Lecture 3

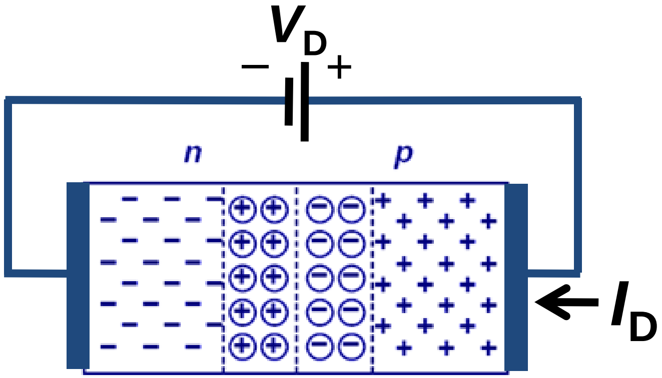
OUTLINE

- PN Junction Diodes (cont'd)
  - Electrostatics (cont'd)
  - *I-V* characteristics
  - Reverse breakdown
  - Small-signal model

Reading: Chapter 2.2-2.3, 3.4

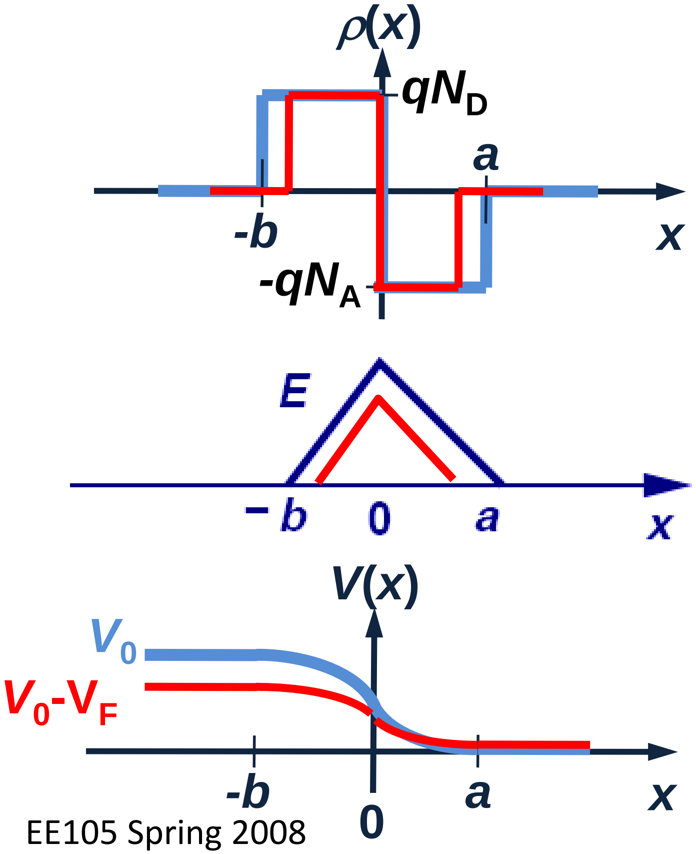
Effect of Applied Voltage

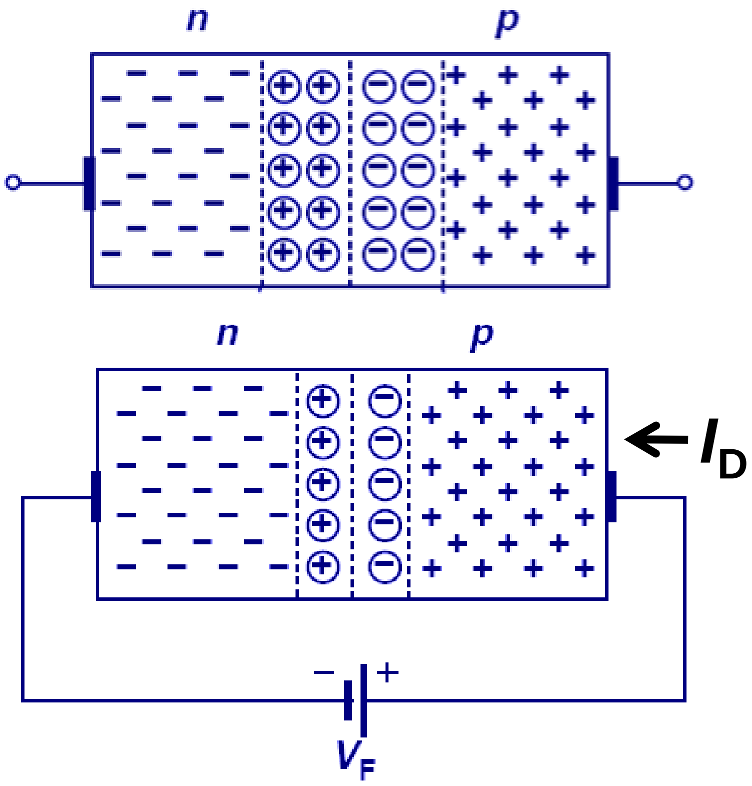
- The quasi-neutral N-type and P-type regions have low resistivity, whereas the depletion region has high resistivity.
  - Thus, when an **external voltage V_D** is applied across the diode, almost all of this voltage **is dropped across the depletion region**. (Think of a voltage divider circuit.)
