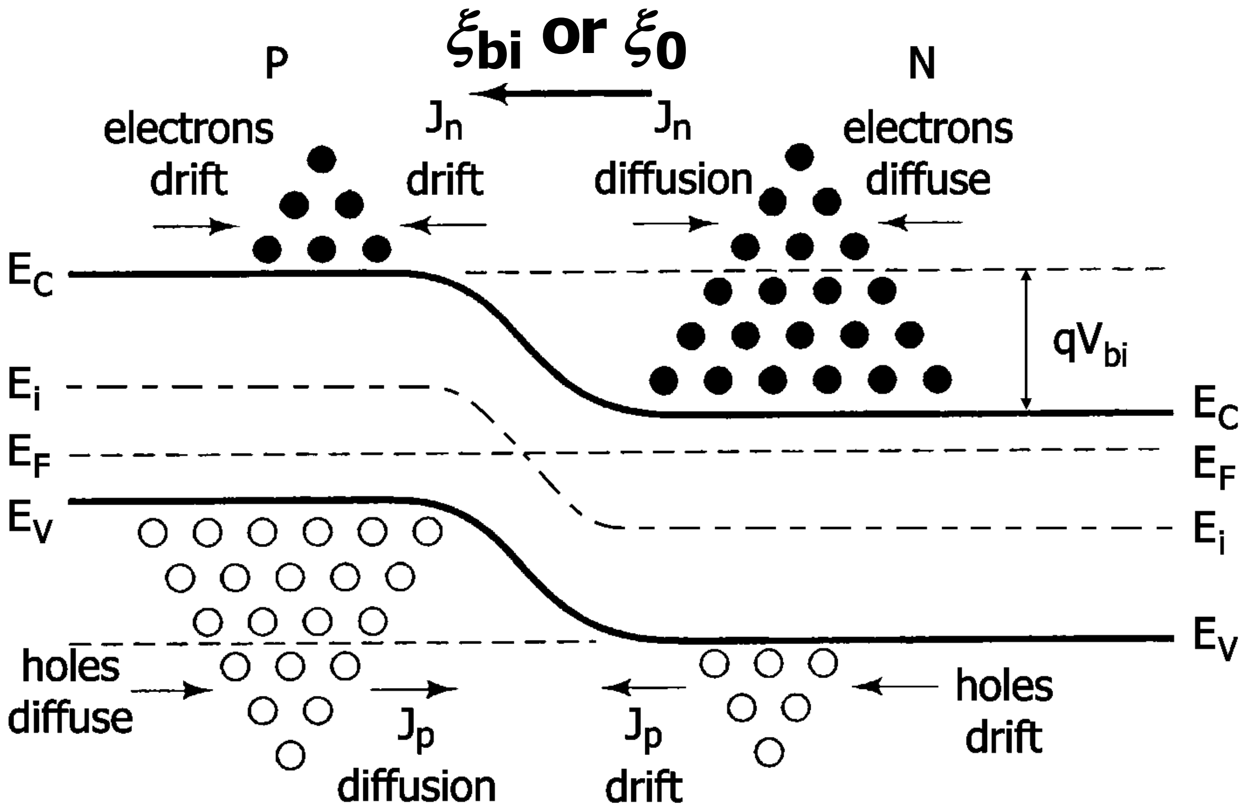
EE2003 Semiconductor Fundamentals

Effect of an Externally Applied Voltage on the P-N Junction

Objectives

- What happens when an external voltage is applied to the terminals of the p-n junction?
- Why does the diode conduct only in one direction?
- Two cases:
  - **Forward bias** – when the p region is made more positive with respect to the n region (large current flow).
  - **Reverse bias** – when the p region is made more negative with respect to the n region (very small current flow)

