Introduction to Diodes

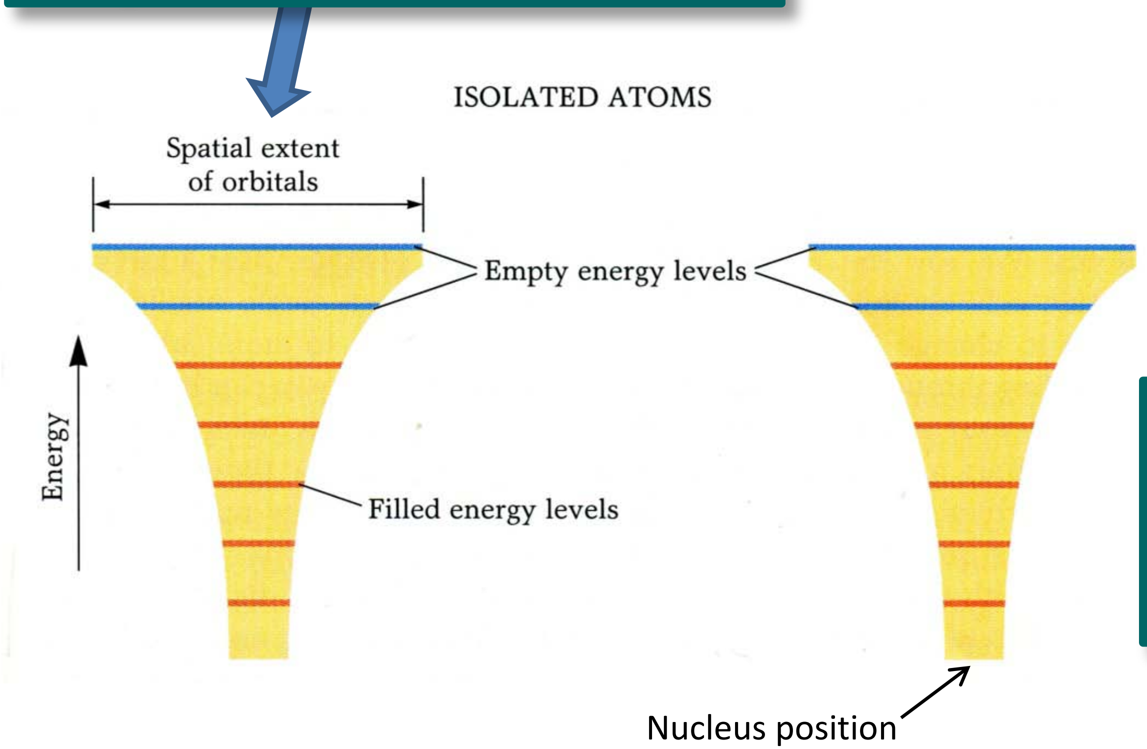
Lecture notes: page 2-1 to 2-19

Sedra & Smith (6th Ed): Sec. 3.* and 4.1-4.4
Sedra & Smith (5th Ed): Sec. 3.7* and Sec. 3.1-3.4

* Includes details of pn junction operation which is not covered in this course

Energy levels in an atom

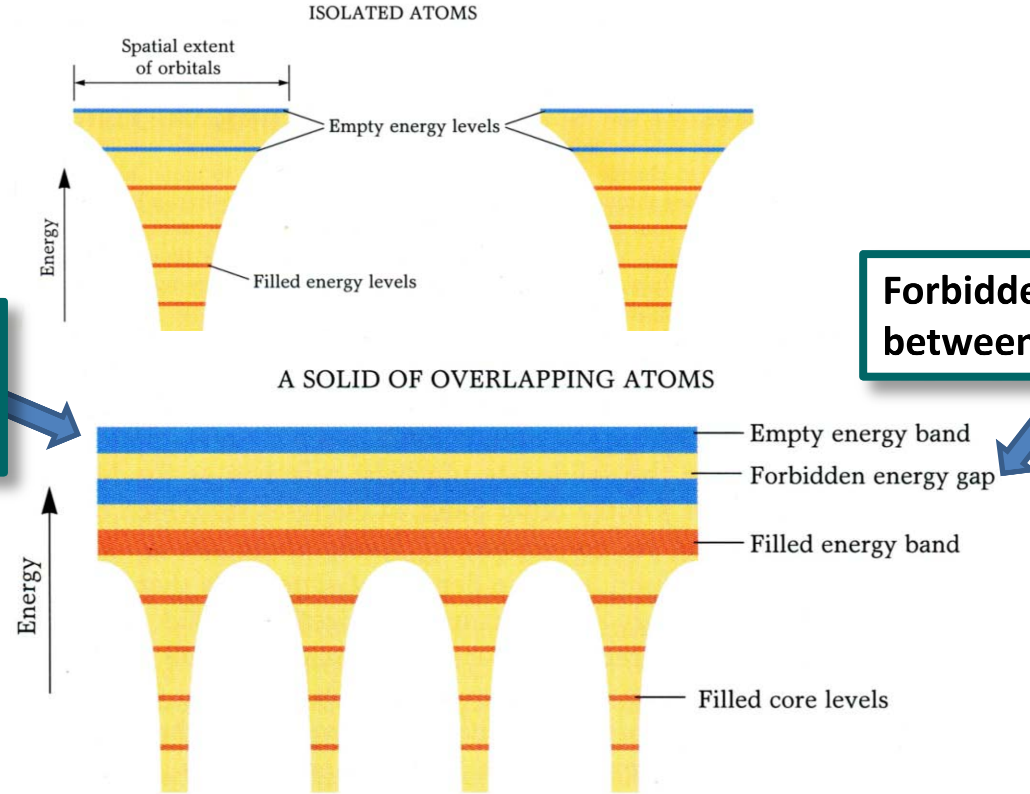
The larger the energy level, the larger is the spatial extent of electron orbital.



- **Discrete energy levels!**
- **Each energy level can be filled with a finite number of electrons.**
- **Lowest energy levels are filled first.**

- Electrons in the last filled energy level are called "valance" electrons and are responsible for the chemical properties of the material.