-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



PN Junction under Forward Bias

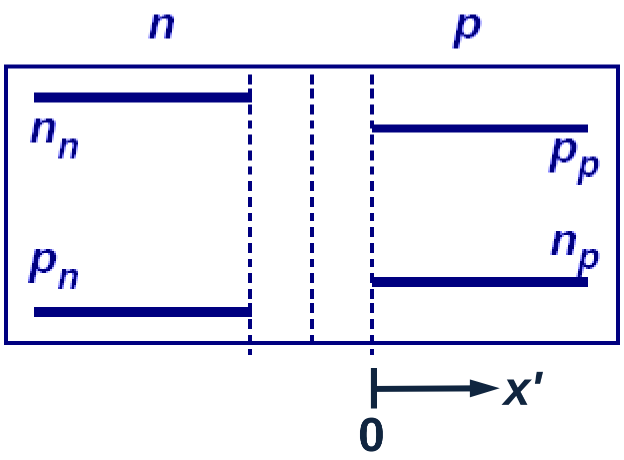
- A forward bias decreases the potential drop across the junction. As a result, the magnitude of the electric field decreases and the width of the depletion region narrows.

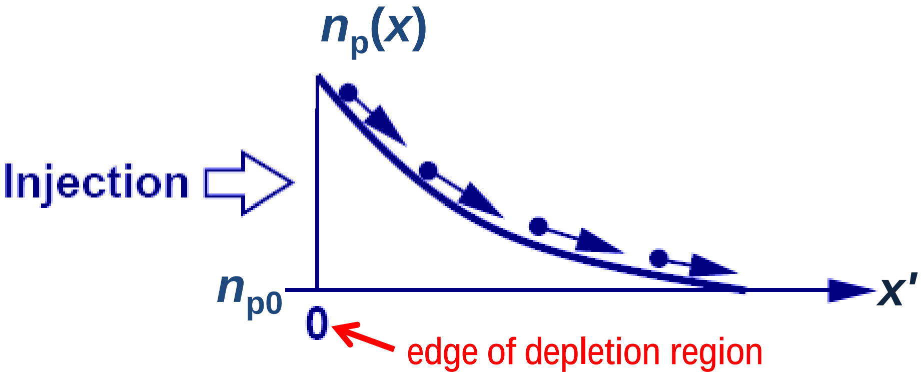




Minority Carrier Injection under Forward Bias

- 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.





Equilibrium 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 (Δp_n, Δn_p)** of minority carriers in the quasi-neutral regions, under forward bias.

