ECE321 – Electronics I

Lecture 4: Physics of Semiconductor Diodes

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Review of Last Lecture

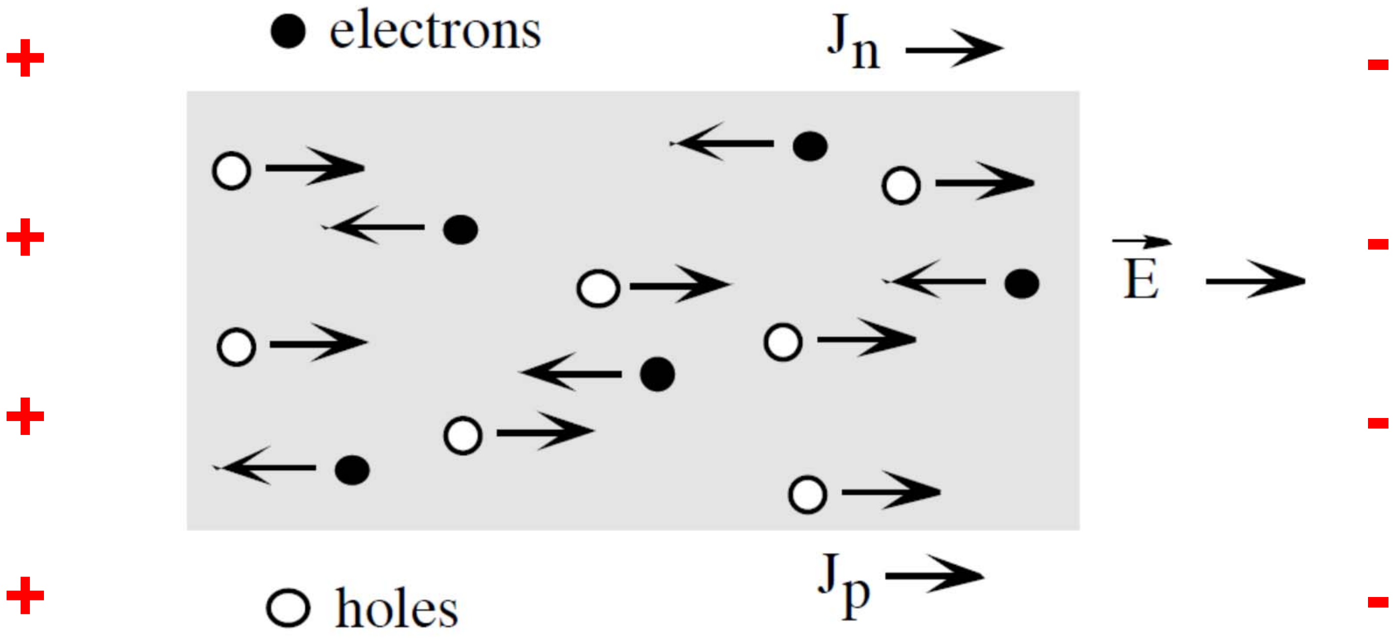
- ☐ **Electrical Property of Materials**
- ☐ **Energy Band Diagrams**
- ☐ **Semiconductor Materials**
- ☐ **n-Type and p-Type Semiconductor Materials**
- ☐ **Mass Action Law**

Today's Lecture

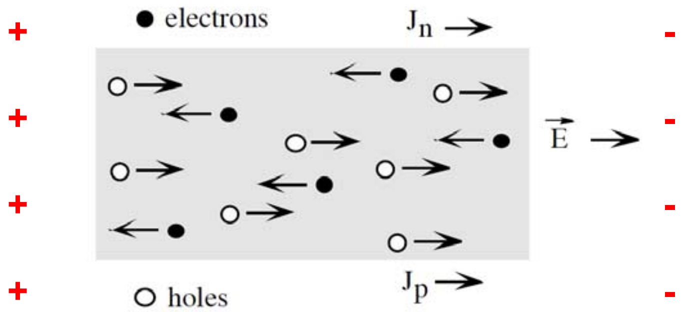
- ☐ **Carrier Transport in Semiconductors**
- ☐ **Drift Current**
- ☐ **Diffusion Current**
- ☐ **PN Junction**
- ☐ **Depletion Region**
- ☐ **Reverse Biased PN Junction**
- ☐ **Forward Biased PN Junction**

Drift Current Due to Electric Field

- ☐ **This is what happens in a typical resistors**
- ☐ **Direction of electrons and holes under externally applied electric field (E) is shown below**



Drift Current Equations in Semiconductor



$$J = \mu_n q E n_o + \mu_p q E p_o$$

n-type silicon has $n_o \approx N_D = 10^{17}$ (atoms/cm^3) at 300 K, $\mu_n = 1350$ cm^2/V•s, $\mu_p = 480$ cm^2/V•s, and the electric field is 10 V/cm. (a) What is the minority hole carrier density p_o (b) What is the total current density J?
(c) What is the resistivity of the material?