Energy Bands in Solids



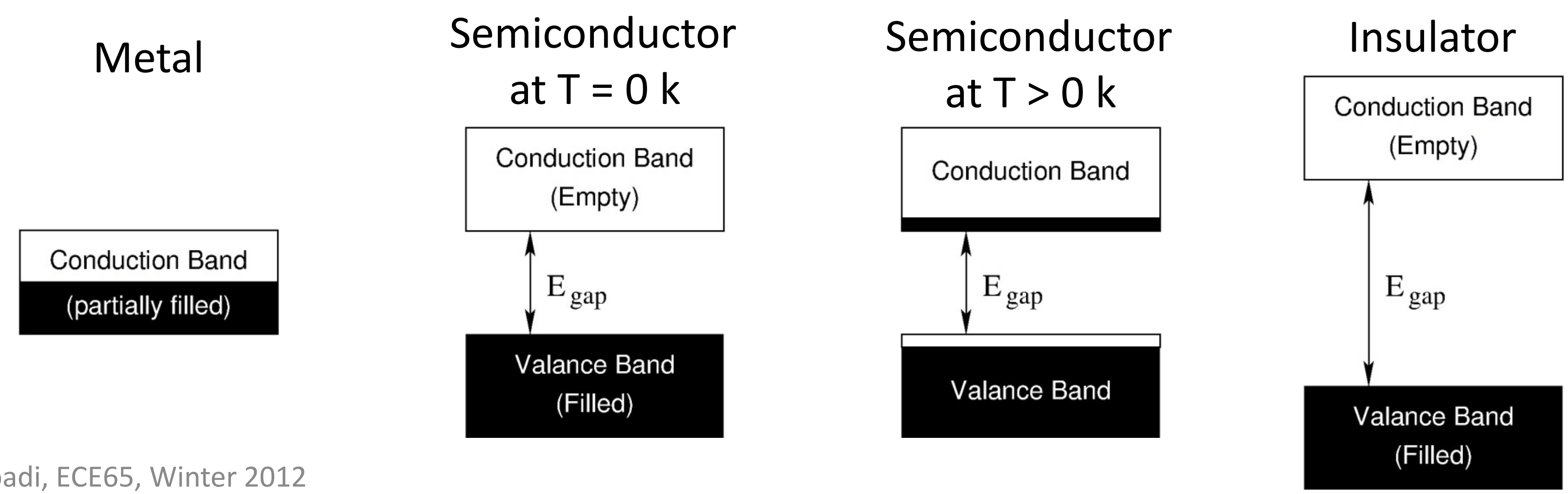
For small inter-distance between ions, energy levels become energy bands.

Forbidden energy gaps between energy bands.

- **Conduction band**: the lowest energy band with electrons NOT tied to the atom.
- **Valance band:** the highest energy band with electrons tied to the atom.
- **Band-Gap** is the energy difference between the top of valance band and the bottom of conduction band

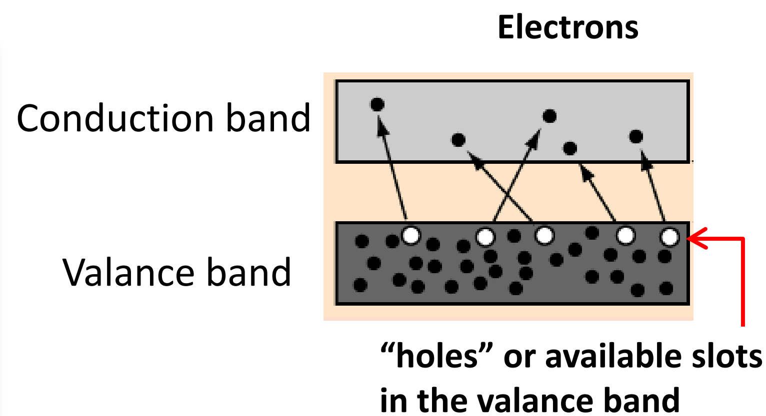
Difference between conductors, semiconductors and insulators

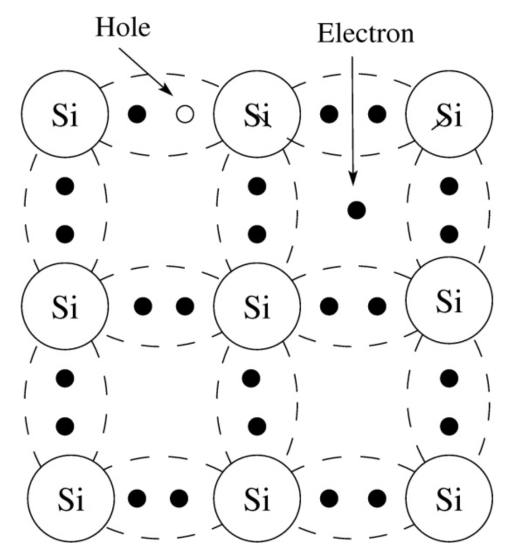
- In a metal, the conduction band is partially filled. These electron can move easily in the material and conduct heat and electricity (Conductors).
- In a semi-conductor at 0 k the conduction band is empty and valance band is full. The band-gap is small enough that at room temperature some electrons move to the conduction band and material conduct electricity.
- An insulator is similar to a semiconductor but with a larger band-gap. Thus, at room temperature very few electrons are in the conduction band.



Electric current in a semiconductor is due to electrons and "holes"

- At $T > 0$ k, some electrons are promoted to the conduction bands.
- A current flows when electrons in the conduction band move across the material (e.g., due to an applied electric field).
- A current also flows when electrons in the valance band jump between available slots in the valance bands (or "holes").
  - An electron moving to the left = a hole moving to the right!
  - We call this is a "hole" current to differentiate this current from that due to conduction band electrons.

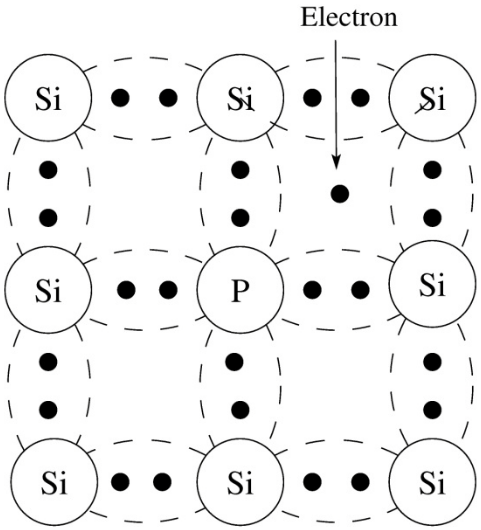




Pure Si Crystal

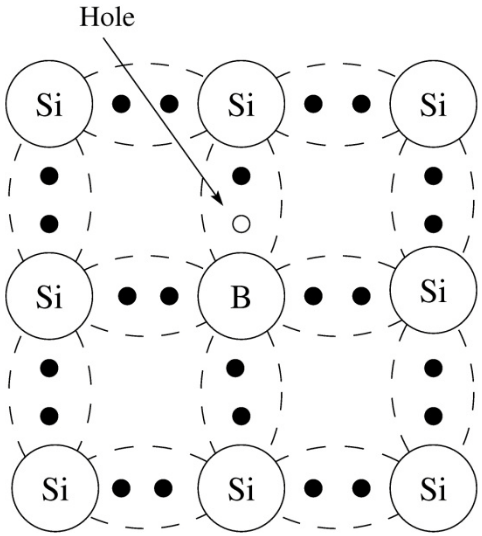
Doping increases the number of charge carriers

Doped n-type Semiconductor



- Donor atom (P doping) has an extra electron which is in the conduction band.
- Charge Carriers:
  - Electrons due to donor atoms
  - Electron-hole pairs due to thermal excitation
  - e: majority carrier, h: minority carrier

Doped p-type Semiconductor



- Acceptor atom (B doping) has one less electrons: a hole in the valance band.
- Charge Carriers:
  - Holes due to acceptor atoms
  - Electron-hole pairs due to thermal excitation
  - h: majority carrier, e: minority carrier

Electric current due to the motion of charge carriers

- **Drift Current:** An electric field forces charge carriers to move and establishes a drift current:

$$I_{drift} = Aqn\mu E$$

- **Diffusion Current:** As charge carrier move randomly through the material, they diffuse from the location of high concentration to that of a lower concentration, setting up a diffusion current:

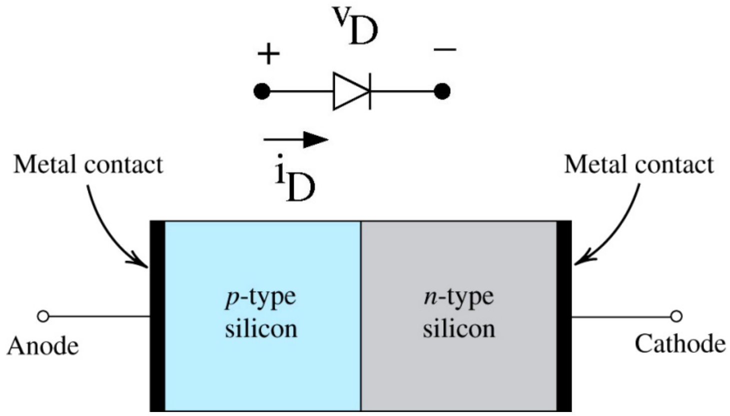
$$I_{diffusion} = -A|q|D\frac{dn}{dx}$$

- **Einstein Relationship:**

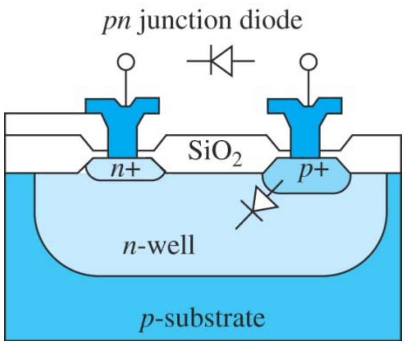
$$\frac{D}{\mu} = V_T = \frac{kT}{|q|}$$

  - V_T is called the Thermal voltage or volt-equivalent of temperature
  - $V_T = 26$ mV at room temperature

Junction diode



Simplified physical structure



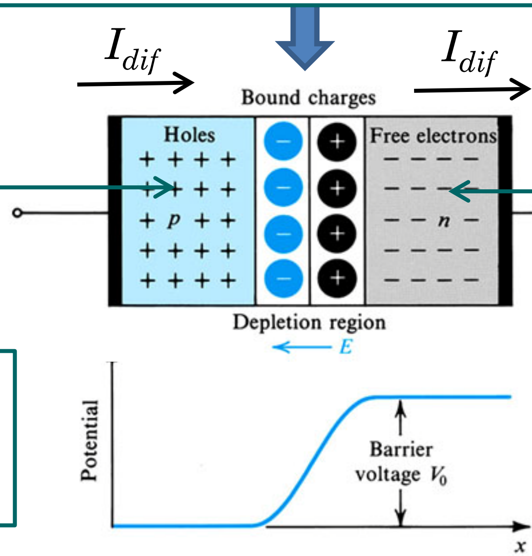
Construction on a CMOS chip

A pn junction with open terminals (<u>excluding minority carriers</u>)

High concentration of h on the p side
Holes diffuse towards the junction

High concentration of e on the n side
Electrons diffuse towards the junction

Holes from the p side and electrons from the n side combine at the junction, forming a depletion region



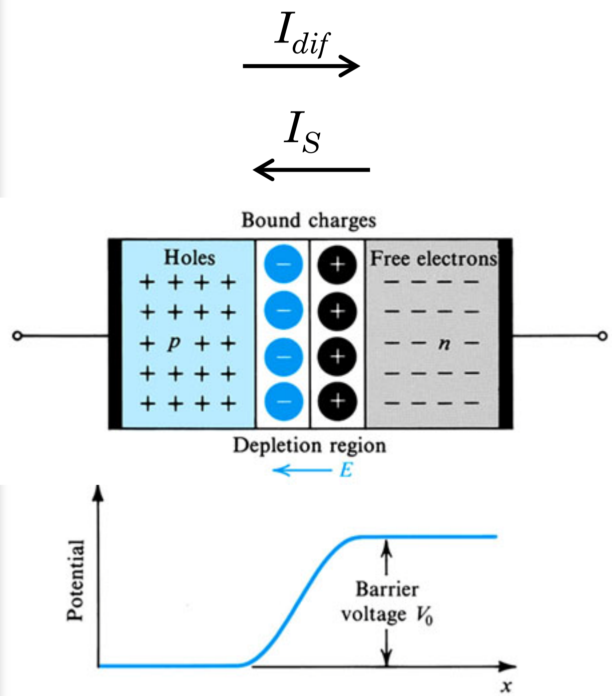
p side is negatively charged because it has lost holes.

n side is positively charged because it has lost electrons.

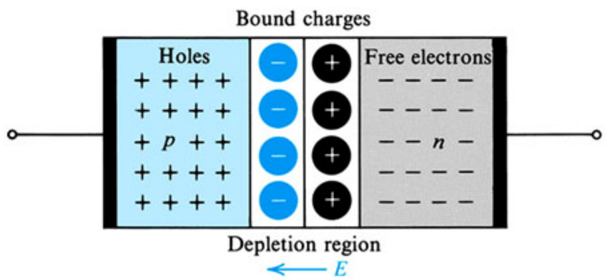
- A potential is formed which inhibits further diffusion of electron and holes (called junction built-in voltage)

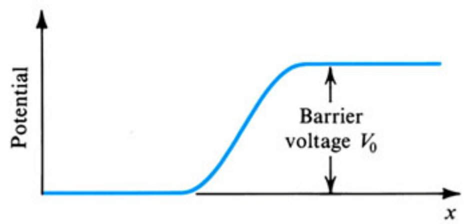
A pn junction with open terminals (<u>including minority carriers</u>)

- Thermally-generated minority carriers on the n side (holes) move toward the depletion region, and are swept into the p side by the potential where the combine with electrons. (similar process for minority carriers on the p side). This sets up a drift current, I_S.
- To preserve charge neutrality, a non-zero $I_{dif} = I_S$ should flow (height of potential is slightly lower).
- **I_{dif} scales exponentially with changes in the voltage barrier.**
- **I_S is independent of the voltage barrier but is a sensitive function of temperature.**



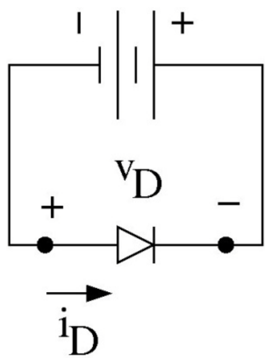
pn Junction with an applied voltage





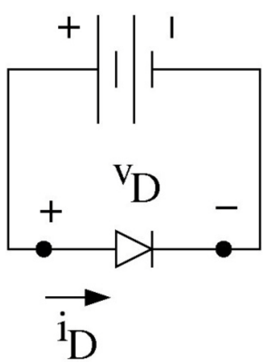
Reverse-Bias:

- Height of the barrier is increased, reducing I_{dif}
- I_{dif} approaches zero rapidly, with $i_D \approx I_S$
- A very small negative i_D !



Forward-Bias:

- Height of the barrier is decreased, increasing I_{dif}
- I_{dif} increases rapidly with v_D leading to $i_D \approx I_{dif}$
- A very large positive i_D !