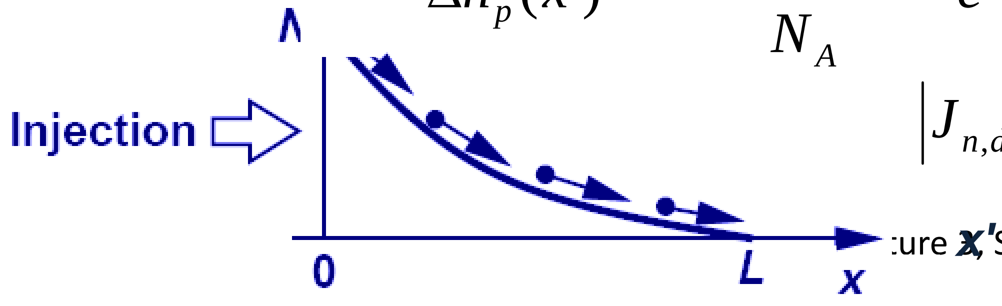
- Within the quasi-neutral regions, the excess minority-carrier concentrations decay exponentially with distance from the depletion region, to zero:

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

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

Notation:

$L_n \equiv$ electron diffusion length (cm)



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

Diode Current under Forward Bias

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

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

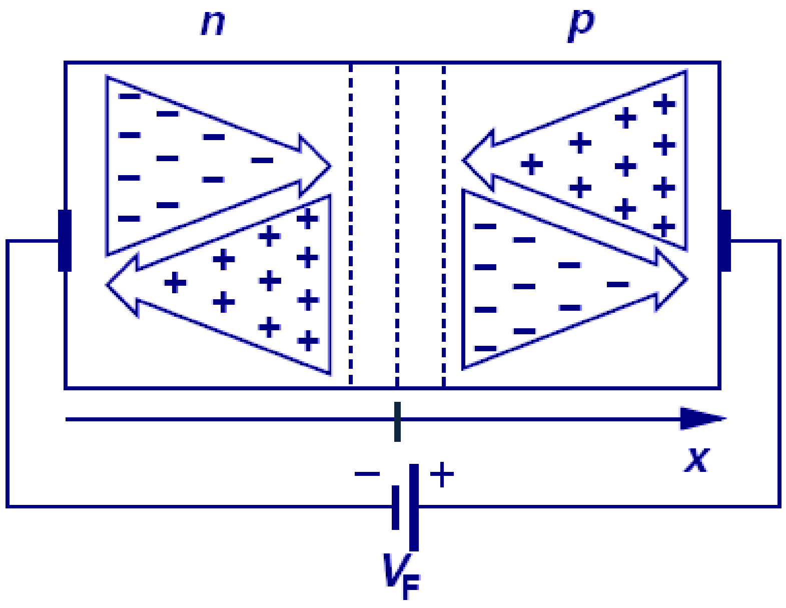
- Assuming that the diffusion current components are constant within the depletion region (*i.e.* no recombination occurs in the depletion region):

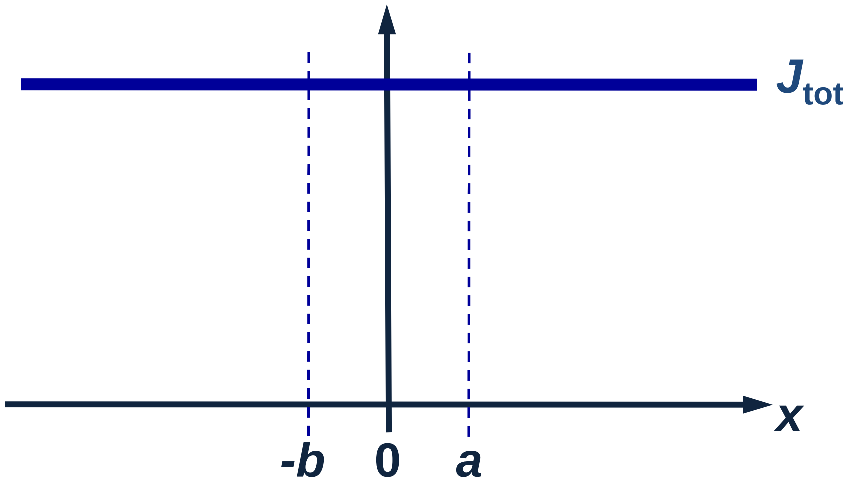
$$J_{n,diff}\Big|_{x=0} = \frac{qD_n n_i^2}{N_A L_n}\left(e^{V_D/V_T} - 1\right) \qquad J_{p,diff}\Big|_{x=0} = \frac{qD_p n_i^2}{N_D L_p}\left(e^{V_D/V_T} - 1\right)$$

