The PN Junction Diode

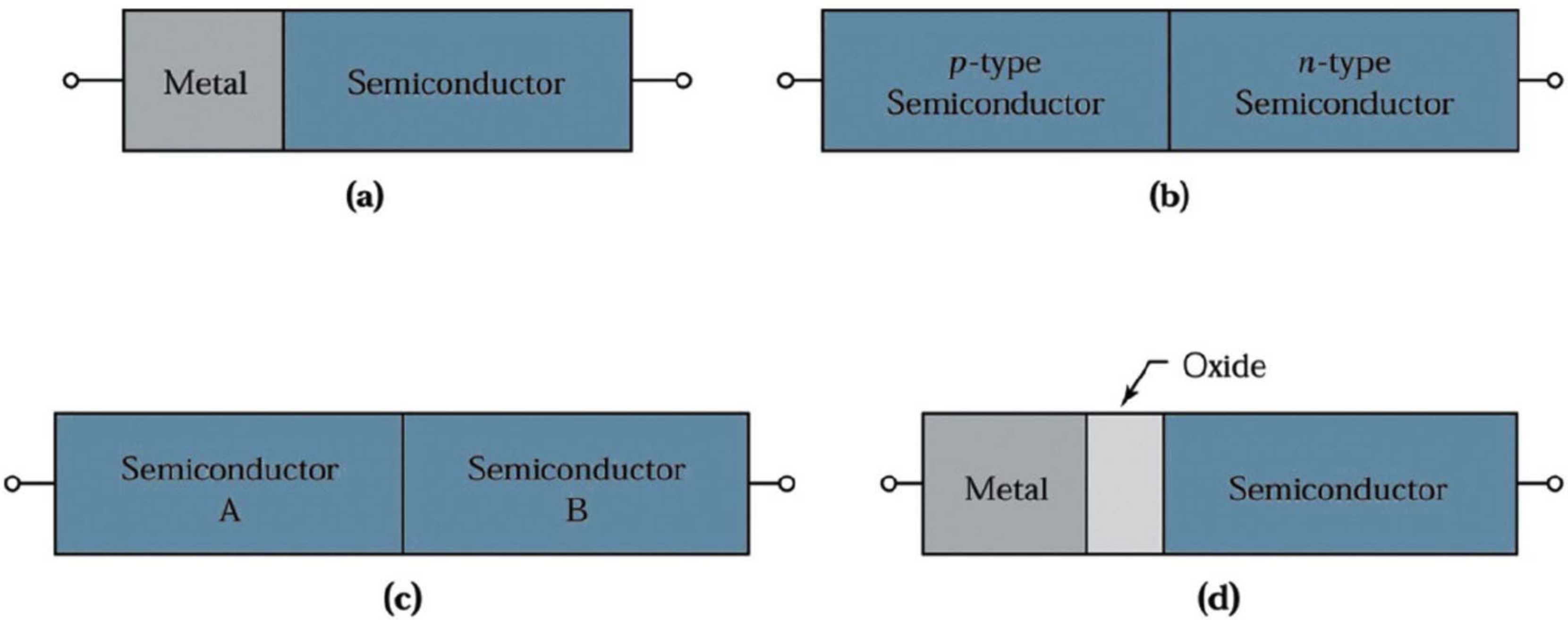
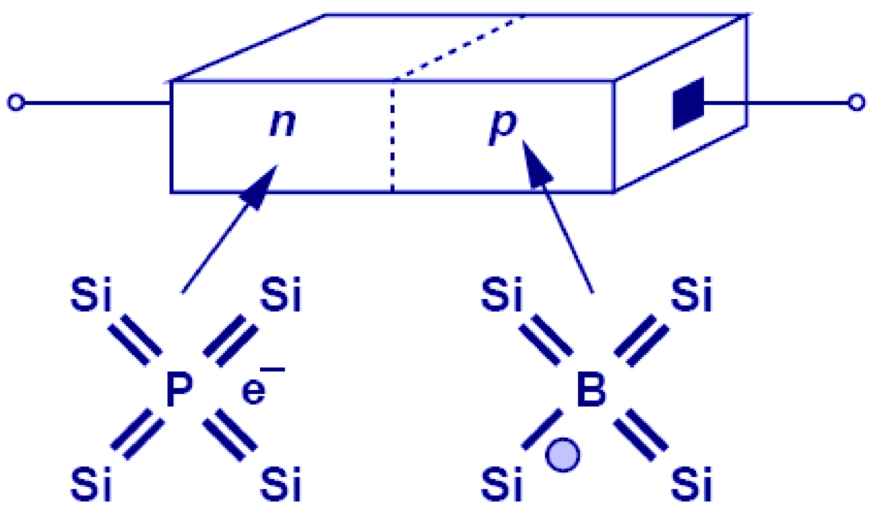


Figure 0.2

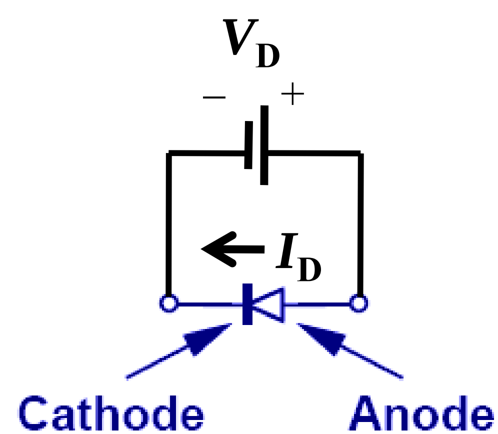
Basic device building blocks. (*a*) Metal-semiconductor interface; (*b*) p-n junction; (*c*) heterojunction interface; and (*d*) metal-oxide-semiconductor structure.