Diode iv characteristics equation

$$i_D = I_S\left(e^{v_D/nV_T} - 1\right)$$

$\boldsymbol{I_S}$: Reverse Saturation Current (10^{-9} to 10^{-18} A)

$\boldsymbol{V_T}$: Volt-equivalent temperature (= 26 mV at room temperature)

$\boldsymbol{n}$: Emission coefficient ($1 \le n \le 2$ for Si ICs)

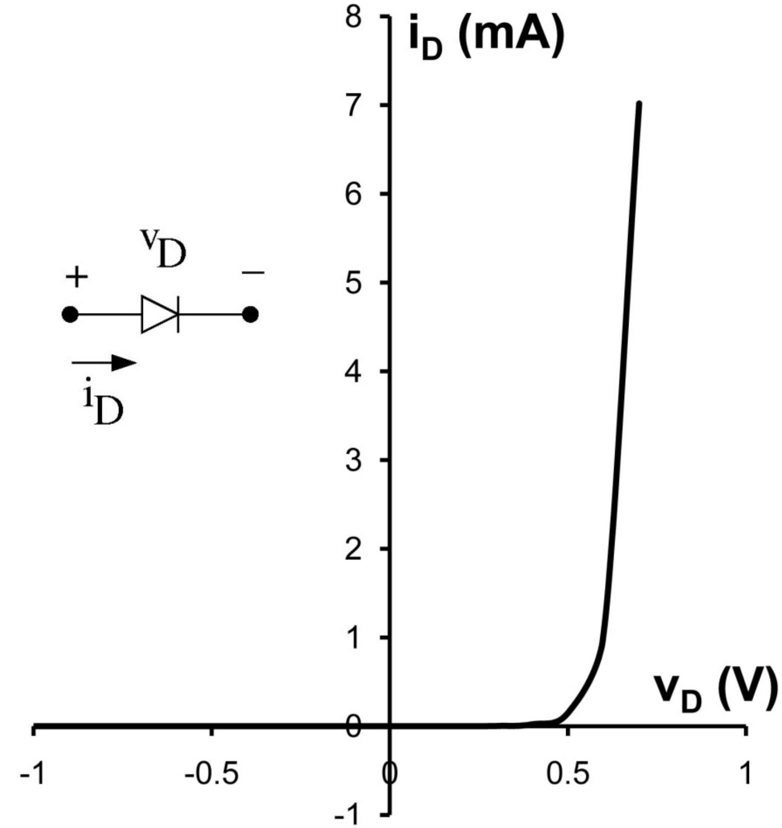
For $|v_D| \ge 3nV_T$

Forward bias: $i_D \approx I_S\, e^{v_D/nV_T}$

Reverse bias: $i_D \approx -I_S$

Sensitive to temperature:

- $\boldsymbol{I_S}$ doubles for every 7°C increase
- $\boldsymbol{V_T} = T/11{,}600$



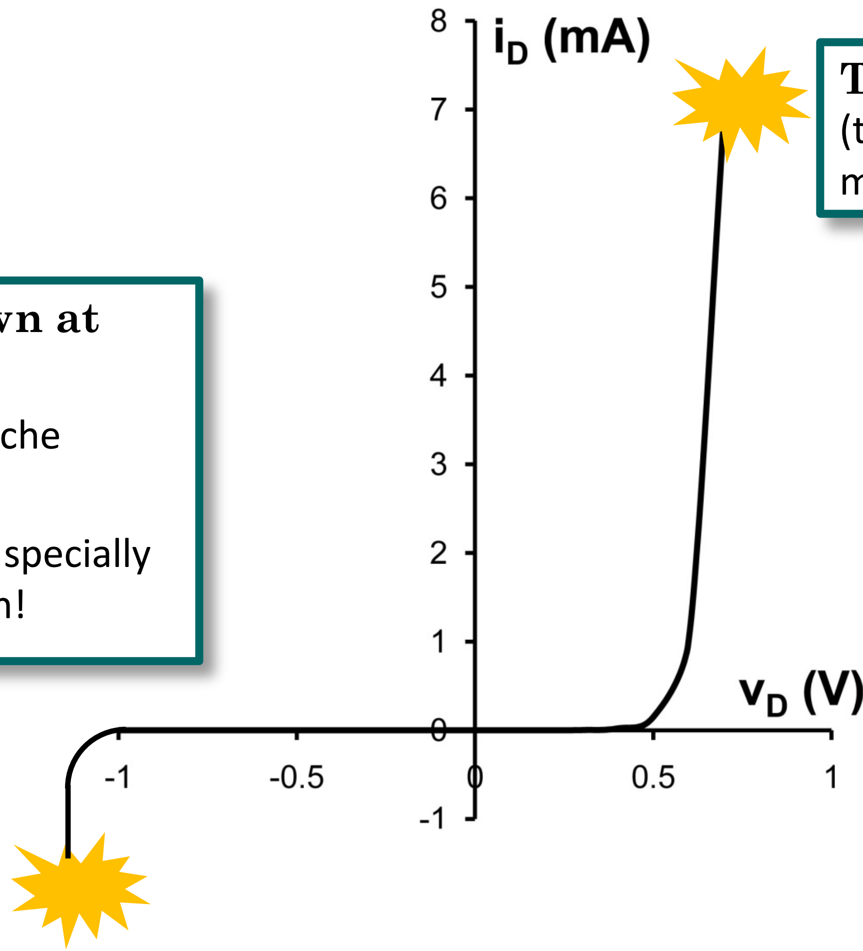
For derivation of diode iv equation, see Sedra & Smith Sec. 3

Diode Limitations

Reverse Breakdown at Zener voltage (V_Z)

(due to Zener or avalanche effects)

Zener diodes are made specially to operate in this region!



Thermal load, $P = i_D v_D$
(typically specified as maximum i_D)

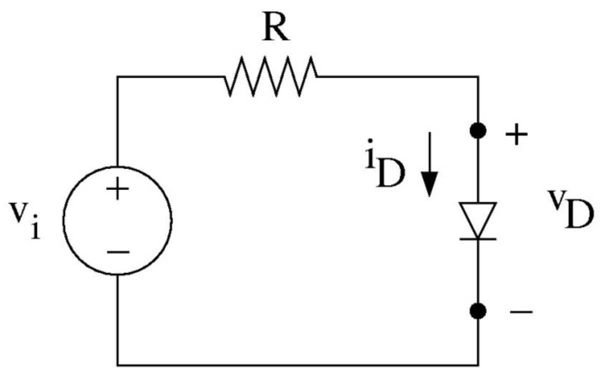
How to solve diode circuits

Diode circuit equations are nonlinear

$$\text{KCL: current } i_D \text{ in all elements}$$

$$\text{KVL: } v_i = R i_D + v_D$$

$$i_D = I_S\left(e^{v_D/nV_T} - 1\right)$$



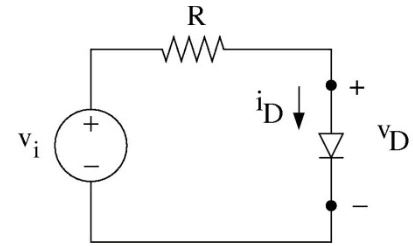
- Two equation in two-unknowns to solve for i_D and v_D
- Non-linear equation: cannot be solved analytically
- **Solution methods:**
  - Numerical (PSpice)
  - Graphical (load-line)
  - Approximation to get linear equations (diode piece-linear model)