Solution

(a) $p_o = \frac{n_i^2}{n_o} = \frac{(1.062 \times 10^{10})^2}{10^{17}} = 1.128 \times 10^3 \left(\frac{\text{holes}}{\text{cm}^3}\right)$

(b)

$$J = (1350)(1.6 \times 10^{-19})(10)(10^{17}) \ + \ (480)(1.6 \times 10^{-19})(10)(1.128 \times 10^3)$$

$$= 216 \ + \ 8.7 \times 10^{-13} \ = \ 216 \ (\frac{\text{A}}{\text{cm}^2})$$

(c) $J = \sigma E = \frac{1}{\rho} E$

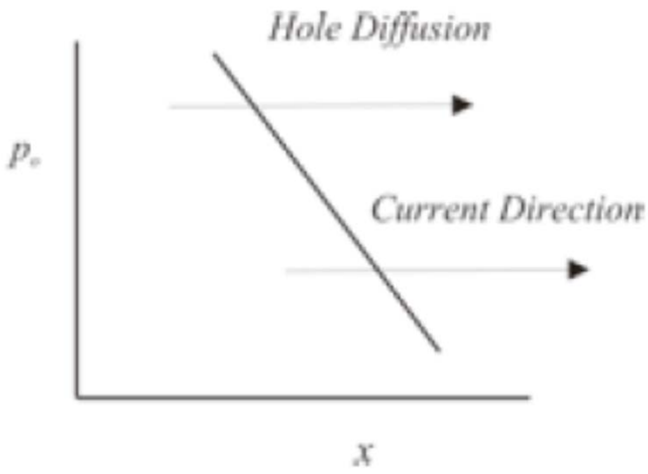
$216 = 10 / \rho \ \rightarrow \ \rho = 46.3$ mΩ·cm

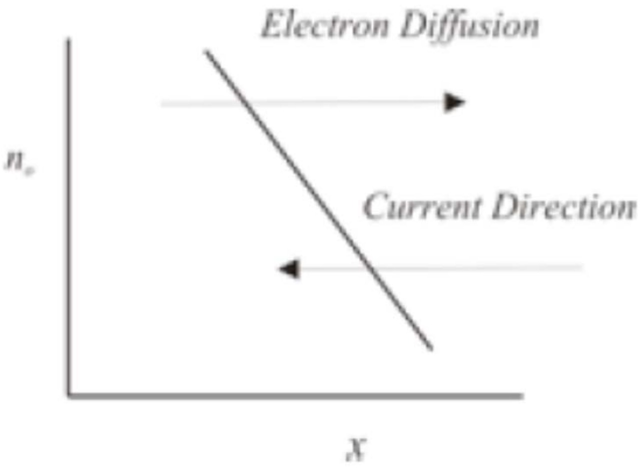
Ref: $\rho_{cu} = 1.7$ μΩ·cm

Diffusion Current Due to Density Gradient

- ☐ **This happens when the carrier concentration is different from one side to the other side**
- ☐ **An analogous case happens in gas container below, where the gas molecules “diffuses” from higher density to lower density**