Thermal Equilibrium

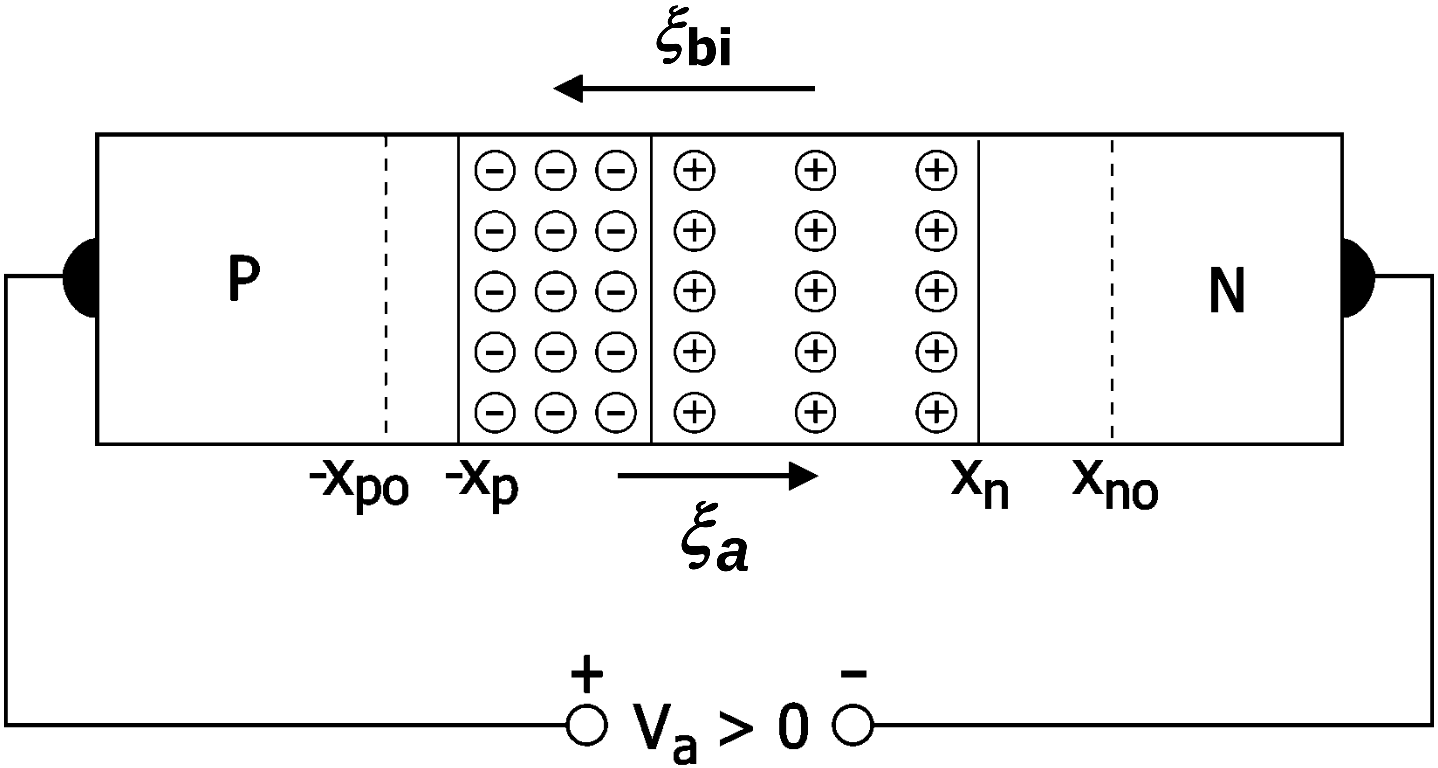


Energy band diagram of a pn junction under thermal equilibrium

Thermal Equilibrium

- Conditions associated with thermal equilibrium:
  - Only those electrons with energy greater than the energy barrier (qV_{bi}) can diffuse from the n to the p region.
  - This diffusion is balanced by the drift of electrons from the p to the n region.
  - Net electron current across the junction = 0
  - A similar situation exists for the holes.

Forward Bias



Schematic of a p-n junction being applied with a forward voltage bias. The directions of the applied and built-in electric field are shown.

Forward Bias

- Conditions associated with forward bias:
  - The applied field opposes the built-in field. The net electric field at the junction becomes smaller, i.e. $\xi = \xi_0 - \xi_a$.
  - Because the net electric field has reduced, the space charge width decreases, i.e. $W < W_0$.
    - The magnitude of the electric field is determined by the amount of positive and negative charges in the n and p regions respectively.
    - Since the overall electric field has decreased, the amount of positive and negative charges must decrease correspondingly.
    - Therefore, the space charge width decreases under forward bias.

$$|\xi_{\mathbf{m}}| = |\xi(x = 0)| = \frac{qN_{\mathrm{A}}x_{\mathrm{p}}}{\varepsilon_{\mathrm{r}}\varepsilon_0} = \frac{qN_{\mathrm{D}}x_{\mathrm{n}}}{\varepsilon_{\mathrm{r}}\varepsilon_0}$$