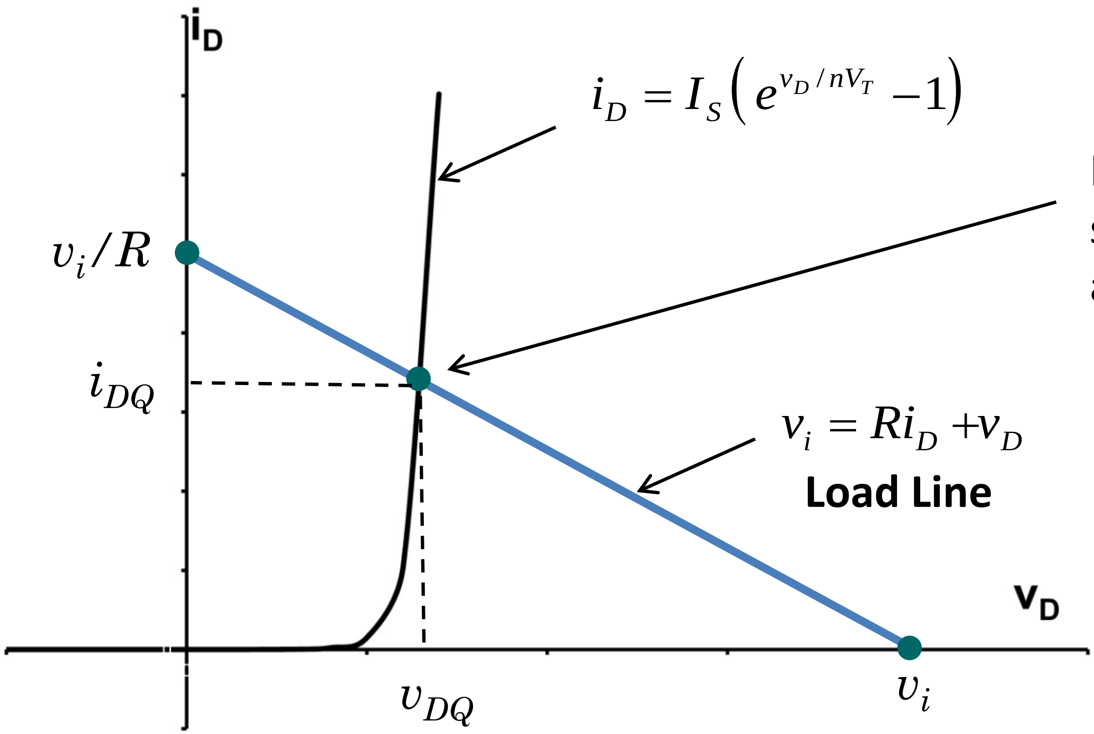
Graphical Solution (Load Line)

$$\text{KCL: current } i_D \text{ in all elements}$$

$$\text{KVL: } v_i = R i_D + v_D$$

$$i_D = I_S \left(e^{v_D / nV_T} - 1 \right)$$

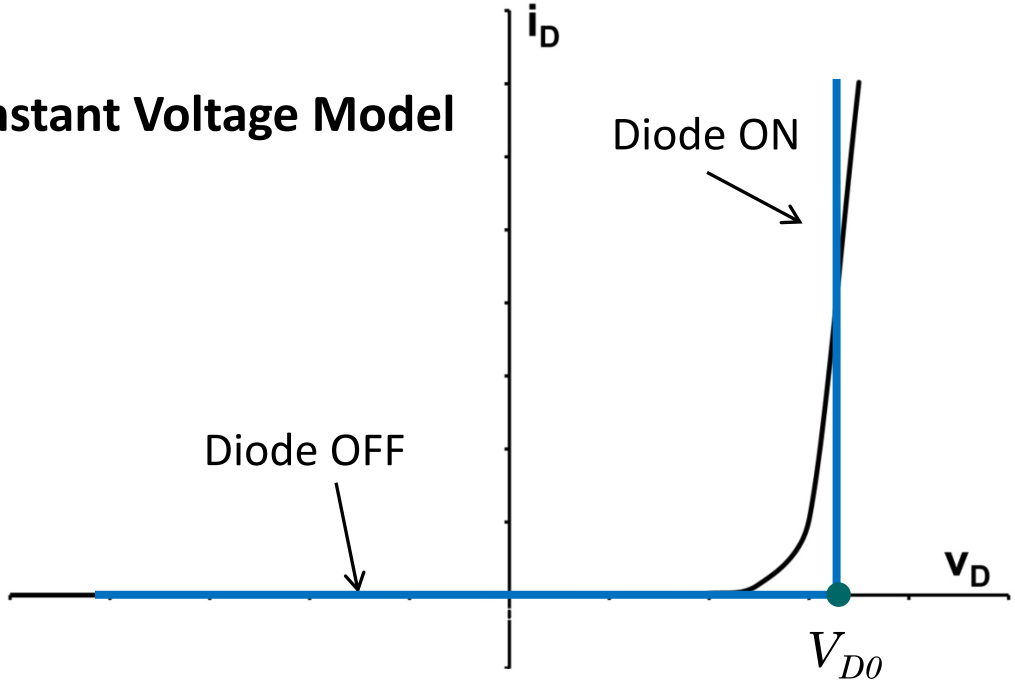




Intersection of two curves satisfies both equations and is the solution

Diode piecewise-linear model: Diode iv is approximated by two lines

Constant Voltage Model

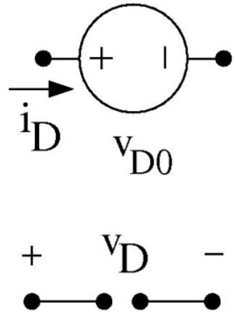


$$\text{Diode ON}: \quad v_D = V_{D0} \quad \text{and} \quad i_D \geq 0$$

$$\text{Diode OFF}: \quad i_D = 0 \quad \text{and} \quad v_D < V_{D0}$$

$$\text{"cut-in" voltage, } V_{D0} = 0.6 - 0.7 \text{ V for Si}$$

Circuit Models:



Recipe for solving diode circuits

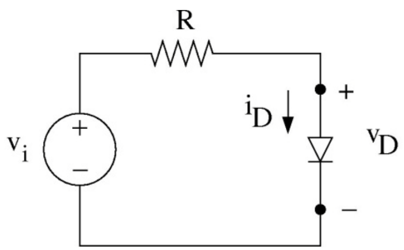
(State of diode is unknown before solving the circuit)

1. Write down all circuit equations and simplify as much as possible
2. Assume diode is one state (either ON or OFF). Use the diode equation for that state to solve the circuit equations and find i_D and v_D
3. Check the inequality associated with that state ("range of validity"). If i_D or v_D satisfy the inequality, assumption is correct. If not, go to step 2 and start with the other state.

NOTE:

- This method works only if we know the values of all elements so that we can find numerical values of i_D and v_D .
- For complicated circuits use diode circuit models.