The PN Junction Diode

- When a P-type semiconductor region and an N-type semiconductor region are in contact, a PN junction diode is formed.



(a)



(b)

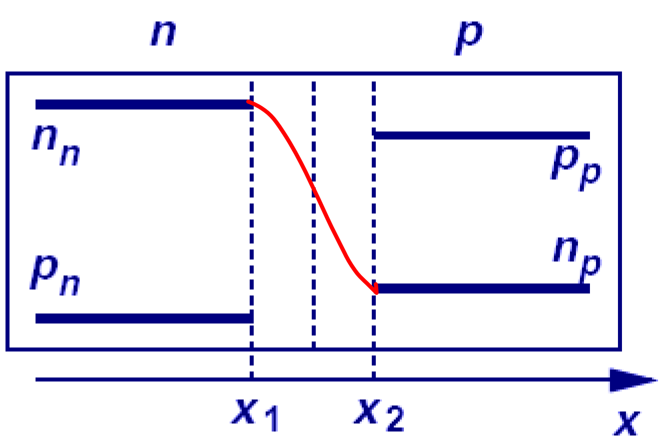
Diode Operating Regions

- In order to understand the operation of a diode, it is necessary to study its behavior in three operation regions: equilibrium, reverse bias, and forward bias.

$V_D = 0$		$V_D < 0$		$V_D > 0$
PN Junction in Equilibrium		**PN Junction Under Reverse Bias**		**PN Junction Under Forward Bias**
• Depletion Region • Built−in Potential	⇨	• Junction Capacitance	⇨	• I/V Characteristics

Carrier Diffusion across the Junction

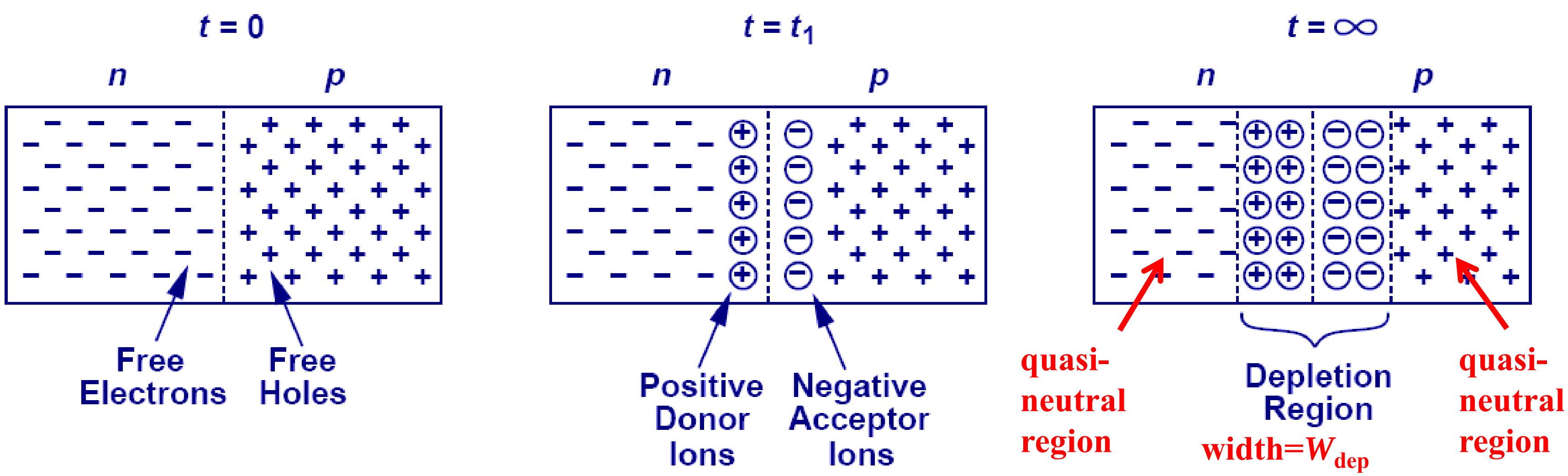
- Because of the difference in hole and electron concentrations on each side of the junction, carriers diffuse across the junction:



Notation:
$n_n \equiv$ electron concentration on N-type side (cm^{-3})
$p_n \equiv$ hole concentration on N-type side (cm^{-3})
$p_p \equiv$ hole concentration on P-type side (cm^{-3})
$n_p \equiv$ electron concentration on P-type side (cm^{-3})