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

Current Components under Forward Bias

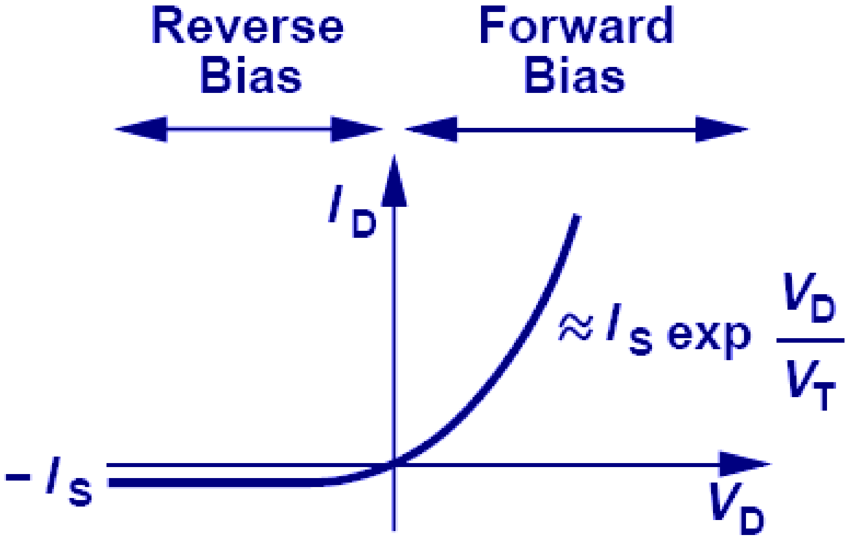
- For a fixed bias voltage, J_{tot} is constant throughout the diode, but $J_n(x)$ and $J_p(x)$ vary with position.





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.



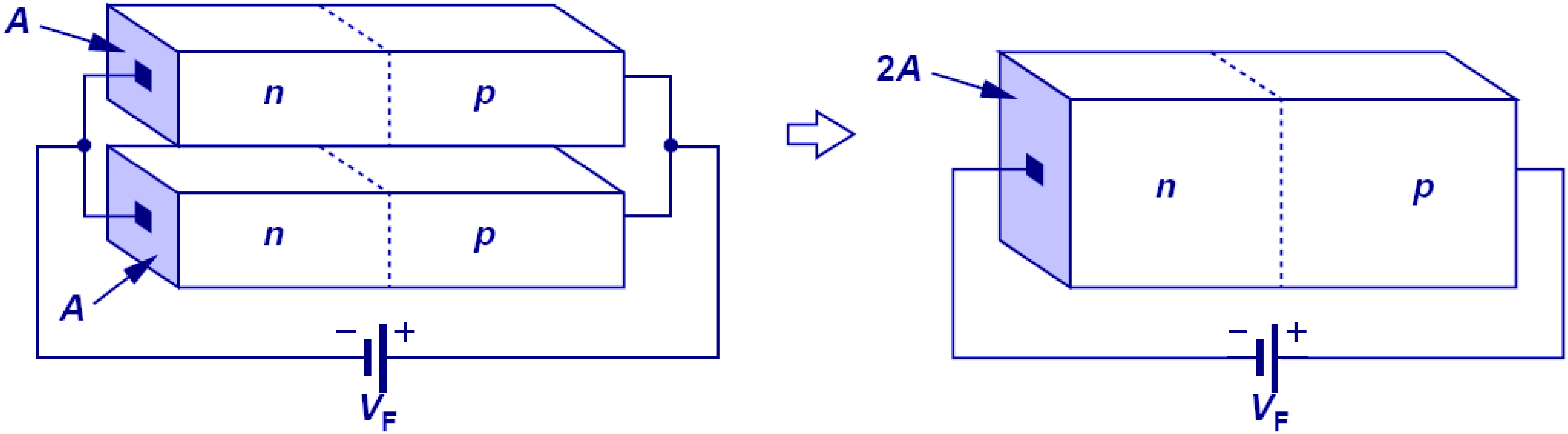
<u>"Ideal diode" equation</u>:

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

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

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.