Example 1: Find i_D and v_D for R = 1k, $v_i = 5$ V, and Si Diode ($V_{D0} = 0.7$ V).



$\text{KCL: current } i_D \text{ in all elements}$

$\text{KVL: } v_i = Ri_D + v_D$

$5 = 10^3\, i_D + v_D$

$\text{Assume diode is OFF: } i_D = 0 \quad \text{and} \quad v_D < V_{D0}$

$5 = 10^3 \times 0 + v_D \ \rightarrow\ v_D = 5\text{ V}$

$v_D = 5\text{ V} > V_{D0} = 0.7\text{ V} \rightarrow \text{Assumption incorrect}$

$\text{Assume diode is ON: } v_D = V_{D0} = 0.7\text{ V} \quad \text{and} \quad i_D \geq 0$

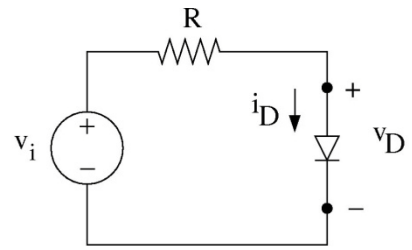
$5 = 10^3\, i_D + 0.7 \ \rightarrow\ i_D = 4.3\text{ mA}$

$i_D = 4.3\text{ mA} > 0 \rightarrow \text{Assumption correct}$

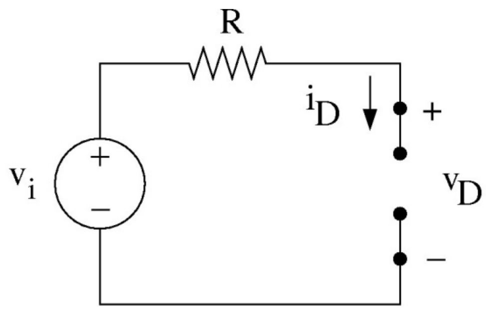
Diode is ON with i_D = 4.3 mA and $v_D = 0.7$ V).

Example 1: Find i_D and v_D for R = 1k, $v_i = 5$ V, and Si Diode ($V_{D0} = 0.7$ V).

Solution with diode circuit models:



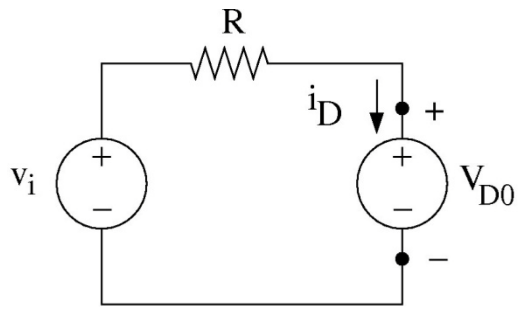
$\text{Diode OFF}: \quad i_D = 0 \quad \text{and} \quad v_D < V_{D0}$



$$5 = 10^3 \times 0 + v_D \;\rightarrow\; v_D = 5\text{ V}$$

$$v_D = 5\text{ V} > V_{D0} = 0.7\text{ V} \;\rightarrow \text{Incorrect!}$$

$\text{Diode ON}: \quad v_D = V_{D0} \quad \text{and} \quad i_D \geq 0$



$$5 = 10^3\, i_D + 0.7 \;\rightarrow\; i_D = 4.3\text{ mA}$$

$$i_D = 4.3\text{ mA} \geq 0 \;\rightarrow \text{Correct!}$$

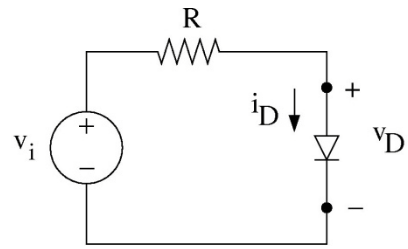
Diode is ON with i_D = 4.3 mA and , $v_D = 0.7$ V.

Parametric solution of diode circuits is desirable!

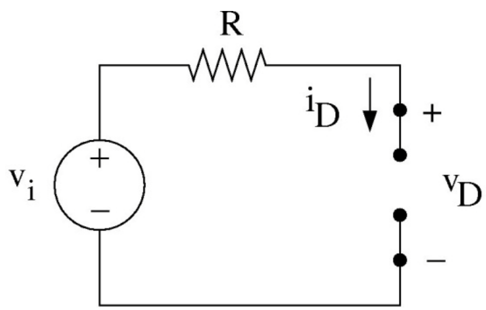
Recipe:

1. Draw a circuit for each state of diode(s).
2. Solve each circuit with its corresponding diode equation.
3. Use the inequality for that diode state (“range of validity”) to find the range of circuit “variable” which leads to that state.

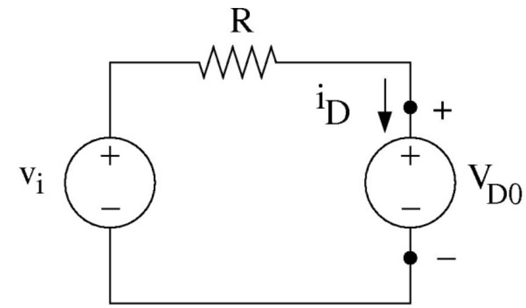
Example 2: Find υ_D in the circuit below for all υ_i .



Diode OFF: $i_D = 0$ and $v_D < V_{D0}$



Diode ON: $v_D = V_{D0}$ and $i_D \geq 0$



Solution

$v_i = \mathrm{R} \times 0 + v_D \rightarrow v_D = v_i$

$v_D < V_{D0} \rightarrow v_i < V_{D0}$

Inequality

$v_D = V_{D0}$

$v_i = \mathrm{R}\, i_D + V_{D0} \rightarrow i_D = (v_i - V_{D0}) / R$

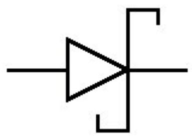
$i_D \geq 0 \rightarrow v_i \geq V_{D0}$

For $v_i \geq V_{D0}$, Diode ON and $v_D = V_{D0}$

For $v_i < V_{D0}$, Diode OFF and $v_D = v_i$

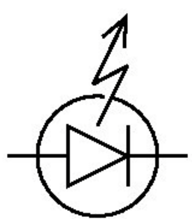
Other types of diodes

Schottky Barrier Diode



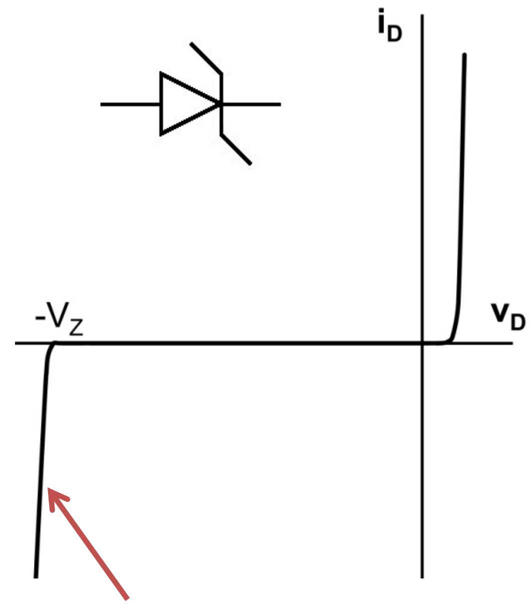
- Large I_S and $V_{D0} \approx 0.3$ V

Light-emitting diode (LED)