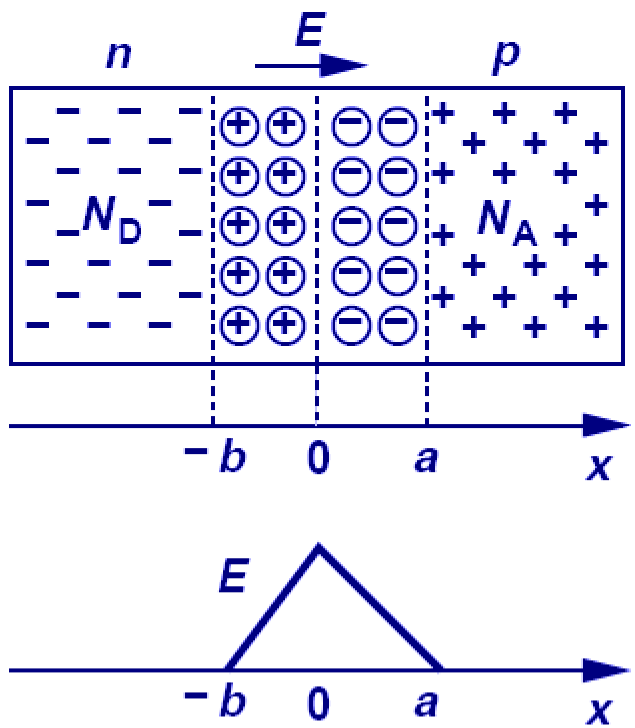
Depletion Region

- As conduction electrons and holes diffuse across the junction, they leave behind ionized dopants. Thus, a region that is depleted of mobile carriers is formed.
  - The charge density in the depletion region is not zero.
  - The carriers which diffuse across the junction recombine with majority carriers, *i.e.* they are annihilated.



Carrier Drift across the Junction

- Because charge density $\neq 0$ in the depletion region, an electric field exists, hence there is drift current.



PN Junction in Equilibrium

- In equilibrium, the drift and diffusion components of current are balanced; therefore the net current flowing across the junction is zero.