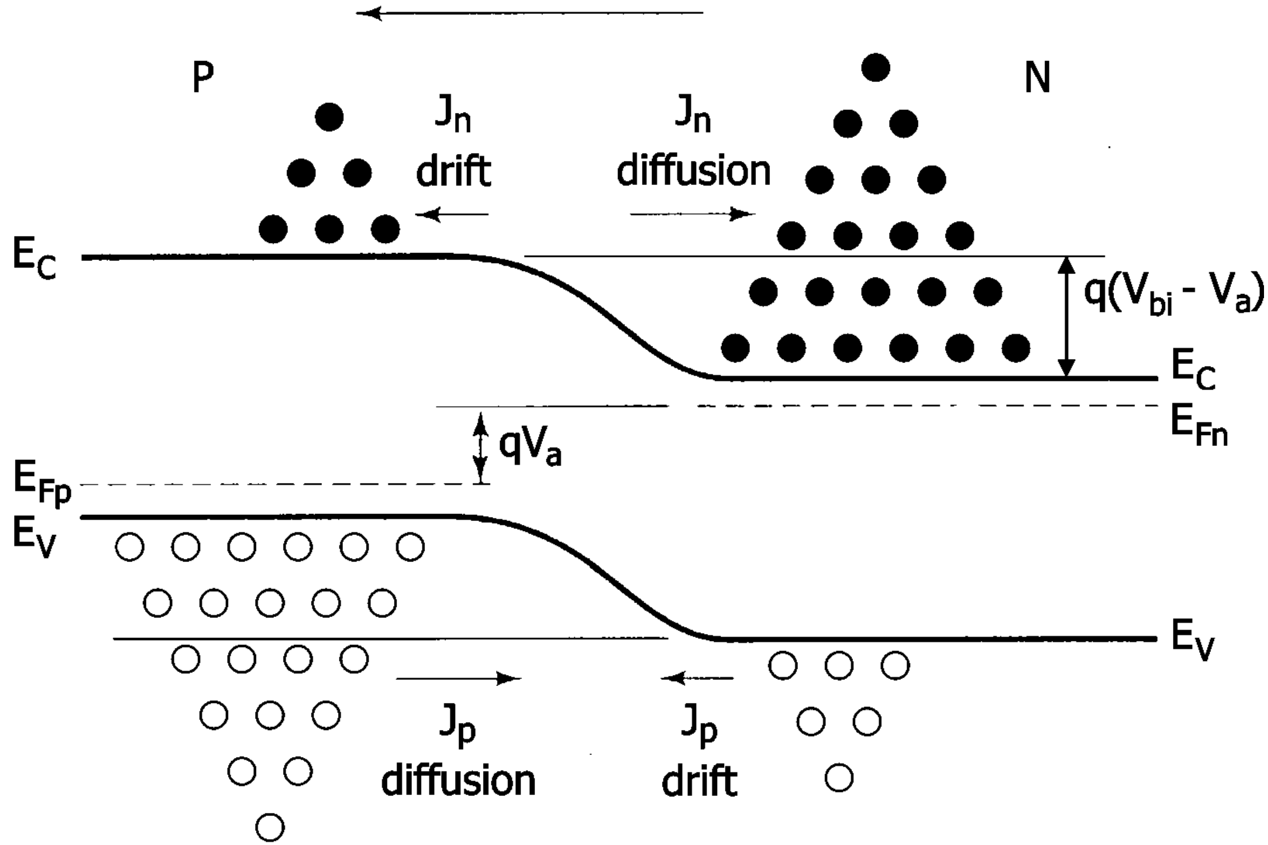
Forward Bias

- Conditions associated with forward bias (cont'd):
  - Since the area under the electric field distribution plot is now lesser than that under thermal equilibrium, the junction potential also decreases, i.e. $V_j = V_{bi} - V_a$.
  - The energy band diagram has to be modified accordingly:
    - Because the electric field is now smaller, the slope of the energy band in the space charge region must decrease.
    - Using the n region as reference, the energy levels in the p region must therefore be **lowered** relative to those in the n region.
    - The Fermi level is no longer constant across all three regions.
    - The difference in the Fermi levels in the neutral n and p regions is proportional to the applied voltage.

$$\xi = \frac{1}{q}\frac{dE}{dx}$$

Forward Bias

$$\xi = \xi_0 - \xi_a$$

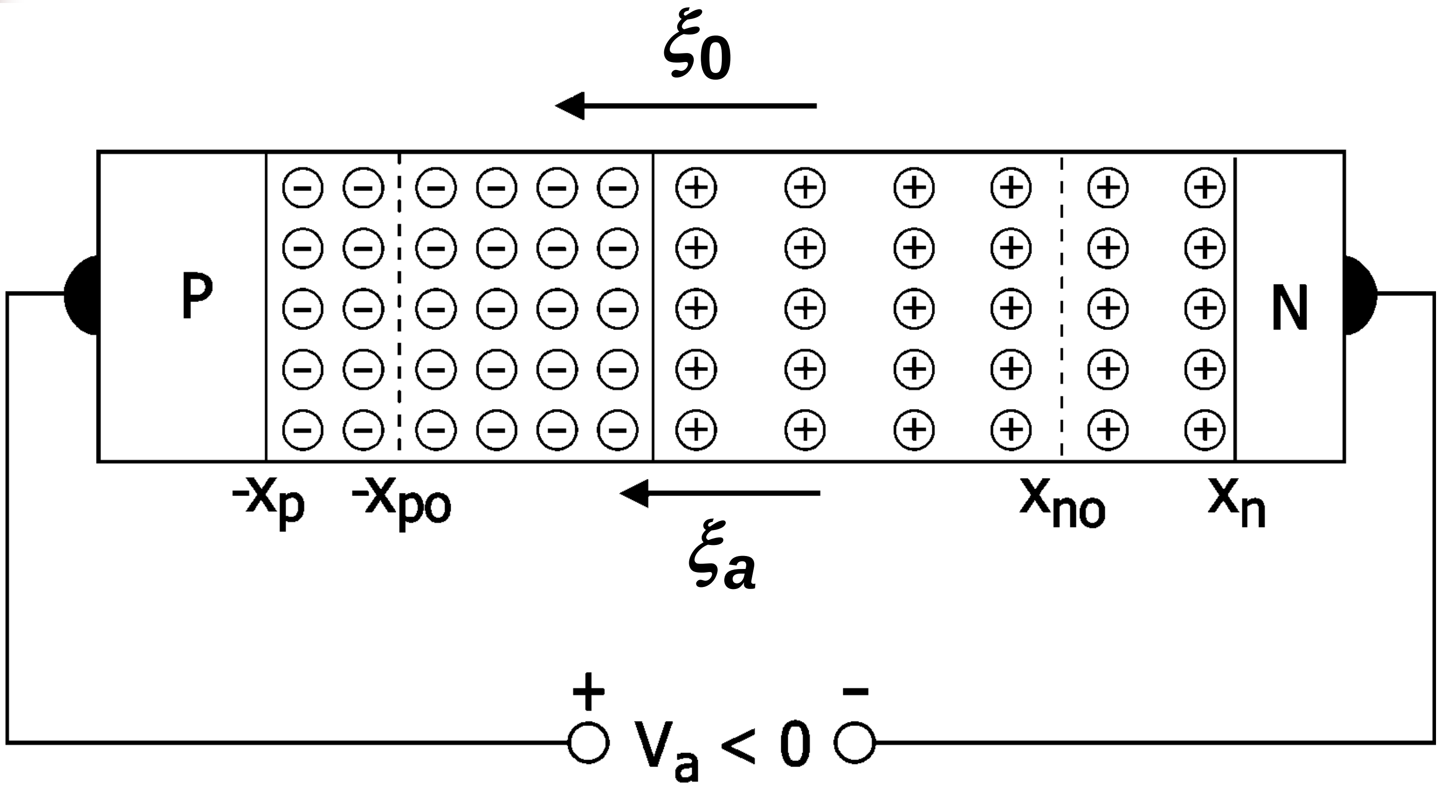


Energy band diagram of a pn junction under forward bias

Forward Bias

- Conditions associated with forward bias (cont'd):
  - Because the **potential barrier** is reduced under forward bias,
    - More electrons are now able to diffuse from the n to the p region.
    - Likewise, more holes are now able to diffuse from the p to the n region.
    - A **net diffusion** of charges across the p-n junction takes place.
    - We commonly say that when a p-n junction is forward biased, electrons are **injected** from the n into the p region and holes are injected from the p into the n region, i.e. under a forward bias, we have **carrier injection** across the p-n junction.
    - Carrier injection is the reason behind the ability of the diode to conduct a large current under a forward bias.

Reverse Bias



A pn junction with an applied reverse-bias voltage showing the directions of the applied field and the built-in field.

