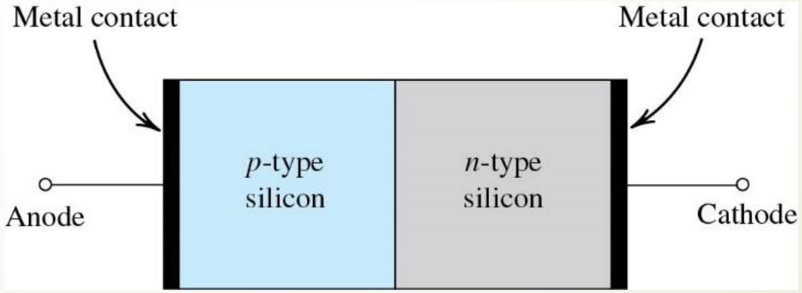
ENGR 305

The pn junction

September 4, 2025

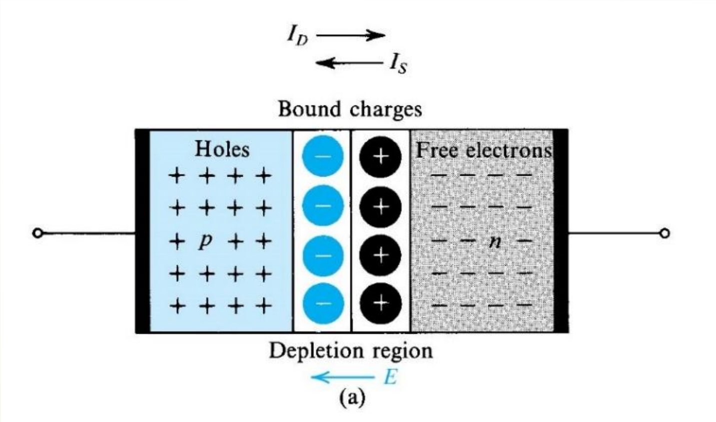
The *pn* junction

- A pn junction consists of a p-type region adjacent to an n-type region.
  - These regions are created in a single silicon crystal by different doping in the two regions.
- External wire connections are made to the *p* and *n* regions through metal contacts.
  - These constitute the diode terminals and are labeled “anode” and “cathode”.



Operation with open-circuit terminals

- The "+" signs in the p-type material denote majority holes.
- The charge of these holes is neutralized by an equal amount of bound negative charge associated with the acceptor atoms.
- The "-" signs in the n-type material indicate majority carrier electrons.
- The charge of these electrons is neutralized by an equal amount of bound positive charge associated with the donor atoms.



Operation with Open-Circuit Terminals

- Concentration of holes is high in the *p* region and low in the *n* region.
  - Holes diffuse across the junction from the *p* side to the *n* side.
- Concentration of electrons is high in the *n* region and low in the *p* region.
  - Electrons diffuse across the junction from the *n* side to the *p* side.
- Diffusion current is the sum of hole diffusion and electron diffusion currents.
  - These two components combine to form the ***diffusion current*** I_D.
  - Diffusion current is due to majority-carrier diffusion.

Depletion region

- Holes that diffuse across the junction into the *n* region quickly recombine with some of the majority carrier electrons there and disappear.
- Some of the bound positive charge near the junction is no longer neutralized by free electrons; it is **uncovered.**
  - A region in the n-material close to the junction is *depleted of free electrons.*
- Electrons that diffuse across the junction into the *p* region quickly recombine with some of the majority holes there and disappear.
- This results in some majority carrier holes disappearing, causing some of the bound negative charge to be uncovered.
  - A region in the p-material close to the junction is *depleted of free holes.*