$$J_{p,drift} = -J_{p,diff}$$

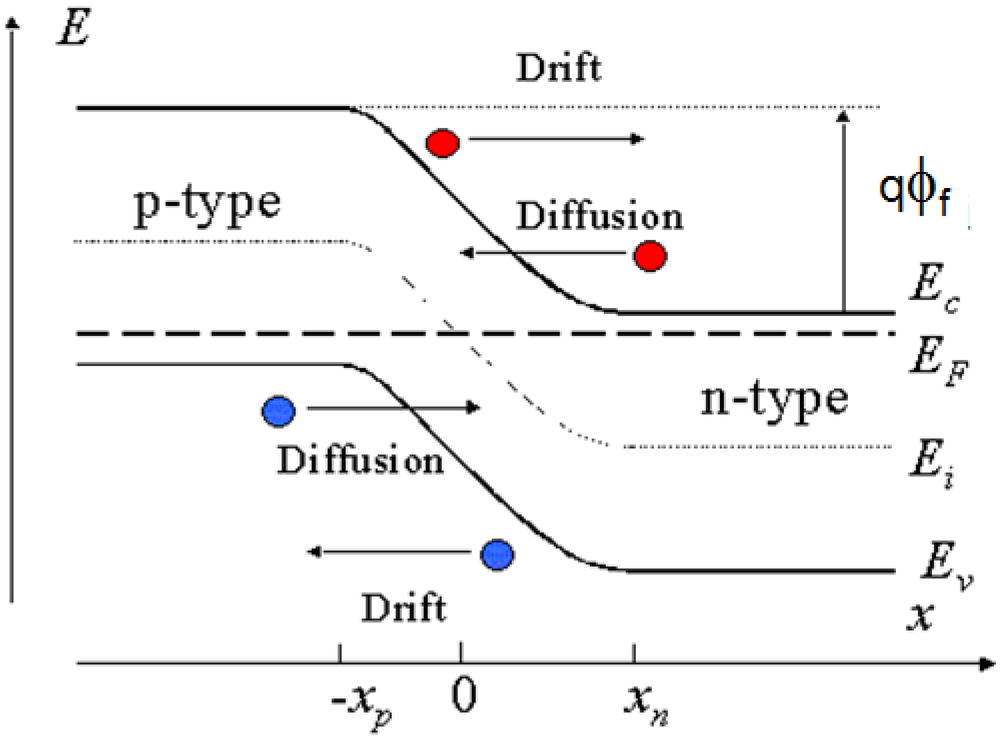
$$J_{n,drift} = -J_{n,diff}$$

$$J_{tot} = J_{p,drift} + J_{n,drift} + J_{p,diff} + J_{n,diff} = 0$$

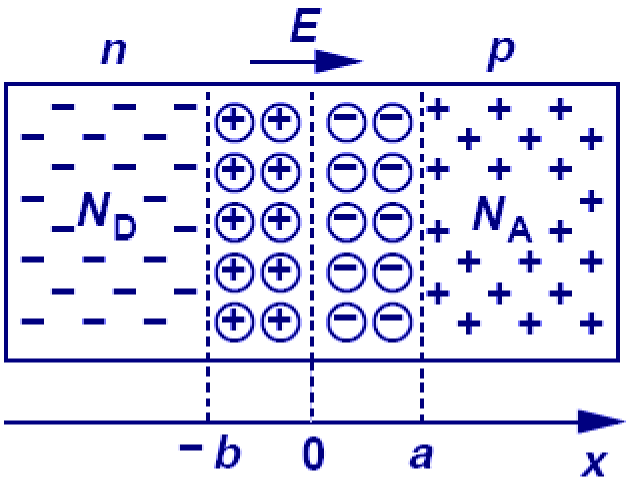
When the applied voltage (V_a) is zero

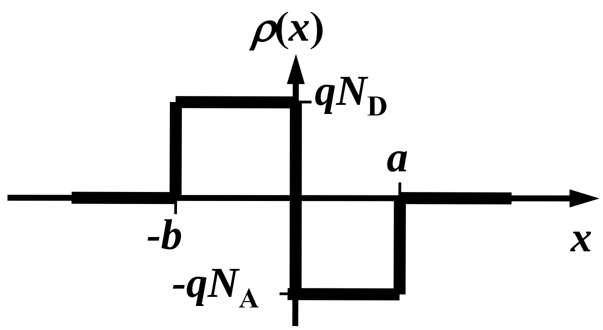
- The diode voltage and current are equal to zero on average
  - Any electron that diffuses through the depletion region from the n-side to the p-side is counterbalanced by an electron that drifts from the p-side to the n-side
  - Any hole that diffuses through the depletion region from the p-side to the n-side is counterbalanced by an hole that drifts from the n-side to the p-side
    - So, at any one instant (well under a nanosecond), we may measure a diode current. This current gives rise to one of the sources of electronic noise.

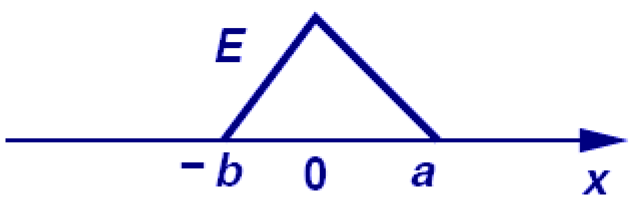
Schematically



The Depletion Approximation







In the depletion region on the **N side**:

$$\frac{dE}{dx} = \frac{\rho}{\varepsilon_{si}} = \frac{qN_D}{\varepsilon_{si}}$$

$$E = \frac{qN_D}{\varepsilon_{si}}(x+b)$$

In the depletion region on the **P side**:

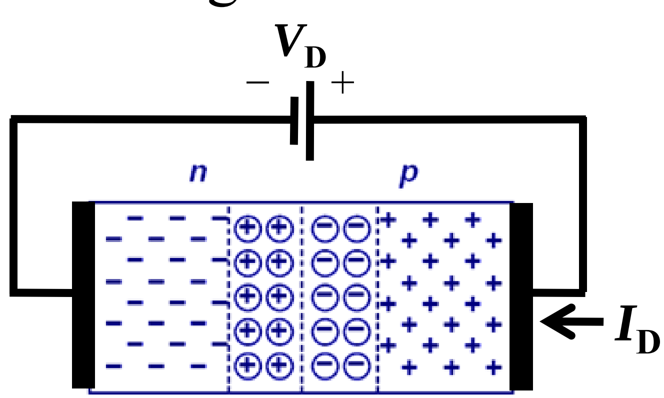
$$\frac{dE}{dx} = \frac{\rho}{\varepsilon_{si}} = \frac{-qN_A}{\varepsilon_{si}}$$

$$E = \frac{qN_A}{\varepsilon_{si}}(a-x)$$

$$\boxed{aN_A = bN_D}$$

Effect of Applied Voltage

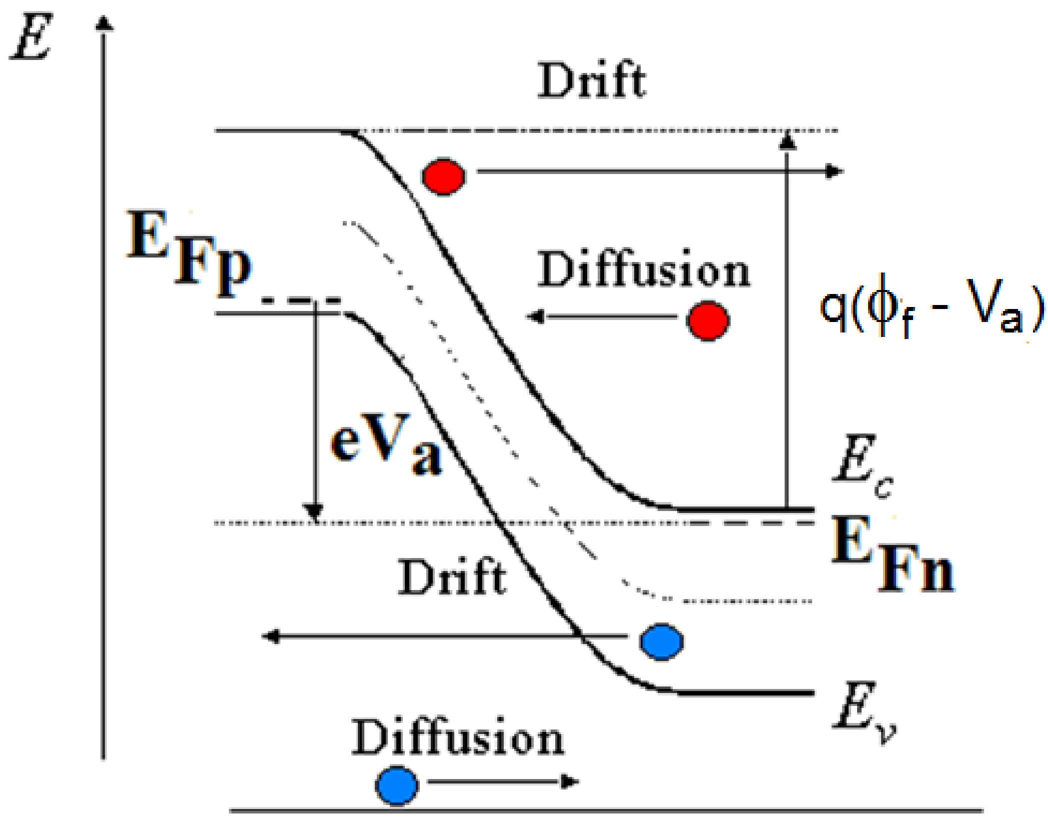
- The quasi-neutral N-type and P-type regions have low resistivity, whereas the depletion region has high resistivity.
  - Thus, when an **external voltage $\boldsymbol{V_D}$** is applied across the diode, almost all of this voltage **is dropped across the depletion region**.
- If $\boldsymbol{V_D} < 0$ (***reverse bias***), the potential barrier to carrier diffusion is increased by the applied voltage.
- If $\boldsymbol{V_D} > 0$ (***forward bias***), the potential barrier to carrier diffusion is reduced by the applied voltage.



