ECE 340: Semiconductor Electronics

Chapter 5: Junction (part I)

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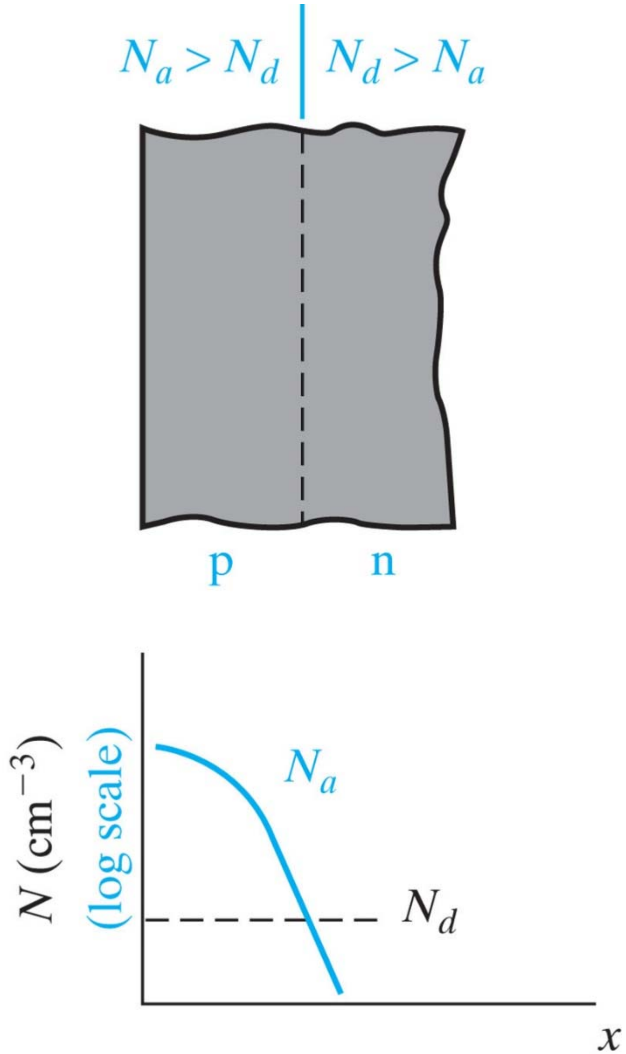
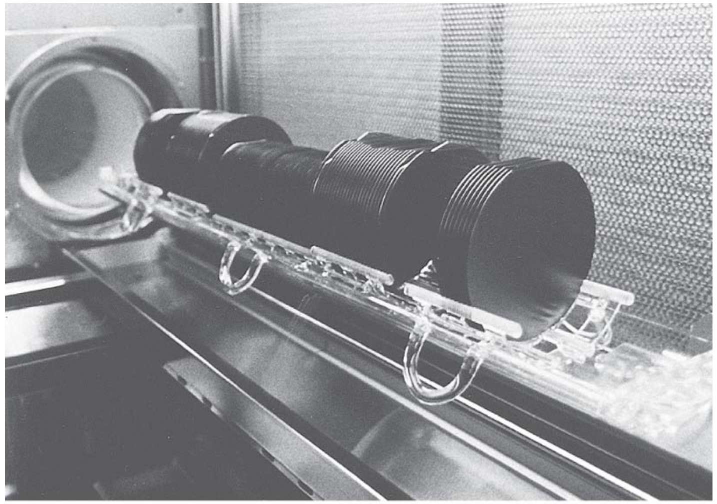
Outline

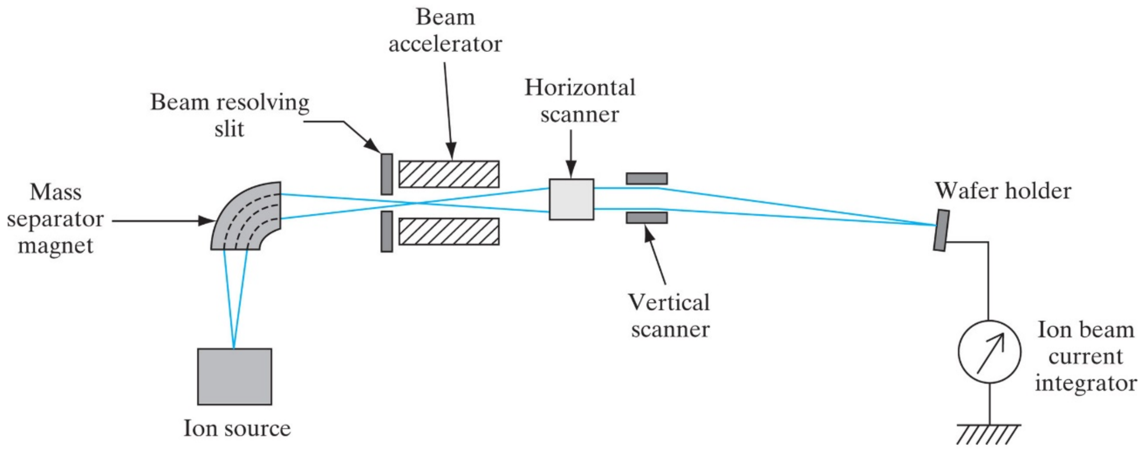
- Fabrication of p-n Junctions
- Equilibrium Condition
  - The Contact Potential
  - Equilibrium Fermi Levels
  - Space Charge at a Junction

