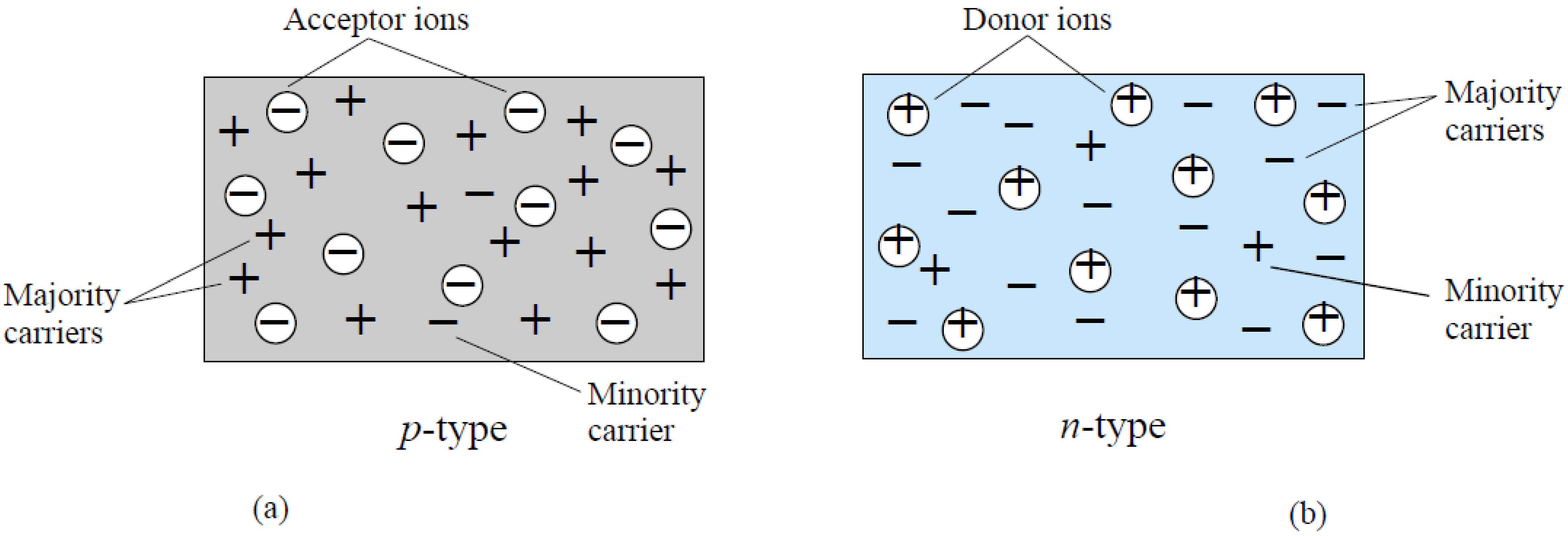
pn Junction

Semiconductor Devices and Circuits

(ECE 181302)

17th September 2021

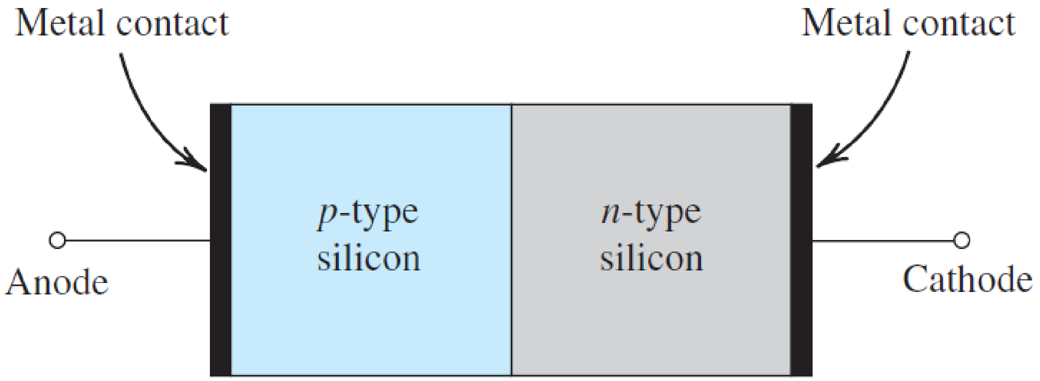
Majority and Minority Carriers



- In a p-type material the hole is the majority carrier and the electron is the minority carrier.
- In an n-type material the electron is the majority carrier and the hole the minority carrier.

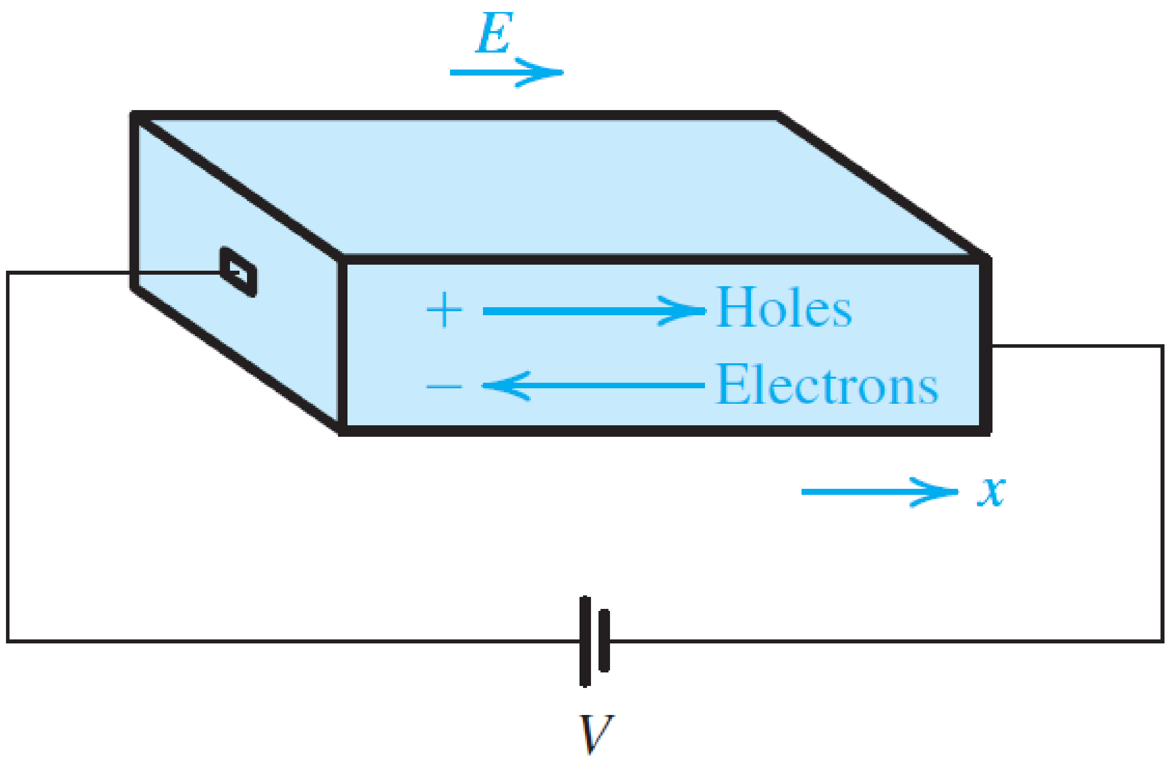
pn Junction

- A *p* type and an *n* type semiconductor brought into close contact creates the *pn* junction – implements the junction diode.
- Plays a dominant role in the structure and operation of the bipolar junction transistor (BJT) and it is very important in the study of MOSFET operation.



