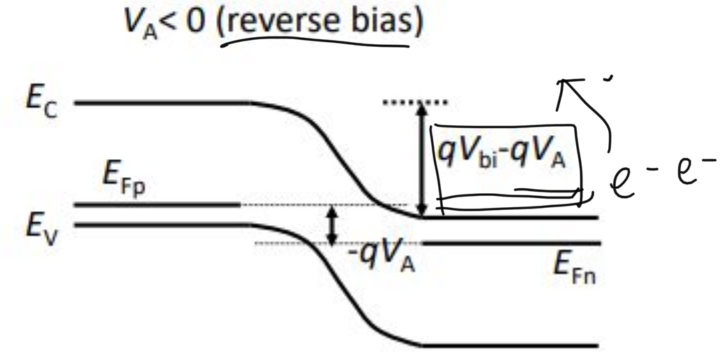
$$V_{bi} = \frac{kT}{q}\ln\left[\frac{N_A N_D}{n_i^2}\right]$$

$$\mathcal{E}_{max,0} = \frac{2V_{bi}}{W_{D,0}}$$

Applied Voltage



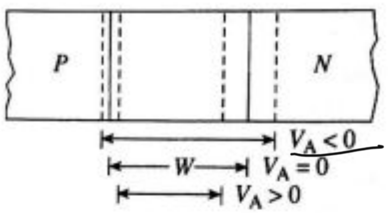


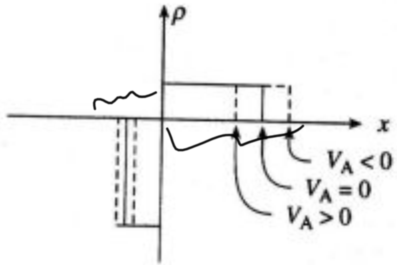


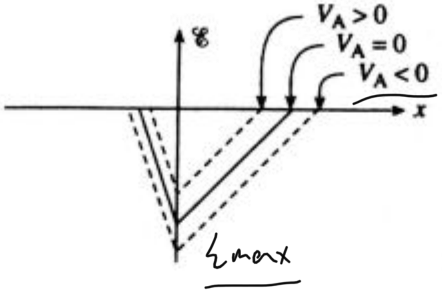
VA>0 pushes P-side bands DOWN, reducing the potential barrier.

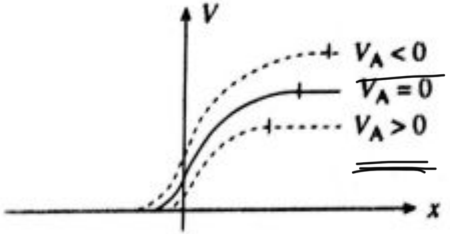
VA<0 pushes P-side bands UP, increasing the barrier.

Applied Voltage









Example 1

300K

$n_i = 10^{10}\ cm^{-3}$

0.0259 eV

A Si step junction maintained at room temperature under equilibrium conditions has *p*-side doping of $N_A = 1 \times 10^{15}$ cm^{-3} and *n*-side doping of $N_D = 5 \times 10^{15}$ cm^{-3}. Compute:

a. V_{bi}

b. x_p, x_n, and W

c. $|\mathcal{E}|$ at x=0

d. ~~V at x=0~~, assuming the quasi-neutral *p*-side is grounded.

e. Make sketches that are roughly to scale of the charge density, electric field, and electrostatic potential as a function of position.

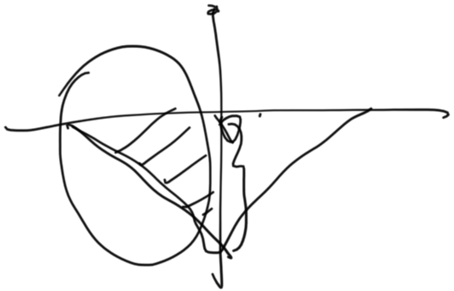
a. $V_{bi} = \frac{kT}{q} \ln\left[\frac{N_A N_D}{n_i^2}\right] = 0.0259 \ln\left[\frac{10^{15} \times 5\times10^{15}}{(10^{10})^2}\right] = 0.639\ V$

b. $x_p = \left[\frac{2\varepsilon_r\varepsilon_0}{q} \cdot \frac{N_D}{N_A} \frac{1}{(N_A+N_D)} \cdot V_{bi}\right]^{\frac{1}{2}}$ $\quad x_n = \left[\frac{2\varepsilon_r\varepsilon_0}{q} \frac{N_A}{N_D} \cdot \frac{1}{(N_A+N_D)} V_{bi}\right]^{\frac{1}{2}}$