Applied voltage is less than zero

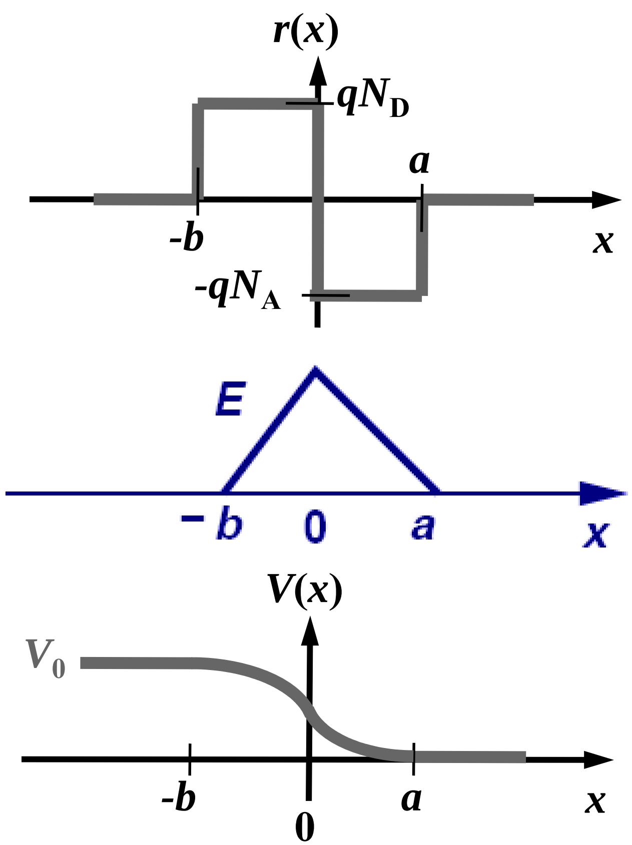
- The energy barrier between the p-side and n-side of the diode became larger.
  - It becomes less favorable for diffusion currents to flow
  - It become more favorable for drift currents to flow
    - The diode current is non-zero
    - The amount of current that flows across the p-n junction depends on the number of electrons in the p-type material and the number of holes in the n-type material
      - Therefore, the more heavily doped the p-n junction is the smaller the current will be that flows when the diode is reverse biased