Drift Current

- When an electrical field *E* is established in a semiconductor crystal, holes are accelerated in the direction of *E*, and free electrons are accelerated in the direction opposite to that of *E*.
- Both hole and electron drift currents are in the direction of *E*.



- Holes acquire a drift velocity: $$v_{p\text{-drift}} = \mu_p E$$

- Free electrons acquire a drift velocity: $$v_{n\text{-drift}} = -\mu_n E$$

- where μ_p is the **hole mobility**, and μ_n is the **electron mobility**. They represent the degree of ease by which holes and electrons move through the silicon crystal in response to the electrical field E.
- For intrinsic silicon μ_p = 480 $\mathrm{cm^2/V \cdot s.}$ and μ_n = 1350 $\mathrm{cm^2/V \cdot s.}$
- μ_n is about 2.5 times μ_p, signifying that electrons move with much greater ease through the silicon crystal than do holes.
- Why is $v_{n\text{-drift}}$ –ve?

Current Due to Drift of Holes

- Drift current due to holes is due to hole charges that cross a plane perpendicular to the *x* direction of the silicon bar.
- The concentration of holes is *p* and that of free electrons is *n*, *A* is the cross-sectional area of the silicon bar and *q* is the magnitude of electron charge.
- In one second, the hole charge that crosses the perpendicular plane in the *x* direction is $Aqpv_{p\text{-drift}}$ coulomb.

$$I_p = Aqpv_{p\text{-drift}} \qquad \text{Or} \qquad I_p = Aqp\mu_p E$$

- The current density J_p is the current per unit cross-sectional area:

$$J_p = \frac{I_p}{A} = qp\mu_p E$$

Current Due to Drift of Free Electrons

$$I_n = -Aqnv_{n\text{-drift}}$$

- Electrons drifting from right to left result in a current component from left to right.
- The convention is to take the direction of current flow as the direction of flow of positive charge and opposite to the direction of flow of negative charge.
- The current density is $J_n = I_n/A$:

$$J_n = qn\mu_n E$$

Total Drift Current Density

- Total current density is sum of *Jp* and *Jn*: $J = J_p + J_n = q(p\mu_p + n\mu_n)E$

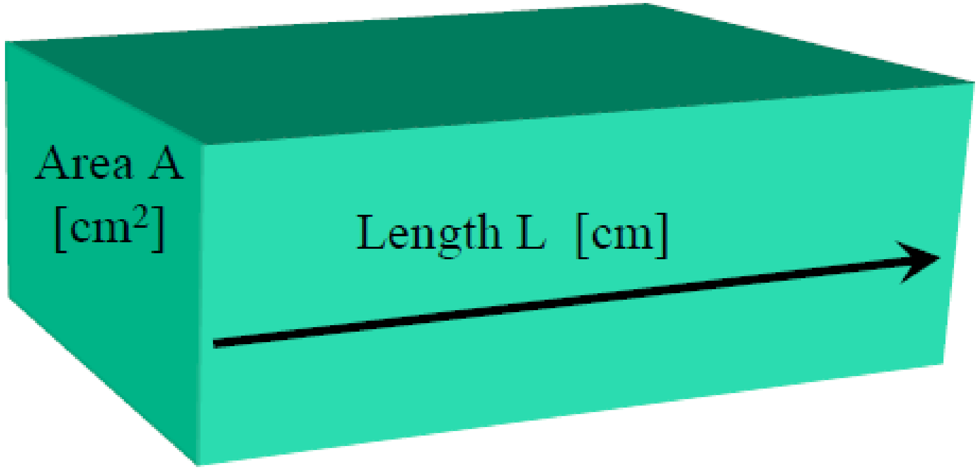
  Written as: $J = \sigma E$ Or $J = E/\rho$

  Where $\sigma = q(p\mu_p + n\mu_n)$ is the conductivity, and

  $$\rho \equiv \frac{1}{\sigma} = \frac{1}{q(p\mu_p + n\mu_n)}$$ is the resistivity

- Which reminds of Ohm's law: $\rho = \frac{E}{J} \quad \frac{\text{V/cm}}{\text{A/cm}^2} = \Omega \cdot \text{cm}.$

Do not confuse Resistance and Resistivity or Conductance and Conductivity



Resistance to current flow along length L (I.e. the electric field is applied along this samples length).

$$R=\rho L/A \quad \text{or in units, } [\text{ohm-cm}][\text{cm}]/[\text{cm}^2]=[\text{ohms}]$$

Diffusion Current

- Carrier diffusion: If there is a concentration gradient of charge carriers (electrons/ holes), then the charge carriers will flow from region of higher concentration to lower one.
- Carrier diffusion occurs when the density of charge carriers in a piece of semiconductor is not uniform.
- This is similar to the law of diffusion in gas or liquids, and the flux F_n of electrons resulting from the diffusion process is directly proportional to the concentration gradient (Fick's law), and giving rise to a current density J_n.

$$F = -D\frac{d\varphi}{dx}$$

Fick's Law of Diffusion

- The flux goes from regions of high concentration to regions of low concentration, with a magnitude that is proportional to the concentration gradient (spatial derivative), or in simplistic terms the concept that a solute will move from a region of high concentration to a region of low concentration across a concentration gradient. In one (spatial) dimension:

$$F = -D\frac{d\varphi}{dx}$$

Where:

- *F* is the **diffusion flux**, of which the dimension is amount of substance per unit area per unit time. *F* measures the amount of substance that will flow through a unit area during a unit time interval.
- *D* is the **diffusion coefficient** or **diffusivity**. Its dimension is area per unit time.
- φ (for ideal mixtures) is the concentration, of which the dimension is amount of substance per unit volume.
- *x* is position, the dimension of which is length.
- *D* is proportional to the squared velocity of the diffusing particles, which depends on the temperature, viscosity of the fluid and the size of the particles according to the Stokes–Einstein relation. In dilute aqueous solutions the diffusion coefficients of most ions are similar and have values that at room temperature are in the range of $(0.6–2)\times10^{-9}$ m^2/s.