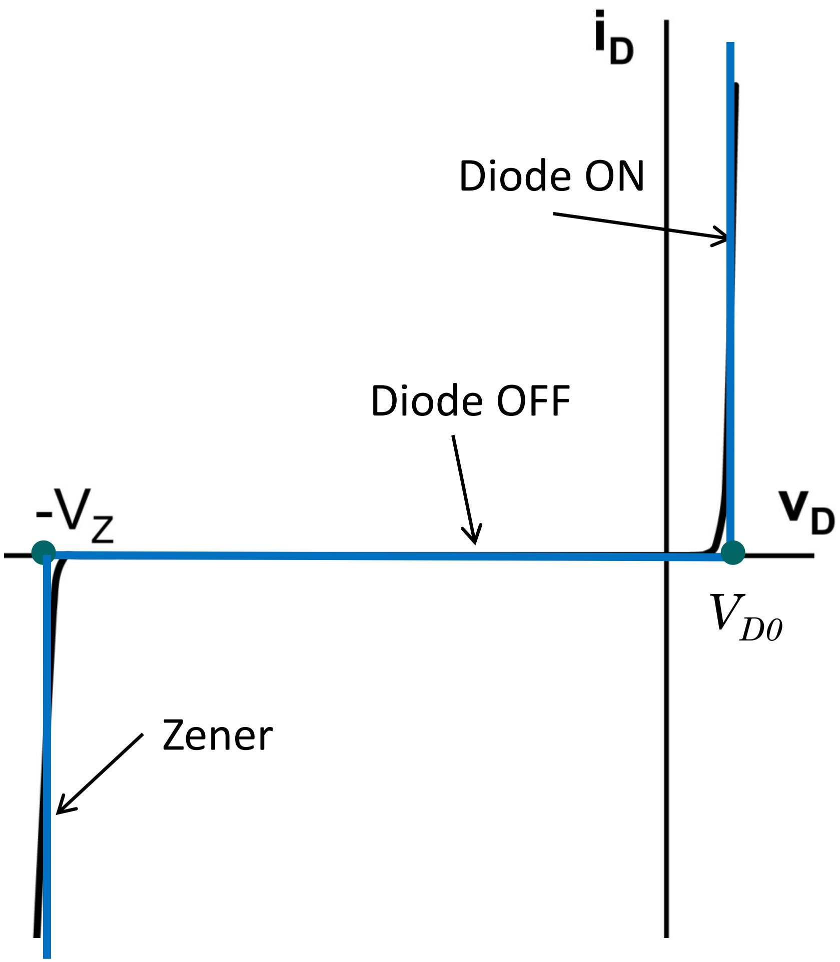
- $V_{D0} = 1.7 - 1.9$ V

Zener Diode



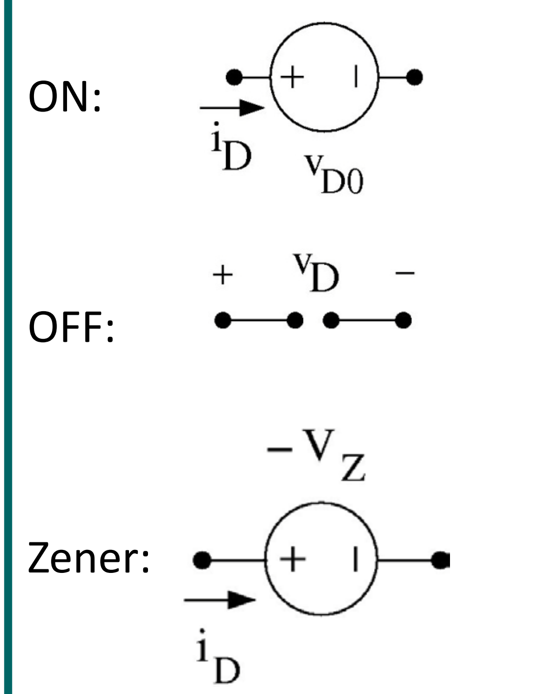
- Made specially to operate in the reverse breakdown region.
- Useful as a “reference” voltage in many circuits.

Zener Diode piecewise-linear model



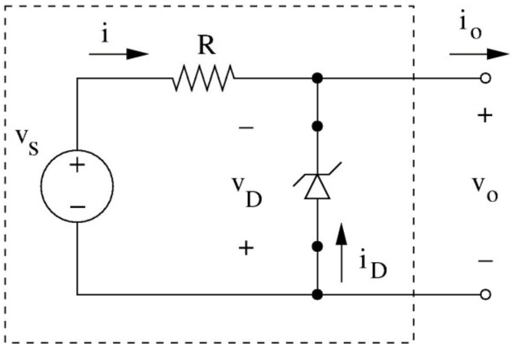
Diode ON:	$v_D = V_{D0}$	and	$i_D \geq 0$
Diode OFF:	$i_D = 0$	and	$v_D < V_{D0}$
Zener:	$v_D = -V_Z$	and	$i_D < 0$

Circuit Models:



Zener diodes are useful in providing reference voltages

Example 3: Find the iv characteristics of the two-terminal circuit below (for $v_o > 0$)



1) Assume diode in Zener region:

$v_D = -V_Z$ and $i_D < 0$

KVL: $v_o = -v_D = V_Z = \text{constant}$ (Independent of i_o !)

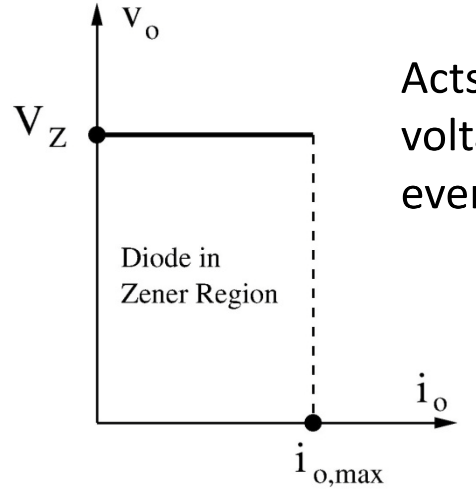
Diode in Zener region for $i_D < 0$

KCL: $i_D = i_o - i$

KVL: $v_s = Ri + V_Z$

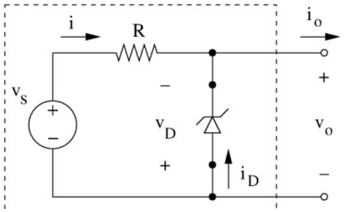
$$i_D = i_o - \frac{v_s - V_Z}{R}$$

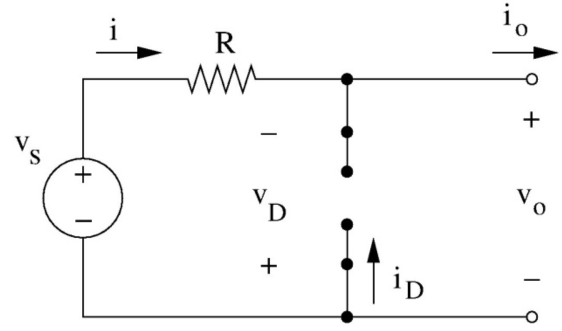
$$i_D < 0 \rightarrow \quad i_o < \frac{v_s - V_Z}{R} = i_{o,\max}$$



Acts as independent voltage sources even if v_s changes!