Diffusion Current Equations





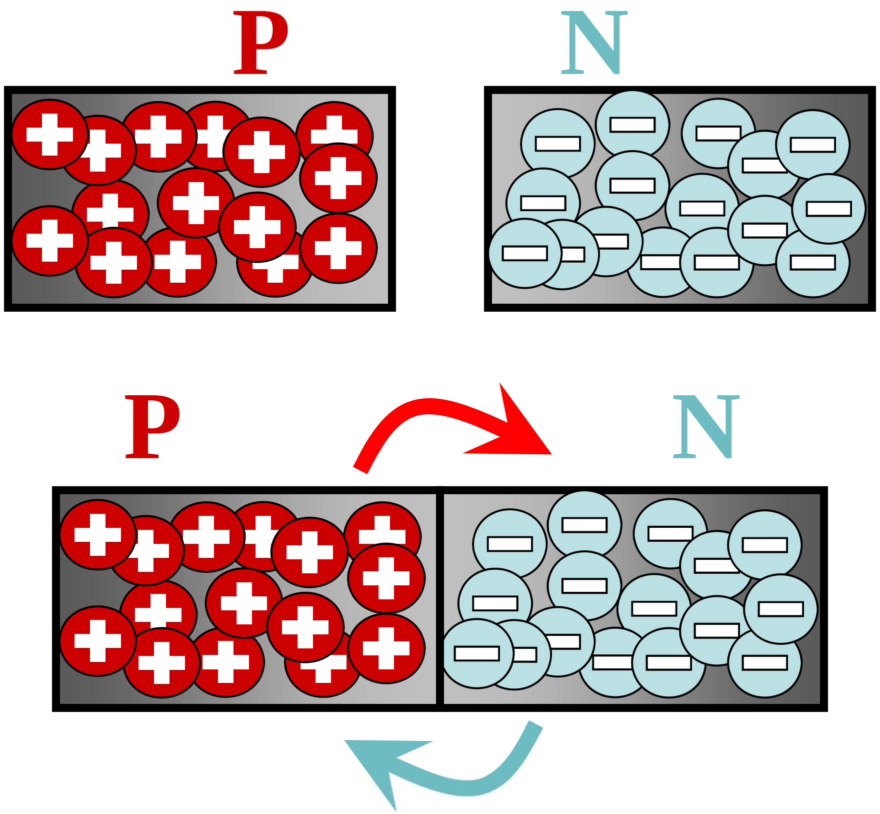
$$J_{pdiff} = qD_p \frac{dp_0}{dx}$$

$$J_{ndiff} = qD_n \frac{dn_0}{dx}$$

D_n and D_p are the electron and hole “diffusion constants”

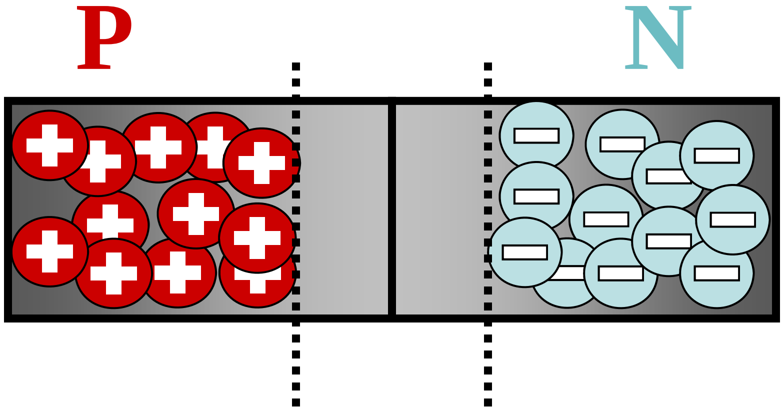
PN Junction

- ❑ **What does happen when P-Type semiconductor meets N-Type Semiconductor?**



PN Junction

- ☐ Some electrons will cross the junction and fill holes. A pair of ions is created each time this happens.
- ☐ As this ion charge builds up, it prevents further charge migration across the junction.
- ☐ The junction goes into equilibrium when the barrier potential prevents further diffusion.
- ☐ At 25 degrees C, the barrier potential for a silicon pn junction is about 0.5 to 0.7 volts.



Depletion Layer

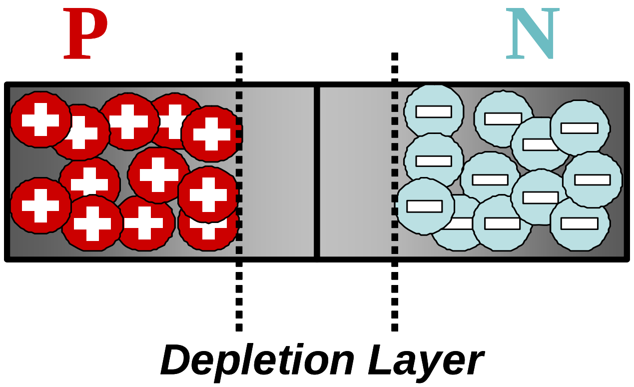
Depletion Region in Equilibrium

- ☐ **The barrier potential across deletion region is computed as:**

$$V_{bi} = V_{th} Ln\left(\frac{N_A \cdot N_D}{n_i^2}\right) \qquad V_{th} = \frac{kT}{q}$$

