CSE 251

Electronic Devices and Circuits

Lecture 7

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Outline

- **Linear** IV characteristics.
- **Non-linear** IV characteristics
- **Piecewise Linear Approximation** of **Non-linear**
- Semiconductor Devices: pn junction Diode
- **pn** junction Diode IV Characteristics: Circuit Model
    - Ideal Diode Model:
    - Constant Voltage Drop (CVD) Model:
    - Constant Voltage Drop with Resistor (CVD+R) Model
    - Exponential Model (Shockley Model):

Current-Voltage (I-V) Characteristics

- I-V characteristic defines the relationship between the **current flow (through), I** and **voltage (across), V** an electronic device or element.

- A tool for understanding the operation of the circuit element.

- The Current-Voltage (I-V) characteristics are found by evaluating the **response** of a device/element under different **excitation** conditions. The behavior of a device depends on the **applied excitation** and can change if the excitation changes.

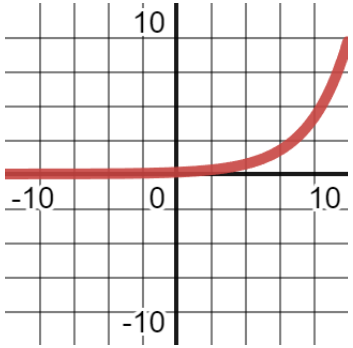
Type of (I-V) Characteristics

1. Linear Devices/Elements: The Current-Voltage relationship is linear i.e. the current through the element is a **linear function** of the applied voltage across it. The relationship can be characterized by:

$$I = kV$$

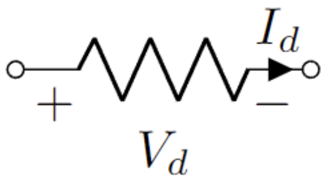
2. Non-Linear Devices/Elements: The Current-Voltage relationship is Non-linear i.e., the current through the element is a **nonlinear function** of the applied voltage across it.

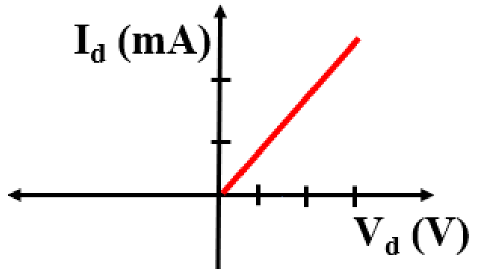
$$I = k\sqrt{V}$$
$$I = kV^2$$
$$I = kV^3$$



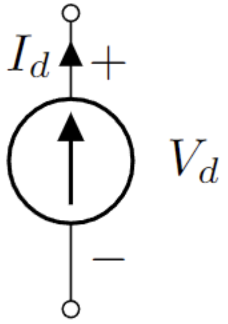
Linear IV Char.

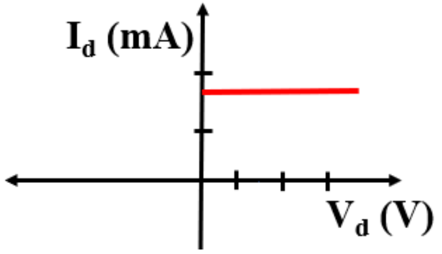
- Resistors



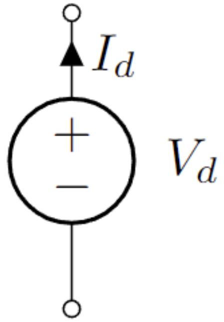


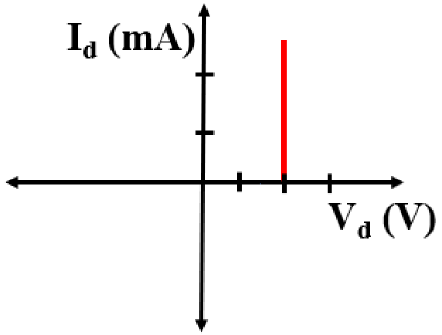
- Current Source





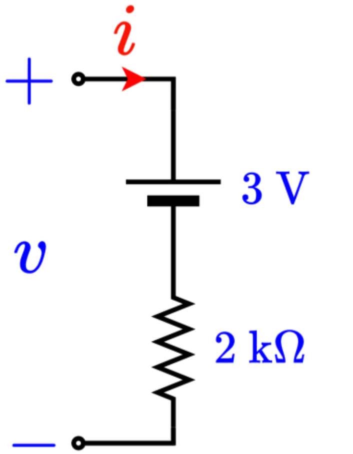
- Voltage Source

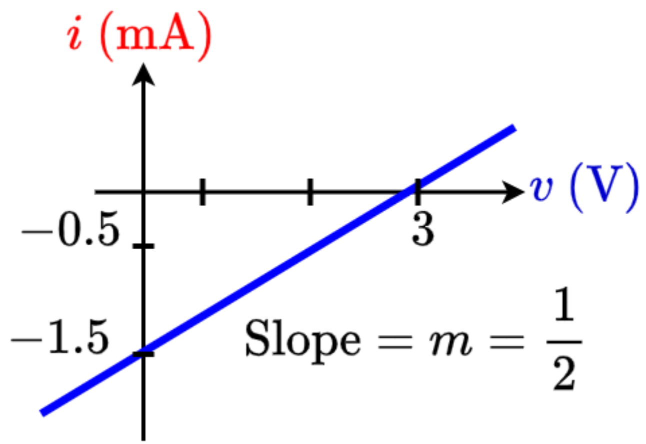




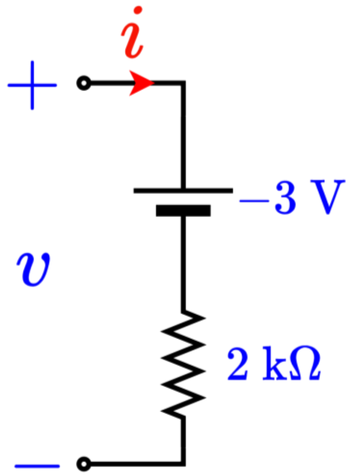
Linear IV Char.

