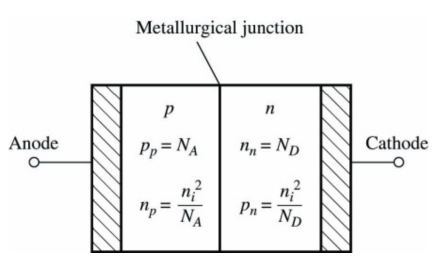
EE105 – Fall 2014
Microelectronic Devices and Circuits

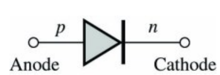
Prof. Ming C. Wu

wu@eecs.berkeley.edu

511 Sutardja Dai Hall (SDH)

Diode Introduction

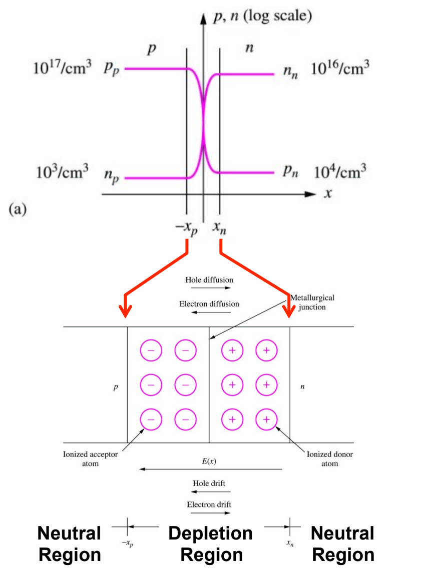




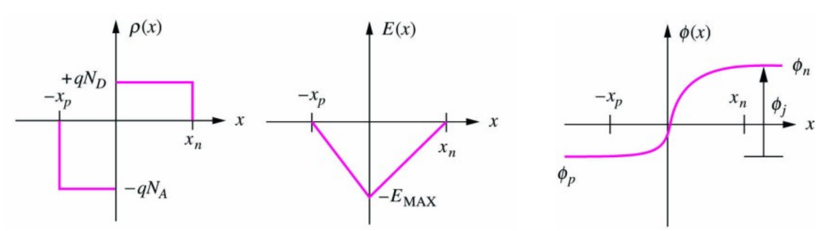
Diode symbol

- **A diode is formed by joining an *n*-type semiconductor with a *p* -type semiconductor.**
- **A *p-n* junction is the interface between *n* and *p* regions.**

pn Junction Electrostatics



Potential Across the Junction



Charge Density — **Electric Field** — **Potential**

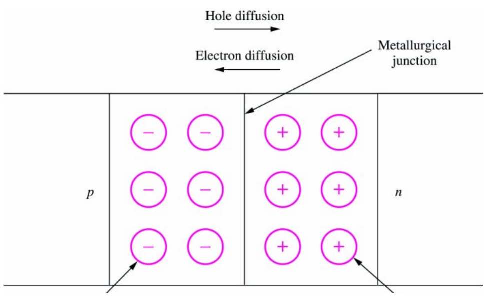
$$\nabla \cdot E = \frac{\rho_c}{\varepsilon_s}$$

$$E(x) = \frac{1}{\varepsilon_s}\int \rho(x)dx$$

$$\phi_j = -\int E(x)dx = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right),$$

$$V_T = \frac{kT}{q} = 0.026V \quad \text{at room temp}$$

Width of Depletion Region



Depletion Width

$$w_{d0} = (x_n + x_p) = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\phi_j}$$

EXAMPLE:
Built-in Potential and Depletion Width

Problem: Find built-in potential and depletion-region width for a given diode

Given data: On *p*-type side: $N_A = 10^{17}/\text{cm}^3$; On *n*-type side: $N_D = 10^{20}/\text{cm}^3$

Assumptions: Room-temperature operation with V_T = 0.025 V

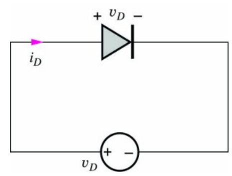
Analysis:

$$\phi_j = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) = (0.025\ \text{V})\ln\left[\frac{(10^{17}/\text{cm}^3)(10^{20}/\text{cm}^3)}{(10^{20}/\text{cm}^6)}\right] = 0.979\text{V}$$

$$w_{d0} = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\phi_j} = 0.113\ \mu\text{m}$$