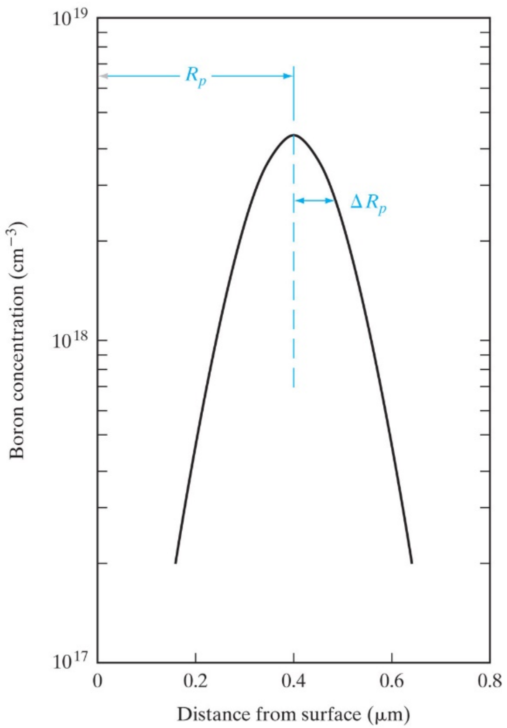
Form pn junction by thermal diffusion



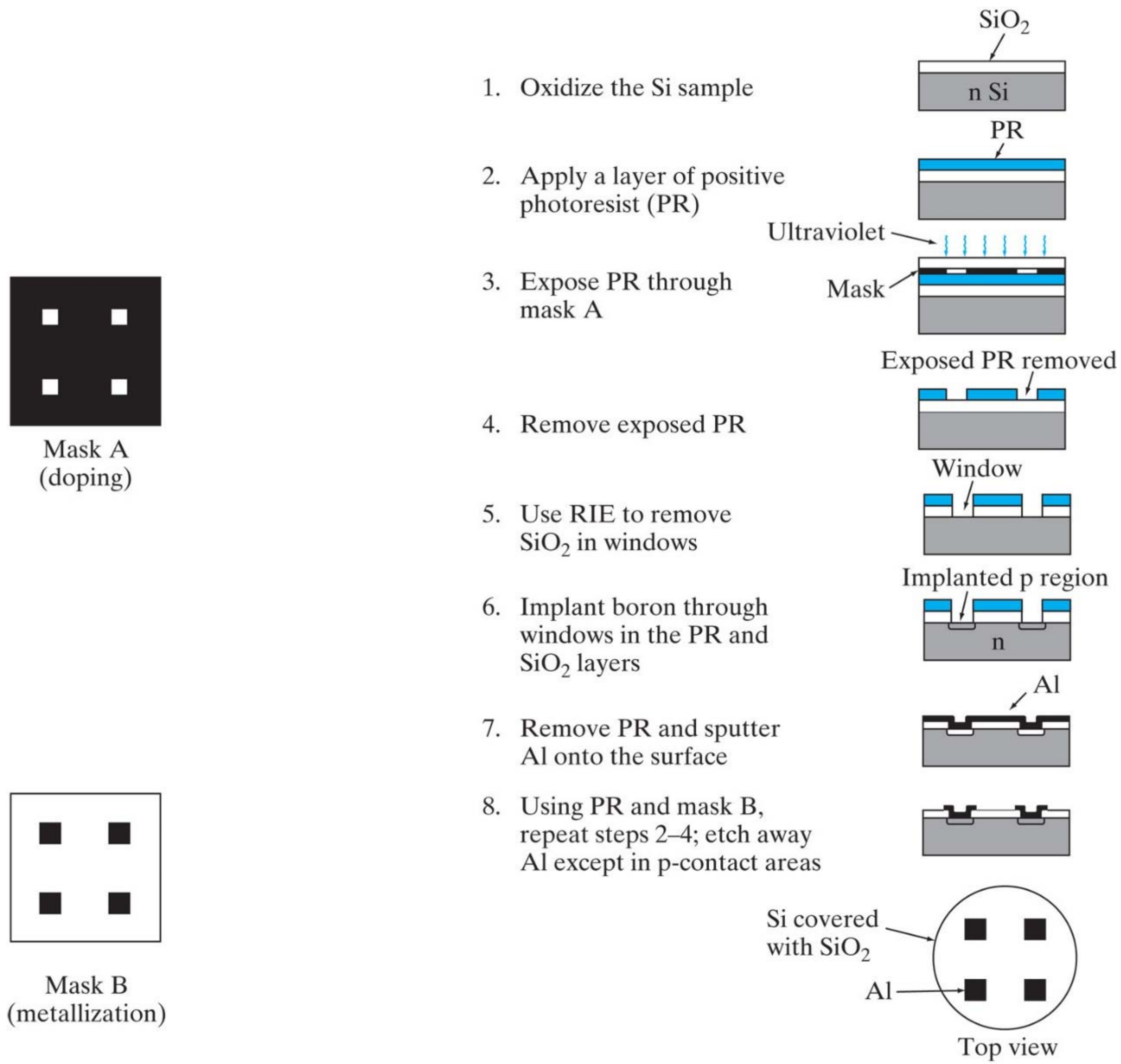


Ion implantation





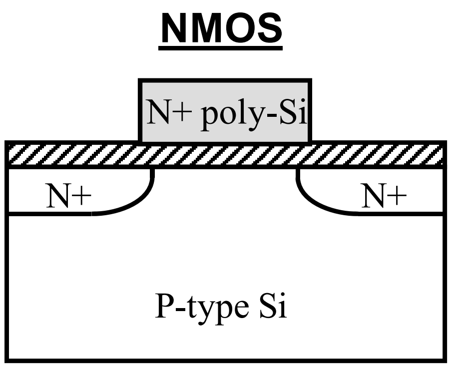
Process flow for pn junction formation



Why do we study pn junction?

PN junction is the basic building block for:

- Transistors: computing and memory
- LEDs (light emitting diode), convert electricity to light
- Lasers: convert electricity to light
- Solar cells: convert sunlight to current
- Photodetectors: detect light
- Rectifiers: convert AC to DC current