Key Diffusion Relationship (Fick's first law)

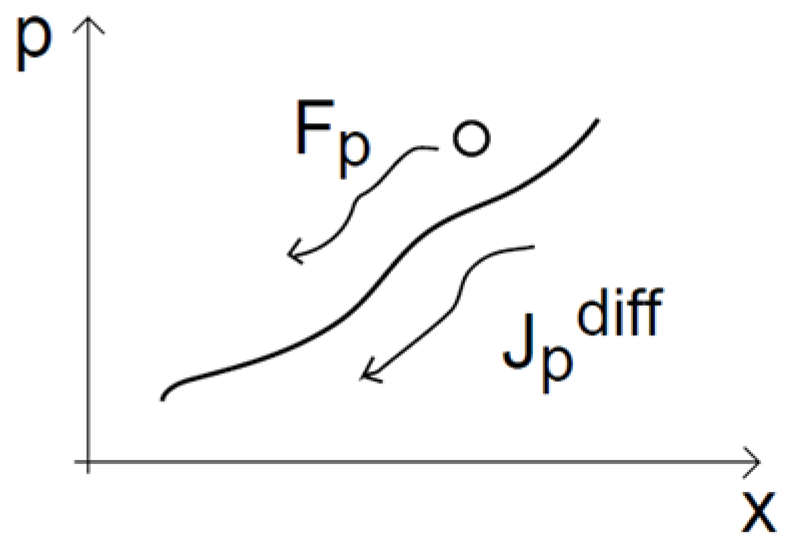
- Diffusion flux ∝ – concentration gradient
- Flux ≡ number of particles crossing unit area per unit time [$cm^{-2} \cdot s^{-1}$]

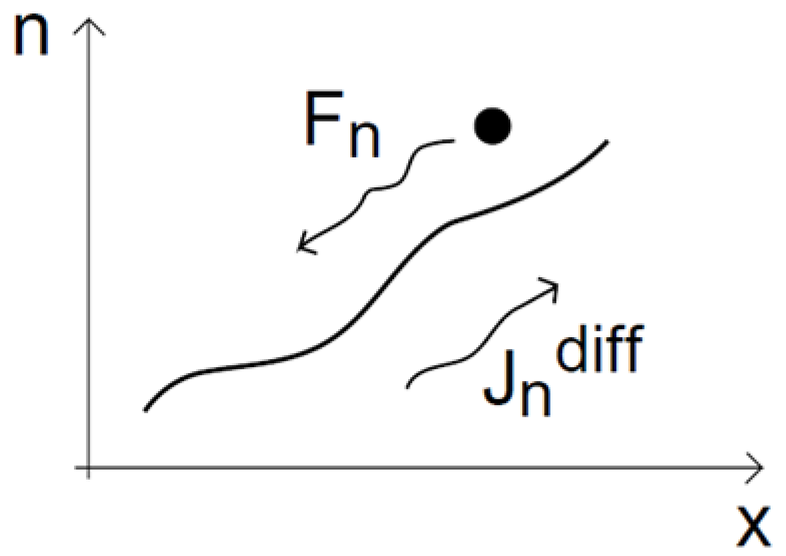
- For electrons: $$F_n = -D_n \frac{dn}{dx}$$
- For holes: $$F_p = -D_p \frac{dp}{dx}$$

- D_n ≡ electron diffusion coefficient [cm^2/s]
- D_p ≡ hole diffusion coefficient [cm^2/s]
- *D* measures the ease of carrier diffusion in response to a concentration gradient
- *D* limited by vibrating lattice atoms and ionized dopants

Diffusion Current Density

- Diffusion current density = charge × carrier flux





$$J_p^{diff} = -qD_p \frac{dp}{dx}$$

$$J_n^{diff} = qD_n \frac{dn}{dx}$$

Relationship between *D* and μ

- At the core of diffusion and drift is same physics: collisions among particles and medium atoms

  $\Rightarrow$ there should be a relationship between D and μ.

- A simple but powerful relationship ties the diffusion constant with the mobility,

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T$$

- Where $V_T = kT/q$. The parameter V_T is known as the **thermal voltage**.
- At room temperature, $T = 300$ K and $V_T = 25.9$ mV.
- The relationship is known as the **Einstein relationship**.

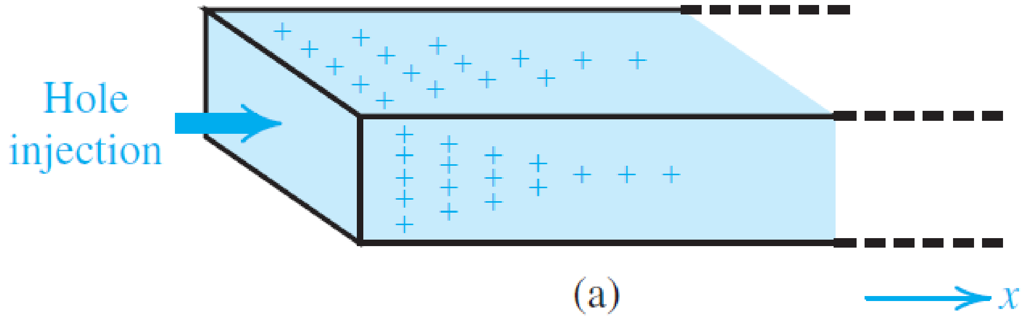
Hole Diffusion Current Density

- If the concentration of holes is made higher in one part of a piece of silicon than in another, then holes will diffuse from the region of high concentration to the region of low concentration.
- Holes injected by doping cause holes to diffuse from left to right along the silicon bar, resulting in a hole current in the *x* direction.
- The magnitude of the current density at any point is proportional to the slope of the concentration profile, or the **concentration gradient**, at that point,

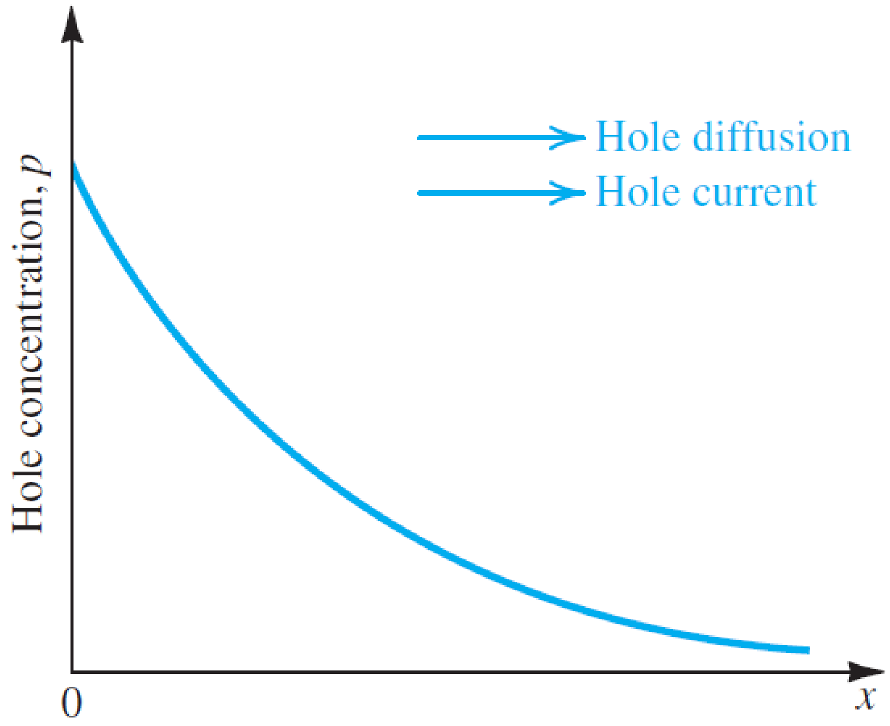
$$J_p = -qD_p \frac{dp(x)}{dx}$$

- Where *Jp* is the hole-current density (A/cm2), *q* is the magnitude of electron charge, *Dp* is a constant called the **diffusion constant** or **diffusivity** of holes; and *p(x)* is the hole concentration at point *x*.
- Note that the gradient *(dp(x)/dx)* is negative, resulting in a positive current in the *x* direction, as should be expected.