Reverse Bias

- Conditions associated with a reverse bias:
  - The applied field appears in the same direction as the built-in field. The net electric field at the junction becomes larger, i.e. $\xi = \xi_0 + \xi_a$.
  - Because the net electric field has increased, the space charge region widens, i.e. $W > W_0$.
  - Since the area under the electric field distribution plot would now be greater than that under thermal equilibrium, the junction potential also increases, i.e. $V_j = V_{bi} - V_a = V_{bi} + |V_a|$.

Reverse Bias

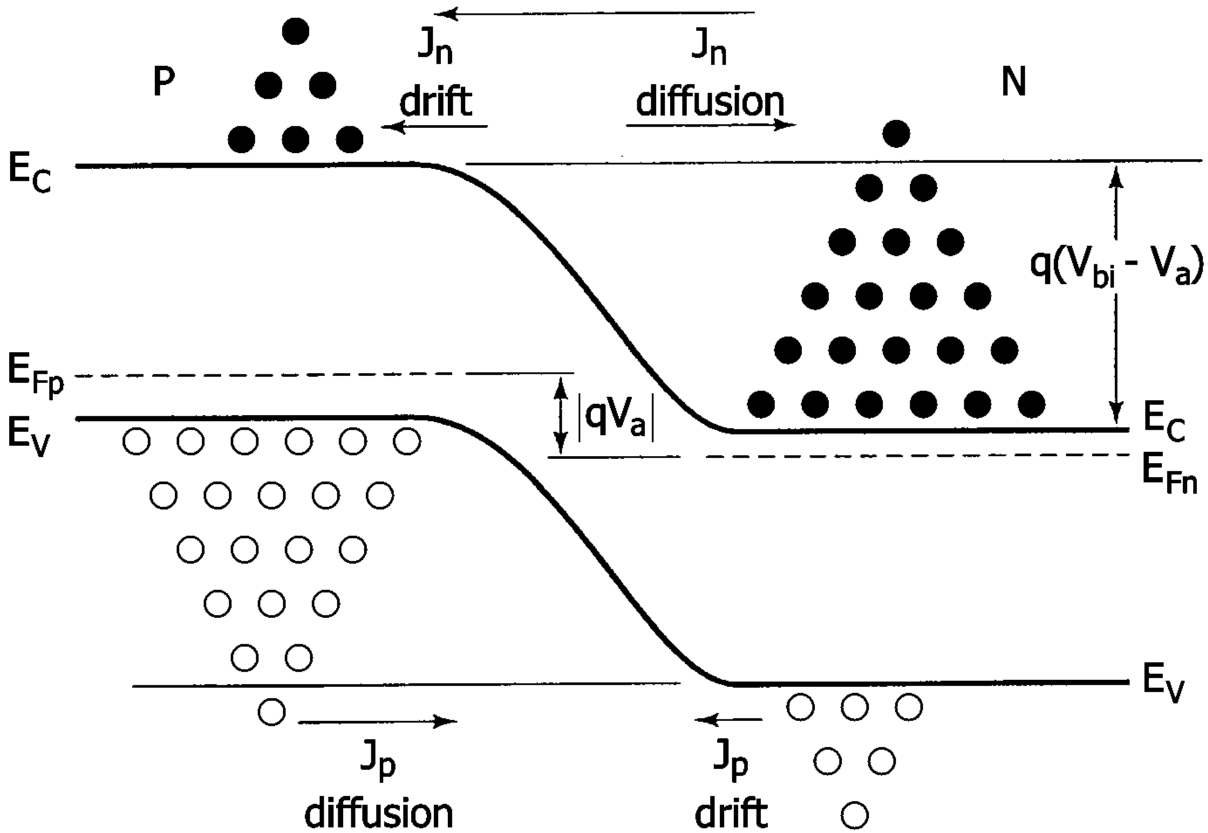
- Conditions associated with a reverse bias (cont'd):
  - The energy band diagram has to be modified accordingly:
    - Because the electric field is now larger, the slope of the energy band in the space charge region must increase.
    - Using the n region as reference, the energy levels in the p region must therefore be **raised**, relative to those in the n region.

Reverse Bias

- Conditions associated with a reverse bias (cont'd):
  - Because the **potential barrier** is enhanced under reverse bias,
    - Fewer electrons can diffuse from n to the p region. Similarly, fewer holes are able to diffuse from the p to the n region.
    - The net current is due to the diffusion of (i) electrons from the p to the edge of the space charge region and then drift across to the n region and (ii) diffusion of holes from the n to the edge of the space charge region and then drift across to the p region.
    - These are minority carriers that are present in very small quantities.
    - Hence, a reverse biased p-n junction does not conduct any current except for a small leakage current.

Reverse Bias

$$\xi = \xi_0 + \xi_a$$



Energy band diagram of a pn junction under reverse bias

Modified Formulae

- All the equations derived previously still apply, but some modifications are needed.
- Since the application of an external bias changes the junction field and hence the junction potential, the term V_{bi} has to be replaced with V_{bi}-V_a.
- **Please remember:**
  - Under forward bias, V_a is positive $\Rightarrow V_{bi} - V_a < V_{bi}$
  - Under reverse bias, V_a is negative $\Rightarrow V_{bi} - V_a > V_{bi}$

Modified Formulae

- Width of space charge regions:

$$x_n = \left\{ \frac{2\varepsilon_r \varepsilon_0 \left(V_{bi} - V_a\right)}{q} \left[\frac{N_A}{N_D\left(N_A + N_D\right)} \right] \right\}^{1/2}$$

$$x_p = \left\{ \frac{2\varepsilon_r \varepsilon_0 \left(V_{bi} - V_a\right)}{q} \left[\frac{N_D}{N_A\left(N_A + N_D\right)} \right] \right\}^{1/2}$$

$$W = \left\{ \frac{2\varepsilon_r \varepsilon_0 \left(V_{bi} - V_a\right)}{q} \left[\frac{N_A + N_D}{N_A N_D} \right] \right\}^{1/2}$$

Modified Formulae

- Maximum electric field:

$$\left|\xi_{\mathbf{m}}\right| = \left|\xi(\boldsymbol{x} = \mathbf{0})\right| = \frac{qN_{\mathbf{A}}x_{\mathbf{p}}}{\varepsilon_{\mathbf{r}}\varepsilon_{\mathbf{0}}} = \frac{qN_{\mathbf{D}}x_{\mathbf{n}}}{\varepsilon_{\mathbf{r}}\varepsilon_{\mathbf{0}}}$$

  - The same expression for the maximum field applies, except that x_n replaces x_{n0} and x_p replaces x_{p0}.