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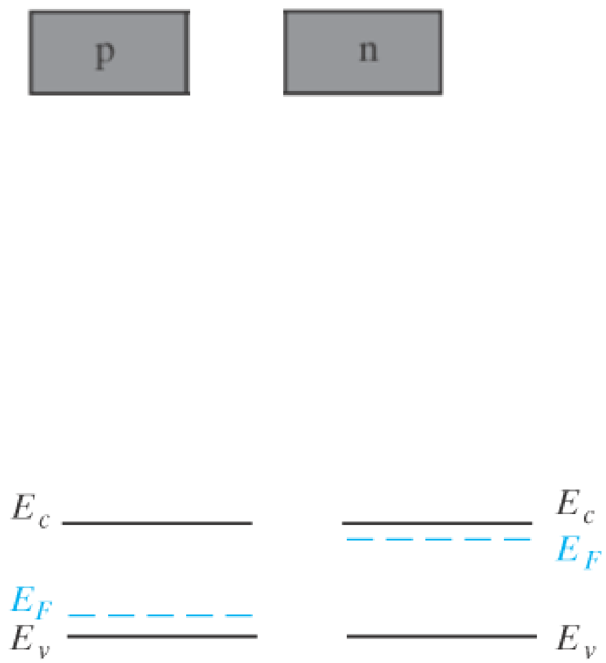
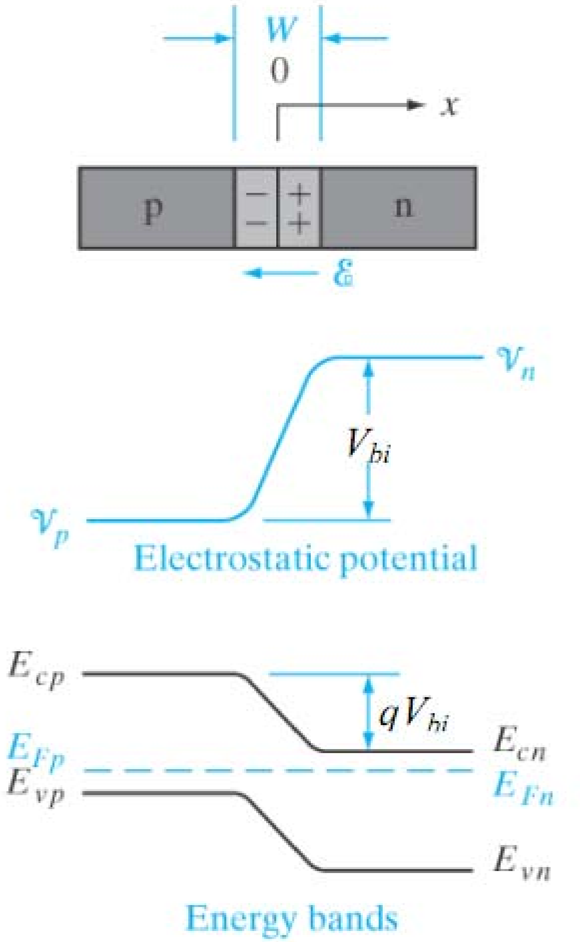
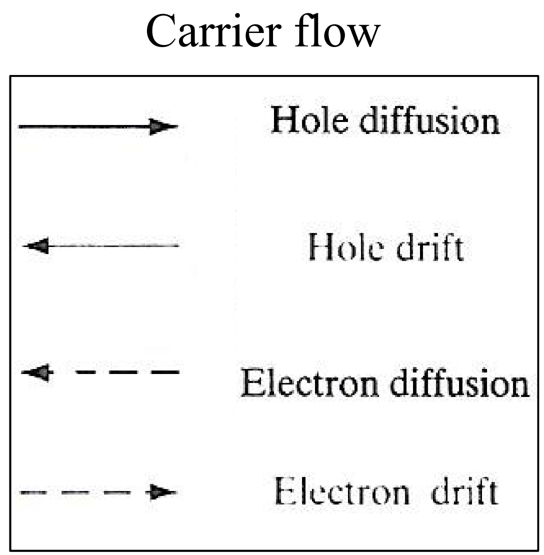
Form PN junction

Isolated n and p region



pn junction at equilibrium





Carrier diffusion → leave behind uncompensated donor (acceptor) ions → resulting electric field→ drift current balances the diffusion current at equilibrium.

At equilibrium

- No net electron or hole current:

$$J_p(drift) + J_p(diff.) = 0$$

$$J_n(drift) + J_n(diff.) = 0$$

- The electric field builds up to the point where the net current is zero at equilibrium.
- The region W with left-behind uncompensated donor (acceptor) ions called transition region.
- The potential difference V_0 across W called contact potential

$$V_0 = V_n - V_p$$

Built-in electric field

- At equilibrium:

$$J_p(x) = q\mu_p p(x)\mathcal{E}(x) - qD_p \frac{dp(x)}{dx} = 0$$

Use Einstein relation $\frac{D}{\mu} = \frac{kT}{q}$

$$\Rightarrow \quad \mathcal{E} = \frac{\boldsymbol{kT}}{\boldsymbol{q}} \frac{\mathbf{1}}{\boldsymbol{p}} \frac{\boldsymbol{dp}}{\boldsymbol{dx}}$$

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

$$\Rightarrow \quad \boldsymbol{dV(x)} = -\frac{\boldsymbol{kT}}{\boldsymbol{q}} \frac{\mathbf{1}}{\boldsymbol{p}} \boldsymbol{dp(x)}$$

Contact potential

$$\Rightarrow \int_{V_p}^{V_n} dV = -\frac{kT}{q}\int_{P_p}^{P_n}\frac{1}{p}\,dp$$

$$\Rightarrow V_n - V_p = -\frac{kT}{q}\left(lnP_p - lnP_p\right)$$

$$\Rightarrow V_0 = \frac{kT}{q}ln\left(\frac{P_p}{P_n}\right)$$ **Contact potential**

Or $$V_0 = \frac{kT}{q}ln\left(\frac{N_a}{n_i^2/N_d}\right) = \frac{kT}{q}ln\left(\frac{N_aN_d}{n_i^2}\right)$$

Carrier concentration ratio

- The hole concentration ratio between p side and n side at the edge of transition region:

$$\frac{P_p}{P_n} = e^{qV_0/kT}$$

Since $\quad P_p n_p = n_i^2 = P_n n_n$

$$\Rightarrow \quad \boxed{\frac{P_p}{P_n} = \frac{n_n}{n_p} = e^{qV_0/kT}}$$

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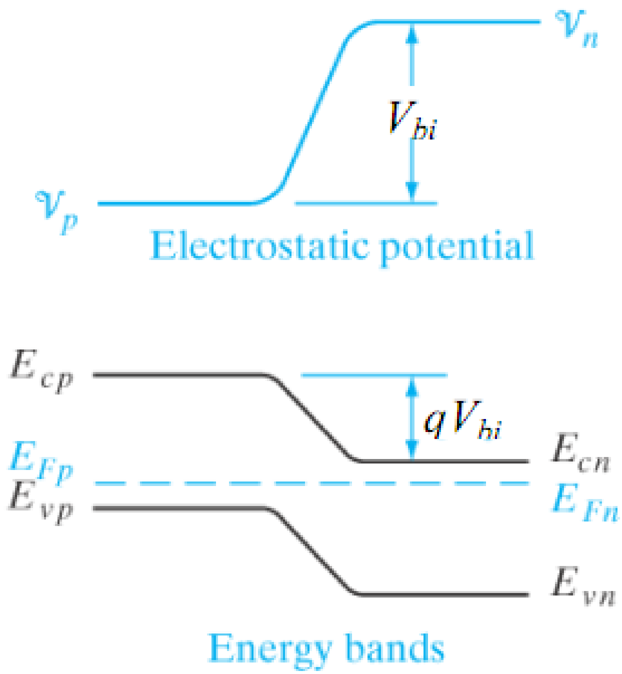
Equilibrium Fermi levels

- At equilibrium, Fermi level on either sides are equal ($E_{Fp} = E_{Fn}$), combine with

$$\frac{P_p}{P_n} = e^{qV_0/kT} = \frac{N_v e^{-(E_{Fp}-E_{vp})/kT}}{N_v e^{-(E_{Fn}-E_{vn})/kT}}$$

$$\Rightarrow \quad qV_0 = E_{vp} - E_{vn}$$

the contact potential times q is equal to the energy difference between n and p region