Electron Concentration Profile and Electron Diffuse Current



(a)



(b)

Electron Diffusion Current Density

- Electron diffusion resulting from an electron concentration gradient gives the electron-current density,

$$J_n = qD_n \frac{dn(x)}{dx}$$

- Where D_n is the diffusion constant or diffusivity of electrons.
- A negative (*dn(x)/dx*) gives rise to a negative current, a result of the convention that the positive direction of current is taken to be that of the flow of positive charge (and opposite to that of the flow of negative charge).
- For holes and electrons diffusing in intrinsic silicon, typical values for the diffusion constants are $D_p = 12\ \mathrm{cm}^2/\mathrm{s}$ and $D_n = 35\ \mathrm{cm}^2/\mathrm{s}$.

Drift-Diffusion Equation

- Where both concentration gradients and electric fields are present the total current is the sum of both drift and diffusion currents:

$$I_{tot} = eA\left(n\mu_n E + p\mu_p E + D_n \frac{dn}{dx} - D_p \frac{dp}{dx} \right)$$

- This equation is normally referred to as the drift-diffusion equation of carriers and is the basic equation that describes carrier movement in semiconductor devices.

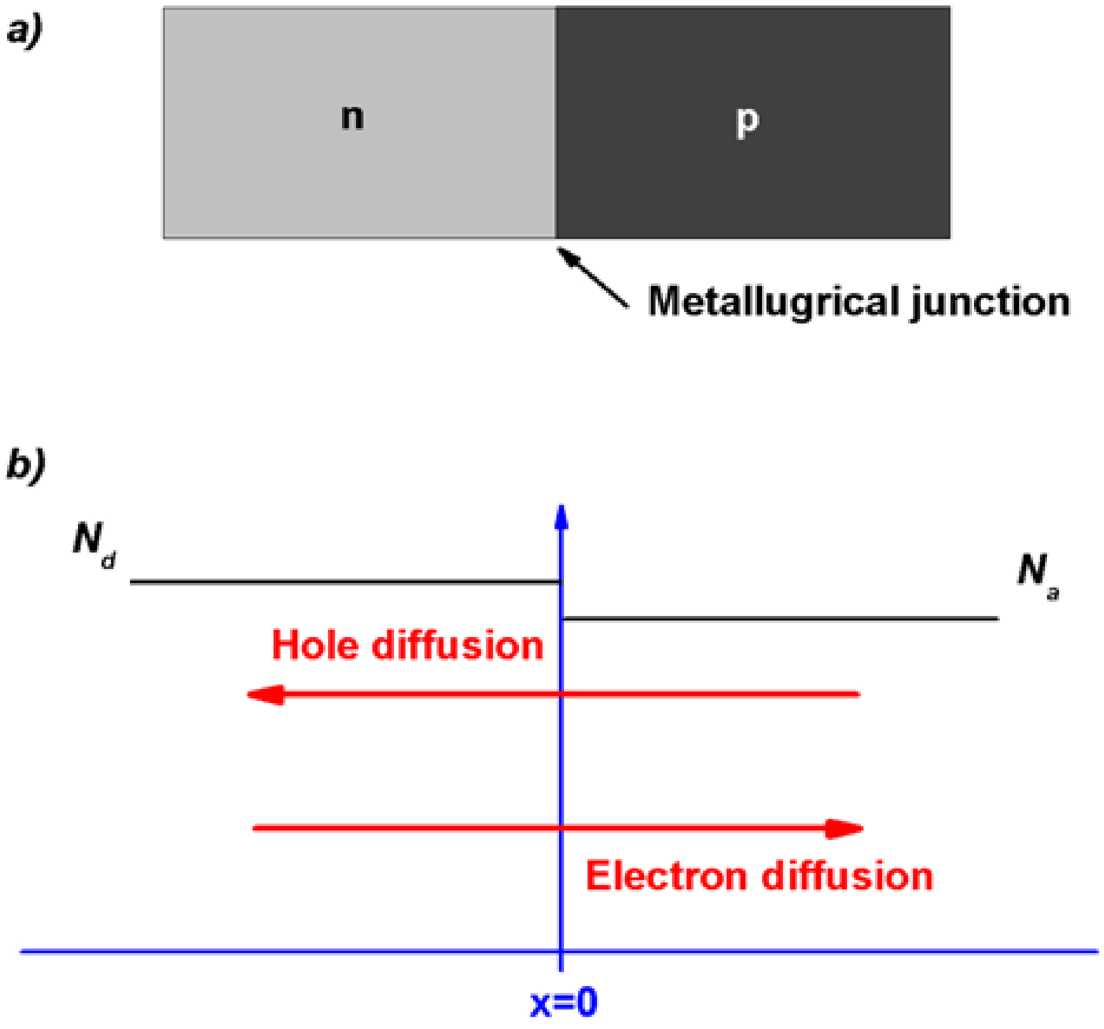
$$J_p = Drift\ current\ + diffusion\ current$$
$$J_n = Drift\ current\ + diffusion\ current$$

Total Current Density

$$\mathbf{J_n = J_n^{drift} + J_n^{diff} = qn\mu_n E + qD_n \frac{dn}{dx}}$$

$$\mathbf{J_p = J_p^{drift} + J_p^{diff} = qp\mu_p E - qD_p \frac{dp}{dx}}$$

$$\mathbf{J_{total} = J_n + J_p}$$



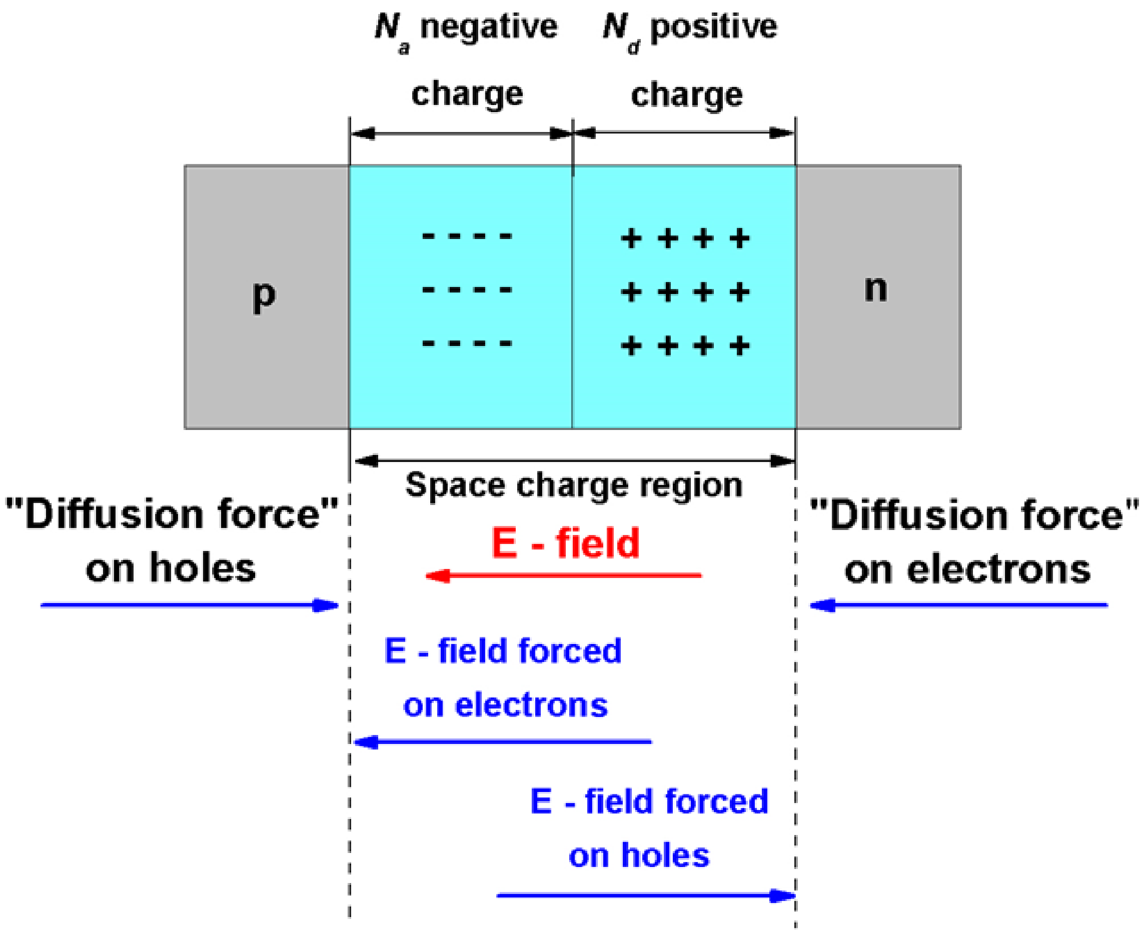
The interface separating the *n* and *p* regions is referred to as the *metallurgical* junction.