Depletion region

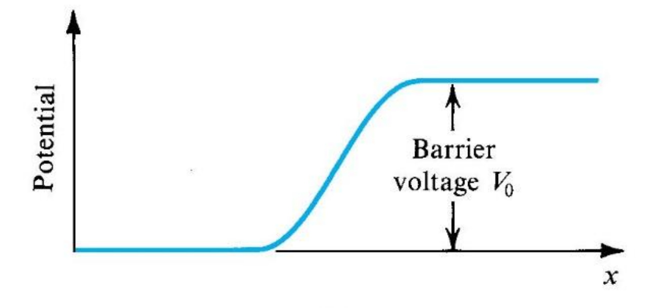
- The **carrier-depletion region** will exist on both sides of the junction
  - The n side is positively charged and the p side is negatively charged.
  - This region is also called the **space-charge region.**
- The charges on both sides of the depletion region cause an electric field *E* to be established across the region.
- A potential difference results across the depletion region, with the *n* side at a positive voltage relative to the *p* side.
- The voltage drop across the depletion region acts as a **barrier** that has to be overcome for holes to diffuse into the *n* region and electrons to diffuse into the *p* region.

Drift current

- There is also a drift current I_S due to minority-carrier drift across the junction.
  - Some thermally generated holes in the *n* material move toward the junction, reaching the edge of the depletion region.
  - The electric field in the depletion region sweeps them across to the *p* side.
  - Some thermally generated electrons in the *p* material move to the edge of the depletion region.
  - The electric field in the depletion region sweeps them across to the *n* side.
  - These two components together make up the ***drift current*** $\boldsymbol{I_S}$.
  - The drift current points from n to p-side, the same direction as the electric field.

Equilibrium conditions

- The drift current is determined by the number of minority carriers that make it to the edge of the depletion region.
- Any minority carriers that get to the edge of the depletion region will be swept across by the electric field E, regardless of the value of E.
- Under open-circuit conditions, $I_D = I_S$. Equilibrium is maintained by the barrier voltage V_0.



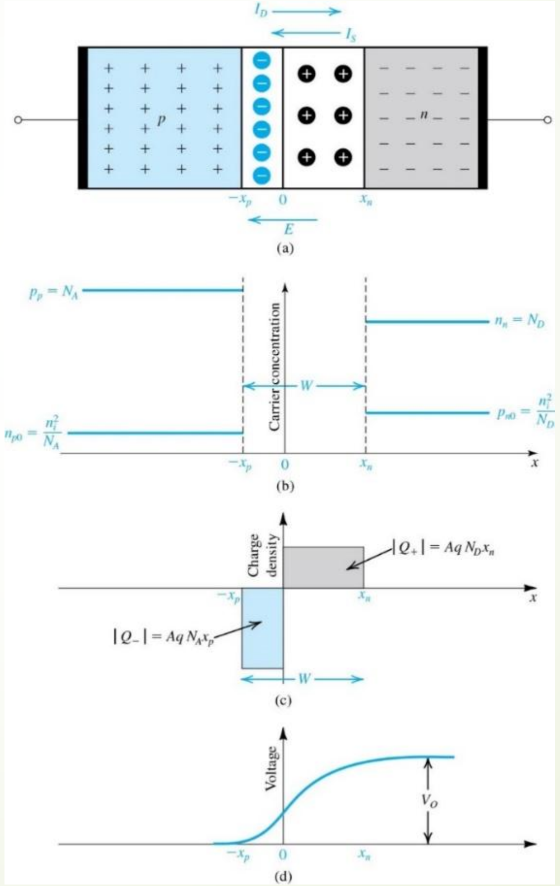
(b)

Junction built-in voltage

- With no external voltage applied, the barrier voltage V_0 can be shown to be
  - $V_0 = V_T ln\left(\frac{N_A N_D}{n_i^2}\right)$
- N_A and N_D are the doping concentrations of the *p* side and *n* side, respectively.
- The voltage $\boldsymbol{V_0}$ is known as the **junction built-in voltage.**
- Typical values for silicon at room temperature range from 0.6 to 0.9 V.

Charge stored in depletion region

(a) A pn junction with the terminals open-circuited.
(b) Carrier concentrations; note that $N_A > N_D$
(c) The charge stored in both sides of the depletion region; $Q_J = |Q_+| = |Q_-|$
(d) The built-in voltage V_0



Width of and charge stored in junction

- The figure shows a pn junction for which $N_A > N_D$.
- The minority carrier concentrations on both sides are denoted by n_{p0} and p_{n0}, where the subscript "0" indicates equilibrium.
- The depletion region extends in both the *p* and *n* regions with equal amounts of charge on both sides.