Diode Equation

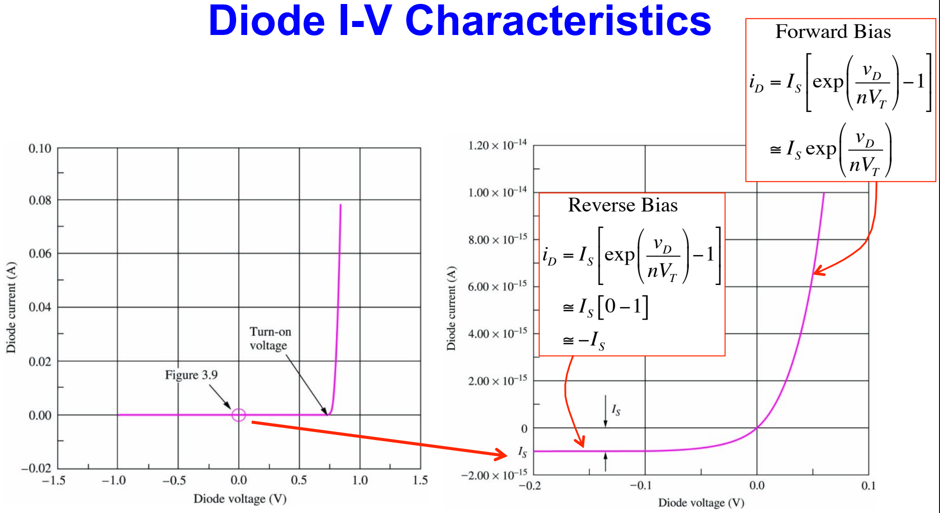
$$i_D = I_S\left[\exp\left(\frac{qv_D}{nkT}\right)-1\right] = I_S\left[\exp\left(\frac{v_D}{nV_T}\right)-1\right]$$



where	I_S	**=**	**reverse saturation current (A)**
	v_D	**=**	**voltage applied to diode (V)**
	q	**=**	**electronic charge (1.60 x 10^{-19} C)**
	k	**=**	**Boltzmann's constant (1.38 x 10^{-23} J/K)**
	T	**=**	**absolute temperature (Kelvins)**
	n	**=**	**non-ideality factor (dimensionless)**
	V_T	**=**	**kT/q = thermal voltage (V) (25 mV at room temp.)**

I_S is typically between 10^{-18} and 10^{-9} A, and is strongly temperature dependent due to its dependence on n_i^2. The non-ideality factor is typically close to 1, but approaches 2 for devices with high current densities. It is assumed to be 1 in this text.

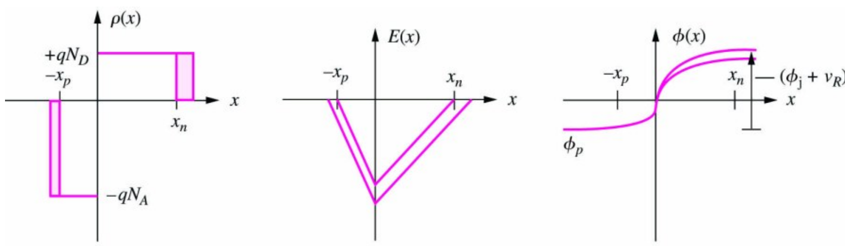
Diode I-V Characteristics



- **The turn-on voltage marks the point of significant current flow.**
- **I_S is called the reverse saturation current.**

Reverse Bias

External reverse bias adds to the built-in potential of the pn junction. The shaded regions below illustrate the increase in the characteristics of the space charge region due to an externally applied reverse bias, v_D.



(a) Space charge density (b) Electric field (c) Electrostatic potential

Depletion Width Increases with Reverse Bias Voltage

External reverse bias also increases the width of the depletion region since the larger electric field must be supported by additional charge.

$$w_d = (x_n + x_p) = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(\phi_j + v_R)}$$

$$w_d = w_{d0}\sqrt{1 + \frac{v_R}{\phi_j}}$$

$$\text{where } w_{d0} = (x_n + x_p) = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\phi_j}$$

Junction Capacitance

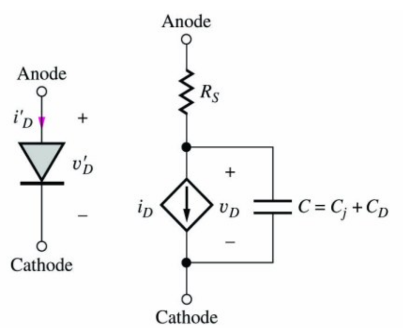
Changes in voltage lead to changes in depletion width and charge. This leads to a capacitance that we can calculate from the charge-voltage dependence.

$$Q_n = qN_D x_n A = q\left(\frac{N_A N_D}{N_A + N_D}\right) w_d A \quad \text{Coulombs}$$

$$C_j = \frac{dQ_n}{dv_R} = \frac{C_{j0} A}{\sqrt{1 + \frac{v_R}{\phi_j}}} \quad \text{F/cm}^2 \quad \text{where } C_{j0} = \frac{\varepsilon_s}{w_{d0}}$$

C_{j0} is the zero bias junction capacitance per unit area.