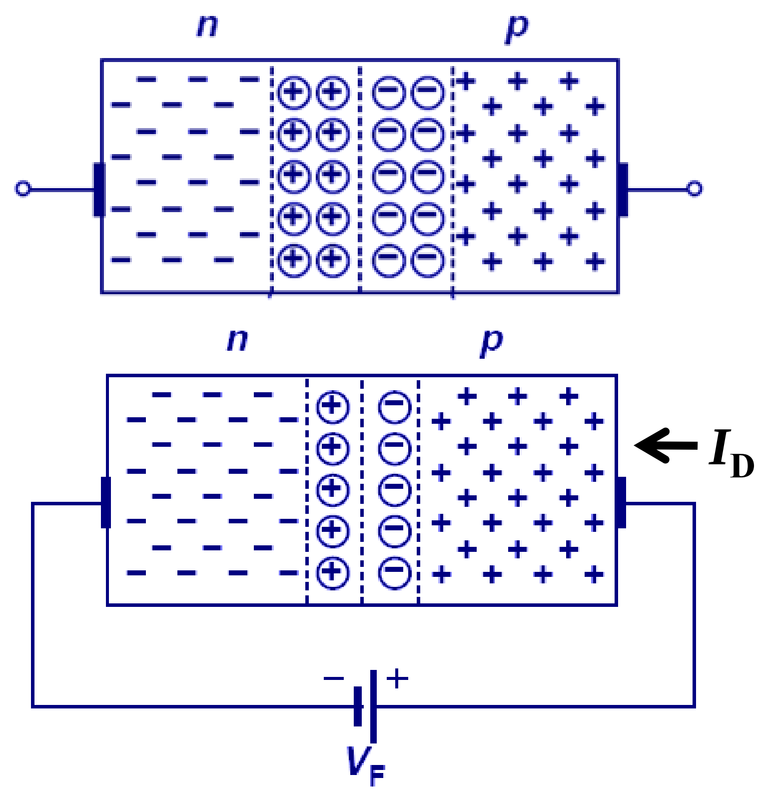
Schematically



PN Junction under Forward Bias

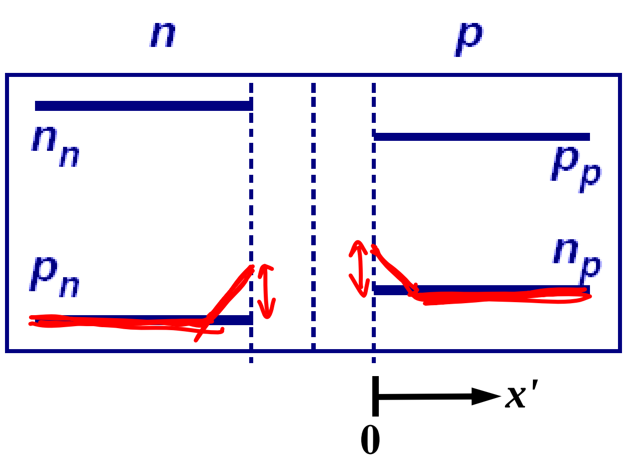
- A forward bias decreases the potential drop across the junction. As a result, the magnitude of the electric field decreases and the width of the depletion region narrows.

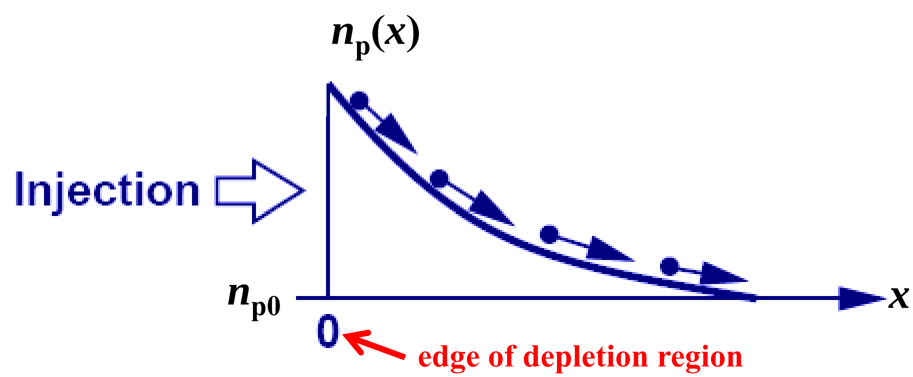




Minority Carrier Injection under Forward Bias

- The potential barrier to carrier diffusion is decreased by a forward bias; thus, carriers diffuse across the junction.
  - The carriers which diffuse across the junction become minority carriers in the quasi-neutral regions; they recombine with majority carriers, "dying out" with distance.





Equilbrium concentration of electrons on the P side:

$$n_{p0} = \frac{n_i^2}{N_A}$$

Minority Carrier Concentrations at the Edges of the Depletion Region

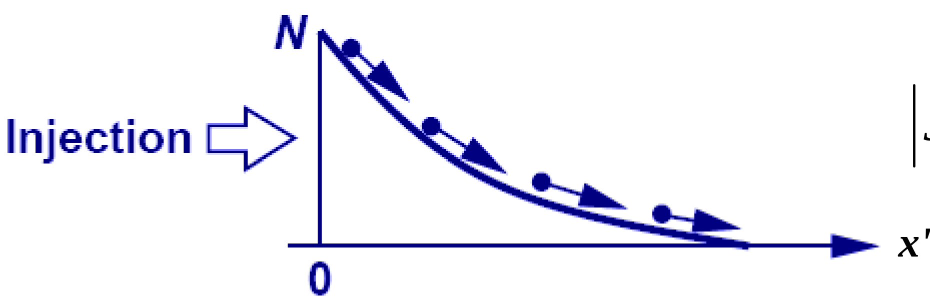
- The minority-carrier concentrations at the edges of the depletion region are changed by the factor $e^{qV_D/kT} = e^{V_D/V_T}$
  - There is an **excess concentration (D$\boldsymbol{p_n}$, D$\boldsymbol{n_p}$)** of minority carriers in the quasi-neutral regions, under forward bias.