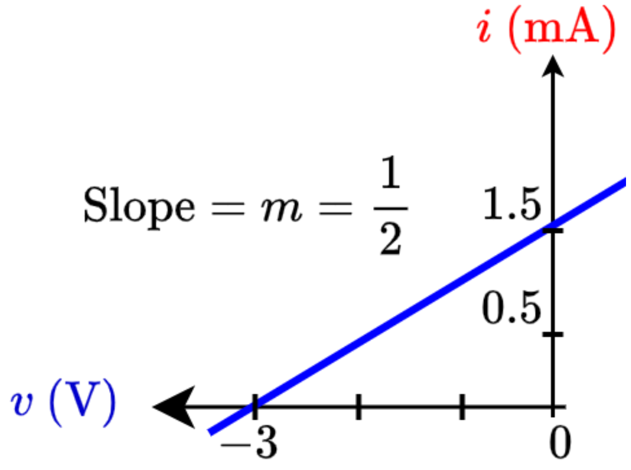
Voltage source in series with a resistor





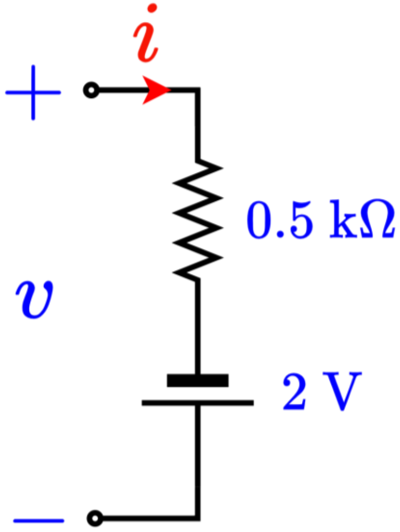
Voltage source in series with a resistor

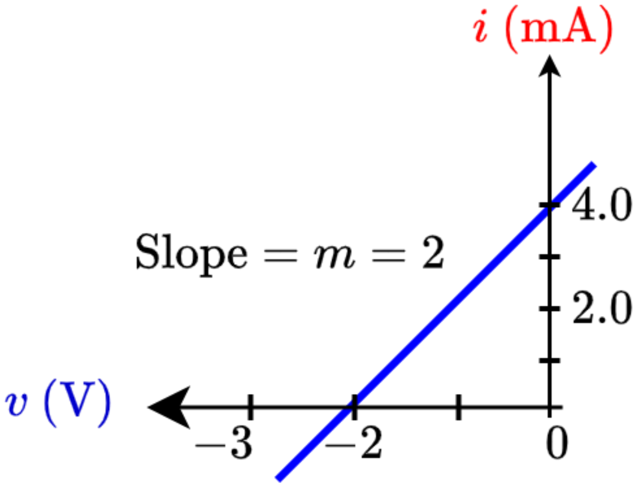




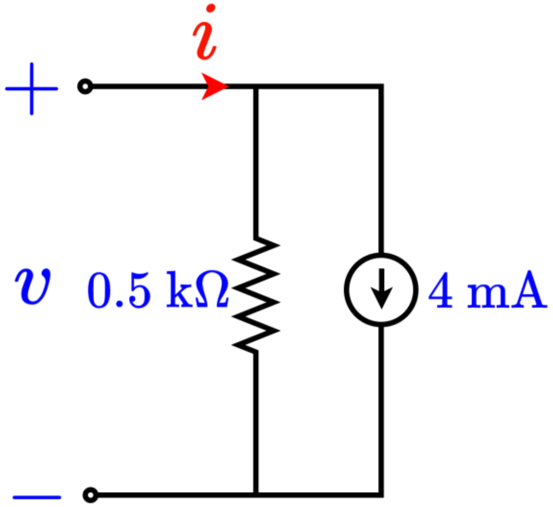
Linear IV Char.

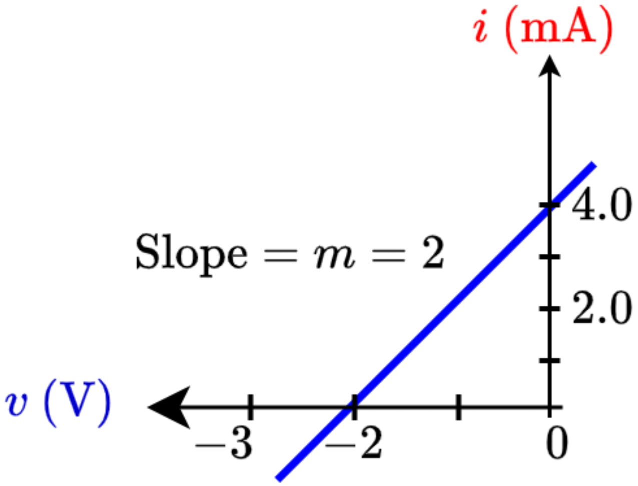
Voltage source in series with a resistor





Current source parallel to a resistor

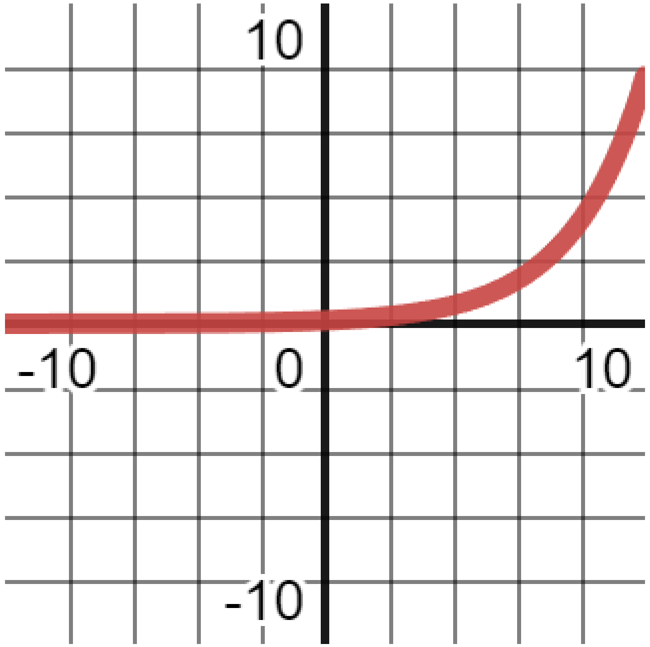




Non-Linear I-V Char.