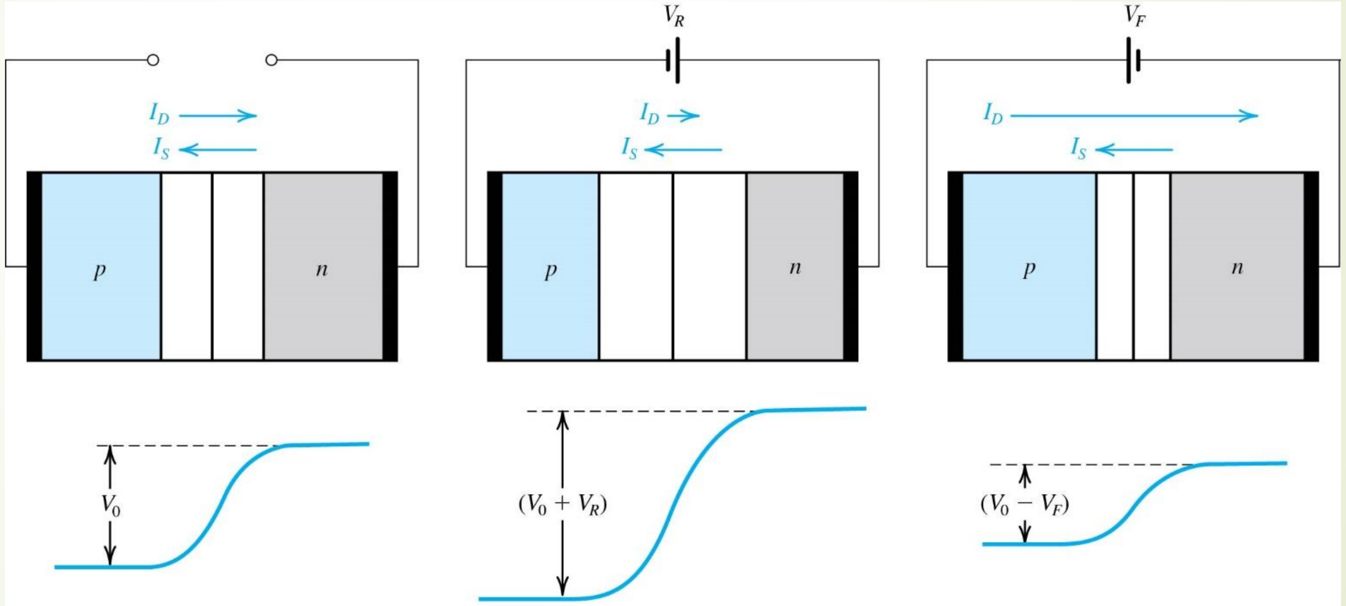
Width of and charge stored in junction.

- With unequal doping concentrations, the depletion region width will be different on the two sides. $|Q_+| = |Q_-|$
- The magnitude of charge on the n-side of junction is $|Q_+| = qAx_nN_D$
- The magnitude of charge on the p-side of junction is $|Q_-| = qAx_pN_A$
- A is the cross-sectional area of the junction in the plane perpendicular to the page.

Depletion region width and charge

- Charge equality means that $qAx_nN_D = qAx_pN_A$
- The depletion width W can be shown to be
  - $W = x_n + x_p = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_0}$
  - Note that ϵ_s is the electrical permittivity of silicon = $11.7\epsilon_0 = 11.7 \times 8.85 \times 10^{-14}\,\frac{F}{\text{cm}} = 1.04 \times 10^{-12} F/cm$
- The value of the depletion width on the n-side is equal to
  - $x_n = W\frac{N_A}{N_A+N_D}$
- The value of the depletion width on the p-side is equal to
  - $x_p = W\frac{N_D}{N_A+N_D}$

The pn junction with applied voltage



(a) Open-circuit (equilibrium)