Example 3 (cont'd)





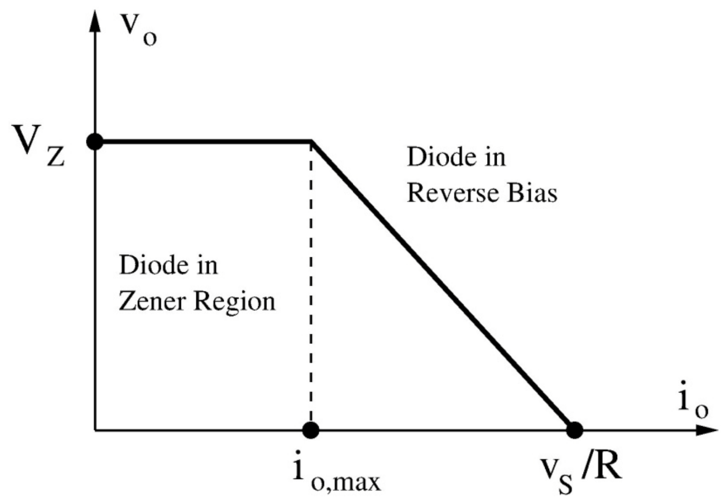
2) Assume diode in reverse bias region:

$i_D = 0 \quad \text{and} \quad -V_Z < v_D < V_{Do}$

KCL: $\quad i = i_o$

KVL: $\quad v_s = Ri_o + v_o$

$v_o = v_s - Ri_o \quad$ (v_o drops as i_o increases)



Diode in reverse-bias region for $-V_Z < v_D < V_{Do}$

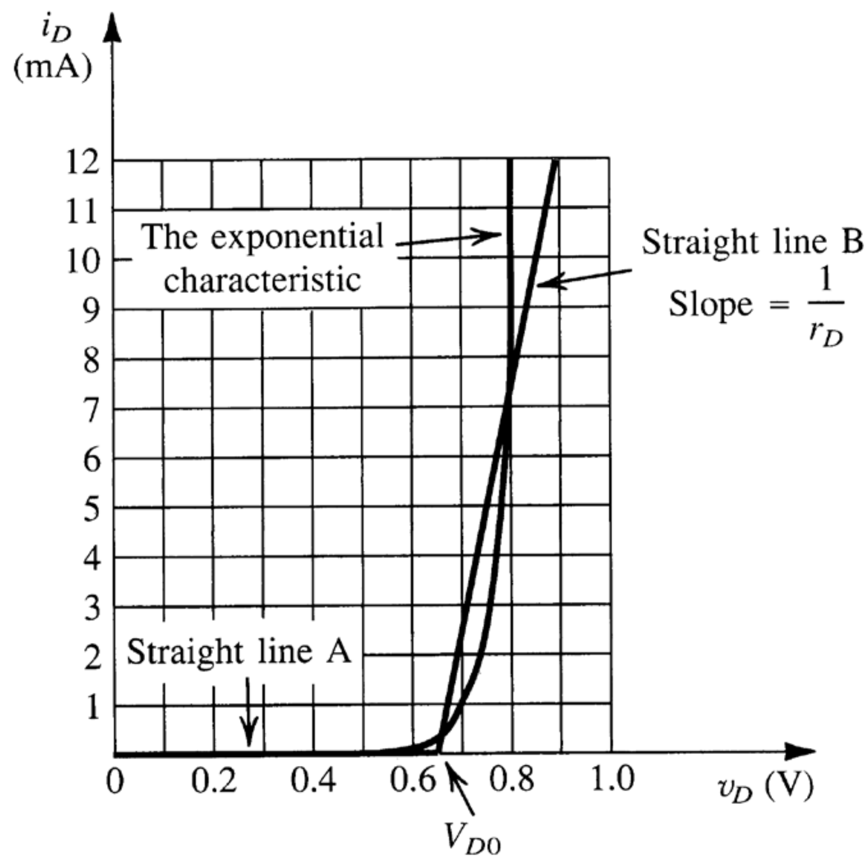
$v_o = -v_D$

$-V_Z < v_D < V_{Do} \rightarrow +V_Z > v_o > -V_{Do}$

$0 \le v_o = v_s - Ri_o < V_Z \rightarrow \dfrac{v_s - V_Z}{R} < i_o \le \dfrac{v_s}{R}$

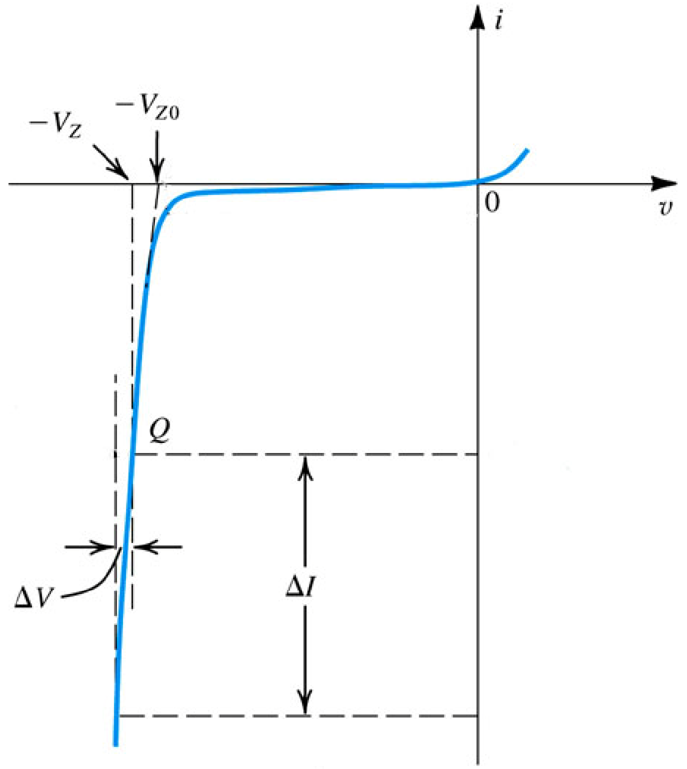
Other piecewise linear models for diode

- Diode iv characteristics can be modeled with a "sloped" line:
  $v_D = V_{D0} + R_D i_D$
  (instead of $v_D = V_{D0}$)
- **Not used often:**
  - Model needs two parameters: (R_D and V_{D0}) and the choice is somewhat arbitrary.
  - Extra work does not justify "increased accuracy"
  - Useful only changes in v_D are important



Other piecewise linear models for diode

- Diode Zener region can also be modeled with a "sloped" line:
  $v_D = -V_{Z0} + R_Z i_D$
  (instead of $v_D = -V_{Z0}$)
- Useful when changes in v_D is important.
  - For example, If we use this model for Example 2, we find*:
    $v_o \approx V_{Z0} - R_Z i_o$
    instead of
    $v_o = V_Z = \text{constant}$



* See lecture notes, page 2-18