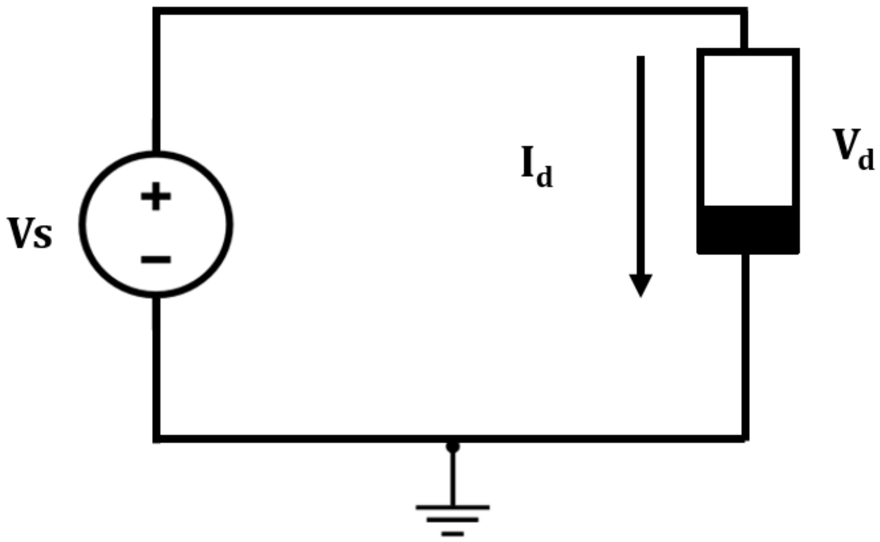
$$I = kV \qquad I = kV^2 \qquad I = \mathrm{A} \cdot \exp(\frac{V}{b})$$

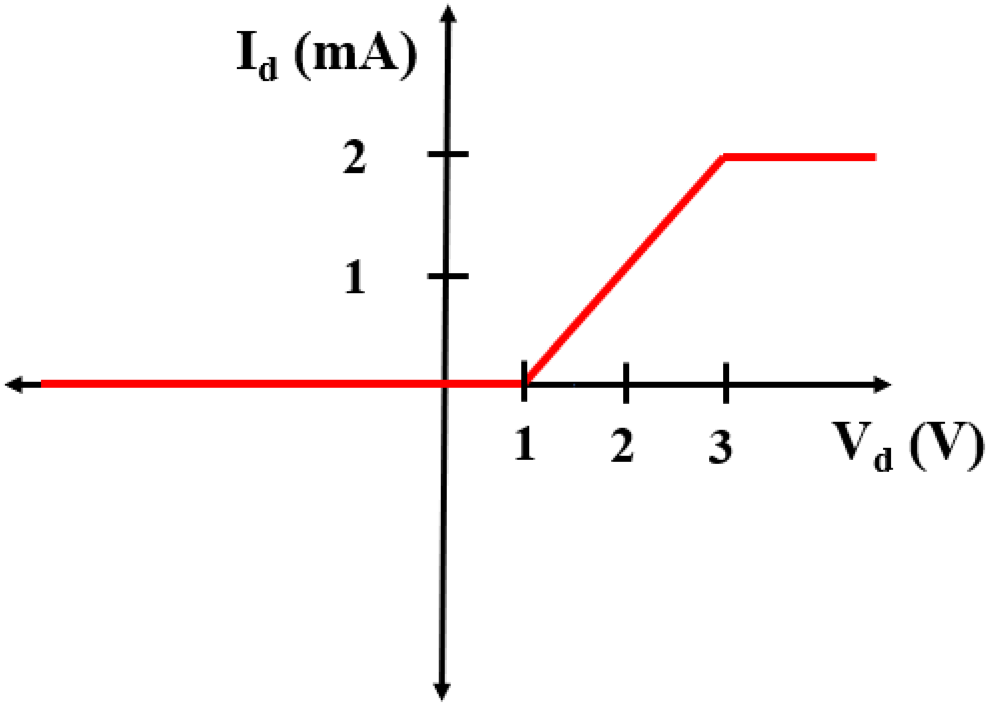
$$y = mx \qquad y = ax^2 \qquad y = \mathrm{A} \cdot \exp(\frac{x}{b})$$



Non-Linear I-V Char.

Example:

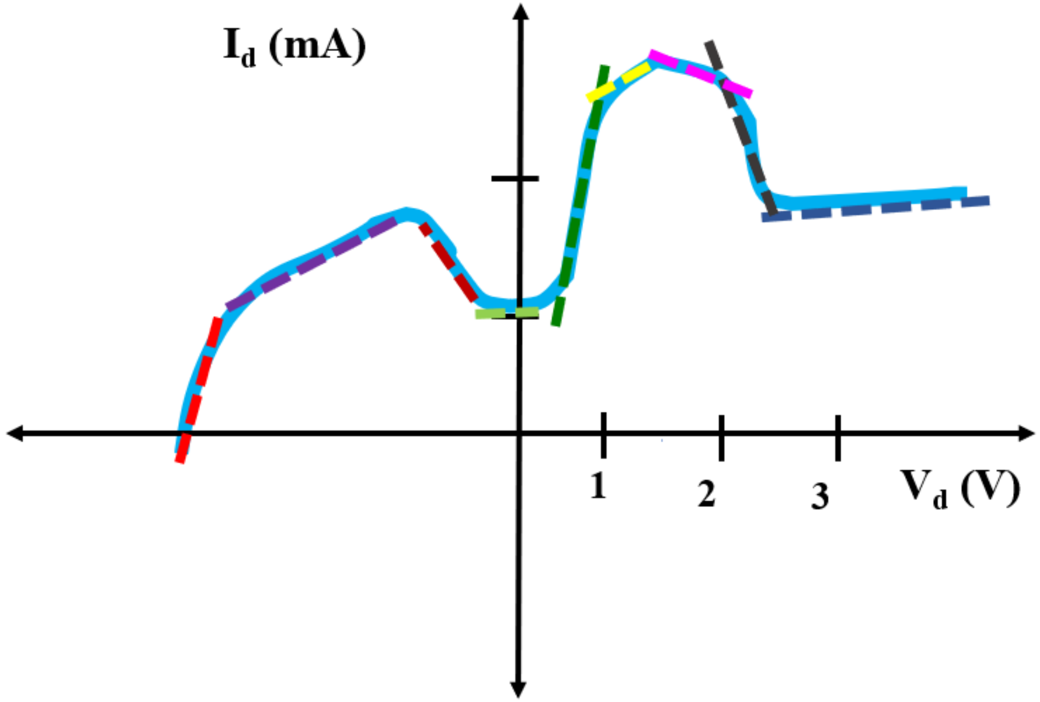




Piecewise linear function is a **Non-linear** function.