Example 1

- Consider a silicon p-n junction at T=300 K with doping concentrations of $N_A=10^{16}$ cm^{-3} and $N_D=10^{15}$ cm^{-3}. You may assume $n_i=1.5\times10^{10}$cm^{-3} at T=300 K.
  - Calculate the width of the space charge region when a reverse-bias voltage of 5 V is applied.
  - What is the space charge width if the reverse bias is increased to 15 V?

Example 1

- The space charge width can be determined using the following equation:

$$W = \left\{ \frac{2\varepsilon_r \varepsilon_0 \left(V_{bi} - V_a\right)}{q} \left[\frac{N_A + N_D}{N_A N_D} \right] \right\}^{1/2}$$

Not very sure what this is

  - For reverse bias, $V_a = -5$ V.
  - To proceed, the built-in voltage, V_{bi} should first be calculated.
  - From example 1 (Electrostatics chapter), we have $V_{bi} = 0.635$ V.

Example 1

- Therefore,

$$\boldsymbol{W} = \left\{ \frac{2(11.7)(8.85\times10^{-14})(0.635+5)}{1.6\times10^{-19}} \left[\frac{10^{16}+10^{15}}{(10^{16})(10^{15})} \right] \right\}^{1/2}$$

$$= 2.83\times10^{-4}\ \text{cm} = 2.83\ \mu\text{m}$$

- Comments:
  - From example 2 (Electrostatics chapter), we determined W_0=0.951 μm.
  - Thus, the space charge region has increased from 0.951 μm at zero bias to 2.83 μm at a reverse bias of 5 V.

Example 1

- We need not re-calculate the new space charge width all over again using the previous equation. Instead, one should note that:

$$\boldsymbol{W} \propto \left(\boldsymbol{V}_{\mathbf{bi}} - \boldsymbol{V}_{\mathbf{a}}\right)^{1/2}$$

- Thus, the new space charge width at $V_a = -15$ V is

$$\boldsymbol{W}^* = \boldsymbol{W} \cdot \left[\frac{\boldsymbol{V}_{\mathbf{bi}} + \mathbf{15}}{\boldsymbol{V}_{\mathbf{bi}} + \mathbf{5}}\right]^{1/2}$$

$$= \mathbf{4.71}\ \mu\mathbf{m}$$

Example 2

- Consider a silicon p-n junction at T=300 K with a p-type doping concentration of N_A=10^{18} cm^{-3}.
  - Determine the n-type doping concentration such that the maximum electric field does not exceed $3\text{x}10^5$ V/cm at a reverse-bias voltage of 25 V.
- The maximum electric field occurs at the metallurgical junction and is given by

$$\xi_m = -\left\{\frac{2q\left(V_{bi} - V_a\right)}{\varepsilon_r \varepsilon_0}\left[\frac{N_A N_D}{N_A + N_D}\right]\right\}^{1/2}$$

Recall (Electrostatics Chapter)

Thermal Equilibrium

$$|\xi_m| = |\xi(x=0)| = \frac{qN_A x_{p0}}{\varepsilon_r \varepsilon_0} = \frac{qN_D x_{n0}}{\varepsilon_r \varepsilon_0}$$

$$x_{n0} = \left\{ \frac{2\varepsilon_r \varepsilon_0 V_{bi}}{q} \left[\frac{N_A}{N_D (N_A + N_D)} \right] \right\}^{1/2}$$

$$x_{p0} = \left\{ \frac{2\varepsilon_r \varepsilon_0 V_{bi}}{q} \left[\frac{N_D}{N_A (N_A + N_D)} \right] \right\}^{1/2}$$

With Applied Voltage

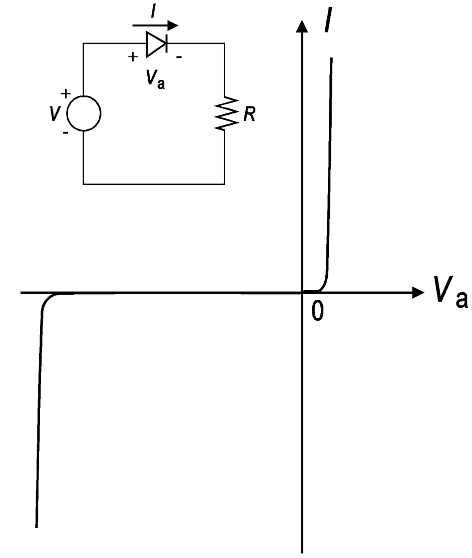
$$|\xi_m| = |\xi(x=0)| = \frac{qN_A x_p}{\varepsilon_r \varepsilon_0} = \frac{qN_D x_n}{\varepsilon_r \varepsilon_0}$$

$$x_n = \left\{ \frac{2\varepsilon_r \varepsilon_0 (V_{bi} - V_a)}{q} \left[\frac{N_A}{N_D (N_A + N_D)} \right] \right\}^{1/2}$$

$$x_p = \left\{ \frac{2\varepsilon_r \varepsilon_0 (V_{bi} - V_a)}{q} \left[\frac{N_D}{N_A (N_A + N_D)} \right] \right\}^{1/2}$$

Example 2

- It should be noted that for a given N_A, ξ_m depends on both V_{bi} and N_D.
- V_{bi} is in turn dependent on N_D via the relation: $V_{bi} = (kT/q)\ln(N_A N_D/n_i^2)$.
- Hence, the problem is quite complicated and cannot be easily solved unless an iterative method is used.
- However, such a precise solution is often not needed in practice.