- Within the quasi-neutral regions, the excess minority-carrier concentrations decay exponentially with distance from the depletion region, to zero:

<u>Notation</u>:
$L_n \equiv$ electron diffusion length (cm)

$$n_p(x') = n_{p0} + \Delta n_p(x')$$

$$\Delta n_p(x') = n_p(x') - n_{p0} = \left(\frac{n_i^2}{N_A} e^{V_D/V_T} - \frac{n_i^2}{N_A}\right) e^{-x'/L_n} = \frac{n_i^2\left(e^{V_D/V_T} - 1\right)}{N_A} e^{-x'/L_n}$$



$$\left|J_{n,diff}\right| = \left|qD_n \frac{dn_p}{dx'}\right| = \frac{qD_n n_i^2}{N_A L_n}\left(e^{V_D/V_T} - 1\right)e^{-x'/L_n}$$

Potential Difference due to $n(x)$, $p(x)$

- **The ratio of carrier densities at two points depends exponentially on the potential difference between these points:**

$$E_F - \boxed{E_{i1}} = kT\ln\left(\frac{n_1}{n_i}\right) \quad \Rightarrow \quad E_{i1} = E_F - kT\ln\left(\frac{n_1}{n_i}\right)$$

Similarly, $\boxed{E_{i2}} = E_F - kT\ln\left(\dfrac{n_2}{n_i}\right)$

Therefore $\quad E_{i1} - E_{i2} = kT\left[\ln\left(\dfrac{n_2}{n_i}\right) - \ln\left(\dfrac{n_1}{n_i}\right)\right] = kT\ln\left(\dfrac{n_2}{n_1}\right)$

$$V_2 - V_1 = \frac{1}{q}\left(E_{i1} - E_{i2}\right) = \frac{kT}{q}\ln\left(\frac{n_2}{n_1}\right)$$

Diode Current under Forward Bias

- The current flowing across the junction is comprised of hole diffusion and electron diffusion components:

$$J_{tot} = J_{p,drift}\Big|_{x=0} + J_{n,drift}\Big|_{x=0} + J_{p,diff}\Big|_{x=0} + J_{n,diff}\Big|_{x=0}$$

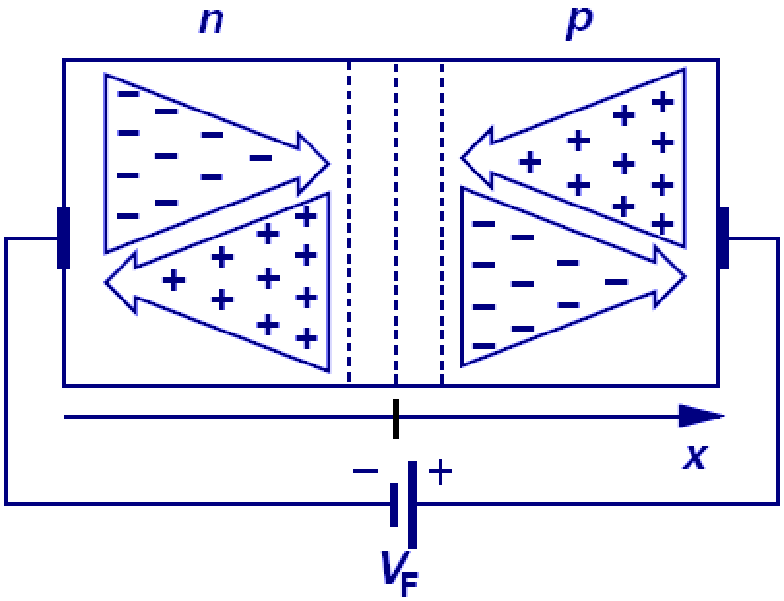
- Assuming that the diffusion current components are constant within the depletion region (*i.e.* no recombination occurs in the depletion region):

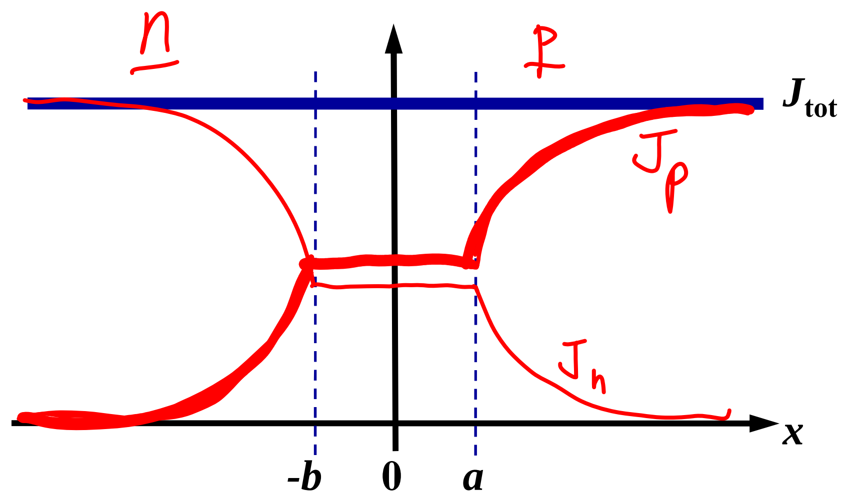
$$J_{n,diff}\Big|_{x=0} = \frac{qD_n n_i^2}{N_A L_n}\left(e^{V_D/V_T} - 1\right) \qquad J_{p,diff}\Big|_{x=0} = \frac{qD_p n_i^2}{N_D L_p}\left(e^{V_D/V_T} - 1\right)$$

$$\boxed{J_{tot} = J_S\left(e^{V_D/V_T} - 1\right) \text{ where } J_S = qn_i^2\left(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p}\right)}$$