Non-Linear I-V Char.: Piecewise Linear Model

- Simplifying non-linear IV characteristics by piecewise linear parts.
- Non-linear functions are usually approximated by a series of linear segments that follow the tangent of the non-linear segment as can be seen from the following figure.



Semiconductor Materials

- Semiconductors are special class of materials (as opposed to conductors and insulators) that fall **between conductors and insulators** in terms of their electrical conductivity.

- By making simple material changes, such as **doping**, these materials can achieve remarkably precise control over electron flow.

- This ability to **control electron flow** makes semiconductors the optimal candidate for building non-linear electrical devices, where electron (current) flow is not always just proportional to the applied voltage.

- As these non-linear devices offer exceptional control over electron flow, the class of devices and circuits are branched under the umbrella term **"Electronics"**

Semiconductor Materials

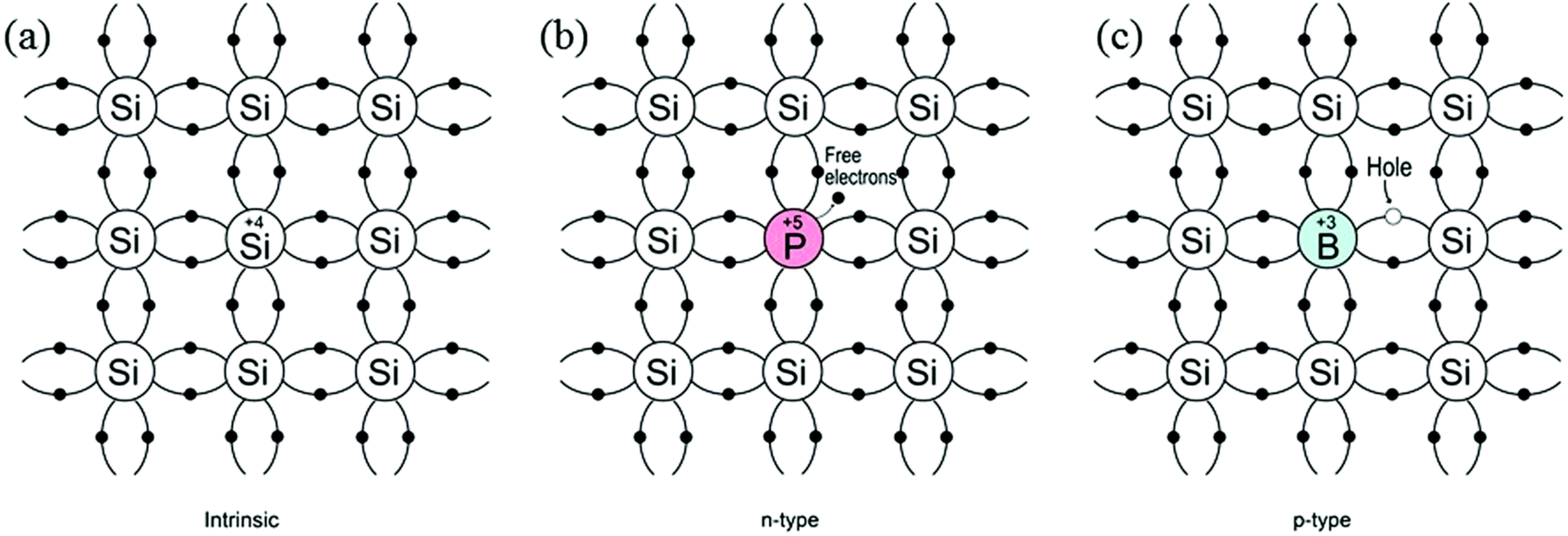
What is doping?

Doping is to deliberately inject atomic level “impurities” into a material (such as an “intrinsic” or **pure semiconductor** such as **Silicon**. These atoms are called dopants.

Usually, the concentration of the “dopant” atoms is much less than the actual concentration of the host material.

Since the atoms being injected are different from the actual material atom, they are considered impurities. A doped semiconductor is also known as “**Extrinsic**” semiconductor.

Semiconductor Materials



n −type doped → Si lattice is riddled with pentavalent atoms

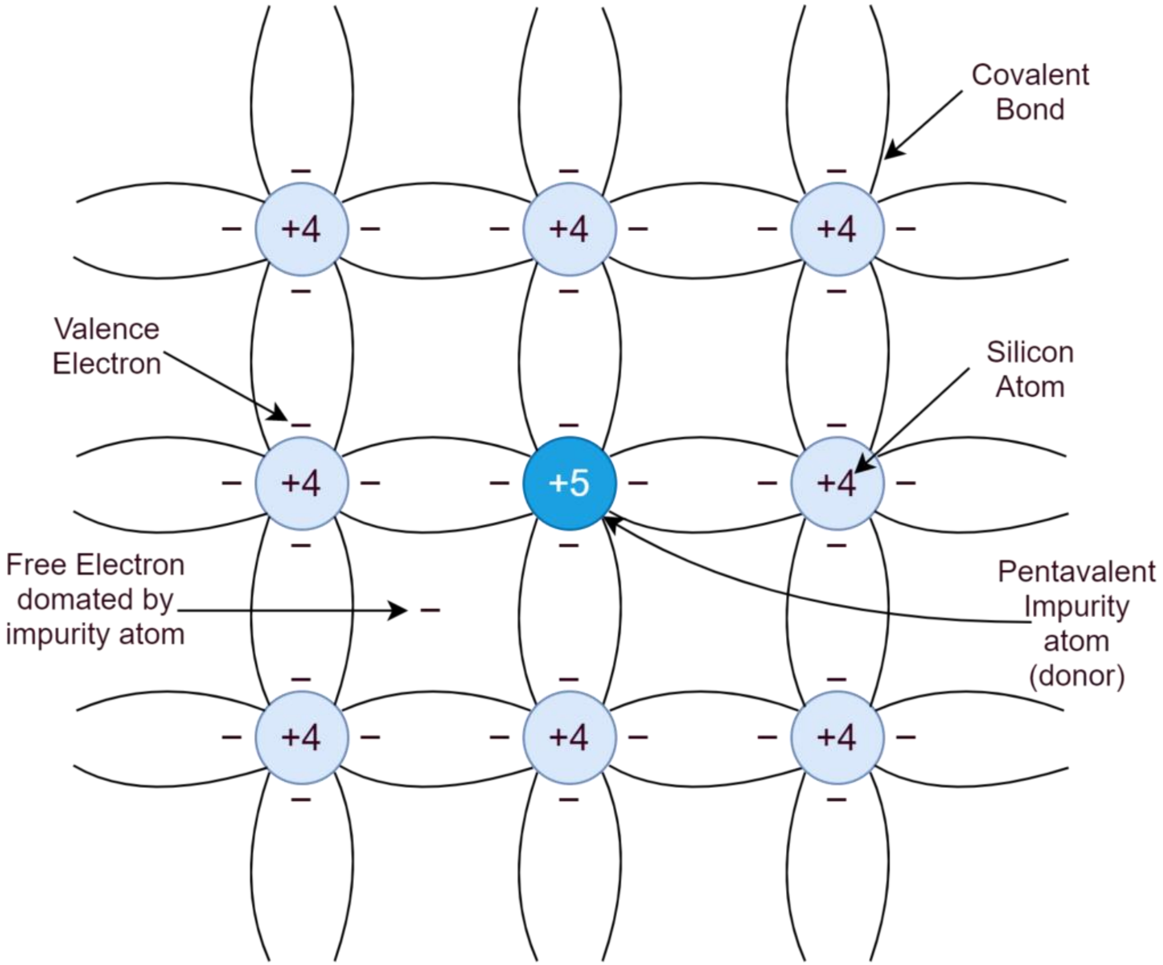
p −type doped → Si lattice is riddled with trivalent atoms