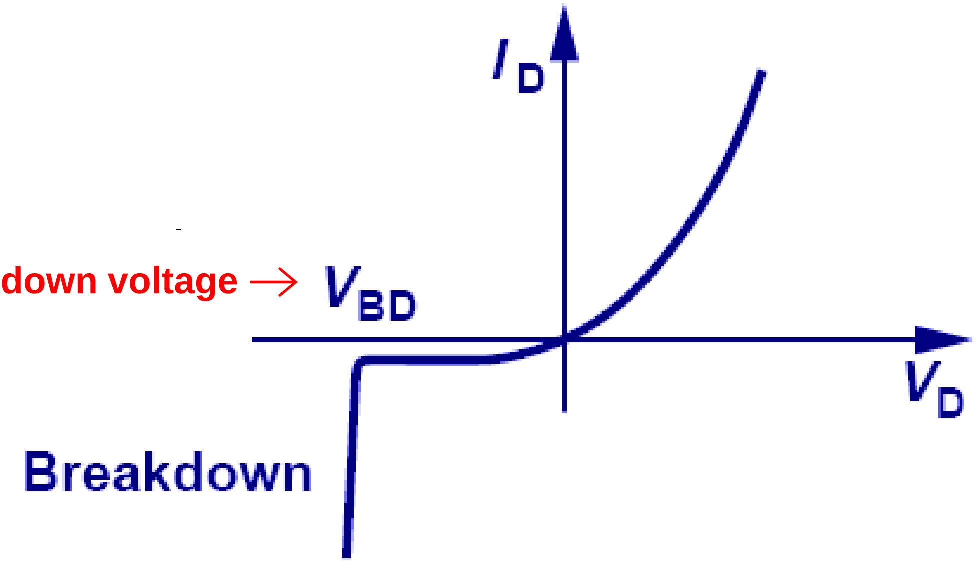
Diode Saturation Current I_S

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

- 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/μm^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, $I_S \cong Aqn_i^{\,2}\left(\frac{D_n}{L_n N_A}\right)$

Reverse Breakdown

- As the reverse bias voltage increases, the electric field in the depletion region increases. Eventually, it can become large enough to cause the junction to break down so that a large reverse current flows:

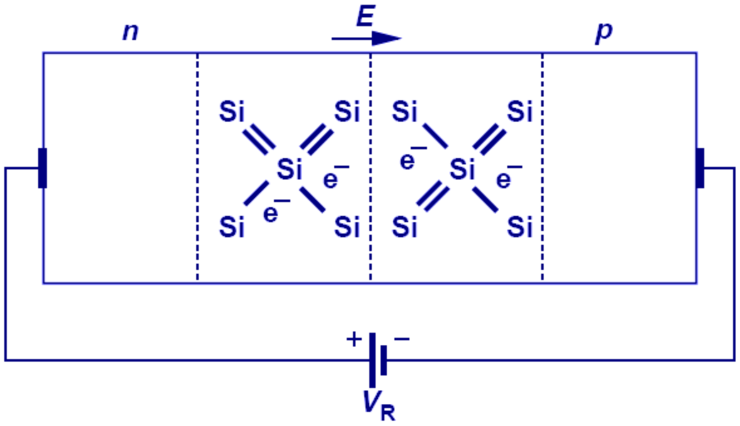


breakdown voltage →

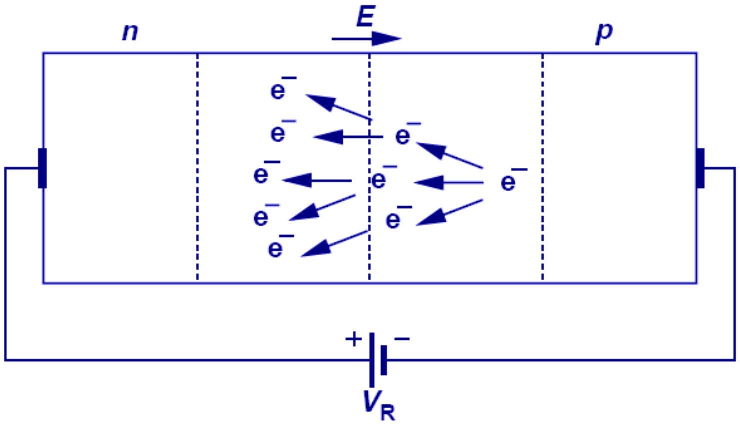
Reverse Breakdown Mechanisms

a) ***Zener breakdown*** occurs when the electric field is sufficiently high to pull an electron out of a covalent bond (to generate an electron-hole pair).