- ☐ **The width of depletion region is computed as:**

$$W = \sqrt{\frac{2\varepsilon_{si}}{q}\frac{N_A + N_D}{N_A \cdot N_D} V_{bi}}$$

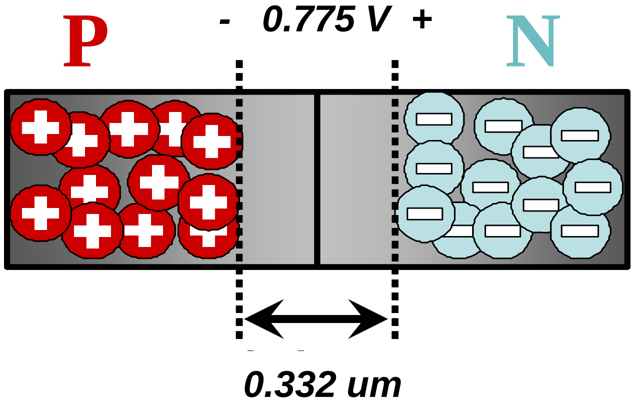


Example: Depletion Region

- **Calculate the built-in potential and depletion width at 300K in a diode if $n_i=1.062\times10^{10}$ cm^{-3}, $\varepsilon_{si} = 1.04\times10^{-12}$ F/cm , $N_A=10^{16}$ cm^{-3}, and $N_D = 10^{17}$ cm^{-3}.**

$$V_{bi} = V_{th} Ln\left(\frac{N_A \cdot N_D}{n_i^2}\right) = 0.026 Ln\left(\frac{10^{16}\cdot 10^{17}}{\left(1.062\times 10^{10}\right)^2}\right) = 0.775 \quad V$$

$$W = \sqrt{\frac{2\varepsilon_{si}}{q}\frac{N_A+N_D}{N_A\cdot N_D}V_{bi}} = \sqrt{\frac{2\times1.04\times10^{-12}}{1.609\times10^{-19}}\frac{10^{16}+10^{17}}{10^{16}\cdot10^{17}}\times0.775} = 3.32\times10^{-5}cm = 0.332um$$



Depletion Region Phenomena

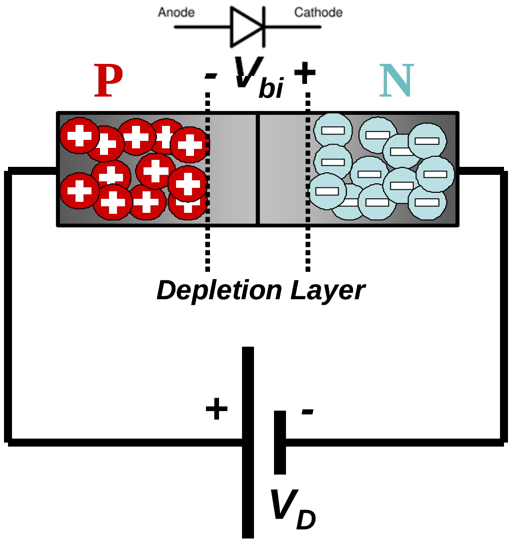
- **The depletion region is so named because it is formed by removal of all free charge carriers leaving none to carry a current.**
- **Depletion region is therefore an insulator region within a conductive material.**
- **Many modern semiconductor devices function based on “depletion region” phenomena.**
- **Example: Diodes, Solar cells, Bipolar Transistors, and MOS Transistors, Variable Capacitance Diodes**

PN Junction Under Applied Voltage

- ☐ **The applied external voltage, V_D, on the diode will directly affects the built-in potential**
  - **In reverse bias, the external voltage adds up to the built-in potential increasing the effect of V_{bi}**
  - **In forward bias, the external voltage is against the built-in potential reducing the effect of V_{bi}**
- ☐ **Depletion region width also depends on the voltage applied to the diode.**
- ☐ **Review:**

$$W = \sqrt{\frac{2\varepsilon_{si}}{q}\frac{N_A + N_D}{N_A \cdot N_D}\left(V_{bi} - V_D\right)}$$