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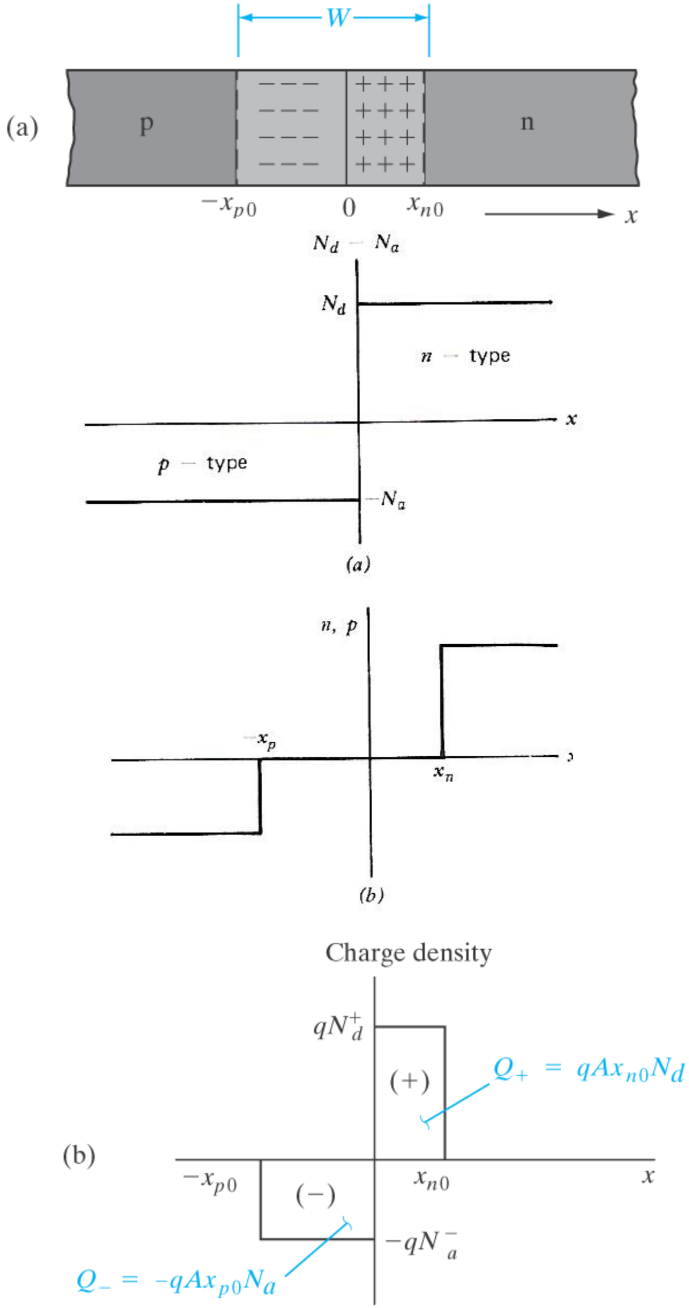
Space charge at a junction

- Depletion approximation: assumption of carrier depletion within W and neutrality outside W.
- Penetration of the space charge region:

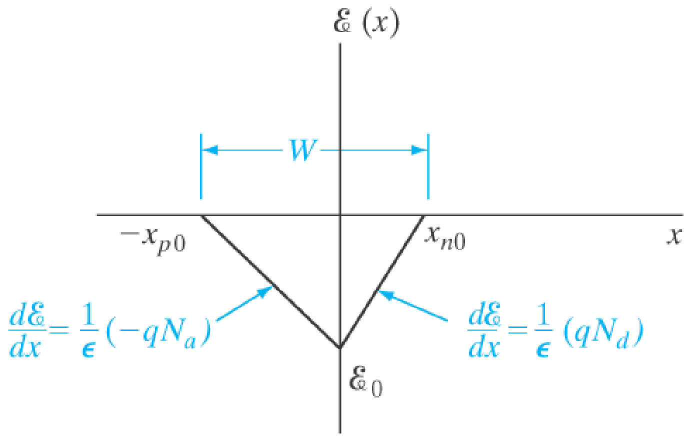
$$Q_+ = Q_-$$

$$qAx_{p0}N_a = qAx_{n0}N_d$$

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



Electric field



- Poisson's equation:

$$\frac{d\mathcal{E}(x)}{dx} = \frac{q}{\epsilon}(p - n + N_d^+ - N_a^-)$$

- If neglect the contributions of carriers in space charge, and assume complete ionization of impurities:

$$\frac{d\mathcal{E}(x)}{dx} = \frac{q}{\epsilon} N_d \qquad 0 < x < x_{n0}$$

$$\frac{d\mathcal{E}(x)}{dx} = -\frac{q}{\epsilon} N_a \qquad -x_{p0} < x < 0$$

Built-in electric field

Built-in field:

$$\mathcal{E}(x) = -\frac{qN_d}{\epsilon}(x_{n0} - x) \quad 0 < x < x_{n0}$$

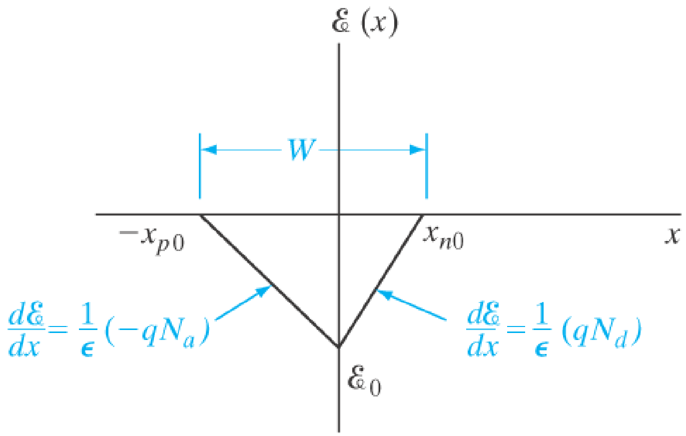
$$\mathcal{E}(x) = -\frac{qN_a}{\epsilon}(x_{p0} + x) \quad -x_{p0} < x < 0$$

- The maximum electric field located at the interface of n and p junction (x=0):

$$\Rightarrow \quad \mathcal{E}_0 = -\frac{q}{\epsilon}N_d x_{n0} = -\frac{q}{\epsilon}N_a x_{p0}$$

maximum electric field

(c)