n-type doping

- n-type materials are doped with pentavalent atoms.

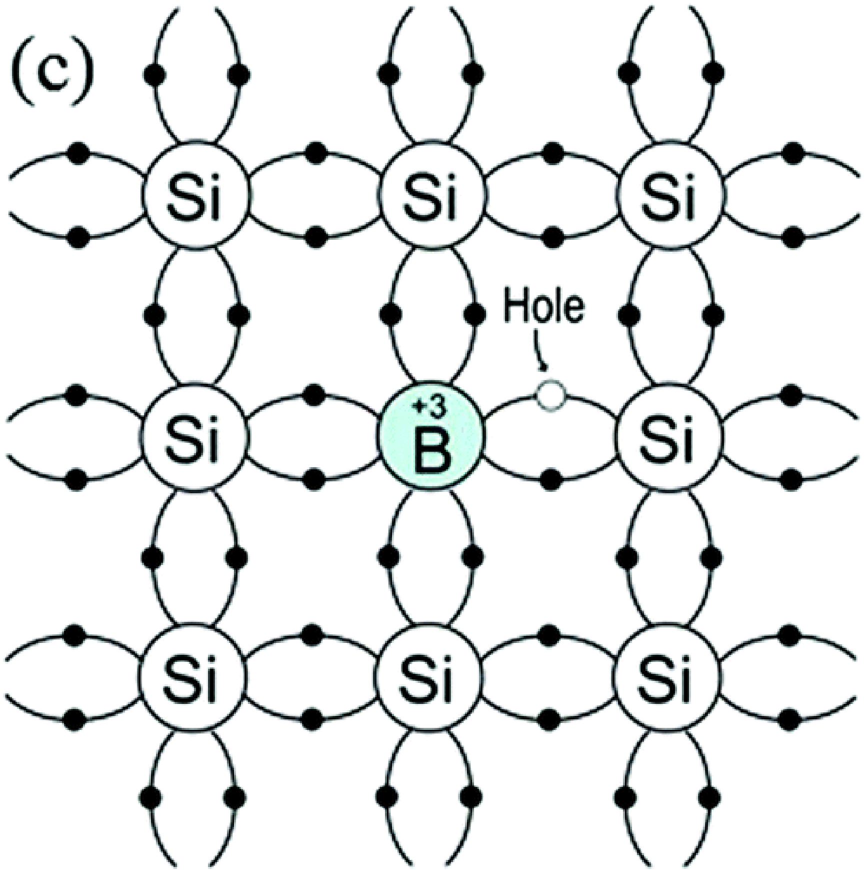
- Pentavalent atoms have one more electron than the surrounding tetravalent **Si** atoms.

- This lone extra electron acts as a **mobile electron** that can flow easily as it is not bonded to any atom.



p-type doping

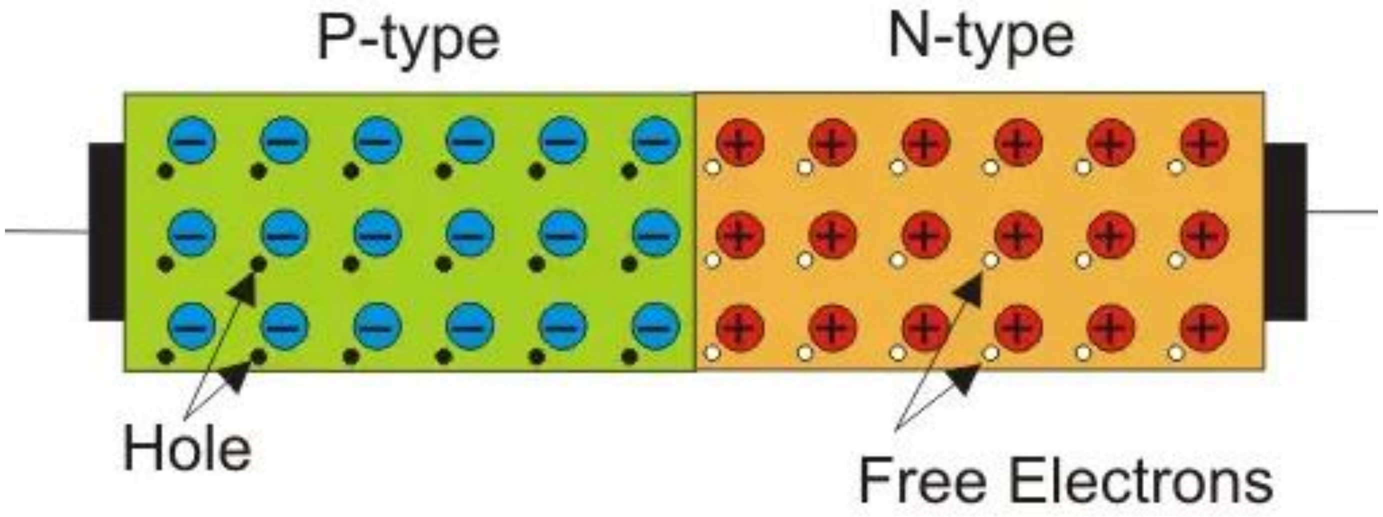
- p-type materials are doped with trivalent atoms.
- Trivalent atoms have one less electron than the surrounding tetravalent Si atoms.
- This absence of an electron (termed as a hole) acts as can flow easily from atom to atom across the material as it is not bonded to any atom. The flow of holes is opposite to the actual flow of electrons.