Creates a ***step junction*** in which the doping concentration is uniform in each region and there is an abrupt change in doping at the junction.

Majority carrier electrons in the *n* region will begin diffusing into the *p* region and majority carrier holes in the *p* region will begin diffusing into the *n* region.

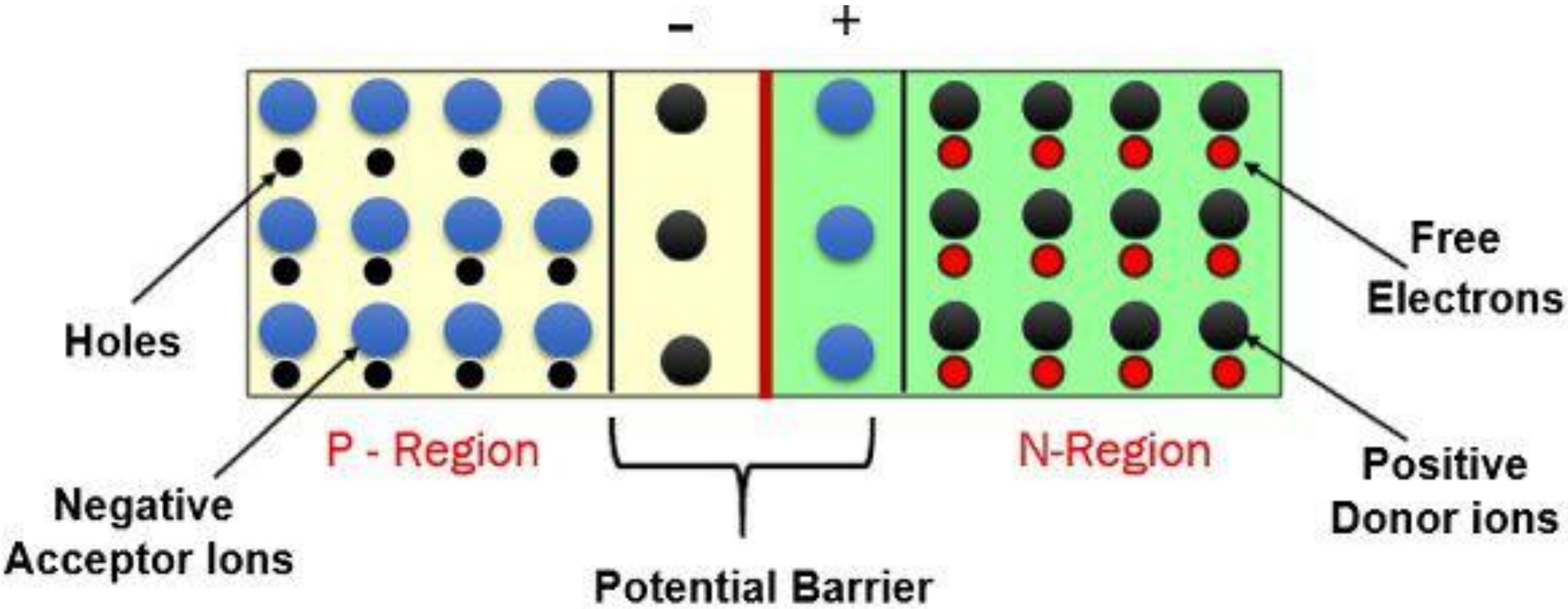
Space Charge Region (SCR)

- Electrons diffuse from the *n* region, positively charged donor atoms are left behind.
- Holes diffuse from the *p* region, they uncover negatively charged acceptor atoms.
- The net positive and negative charges in the *n* and *p* regions induce an electric field in the region near the metallurgical junction, in the direction from the positive to the negative charge, or from the *n* to the *p* region.
- The net positively and negatively charged regions are referred to as the ***space charge region (SCR).***
- Essentially all electrons and holes are swept out of the space charge region by the electric field.
- Since the space charge region is depleted of any mobile charge, this region is also referred to as the ***depletion region***.



Diffusion Current I_D in the *pn* Junction

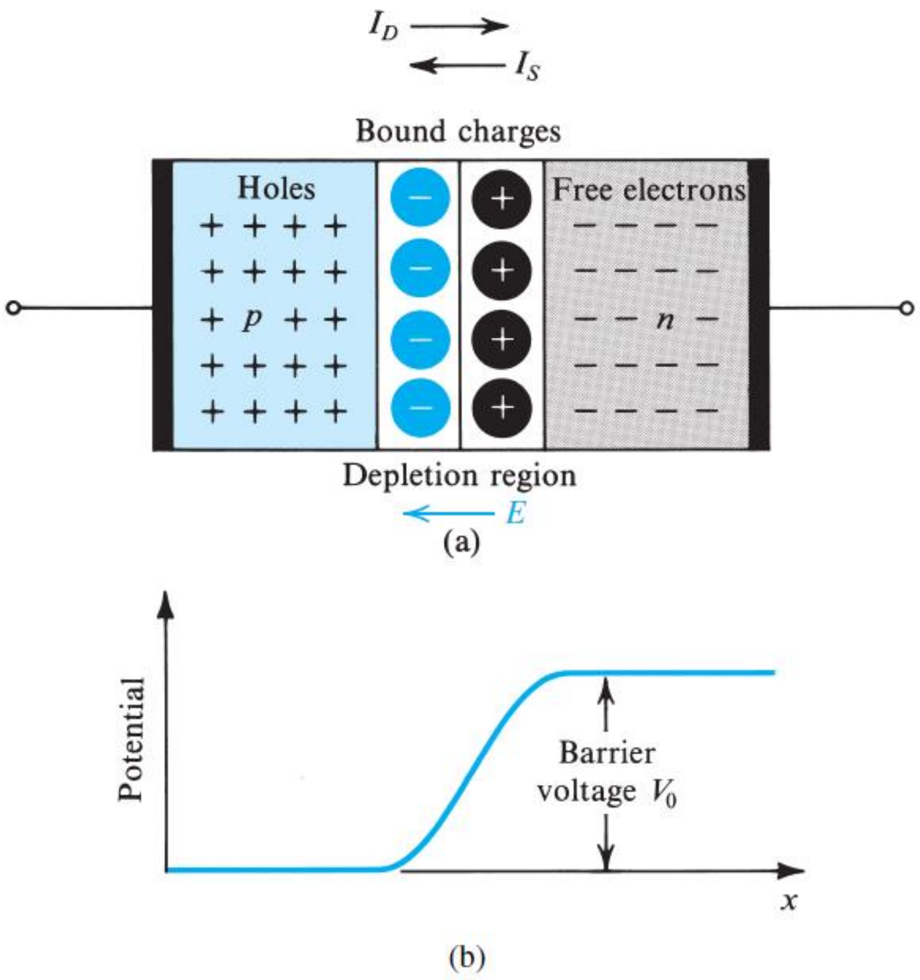
- Concentration of holes is high in the *p* region and low in the *n* region, holes diffuse across the junction from the *p* side to the *n* side.
- Electrons diffuse across the junction from the *n* side to the *p* side.
- These two current components add together to form the diffusion current I_D, whose direction is from the *p* side to the *n* side.
- The holes that diffuse across the junction into the *n* region quickly recombine with majority electrons present.
- Recombination process results also in the disappearance of some free electrons from the *n*-type material leaving the bound positive charge **uncovered**.
- Recombination results in region *depleted of free electrons* close to the junction, and it contains uncovered bound positive charge.