Potential

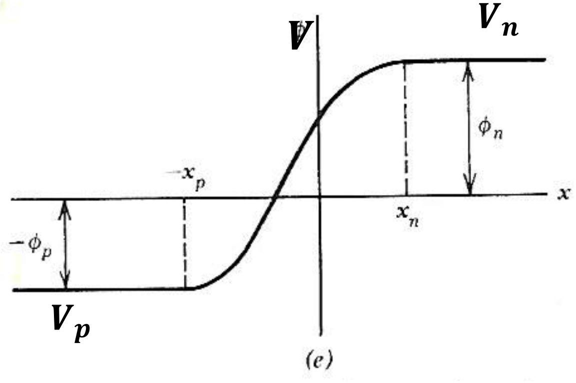
- Potential variation across the junction:

$$V(x) = V_n - \frac{qN_d}{2\epsilon_s}(x_n - x)^2 \qquad 0 < x < x_{n0}$$

$$V(x) = V_p - \frac{qN_a}{2\epsilon_s}\left(x + x_p\right)^2 \qquad -x_{p0} < x < 0$$

where $V_n = \frac{kT}{q} ln \frac{N_d}{n_i}$

$$V_p = -\frac{kT}{q} ln \frac{N_a}{n_i}$$



- Built-in variation:

$$V_0 = V_n - V_p = \frac{kT}{q} ln \frac{N_d N_a}{n_i}$$

The contact potential

- The contact potential can also be obtained by

$$\mathcal{E}(\boldsymbol{x}) = -\frac{\boldsymbol{dV(x)}}{\boldsymbol{dx}} \quad \text{or} \quad \textbf{-}\boldsymbol{V_0} = \int_{-x_{p0}}^{x_{n0}} \mathcal{E}(\boldsymbol{x})\boldsymbol{dx}$$

$$\boldsymbol{V_0} = -\frac{\mathbf{1}}{\mathbf{2}}\mathcal{E}_0 W = \frac{\mathbf{1}}{\mathbf{2}}\frac{q}{\epsilon} N_d x_{n0} W$$

Since $x_{p0}N_a = x_{n0}N_d$ and $x_{p0} + x_{n0} = W$

$$\Rightarrow \boxed{\boldsymbol{V_0} = \frac{\mathbf{1}}{\mathbf{2}}\frac{q}{\epsilon}\frac{N_a N_d}{N_a + N_d} W^2}$$

Depletion width

- The depletion width is:

$$\boldsymbol{W} = \left[\frac{2\epsilon V_0}{q}\left(\frac{N_a+N_d}{N_a N_d}\right)\right]^{1/2} = \left[\frac{2\epsilon V_0}{q}\left(\frac{1}{N_d}+\frac{1}{N_a}\right)\right]^{1/2}$$

where $\boldsymbol{V_0} = \frac{kT}{q} ln\left(\frac{N_a N_d}{n_i^2}\right)$

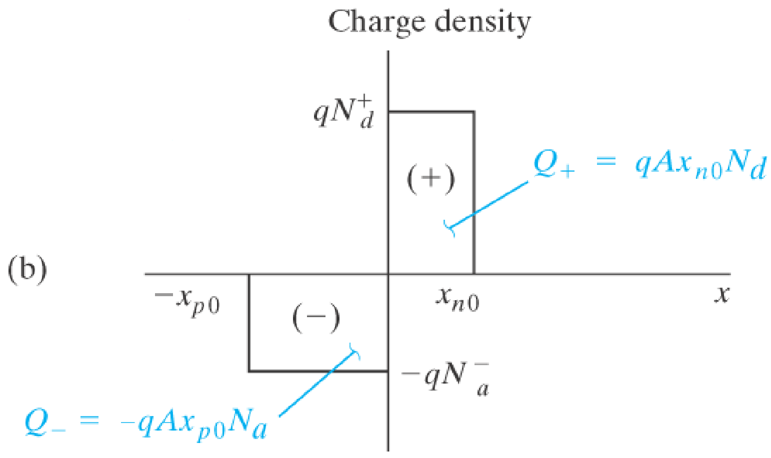
- The transition width $\boldsymbol{W} \propto \sqrt{\boldsymbol{V_0}}$. Applying voltage to increase or decrease the potential $\boldsymbol{V_0}$, can modulate the depletion width of the junction.

Penetration depth

- The penetration of the transition region into the n and p region:

$$x_{p0} = W\frac{N_d}{N_a + N_d}$$

$$x_{n0} = W\frac{N_a}{N_a + N_d}$$



- The transition region extends farther into the side with lighter doping.

One-side junction

- If $N_a \gg N_d$, as in a p⁺n junction:

$$\boldsymbol{W} = \sqrt{\frac{\boldsymbol{2\epsilon V_0}}{qN_d}}$$

$$x_{p0} = W\frac{N_d}{N_a + N_d} \approx 0$$

- What abut a n⁺p junction?
- Generally:

$$\boldsymbol{W} = \sqrt{\frac{\boldsymbol{2\epsilon V_0}}{qN}}$$

Where $\boldsymbol{\frac{1}{N} = \frac{1}{N_d} + \frac{1}{N_a} \approx \frac{1}{lighter\ dopant\ density}}$

- **Ex:** An abrupt silicon p-n junction has p-side $N_A = 10^{18}\ cm^{-3}$, and n-side $N_D = 5x10^{15}\ cm^{-3}$. A) Calculate Fermi levels and built-in potential at equilibrium, B) How wide is the depletion region C) What is the maximum electric field.

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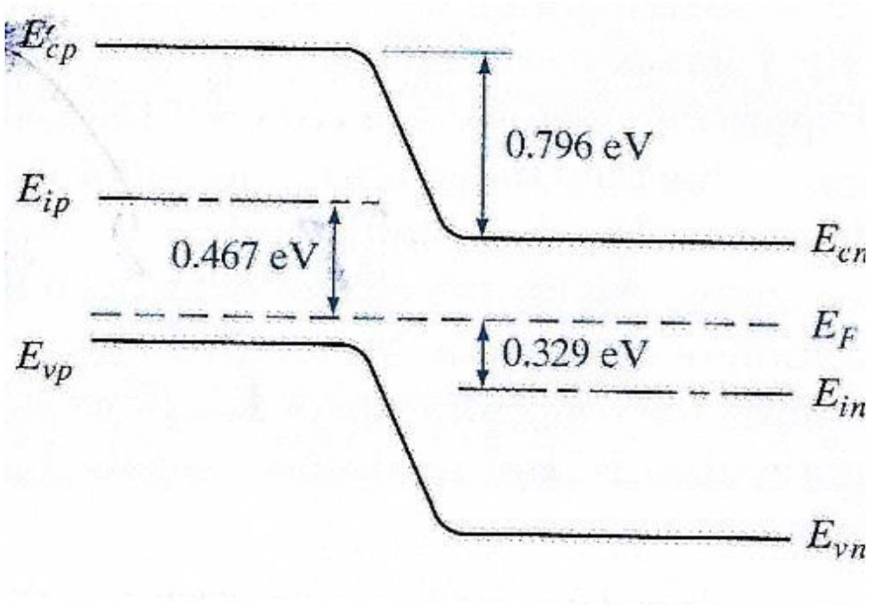
$$E_{ip} - E_F = \frac{kT}{q} ln\left(\frac{P_p}{n_i}\right) = 0.467eV$$