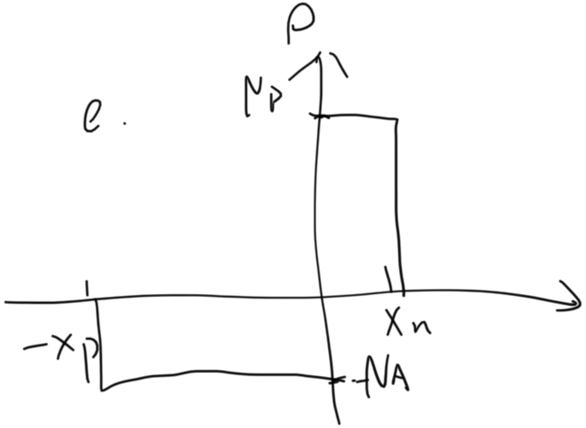
$W = x_p + x_n$

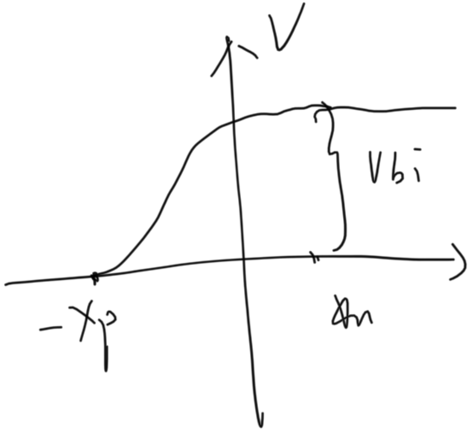
c. $|\mathcal{E}|$ $x=0$ $|\mathcal{E}|_{max} = \left|\frac{-qN_D}{\varepsilon_r\varepsilon_0}\cdot x_n\right| = \left|\frac{-qN_A}{\varepsilon_r\varepsilon_0}\cdot x_p\right|$ $|N_D\cdot x_n| = |N_A\cdot x_p|$

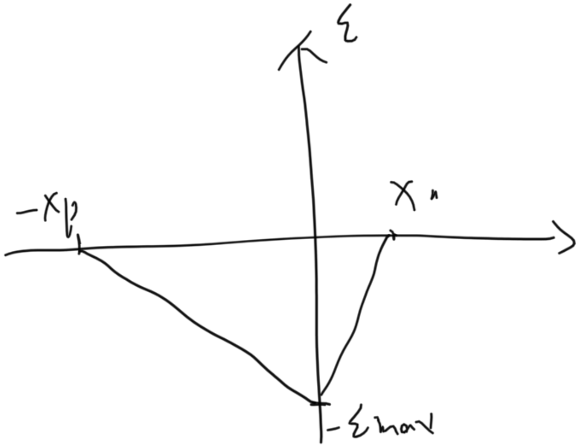
d. ___ $V(0) = \frac{1}{2}|\mathcal{E}|_0\cdot x_p$



e.