–
+
Holes
Negative
Acceptor Ions
P - Region
Potential Barrier
N-Region
Free
Electrons
Positive
Donor ions

- Similarly electrons from *n* region diffuse across the junction into the *p* region recombine with majority holes leaving some of the bound negative charge to uncovered.
- **Depletion region:** A **carrier-depletion region** exists on both sides of the junction, with the *n* side of the region positively charged and the *p* side negatively charged which is called the **space-charge region**.
- The charges on both sides of the depletion region establishes an electric field *E* across the region and hence a potential difference V_0 results across the depletion region, with the *n* side at a positive voltage relative to the *p* side.
- Electric field *E* opposes the diffusion of holes into the *n* region and electrons into the *p* region.
- 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.
- The larger the barrier voltage, the smaller the number of carriers that will be able to overcome the barrier, and hence the lower the magnitude of diffusion current.
- The barrier voltage V_0 limits the carrier diffusion process.
- Diffusion current I_D depends strongly on the voltage drop V_0 across the depletion region.

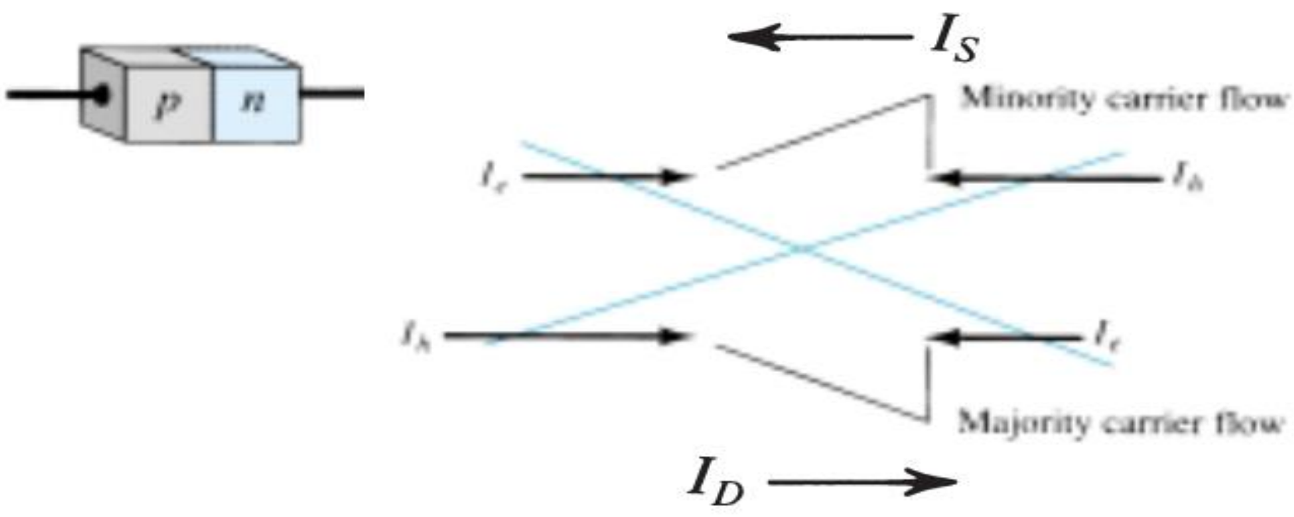
Open Circuited *pn* Junction

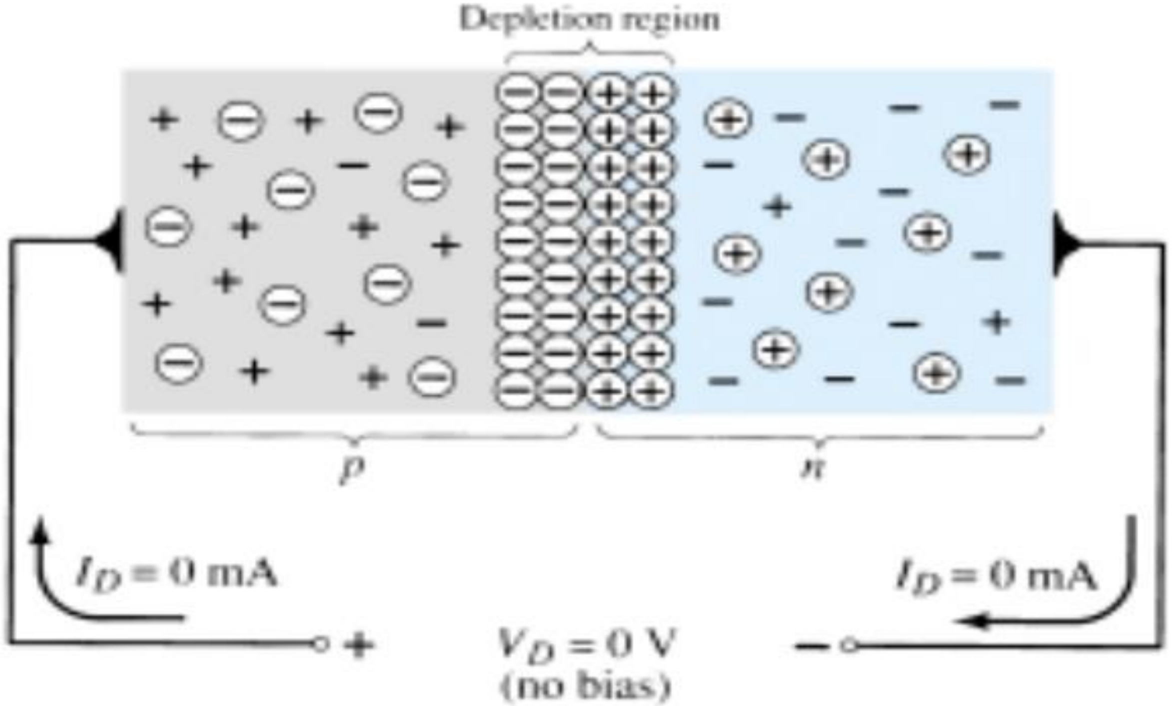


Drift Current I_S in the *pn* Junction

- Thermally generated holes in the *n* material that reach the edge of the depletion region experience the electric field *E* in the depletion region.
- Electric field *E* sweeps the holes across into the *p* side.
- Similarly, thermally generated minority electrons in the *p* material at the edge of the depletion region are swept by the electric field *E* in the depletion region across to the *n* side.
- The two drift current components—electrons moved by drift from *p* to *n* and holes moved by drift from *n* to *p*—add together to form the drift current $\boldsymbol{I_S}$, whose direction is from the *n* side to the *p* side of the junction.