b) ***Avalanche breakdown*** occurs when electrons and holes gain sufficient kinetic energy (due to acceleration by the E-field) in-between scattering events to cause electron-hole pair generation upon colliding with the lattice.

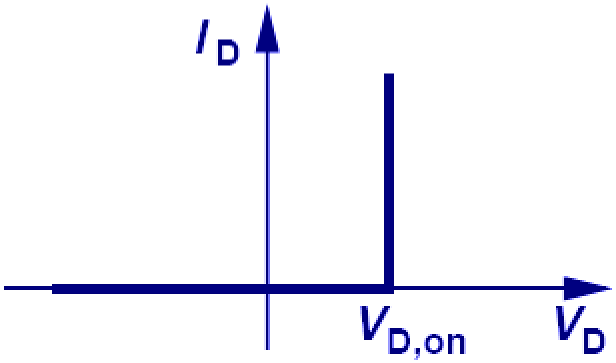


(a)



(b)

Constant-Voltage Diode Model



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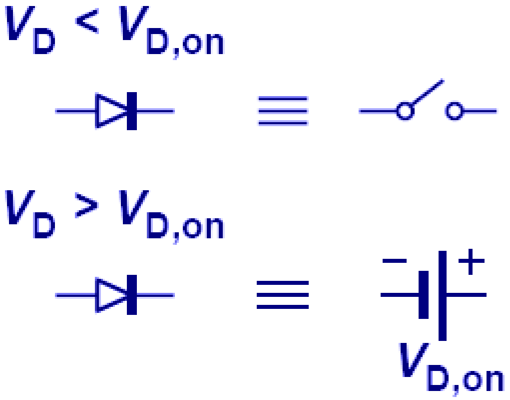
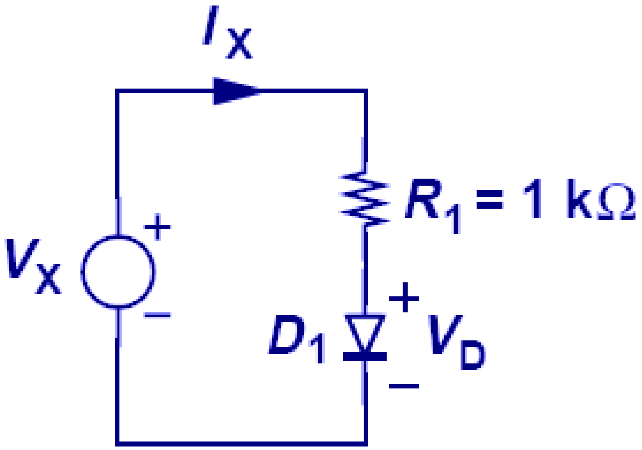


(b)

- If $V_D < V_{D,on}$: The diode operates as an open circuit.
- If $V_D \geq V_{D,on}$: The diode operates as a constant voltage source with value $V_{D,on}$.