p-type

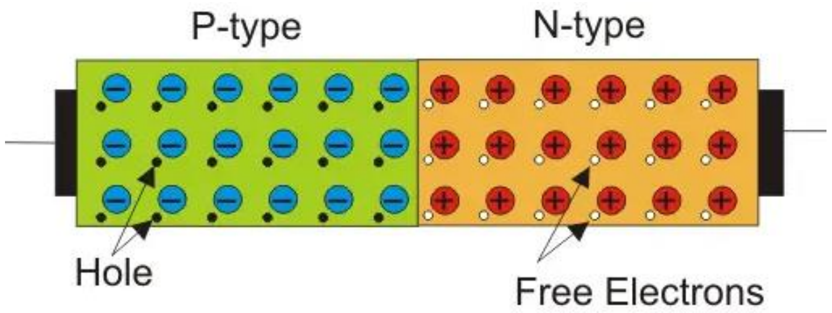
Semiconductor Devices: Diode

- **Diode** is the most basic semiconductor device.
- It is made by doping an intrinsic semiconductor (**Si**) half as **p-type** and the other half as **n-type**.



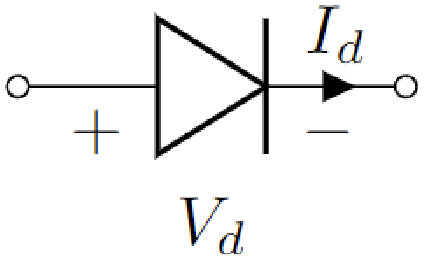
The **pn** junction diode: Physical characteristics