- Drift current is determined by the number of minority carriers that make it to the edge of the depletion region and get swept across by *E* irrespective of the value of *E* or, correspondingly, of V_0.
- Under open-circuit conditions no external current exists; i.e. the two opposite currents I_D and I_S across the junction must be equal in magnitude.

$$I_D = I_S$$


p
n
I_S
Minority carrier flow
I_e
I_h
I_h
I_e
Majority carrier flow
I_D


Depletion region
p
n
$I_D = 0$ mA
$I_D = 0$ mA
+
$V_D = 0$ V
(no bias)
–

Junction Barrier Voltage

- With no external voltage applied, the barrier voltage V_0 across the *pn* junction is given by

$$V_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

- where N_A and N_D are the doping concentrations of the *p* side and *n* side of the junction, respectively.
- V_0 also known as **junction built-in voltage** depends both on doping concentrations and on temperature.
- Where $V_T = kT/q$. The parameter V_T is known as the **thermal voltage**.
- At room temperature, T = 300 K and V_T = 25.9 mV.
- Typically, for silicon at room temperature, V_0 is in the range of 0.6 V to 0.9 V.

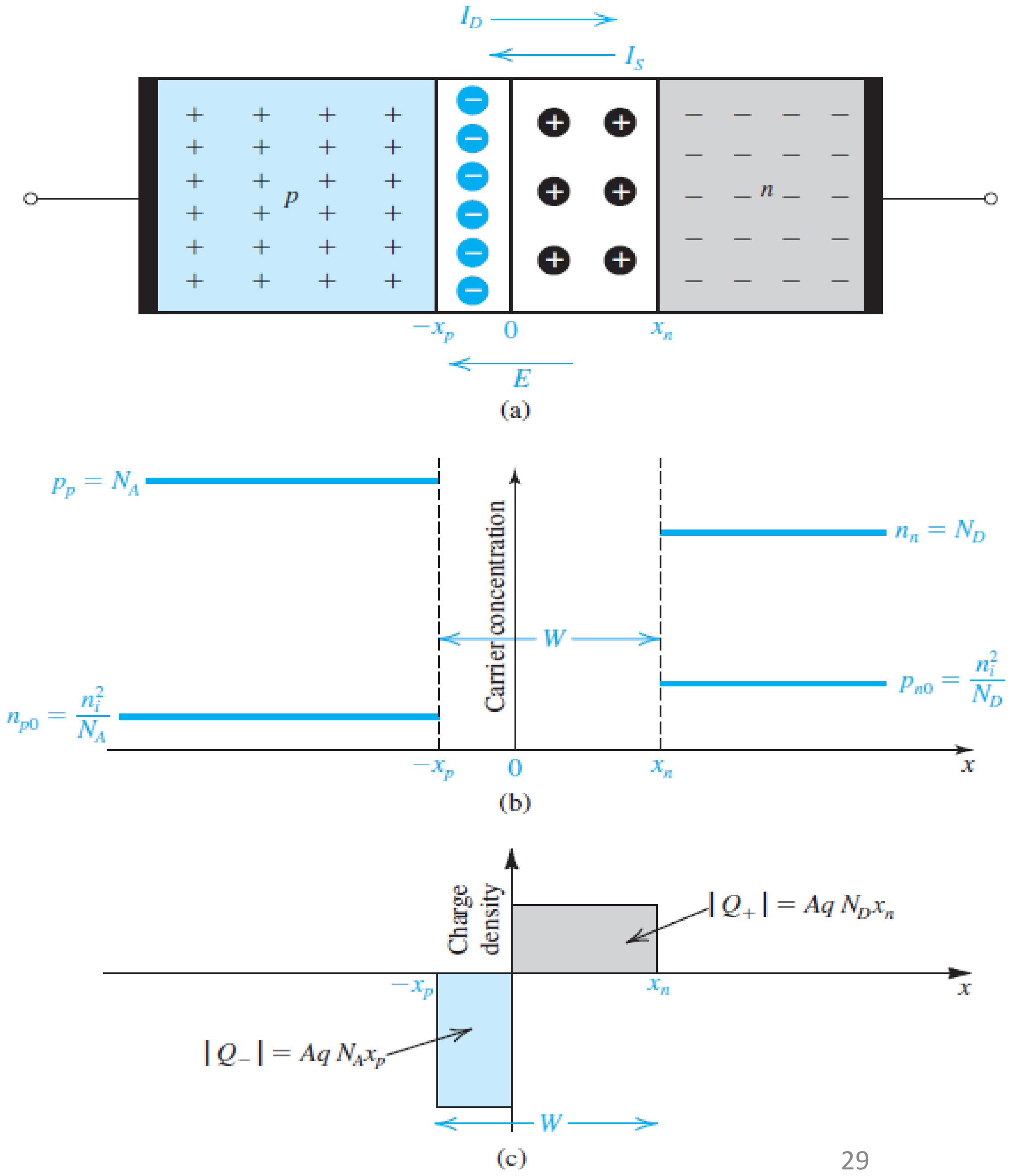
Charge Stored in the Depletion Region

- $N_A > N_D$
- Width of the depletion layer will not be the same on the two sides.
- Depletion layer will extend deeper into the more lightly doped material.
- Width of the depletion region in the p side: x_p is smaller than in the n side by x_n.
- Magnitude of the charge on the n side of the junction is

$$|Q_+| = qAx_nN_D$$

- Magnitude of the charge on the p side of the junction is

$$|Q_-| = qAx_pN_A$$



Width of the Depletion Region

- By the charge equality condition;

$$qAx_nN_D = qAx_pN_A \qquad \text{or} \qquad \frac{x_n}{x_p} = \frac{N_A}{N_D}$$

- The width W of the depletion layer is

$$W = x_n + x_p = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_0} \qquad \text{and} \qquad \begin{aligned} x_n &= W\frac{N_A}{N_A + N_D} \\ x_p &= W\frac{N_D}{N_A + N_D} \end{aligned}$$