(b) Reverse bias

(c) Forward bias

The pn junction with applied voltage

- Applying a voltage so that the *p* side is made more positive than the *n* side, it is called a **forward-bias voltage.**
  - The applied voltage subtracts from the built-in voltage V_0, resulting in a barrier $(V_0 - V_F)$.
  - This causes a reduction in depletion-region charge and a narrower depletion width W.
- If we make the *n* side more positive than the *p* side, it is said to be a **reverse-bias voltage.**
  - The applied reverse-bias voltage V_R increases the effective barrier voltage to $(V_0 + V_R)$.
  - This reduces the number of holes that diffuse into the n region and the number of electrons that diffuse into the p region.
  - A reverse-bias voltage of about 1 volt is sufficient to cause the diffusion current $I_D \cong 0$.
  - This causes an increase in the depletion-region charge and a wider depletion width W.

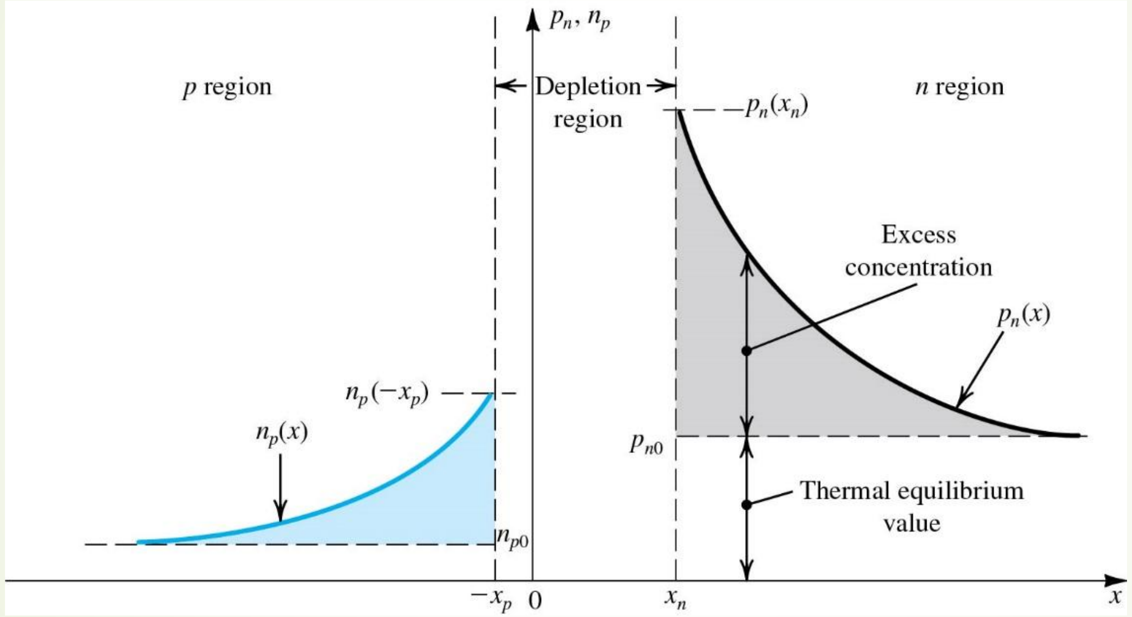
The pn junction with *reverse bias* applied

- The width of the depletion region with V_R is given by
  - $W = x_n + x_p = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 + V_R)}$
- The magnitude of charge stored on either side of the junction is given by
  - $Q_J = A\sqrt{2\epsilon_s q\left(\frac{N_A N_D}{N_A + N_D}\right)(V_0 + V_R)}$

Current-voltage relationship of junction

- Consider a junction with a forward-bias voltage applied.
  - The forward bias lowers the barrier voltage to $(V_0 - V)$.
  - This allows a greater number of holes to diffuse into the *n* region.
- The concentration of holes in the n region increases significantly.
  - The steady-state concentration at the *edge* of the depletion region (at x_n) is given by
  - $p_n(x_n) = p_{n0}e^{V/V_T}$
- The forward bias results in an **excess concentration** of minority holes, given by
  - Excess concentration = $p_{n0}e^{V/V_T}$- p_{n0} = $p_{n0}\left(e^{V/V_T} - 1\right)$

Steady-state minority carrier concentration profiles



The figure shows the minority-carrier distribution in a forward-biased pn junction. We assume the *p* region is more heavily doped than the *n* region.