Internal Structure



Circuit Schematic

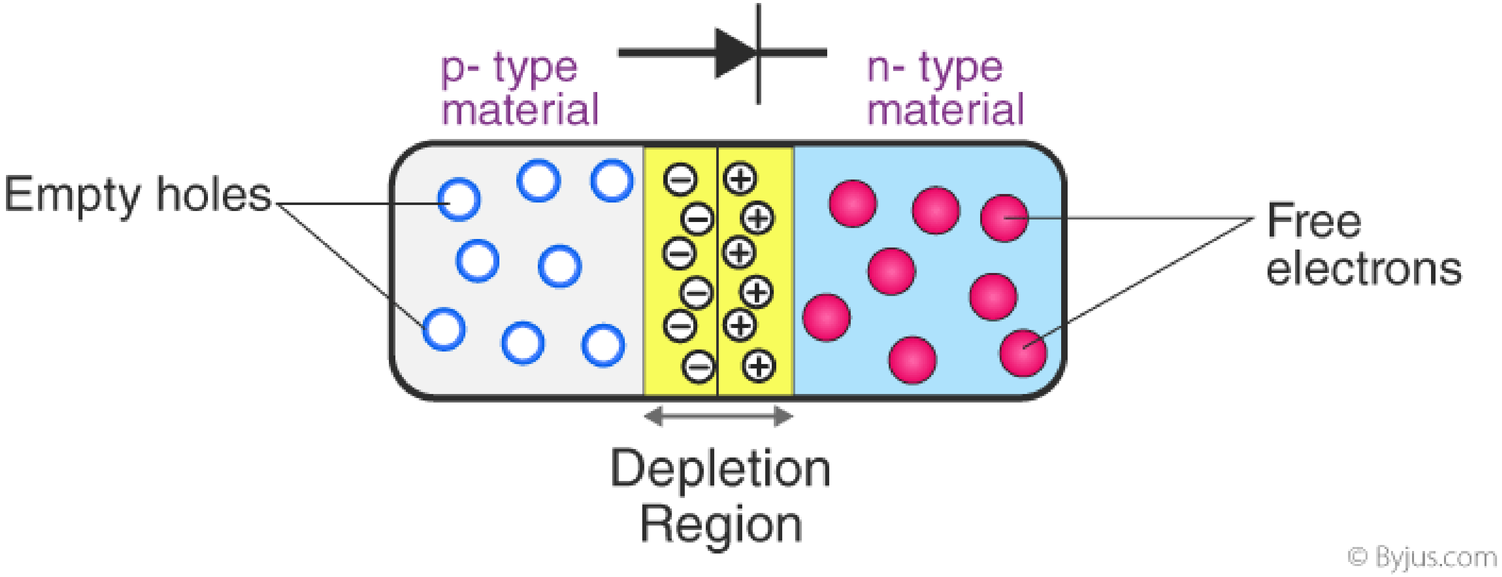
Anode



Cathode

Real device image

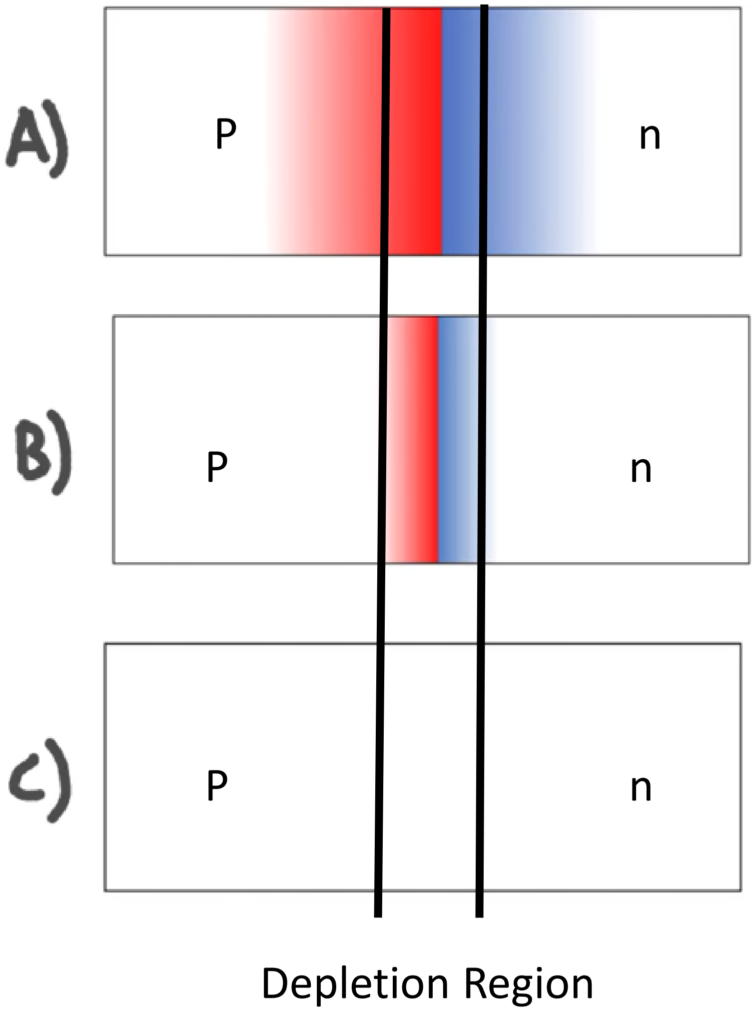
p-n junction



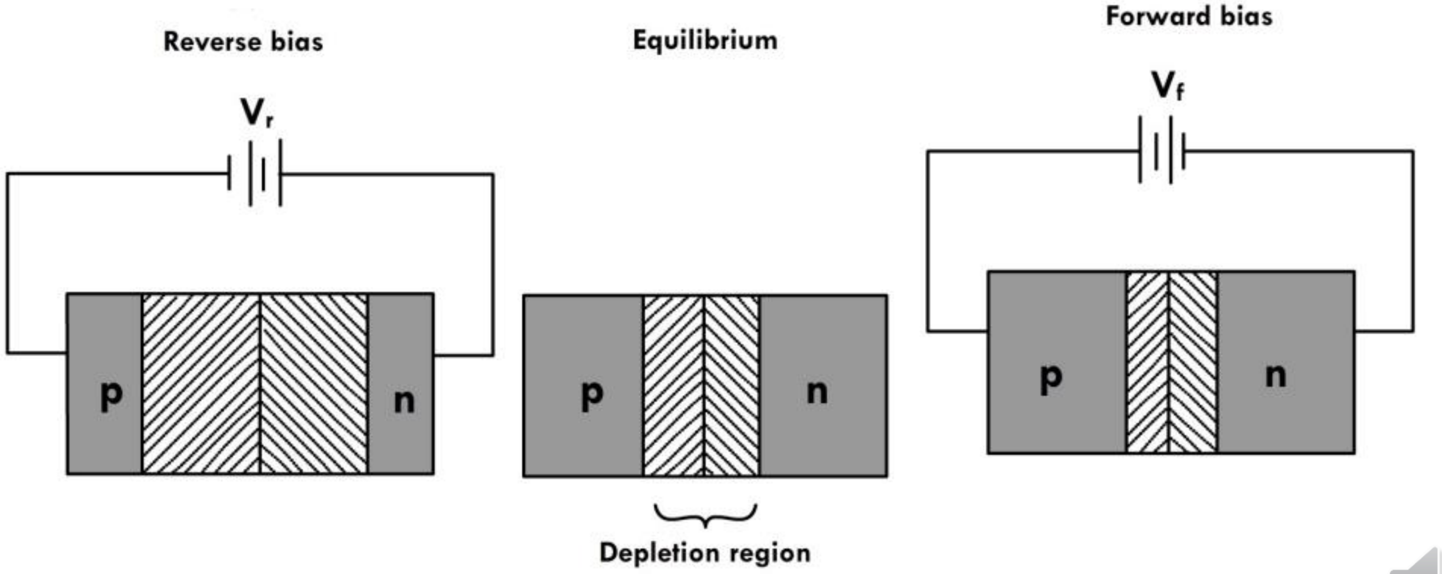
Threshold voltage- for silicon about 0.7V
- for germanium about 0.3V.

https://byjus.com/physics/p-n-junction/

The **pn** junction diode: Modes of operation

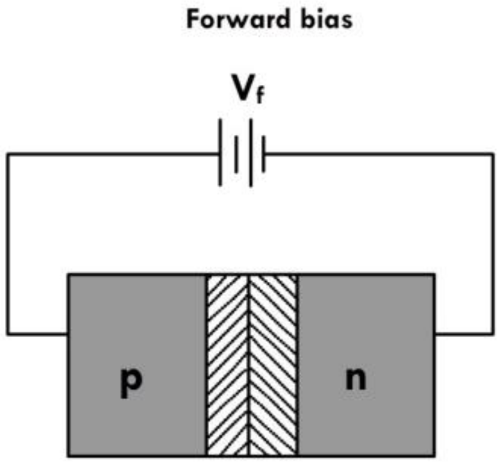


A) Reverse Bias
B) No Bias
C) Forward Bias

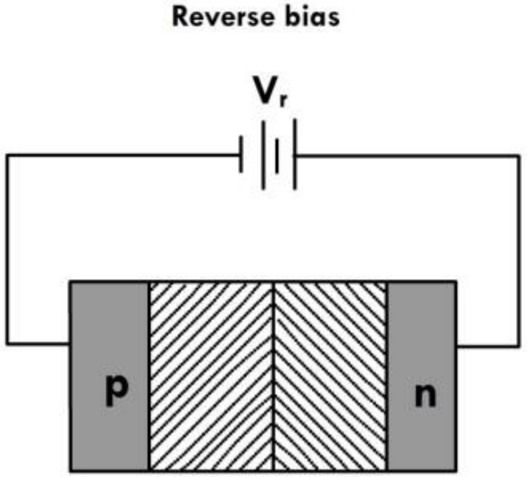


The **pn** junction diode: 2 Modes of operation

1. Forward Bias (FB):
    - Depletion Region is **constricted**.
    - ***Allow*** electrons to flow through the junction
    - Ideally acts as a **short circuit**