$$E_F - E_{in} = \frac{kT}{q} ln\left(\frac{n_n}{n_i}\right) = 0.329eV$$

$$qV_0 = E_{ip} - E_{in} = 0.796eV$$

or $$V_0 = \frac{kT}{q} ln\left(\frac{N_a N_d}{n_i^2}\right) = 0.796eV$$



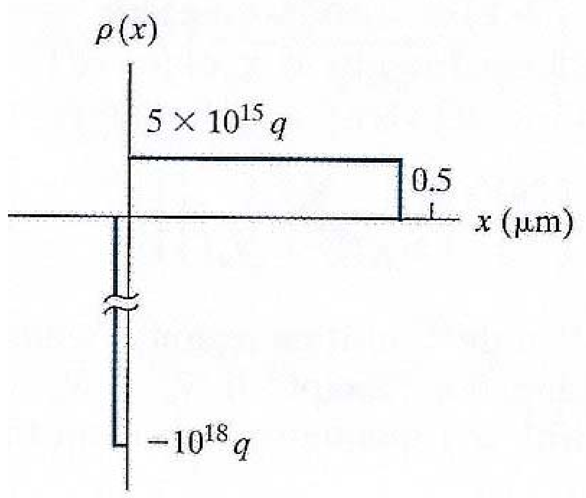
- **<u>Ex:</u>** An abrupt silicon p-n junction has p-side $N_A = 10^{18}$ cm^{-3}, and n-side $N_D = 5\text{x}10^{15}$ cm^{-3}. A) Calculate Fermi levels and built-in potential at equilibrium, B) How wide is the depletion region C) What is the maximum electric field.

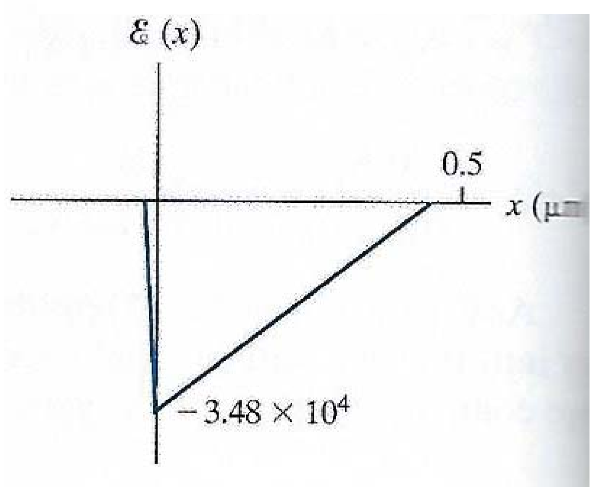
$$\boldsymbol{W}=\left[\frac{2\epsilon V_0}{q}\left(\frac{1}{N_d}+\frac{1}{N_a}\right)\right]^{1/2} = \mathbf{0.457}\mu m$$

$$x_{p0} = W\frac{N_d}{N_a + N_d} = 2.27 \times 10^{-3}\mu m$$

$$x_{n0} = W\frac{N_a}{N_a+N_d} = 0.455\mu\text{m}$$

$$\mathcal{E}_0 = -\frac{q}{\epsilon}N_d x_{n0} = -3.48 \times 10^4 V/cm$$





Arbitrarily doped semiconductor

Define $\boldsymbol{\phi = E_F - E_i}$, the Poisson equation can be written as:

Space charge density

$$\frac{d^2\phi}{dx^2} = -\frac{d\mathcal{E}(x)}{dx} = -\frac{\rho}{\epsilon} = -\frac{q}{\epsilon}(p - n + N_d \ - N_a\ )$$

permittivity of the medium

The carrier concentration: $n = n_i e^{(\frac{q\phi}{kT})}$ $\quad p = n_i e^{(-\frac{q\phi}{kT})}$

$$\Rightarrow \quad \frac{d^2\phi}{dx^2} = \frac{q}{\epsilon}(2n_i sinh\frac{q\phi}{kT} + N_d \ - N_a\ )$$

$$\sinh(x) = (e^x - e^{-x})/2$$

Two special cases

- Dopant concentration varies gradually with position,
  - Example: diffused n type region

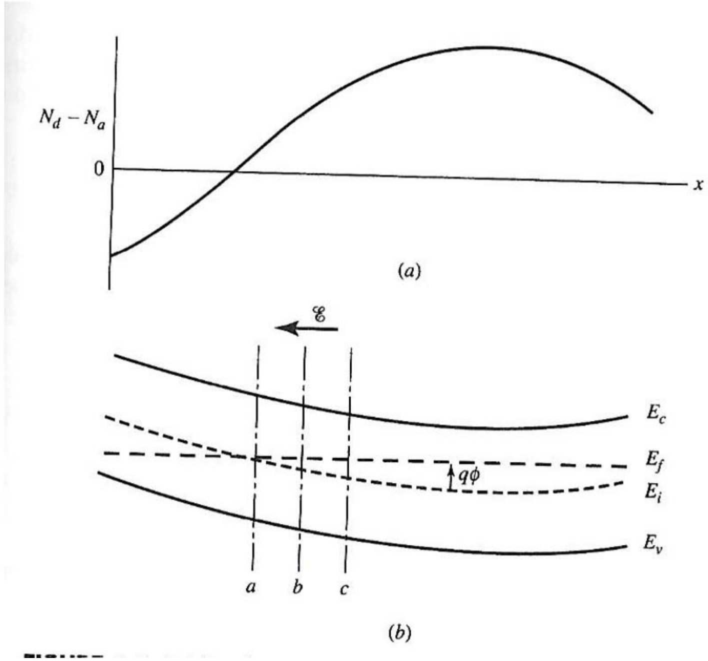
- Abrupt special variations of dopant concentration
  - PN junction