Minority-carrier distribution near junction

- As the injected holes diffuse into the n material, some will recombine with majority electrons.
- The excess hole concentration will decay exponentially with distance:
  - $p_n(x) = p_{n0} + p_{n0}\left(e^{V/V_T} - 1\right)e^{-\frac{(x-x_n)}{L_p}}$
- The exponential decay is characterized by the constant L_p, called the **diffusion length** of holes in the *n* material.
- The smaller the value of L_p, the faster the injected holes will recombine with majority electrons, causing a steeper decay of minority-carrier concentration.

Diffusion current in pn junction

- From our study of diffusion, we can find the value of hole-diffusion current density as
  - $J_p(x) = -qD_p \frac{dp_n(x)}{dx}$
- Substituting for $p_n(x)$,
  - $J_p(x) = q\left(\frac{D_p}{L_p}\right) p_{n0}\left(e^{V/V_T} - 1\right) e^{-\frac{(x-x_n)}{L_p}}$
- The value of $J_p(x)$ is highest at $x = x_n$
  - $J_p(x_n) = q\left(\frac{D_p}{L_p}\right) p_{n0}\left(e^{V/V_T} - 1\right)$ and decays exponentially further away from the junction.

Diffusion current in pn junction

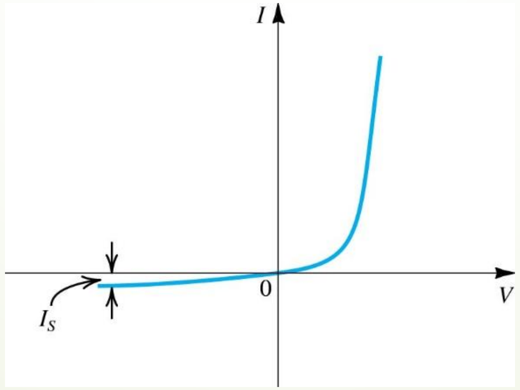
- A similar development can be applied to the electrons that are injected from the *n* to the *p* region.
- The resulting electron diffusion current is given by
  - $J_n(-x_p) = q\left(\frac{D_n}{L_n}\right) n_{p0}\left(e^{V/V_T} - 1\right)$
- The values for hole and electron diffusion currents do not change within the *depletion* region. Adding the two and multiplying by junction area A to get the current *I* gives
  - $I = Aq\left(\frac{D_p}{L_p} p_{n0} + \frac{D_n}{L_n} n_{p0}\right)\left(e^{V/V_T} - 1\right)$

Diffusion current in pn junction

- Substituting for $p_{n0} = n_i^2/N_D$ and for $n_{p0} = n_i^2/N_A$ gives
  - $I = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)\left(e^{V/V_T} - 1\right)$
- For a negative V, with a magnitude of a few times V_T, the exponential term is essentially zero.
  - This causes the current across the junction to be negative and constant.
  - The current in this case is I_S.
- Thus, $I = I_S\left(e^{V/V_T} - 1\right)$
- Where $I_S = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)$

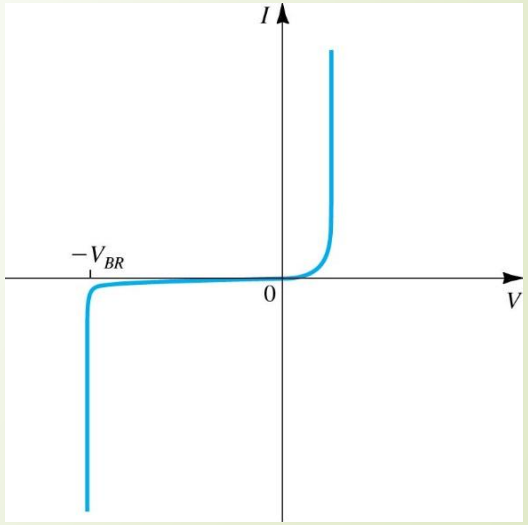
The pn junction *I-V* characteristics

- In the reverse direction, the current saturates at a value of $-I_S$.
  - I_S is called the **saturation current.**
  - It is also referred to as the **scale current,** being directly proportional to A, the cross-sectional area.