- Charge stored on either side of the depletion region expressed in terms of W is:

$$Q_J = |Q_+| = |Q_-|$$

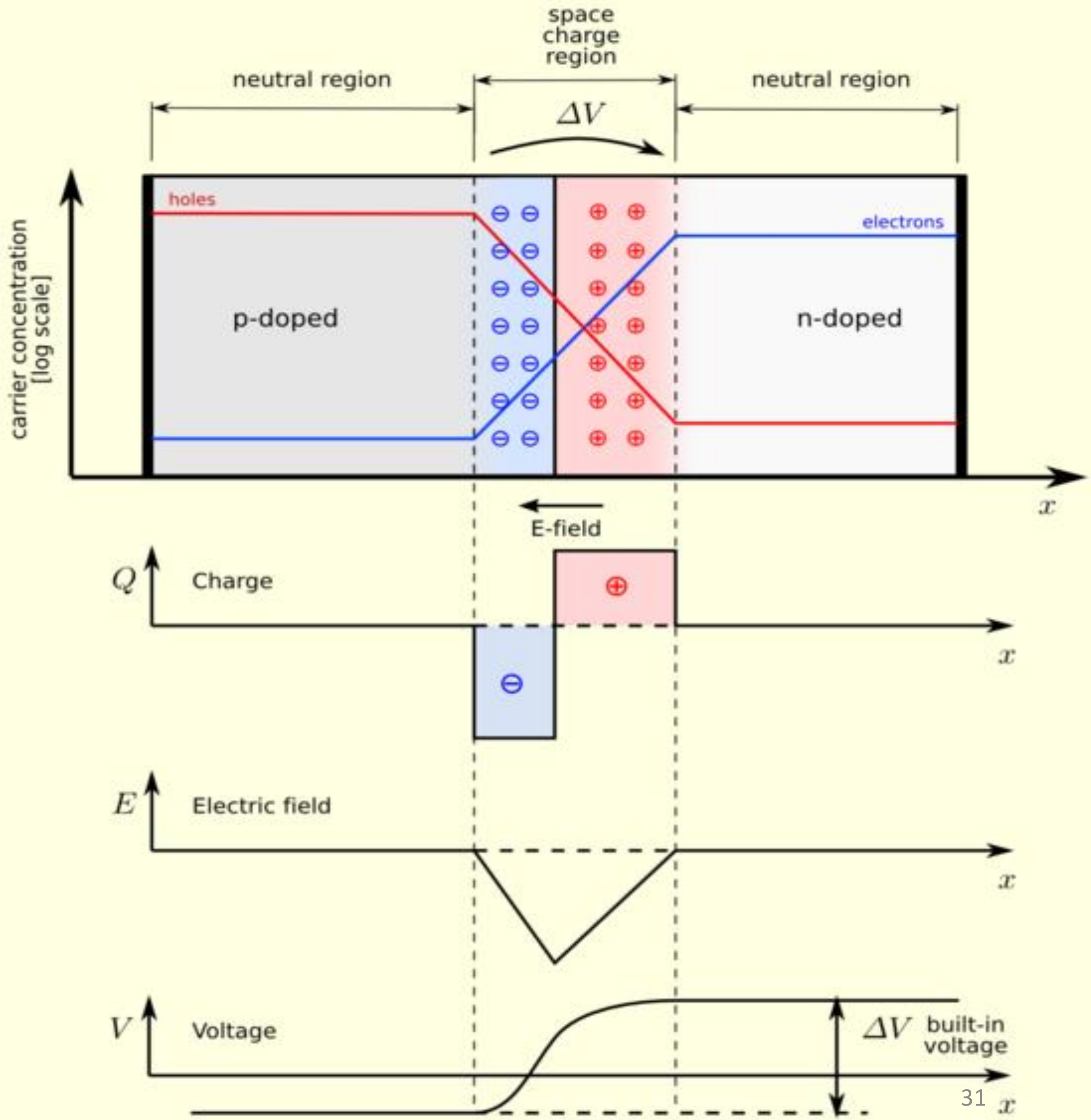
$$Q_J = Aq\left(\frac{N_AN_D}{N_A + N_D}\right)W \qquad \text{also expressed as} \qquad Q_J = A\sqrt{2\epsilon_s q\left(\frac{N_AN_D}{N_A + N_D}\right)V_0}$$

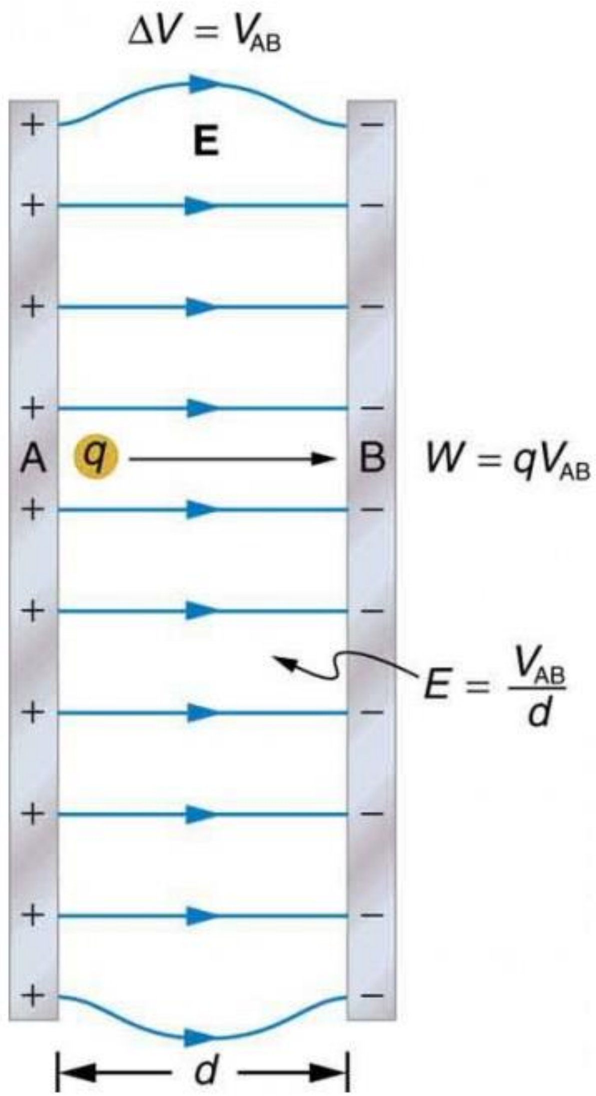
Open Circuited *pn* Junction

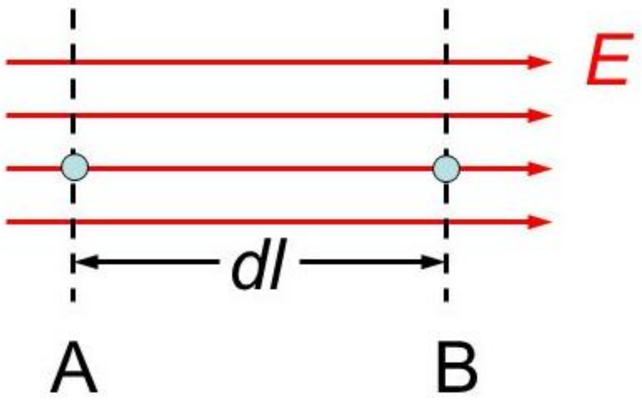
$$E = \int \frac{\rho(x)}{\varepsilon_r \varepsilon_0} dx$$

$Q = \rho$

$$V = -\int E(x) dx$$







- The potential difference between two points in an electric field is known to be:

$$V_A - V_B = -\int_A^B \vec{E} \bullet d\vec{l}$$

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