Case I: Gradual-variation, Quasi-neutrality

- Majority carrier distribution does not differ much from the donor (or acceptor) distribution, so that the semiconductor region is nearly neutral or quasi-neutral. $n \approx N_d$, or $p \approx N_a$.
- This quasi-neutrality approximation is more valid for slowly varying dopant densities. Then:

$$\mathcal{E} = \frac{kT}{q}\frac{1}{N_a}\frac{dN_a}{dx}$$

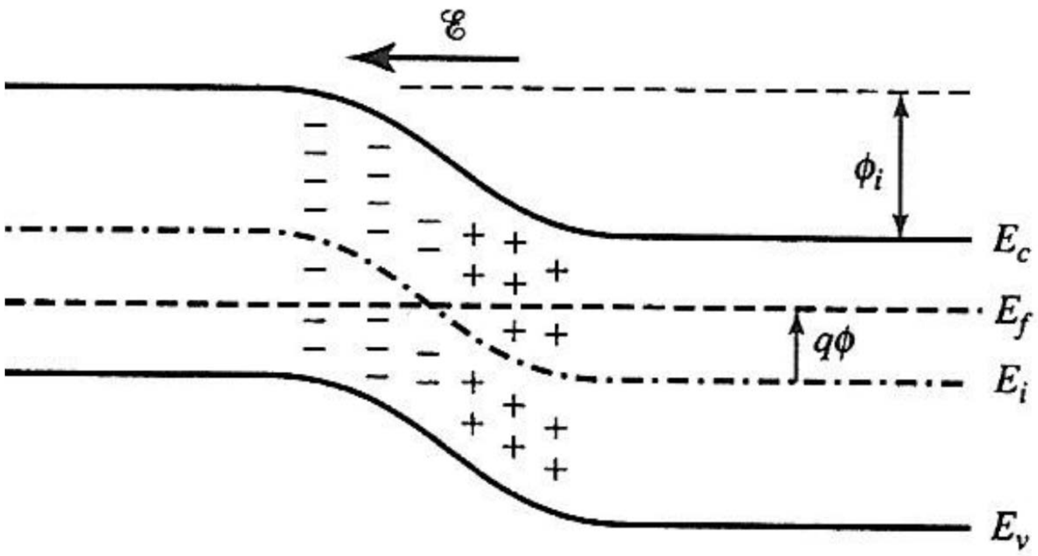
$$\mathcal{E} = -\frac{kT}{q}\frac{1}{N_d}\frac{dN_d}{dx}$$



Case II: steep gradient

- In steep gradient, such as pn junction, the transition region is treated as if it were depleted of mobile carriers, i.e depletion approximation.

- The approximation is valid, because $\boldsymbol{\phi} = \boldsymbol{E_F} - \boldsymbol{E_i}$ is small in the transition region. Since carrier concentration decrease rapidly as $\boldsymbol{\phi}$ becomes small, and are, consequently, much less in the transition region than in the neutral regions.



Case II: steep gradient, depletion approximation

- The Poisson equation can be simplified to:

$$\frac{d\mathcal{E}(x)}{dx} = \frac{q}{\epsilon}(N_d - N_a)$$

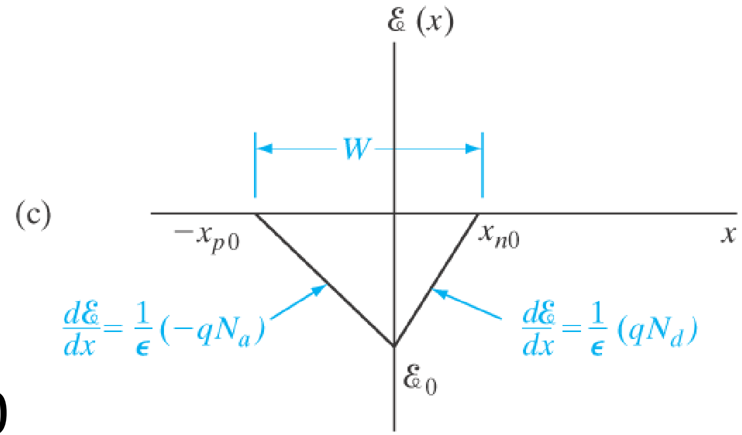
- For example:
  - Step junction (abrupt junction)
  - Linearly graded junction

Step junction: electric field and potential

- The electric field:

$$\mathcal{E}(x) = -\frac{qN_d}{\epsilon}(x_{n0} - x) \quad 0 < x < x_{n0}$$

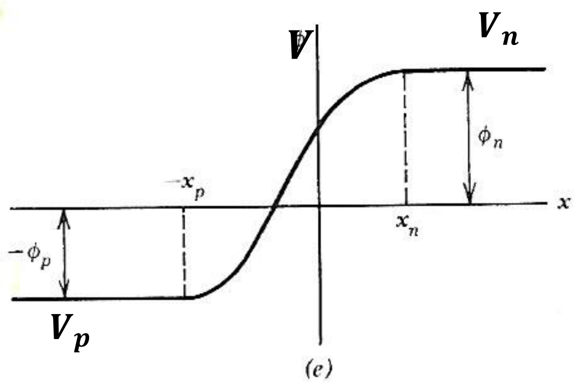
$$\mathcal{E}(x) = -\frac{qN_a}{\epsilon}(x_{p0} + x) \quad -x_{p0} < x < 0$$