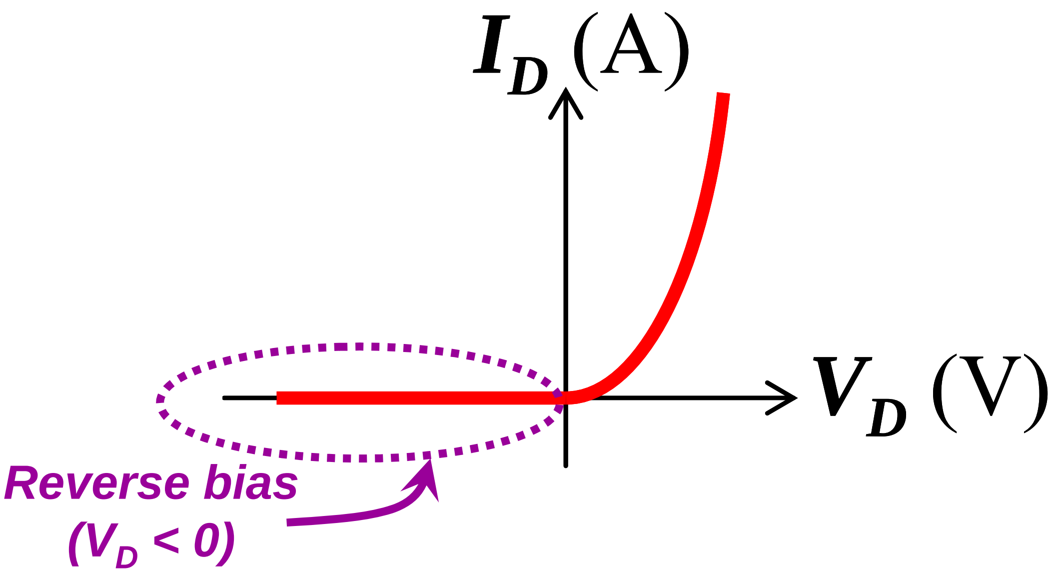
$$V_{bi} = V_{th} Ln\left(\frac{N_A \cdot N_D}{n_i^2}\right) \qquad V_{th} = \frac{kT}{q}$$



Reverse Biased PN Junction

☐ In CMOS transistors, that are currently used in semiconductor industry, all PN junctions are normally in reverse bias condition.

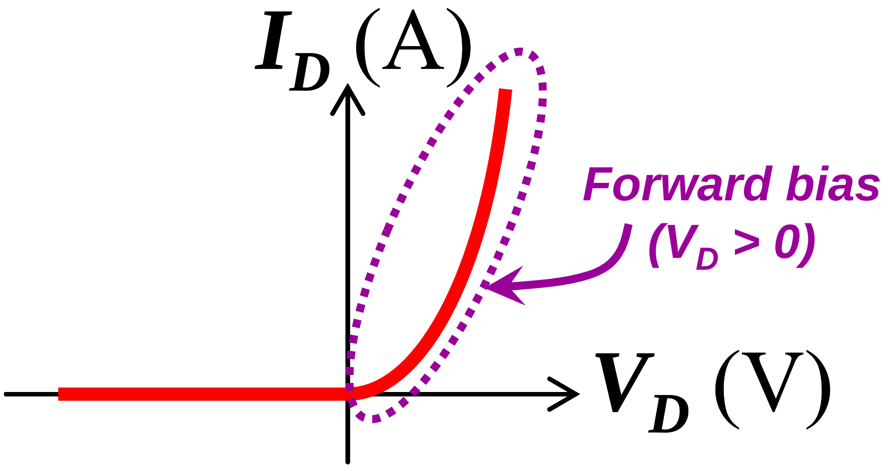
☐ When $V_D<0$ the width of depletion region increases which results in no conduction.



Forward Biased PN Junction

- ☐ **When $0<V_D<V_{bi}$ the width of depletion region decreases.**
- ☐ **Once $V_D>=V_{bi}$, then depletion region disappears and the diode starts conducting.**
- ☐ **The current in a diode can then be approximated as:**