SPICE Model for pn Junction Diode



$$i_D = IS\left[\exp\left(\frac{v_D}{NV_T}\right) - 1\right]$$

$$C_D = \text{TT}\frac{i_D}{NV_T} \quad \text{for} \quad v_D \geq 0 \qquad C_j = \frac{CJO}{\left(1 - \frac{v_D}{VJ}\right)^M} RAREA \quad \text{for} \quad v_D \leq 0$$

R_s **: series resistance**

The current controlled current source models the ideal exponential behavior of the diode.

Capacitor C includes depletion-layer capacitance for the reverse-bias region and diffusion capacitance associated with the junction under forward bias.

Typical default values:

IS = 10 fA, R_s = 0 Ω, transit time TT = 0, N = 1

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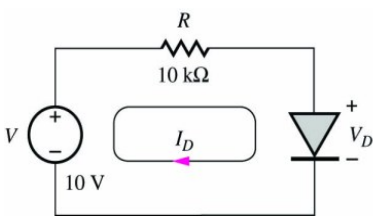
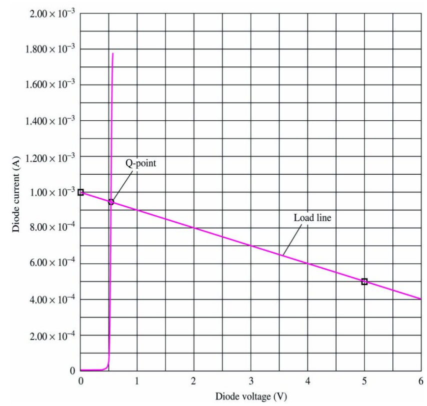
DC Analysis of Diode Circuit: Load-Line Analysis



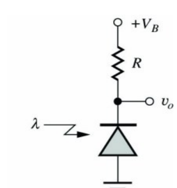
$$V = I_D R + V_D$$

$$= I_S \exp\left(\frac{v_D}{nV_T}\right) R + V_D$$

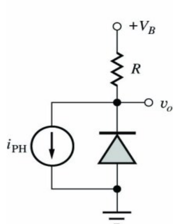


Solve the nonlinear equation for operating point, (I_D , V_D), either numerically or graphically

Photo Diodes and Photodetectors



(a)



(b)

If the depletion region of a *pn* junction diode is illuminated with light with sufficiently high frequency, photons can provide enough energy to cause electrons to jump the semiconductor bandgap to generate electron-hole pairs:

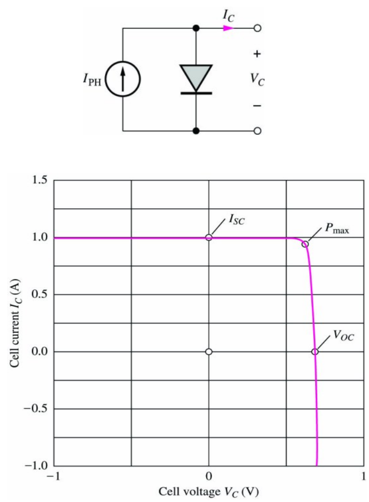
$$E_P = h\upsilon = \frac{hc}{\lambda} \geq E_G$$

h **=Planck's constant = 6.626 x 10^{-34} J-s**
υ = frequency of optical illumination
l = wavelength of optical illumination
c **= velocity of light = 3 x 10^{8} m/s**
Photon-generated current can be used in photodetector circuits to generate an output voltage

$$v_O = i_{PH} R$$

The diode is reverse-biased to enhance depletion-region width and electric field.

Solar Cells and Light-Emitting Diodes



In solar cell applications, optical illumination is steady, and dc current I_{PH} is generated. The goal is to extract power from the cell, and the *i-v* characteristics are plotted in terms of cell current and cell voltage. For a solar cell to supply power to an external circuit, the $I_C V_C$ product must be positive, and the cell should be operated near the point of maximum output power P_{max}.

Light-Emitting Diodes (LEDs) use recombination processes in the forward-biased *pn* junction diode to produce light. When a hole and electron recombine, an energy equal to the bandgap of the semiconductor is released as a photon.