Example: Diode DC Bias Calculations



$$V_X = I_X R_1 + V_D \cong I_X R_1 + V_T \ln \frac{I_X}{I_S}$$

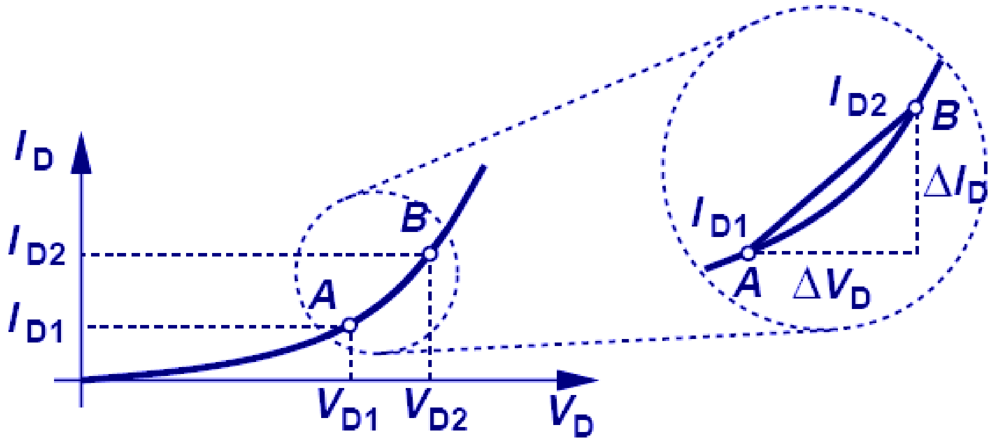
$$I_X = 2.2\text{mA for } V_X = 3\text{V}$$

$$I_X = 0.2\text{mA for } V_X = 1\text{V}$$

- This example shows the simplicity provided by a constant-voltage model over an exponential model.
- Using an exponential model, iteration is needed to solve for current. Using a constant-voltage model, only linear equations need to be solved.

Small-Signal Analysis

- Small-signal analysis is performed at a DC bias point by perturbing the voltage by a small amount and observing the resulting linear current perturbation.
  - If two points on the *I*-*V* curve are very close, the curve in-between these points is well approximated by a straight line:



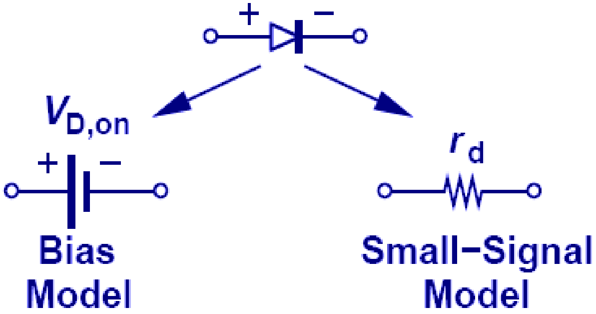
$$\frac{\Delta I_D}{\Delta V_D} \cong \left.\frac{dI_D}{dV_D}\right|_{V_D=V_{D1}}$$

$$= \frac{I_s}{V_T} e^{V_{D1}/V_T} \cong \frac{I_{D1}}{V_T}$$

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots$$

Diode Small-Signal Model

- Since there is a linear relationship between the small-signal current and small-signal voltage of a diode, the diode can be viewed as a linear resistor when only small changes in voltage are of interest.



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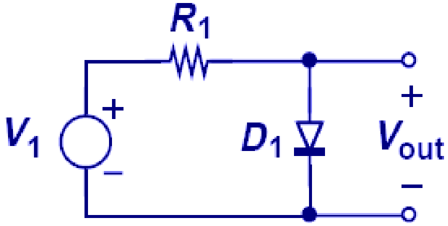

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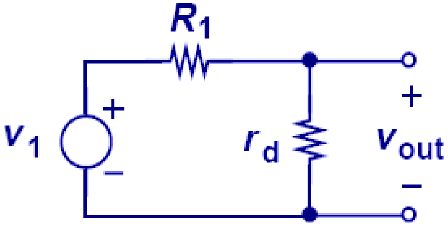


(c)

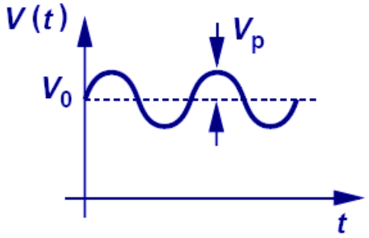
Small-Signal Resistance
(or Dynamic Resistance)

$$\boxed{r_d = \frac{V_T}{I_D}}$$

Small Sinusoidal Analysis

- If a sinusoidal voltage with small amplitude is applied in addition to a DC bias voltage, the current is also a sinusoid that varies about the DC bias current value.