$$I_D = I_S\left(e^{V_D/V_{th}} - 1\right) \qquad V_{th} = \frac{kT}{q}$$



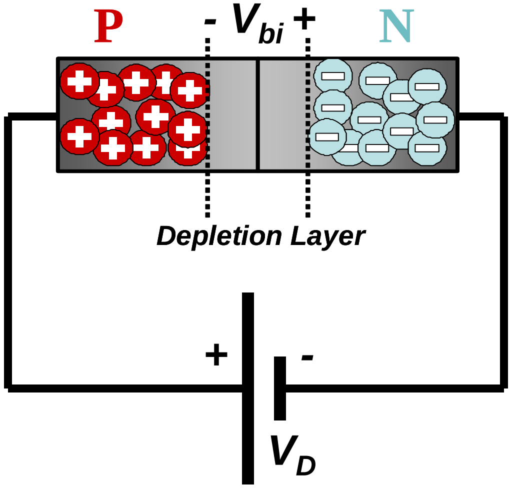
Diode’s Parasitic Capacitance

- **The depletion region, which act as an insulator, behaves like a capacitor in a PN junction.**
- **The “junction capacitance” can be calculated as:**

$$C_j = \frac{\varepsilon_{si} A}{W} = \frac{\varepsilon_{si} A}{\sqrt{\frac{2\varepsilon_{si}}{q}\frac{N_A + N_D}{N_A \cdot N_D}\left(V_{bi} - V_D\right)}} = \frac{A\sqrt{\frac{q\varepsilon_{si}}{2}\frac{N_A \cdot N_D}{N_A + N_D}V_{bi}}}{\sqrt{1 - \frac{V_D}{V_{bi}}}} = \frac{C_{j0}}{\sqrt{1 - \frac{V_D}{V_{bi}}}}$$

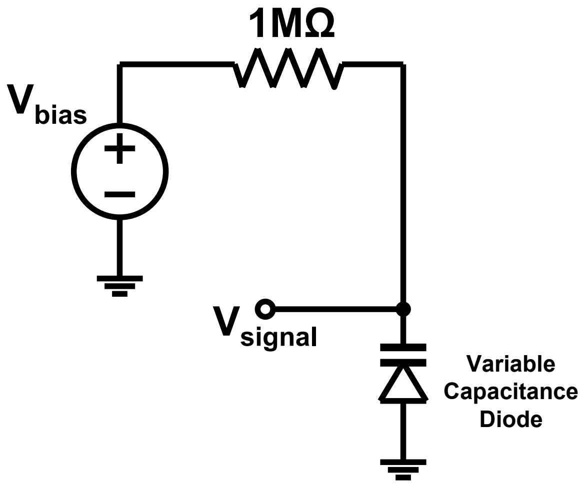
Where:

$$V_{bi} = V_{th} Ln\left(\frac{N_A \cdot N_D}{n_i^2}\right) \qquad V_{th} = \frac{kT}{q}$$

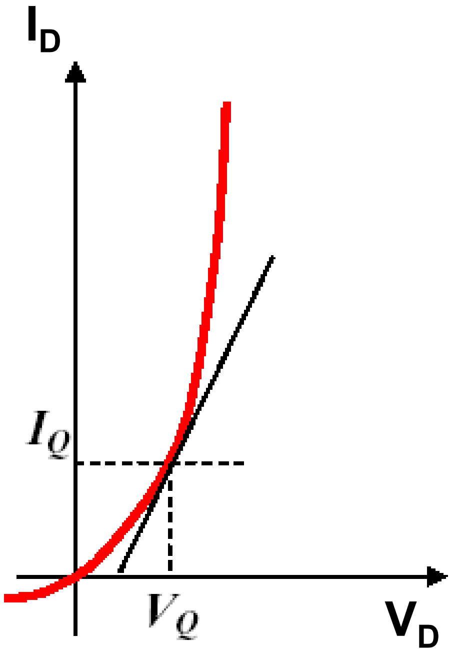


Variable Capacitance Diode (Varactor)

- **Generally, the junction capacitance in a diode is undesirable because it slows down the switching of the diode.**
- **Sometimes, we make a good use of this “parasitic capacitance”.**
- **The capacitance of a reverse bias diode can be adjusted by the amount of bias on a diode.**
- **If the AC input signal is small enough, the reverse bias diode can be seen as a capacitor, whose value can be adjusted by its reverse bias voltage.**



Small Signal Model for Diodes



$$I_D = I_S\left(e^{V_D/V_{th}} - 1\right) \qquad V_{th} = \frac{kT}{q}$$

Dynamic (Small Signal) Conductance

$$g_d = \left(\frac{dI_D}{dV_D}\right)_{V_D=V_Q} = \frac{I_S}{V_{th}} e^{V_Q/V_{th}} \approx \frac{I_Q}{V_{th}}$$

Dynamic (Small Signal) Resistance

$$r_d = \frac{1}{g_d} = \frac{V_{th}}{I_Q}$$