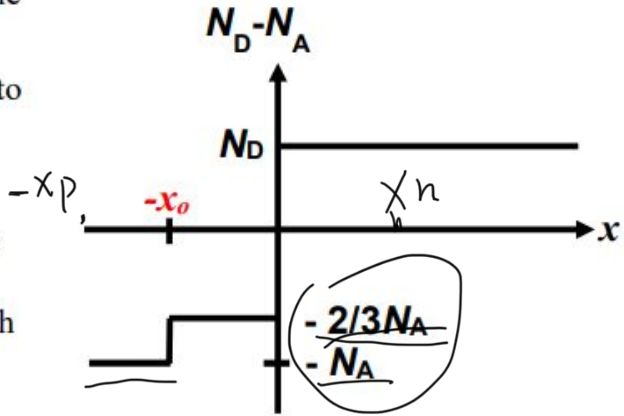


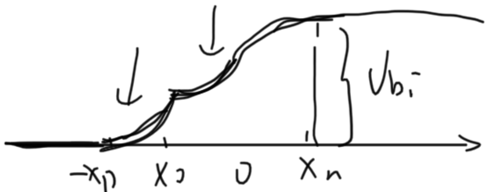


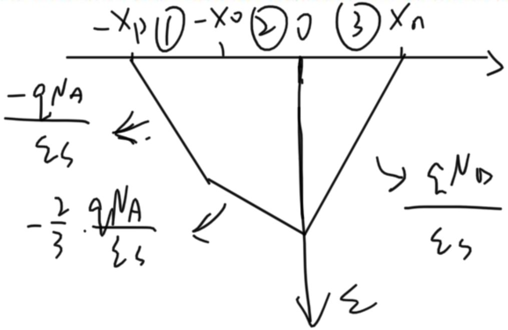
Example 2

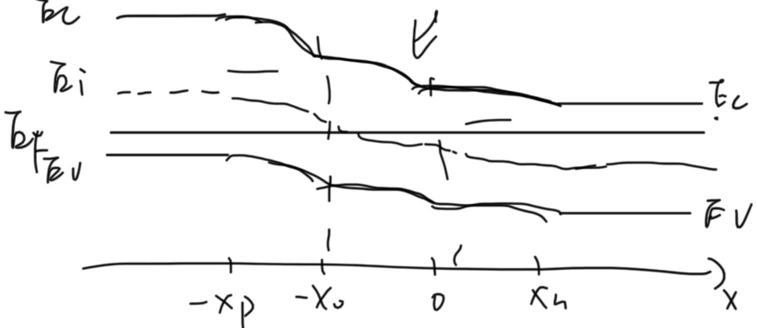
A pn junction diode has the doping profile sketched in the figure below. Make the assumption that $|x_p| > |x_o|$.

a. Sketch the equilibrium energy band diagram for the junction, taking the doping to be nondegenerate.
b. Based on your energy band diagram, sketch the potential and electric field as a function of x.
c. Now, invoking the depletion approximation, obtain an expression for the charge density for all x.
d. Thus, obtain an expression for the electric field, $\mathcal{E}(x)$ for all x. Does it agree with your sketch? (If not, you might want to correct your sketch.)
e. Derive an expression for the built-in voltage V_{bi} that exists across the junction under equilibrium conditions. Indicate the polarity of the built-in voltage.

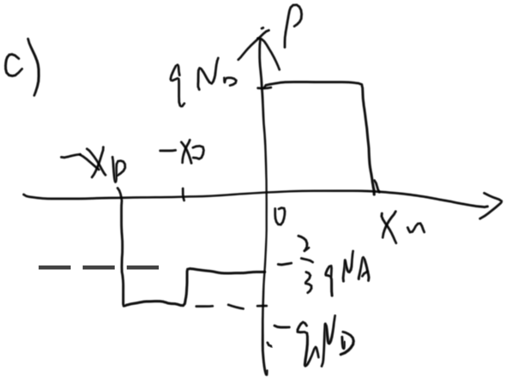








c)



$$\rho = \begin{cases} -qN_A & -x_p < x < -x_0 \\ -\frac{2}{3}qN_A & -x_0 \le x < 0 \\ qN_D & 0 \le x \le x_n \\ 0 & \text{elsewhere} \end{cases}$$

d) $\frac{d\mathcal{E}}{dx} = \frac{\rho}{\varepsilon_s}$

$$\frac{d\mathcal{E}}{dx} = \begin{cases} -\frac{qN_A}{\varepsilon_s} & \_\_\_\_\_\_ \\ -\frac{2}{3}\frac{qN_A}{\varepsilon_s} & \_\_\_\_\_\_ \\ \frac{qN_D}{\varepsilon_s} & \_\_\_\_\_\_ \end{cases}$$

(1) $\mathcal{E} = \int_{-x_p}^{-x} \frac{d\mathcal{E}}{dx} = \frac{-q}{\varepsilon_r\varepsilon_0} N_A \cdot \int_{-x_p}^{x} dx = \frac{-qN_A}{\varepsilon_r\varepsilon_0}(x+x_p)$

$// \frac{-q}{\varepsilon_r\varepsilon_0} N_A\left(\frac{2}{3}x - \frac{1}{3}x_0 + x_p\right)$

(2) $\mathcal{E} = \int_{\mathcal{E}(-x_0)}^{\mathcal{E}(x)} = \mathcal{E}(x) - \mathcal{E}(-x_0) = \int_{-x_0}^{x} -\frac{2}{3}\frac{qN_A}{\varepsilon_r\varepsilon_0}\,dx - \mathcal{E}(x_0) = -\frac{2}{3}\frac{qN_A}{\varepsilon_r\varepsilon_0}(x+x_0) - \left(\frac{-qN_A}{\varepsilon_r\varepsilon_0}\right)(x_p - x_0)$

③ $\int_{\mathcal{E}(0)}^{\mathcal{E}(x)} = \mathcal{E}(x) - \mathcal{E}(0) = \frac{q N_D}{\varepsilon_r \varepsilon_0} \int_0^x dx - \mathcal{E}(0) = \frac{q N_D}{\varepsilon_r \varepsilon_0} \cdot x - \underline{\frac{q N_D}{\varepsilon_r \varepsilon_0} x_n}$

$$= -\frac{q N_D}{\varepsilon_r \varepsilon_0} (x_n - x)$$

e). $V_{bi} = -\int_{-x_p}^{x_n} \mathcal{E}(0$

Thanks