$$V_D(t) = V_0 + V_p \cos \omega t$$



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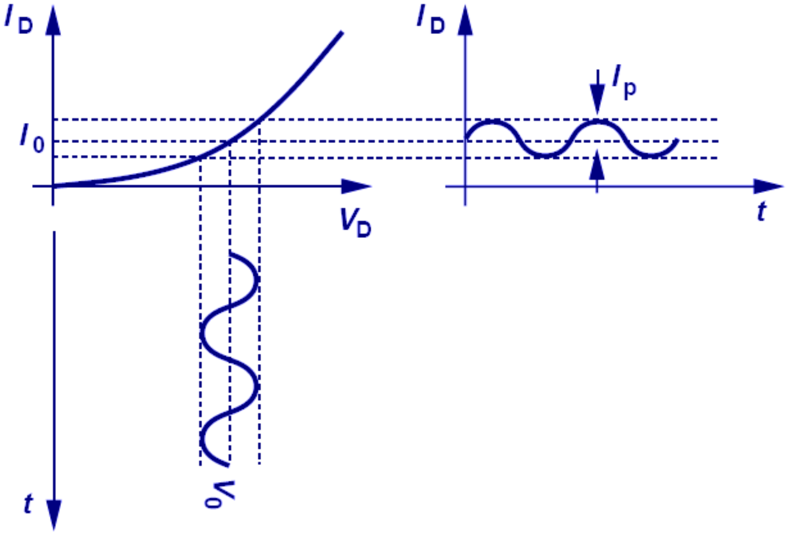
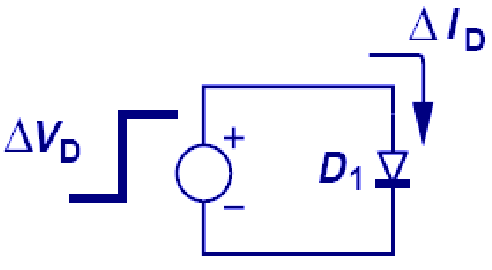


(b)

$$I_D(t) = I_0 + I_p \cos \omega t \cong I_s \exp\left(\frac{V_0}{V_T}\right) + \frac{V_p \cos \omega t}{(V_T / I_0)}$$

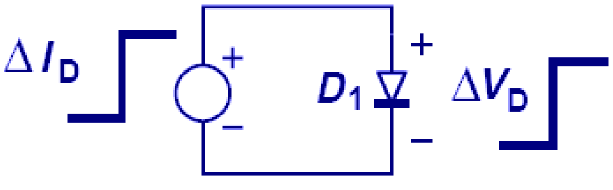
Cause and Effect

- In (a), voltage is the cause and current is the effect. In (b), current is the cause and voltage is the effect.



(a)

$$\Delta I_D = \frac{\Delta V_D}{r_d} = \Delta V_D \frac{I_{D1}}{V_T}$$



(b)

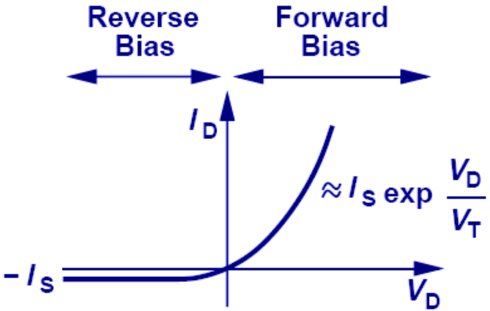
$$\Delta V_D = \Delta I_D \, r_d = \Delta I_D \frac{V_T}{I_{D1}}$$

Summary: PN-Junction Diode *I-V*

- Under forward bias, the potential barrier is reduced, so that carriers flow (by diffusion) across the junction
  - Current increases exponentially with increasing forward bias
  - The carriers become minority carriers once they cross the junction; as they diffuse in the quasi-neutral regions, they recombine with majority carriers (supplied by the metal contacts)

"injection" of minority carriers

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



- Under reverse bias, the potential barrier is increased, so that negligible carriers flow across the junction
  - If a minority carrier enters the depletion region (by thermal generation or diffusion from the quasi-neutral regions), it will be swept across the junction by the built-in electric field

"collection" of minority carriers