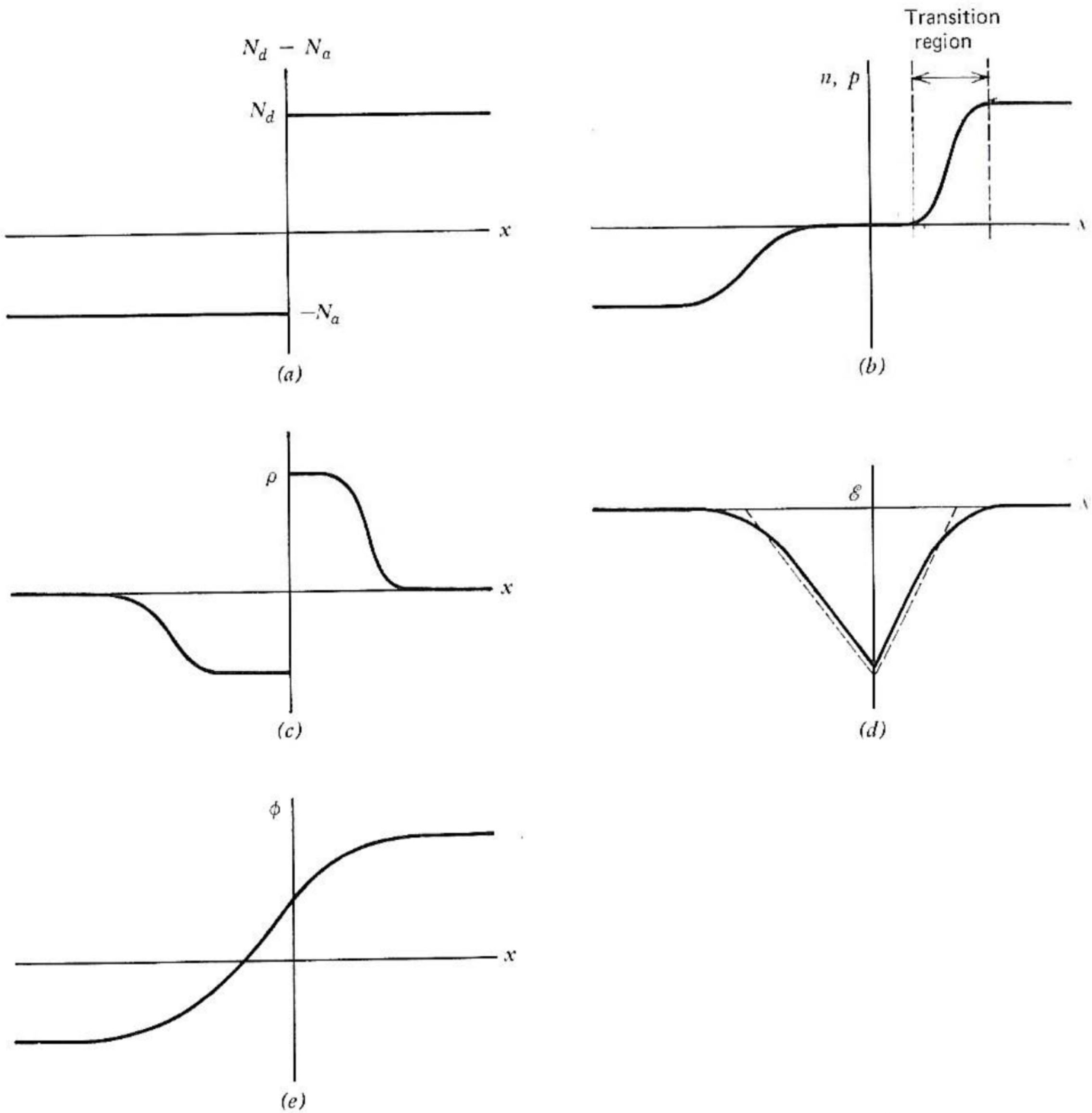
- The potential:

$$V(x) = V_n - \frac{qN_d}{2\epsilon_s}(x_n - x)^2 \qquad 0 < x < x_{n0}$$

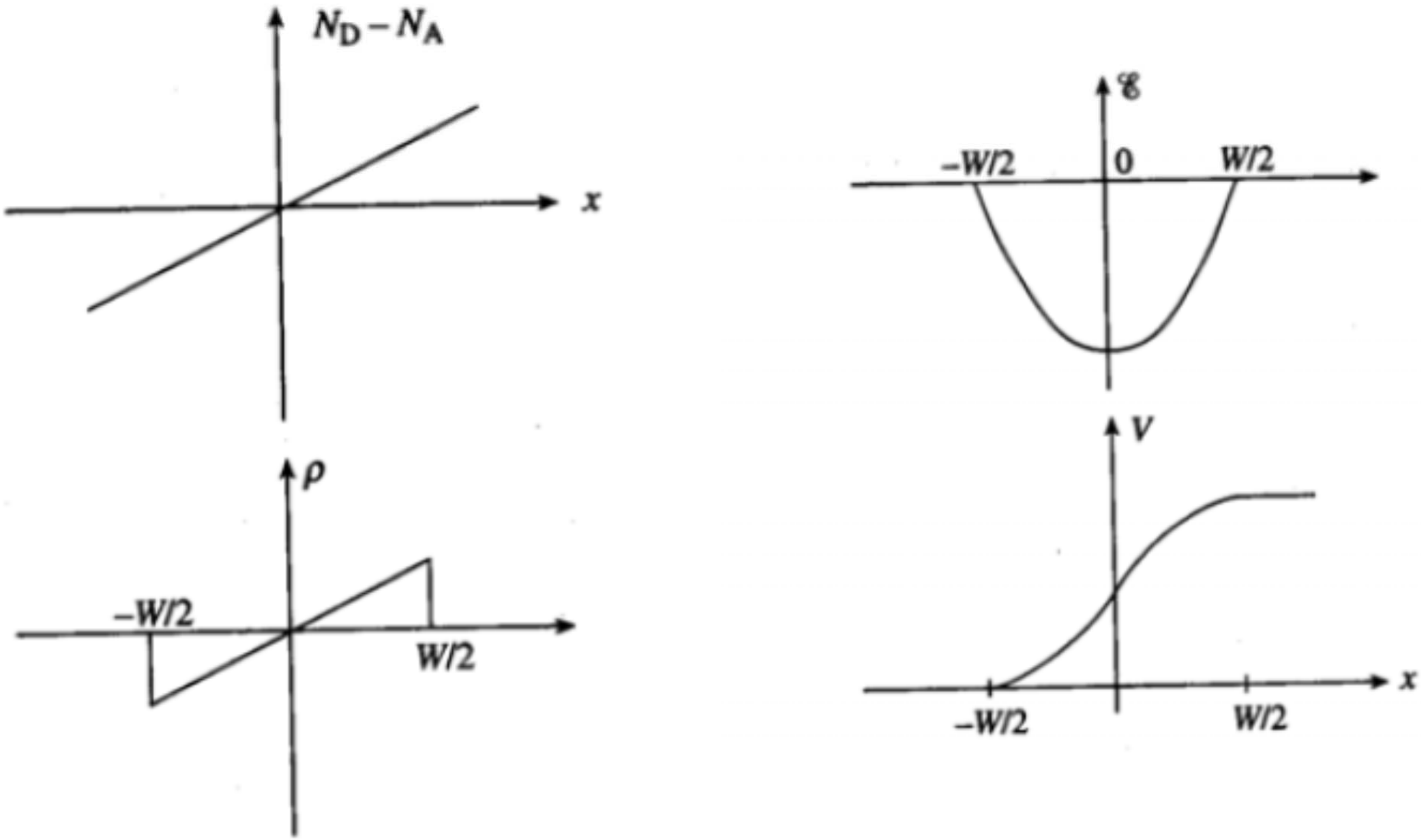
$$V(x) = V_p - \frac{qN_a}{2\epsilon_s}(x + x_p)^2 \qquad -x_{p0} < x < 0$$



Step junction considering a gradual transition



Linearly Graded Junction



Linear graded junction

- The dopant concentration: $N_d - N_a = \alpha x$
- The field varies quadratically and the potential varies as the third power of position in the space charge region