Example 2

- Since $-V_a = 25 >> V_{bi}$ (~0.7 V),

$$V_{bi} - V_a >> V_{bi} \Rightarrow V_{bi} - V_a \approx -V_a$$

- Therefore,

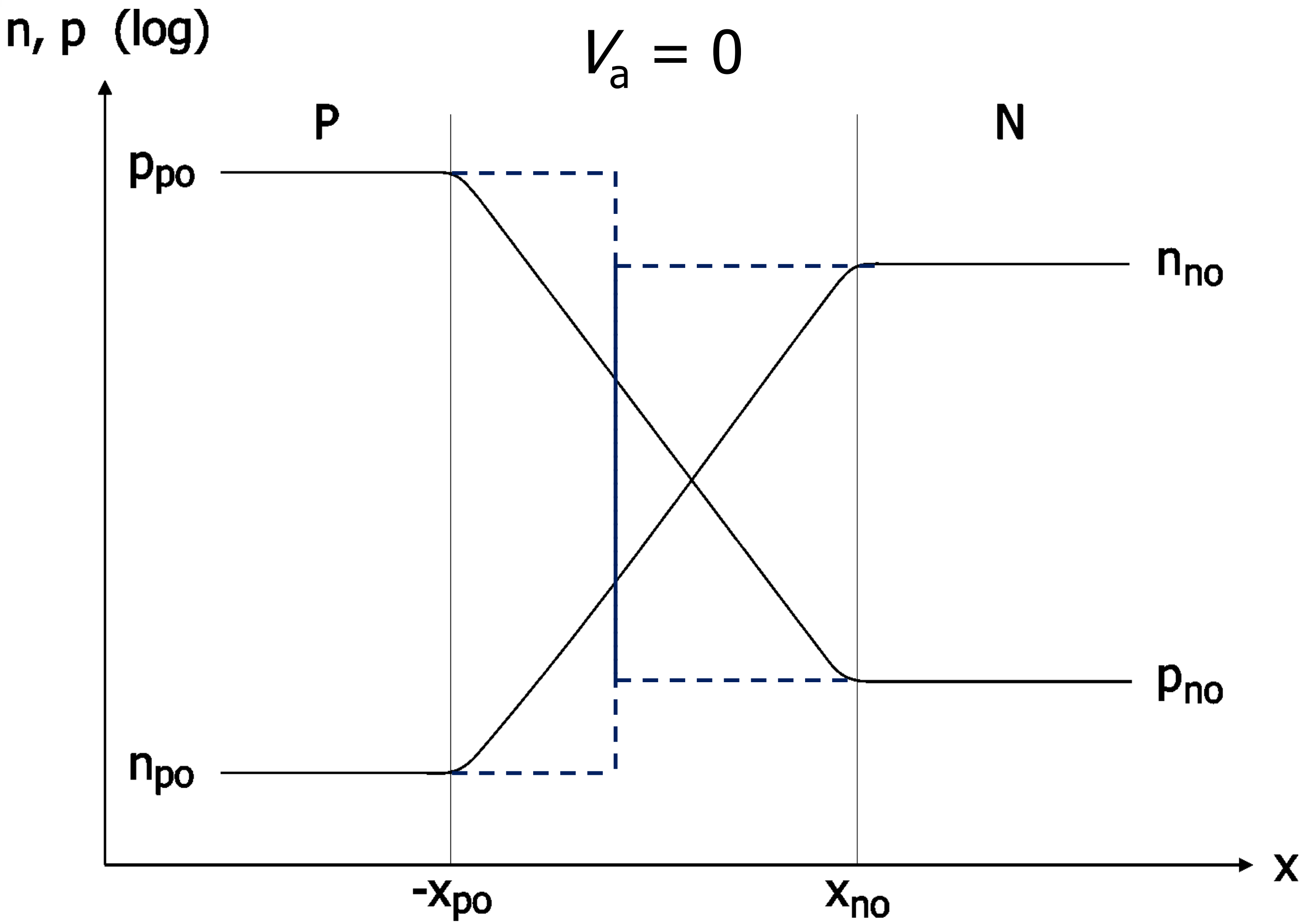
$$\xi_m = -\left\{\frac{2q(-V_a)}{\varepsilon_r \varepsilon_0}\left[\frac{N_A N_D}{N_A + N_D}\right]\right\}^{1/2}$$