Current Components under Forward Bias

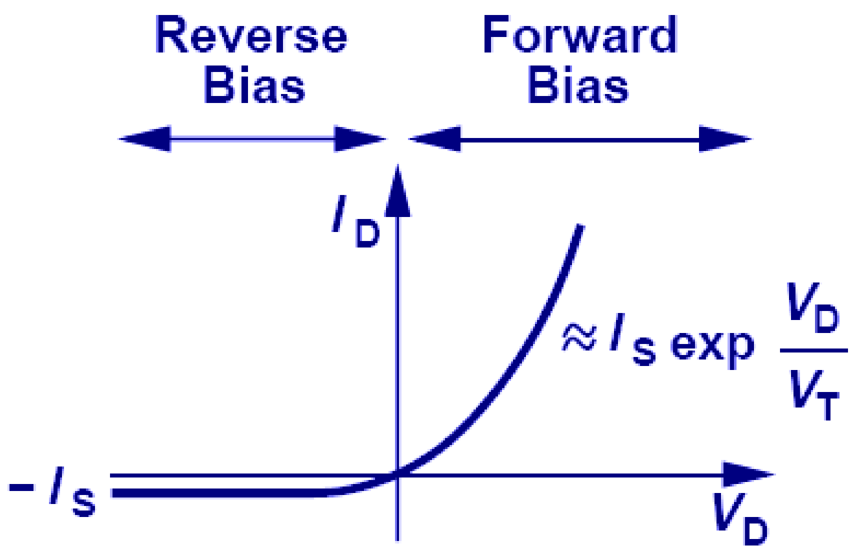
- For a fixed bias voltage, J_{tot} is constant throughout the diode, but $J_n(x)$ and $J_p(x)$ vary with position.





I-V Characteristic of a PN Junction

- Current increases exponentially with applied forward bias voltage, and "saturates" at a relatively small negative current level for reverse bias voltages.



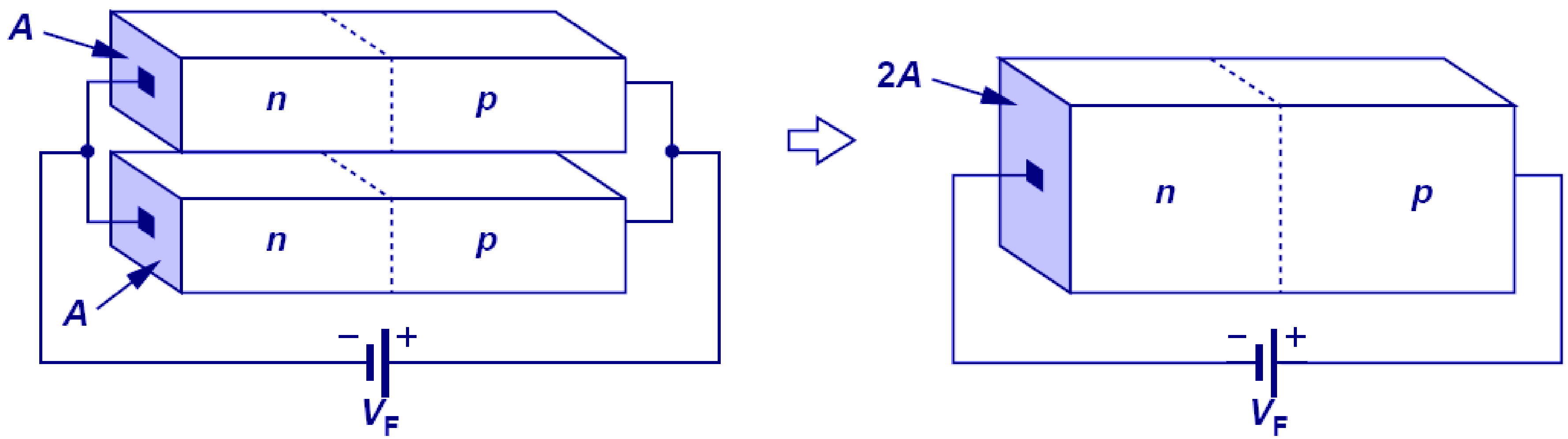
"Ideal diode" equation:

$$I_D = I_S\left(e^{V_D/V_T} - 1\right)$$

$$I_S = AJ_S = Aqn_i^2\left(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p}\right)$$

Parallel PN Junctions

- Since the current flowing across a PN junction is proportional to its cross-sectional area, two identical PN junctions connected in parallel act effectively as a single PN junction with twice the cross-sectional area, hence twice the current.



Diode Saturation Current I_S

$$I_S = Aqn_i^{\,2}\left(\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D}\right)$$

- I_S can vary by orders of magnitude, depending on the diode area, semiconductor material, and net dopant concentrations.
  - typical range of values for Si PN diodes: 10^{-14} to 10^{-17} A/mm^2
- In an asymmetrically doped PN junction, the term associated with the more heavily doped side is negligible:
  - If the P side is much more heavily doped, $I_S \cong Aqn_i^{\,2}\left(\frac{D_p}{L_p N_D}\right)$
  - If the N side is much more heavily doped, $I_S \cong Aqn_i^{\,2}\left(\frac{D_n}{L_n N_A}\right)$

What the Ideal Diode Equation Doesn't Explain

- I-V characteristics under large forward and reverse bias conditions
  - Large current flow when at a large negative voltage (Breakdown voltage, V_{BR})
  - 'Linear' relationship between I_D and V_D at reasonably large positive voltages ($V_a > \phi_f$)