Reverse breakdown

- As the magnitude of the reverse-bias voltage V is increased, a value is reached at which a very large reverse current flows.
- As V reaches the value V_{BR}, the dramatic increase in reverse current is accompanied by a very small increase in the reverse voltage.
  - This is called **junction breakdown.**
  - This is a nondestructive phenomenon.
  - Current must be limited to a "safe" value.



Capacitive effects in the pn junction

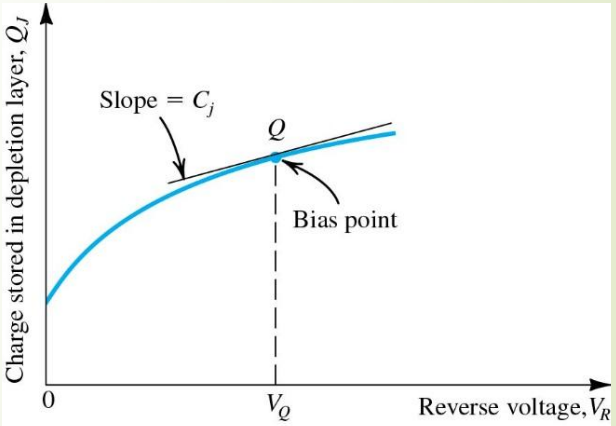
- The two charge-storage mechanisms in the pn junction are
  - Charge stored in the depletion region (bound charge)
    - Predominates when the junction is reverse-biased
  - The minority-carrier charge stored in the *n* and *p* materials as a result of carrier injection
    - Predominates when the junction is forward-biased

Depletion or junction capacitance

- When a *pn* junction is *reverse biased* with a voltage V_R, the charge stored on either side of the depletion region is given by
  - $Q_J = A\sqrt{2\epsilon_s q \frac{N_A N_D}{N_A+N_D}(V_0 + V_R)}$
- For a given pn junction, $Q_J = \alpha\sqrt{V_0 + V_R}$
- The quantity α is given by
  - $\alpha = A\sqrt{2\epsilon_s q \frac{N_A N_D}{N_A+N_D}}$
- For the pn junction, $Q_J$is nonlinearly related to the reverse-biased voltage.

Depletion or junction capacitance

- We assume the junction is operating at a point Q and define a capacitance, C_J that relates the change in charge to a change in voltage V_R
  - $C_J = \left.\frac{dQ_J}{dV_R}\right|_{V_R=V_Q}$
- Relating this to our expression for Q_J yields
  - $C_J = \frac{\alpha}{2\sqrt{V_0+V_R}}$



Diffusion capacitance

- This is related to the minority-carrier distributions in the *p* and *n* materials.
- The excess hole charge stored in the *n* region can be found from the shaded area under the exponential as
  - $Q_p = Aq[p_n(x_n) - p_{n0}]L_p$
- From previous expressions, we can obtain $Q_p = \frac{L_p^2}{D_p} I_p$.
- The factor that relates Q_p to I_p is $\tau_p = L_p^2/D_p$ $(Q_p = \tau_p I_p)$
- The time constant $\tau_p$is the **minority-carrier (hole) lifetime.**
- It is defined as the average time it takes for a hole injected into the n region to recombine with a majority electron.

Diffusion capacitance

- For the electron charge stored in the *p* region, $Q_n = \tau_n I_n$.
  - Here τ_n is the electron lifetime in the p region.
- Total excess minority-carrier charge is given by $Q = \tau_p I_p + \tau_n I_n$
- We can express this in terms of the diode current $I = I_p + I_n$ as $Q = \tau_T I$
- τ_T is referred to as the **mean transit time** of the junction.
- For small changes around a bias point, we define an **incremental diffusion capacitance $C_d = \frac{dQ}{dV}$**.
- Approximating $I \cong I_S e^{V/V_T}$, we can show that $C_d = \left(\frac{\tau_T}{V_T}\right) I$
  - This is directly proportional to the forward current.