- We require

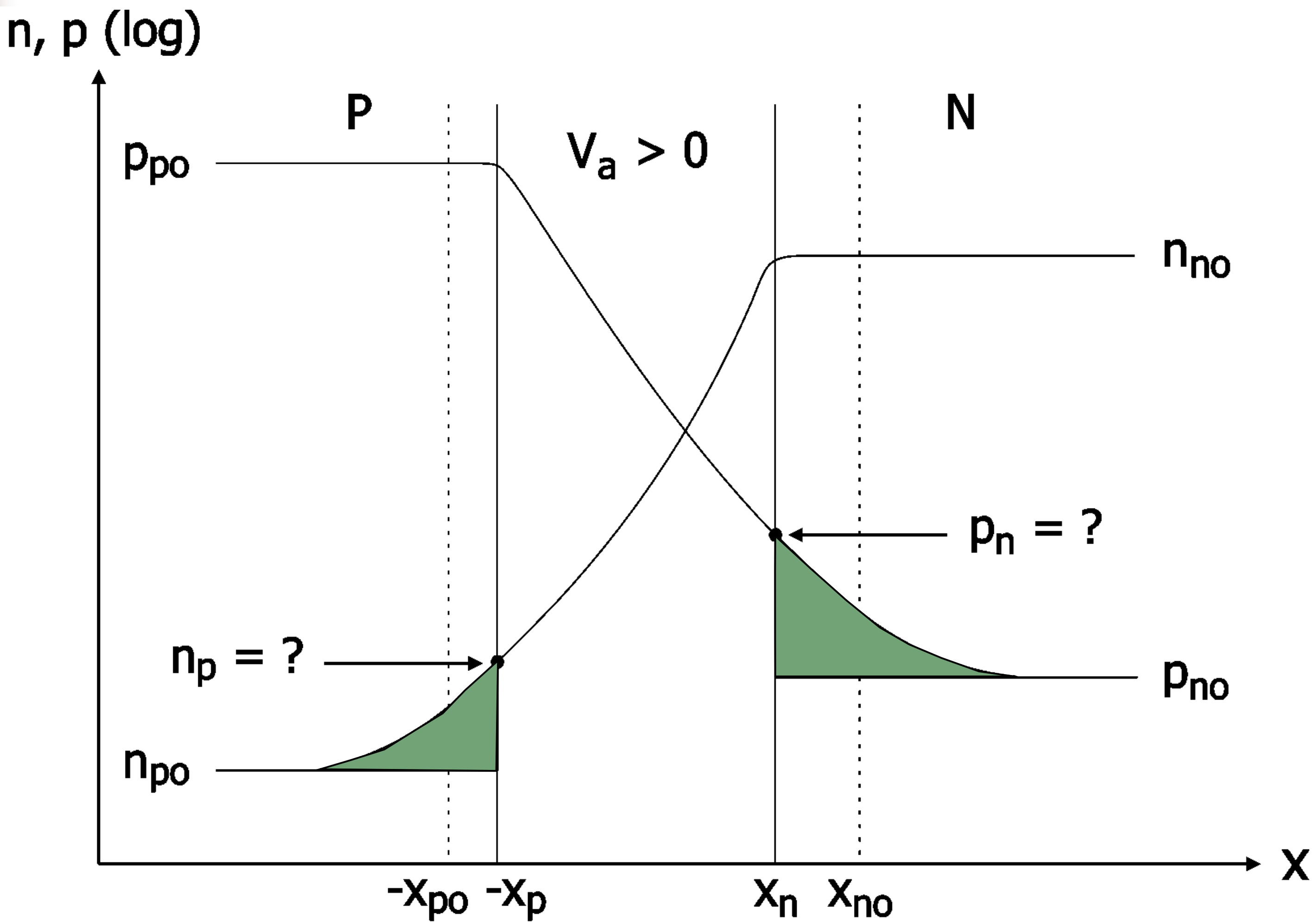
$$\xi_m = -\left\{\frac{2q(-V_a)}{\varepsilon_r \varepsilon_0}\left[\frac{N_A N_D}{N_A + N_D}\right]\right\}^{1/2} \leq 3 \times 10^5 \text{ V/cm}$$

$$N_D \leq 1.18 \times 10^{18} \text{ cm}^{-3}$$

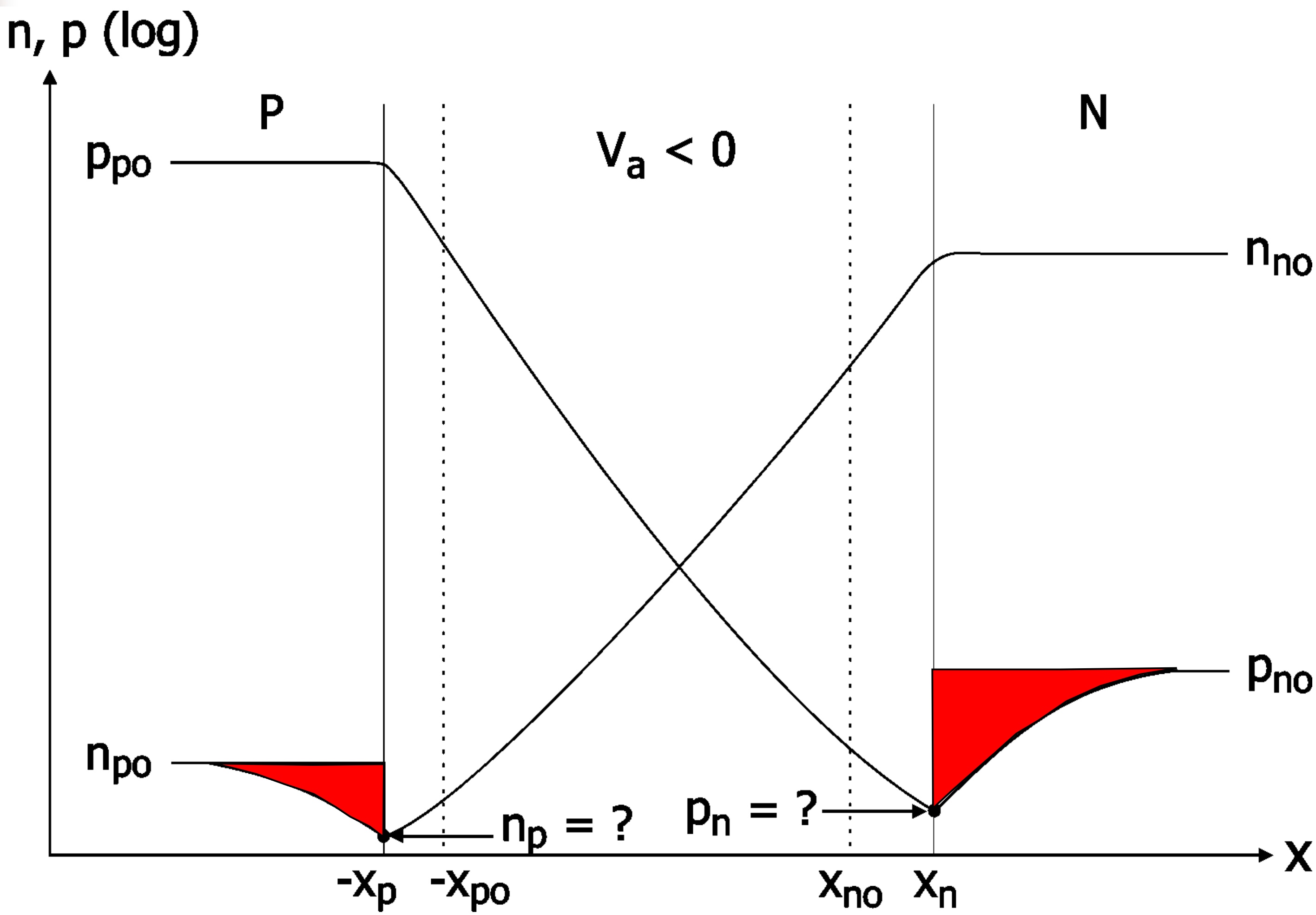
Carrier Distributions – Thermal Equilibrium



Carrier Distributions – Forward Bias



Carrier Distributions – Reverse Bias



Minority Carrier Densities

- Under an applied voltage bias, the minority carrier densities at the depletion edges are modified, either due to charge injection under forward bias, or charge extraction under reverse bias.
- As we will see in the next section, the subsequent transport **(diffusion)** of these minority carriers in the respective quasi-neutral n and p regions determines the amount of current flow in the diode at a given bias.
- Hence, it is of interests to be able to relate the change in minority carrier densities at the depletion edges to the applied voltage bias as this would help establish the boundary condition needed to solve the continuity equations.

Minority Carrier Densities

- Recall:

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

- At normal operating temperature (for example 300 K and above), the dopant atoms are fully ionized. Moreover, the dopant concentration is usually in the order of 10^{16} cm^{-3} >> n_i (=$1.5\text{x}10^{10}$ cm^{-3}). Hence,

$$n_{no} \approx N_D\,, \quad p_{no} \approx \frac{n_i^2}{N_D}$$

$$p_{po} \approx N_A\,, \quad n_{po} \approx \frac{n_i^2}{N_A}$$

Minority Carrier Densities

- Rewriting the expression for the built-in potential:

$$V_{\text{bi}} = \frac{kT}{q}\ln\left(\frac{p_{\text{p0}}}{p_{\text{n0}}}\right) = \frac{kT}{q}\ln\left(\frac{n_{\text{n0}}}{n_{\text{p0}}}\right)$$

$$\Rightarrow \quad p_{\text{n0}} = p_{\text{p0}} e^{-qV_{\text{bi}}/(kT)}$$

$$n_{\text{p0}} = n_{\text{n0}} e^{-qV_{\text{bi}}/(kT)}$$

  - The minority carrier concentration at the depletion edge is exponentially related to the majority carrier concentration at the opposite depletion edge through the built-in potential V_{bi}.

Minority Carrier Densities

- The same relationship applies under an external bias, with V_{bi} replaced by V_{bi} - V_a, i.e.

$$p_n = p_p e^{-q(V_{bi}-V_a)/(kT)},\ n_p = n_n e^{-q(V_{bi}-V_a)/(kT)}$$

- If the applied bias is moderately low such that **low-level injection** condition prevails, $p_p \approx p_{p0}$ and $n_n \approx n_{n0}$. Therefore,

$$p_n = p_{p0} e^{\frac{-q(V_{bi}-V_a)}{kT}} = p_{p0} e^{\frac{-qV_{bi}}{kT}} e^{\frac{qV_a}{kT}} = p_{n0} e^{\frac{qV_a}{kT}}$$

$$n_p = n_{n0} e^{\frac{-q(V_{bi}-V_a)}{kT}} = n_{n0} e^{\frac{-qV_{bi}}{kT}} e^{\frac{qV_a}{kT}} = n_{p0} e^{\frac{qV_a}{kT}}$$

Note: $e^{-\frac{q(V_{bi}-V_a)}{kT}} = e^{-\frac{qV_{bi}}{kT}} \cdot e^{\frac{qV_a}{kT}} \quad \left(e^{a+b} = e^a \cdot e^b\right)$

Minority Carrier Densities

- '**Excess**' minority carrier densities:

$$\Delta p_{\mathrm{n}} = p_{\mathrm{n0}} e^{qV_{\mathrm{a}}/kT} - p_{\mathrm{n0}} = p_{\mathrm{n0}} \left(e^{qV_{\mathrm{a}}/kT} - 1 \right)$$

$$\Delta n_{\mathrm{p}} = n_{\mathrm{p0}} e^{qV_{\mathrm{a}}/kT} - n_{\mathrm{p0}} = n_{\mathrm{p0}} \left(e^{qV_{\mathrm{a}}/kT} - 1 \right)$$

- Forward bias: $V_a > 0$, V_a usually >> kT/q

$$\Delta p_{\mathrm{n}} = p_{\mathrm{n0}} e^{qV_{\mathrm{a}}/kT}, \ \Delta n_{\mathrm{p}} = n_{\mathrm{p0}} e^{qV_{\mathrm{a}}/kT}$$

- Reverse bias: $V_a < 0$, $|V_a|$ usually >> kT/q

$$\Delta p_{\mathrm{n}} = -p_{\mathrm{n0}}, \ \Delta n_{\mathrm{p}} = -n_{\mathrm{p0}}$$

Summary

- P-N junction under non-equilibrium:
  - Why a p-n junction conducts only in the forward-bias mode, and not in the reverse-bias mode.
  - Understand how the electrostatics are changed under a non-zero voltage bias.
  - Understand the terms carrier "injection" and "extraction", as applied to forward and reverse bias, respectively.
  - How the minority carrier concentrations at the edges of the space charge region under a given voltage bias are calculated.