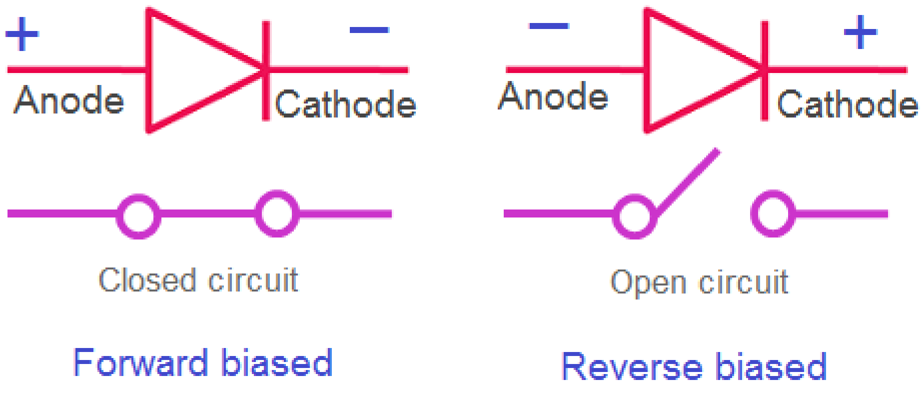


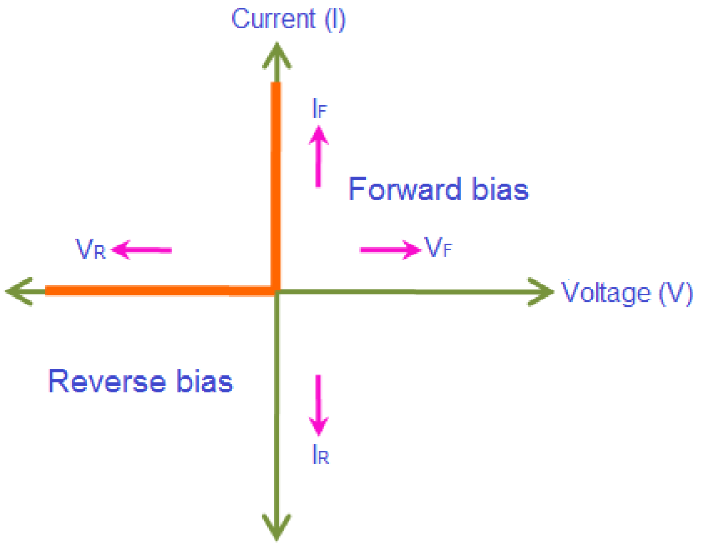
2. Reverse Bias (RB):
    - Depletion Region is **expanded**.
    - Bars / does not allow electron flow through the junction.
    - Ideally acts as an **open circuit**



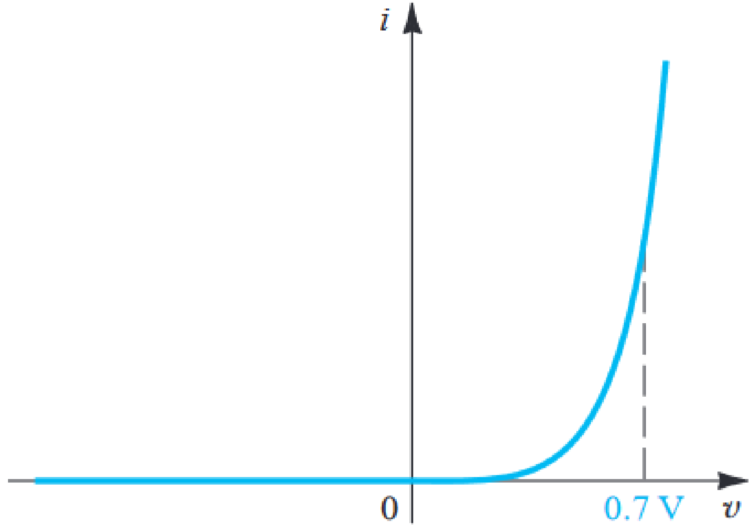
Diode Circuit Models

Ideal *Versus* Real Diode





Constant Voltage Drop
(CVD) Model



Ideal Model

Real / Shockley Model

Low Accuracy

Simple

CVD with resistance
(CVD+R) Model

Increased Accuracy

More Complex

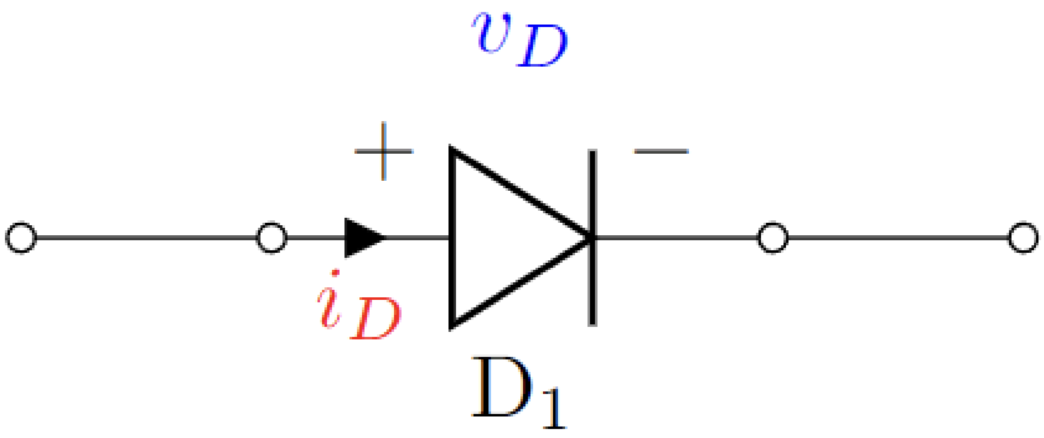
Diode Circuit Models

1. **Ideal Diode** Model:
2. **Constant Voltage Drop (CVD)** Model:
3. **Constant Voltage Drop with Resistor (CVD+R)** Model
4. **Exponential** Model (Shockley Model):

Piecewise Linear IV Models

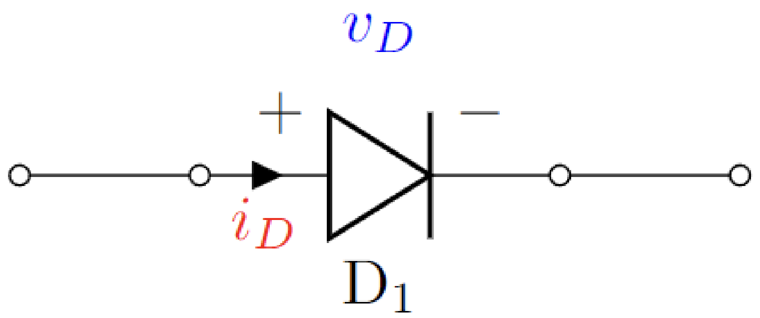
v_D: Total Voltage Across diode
v_d: AC component of the Voltage
V_d: DC component of Voltage

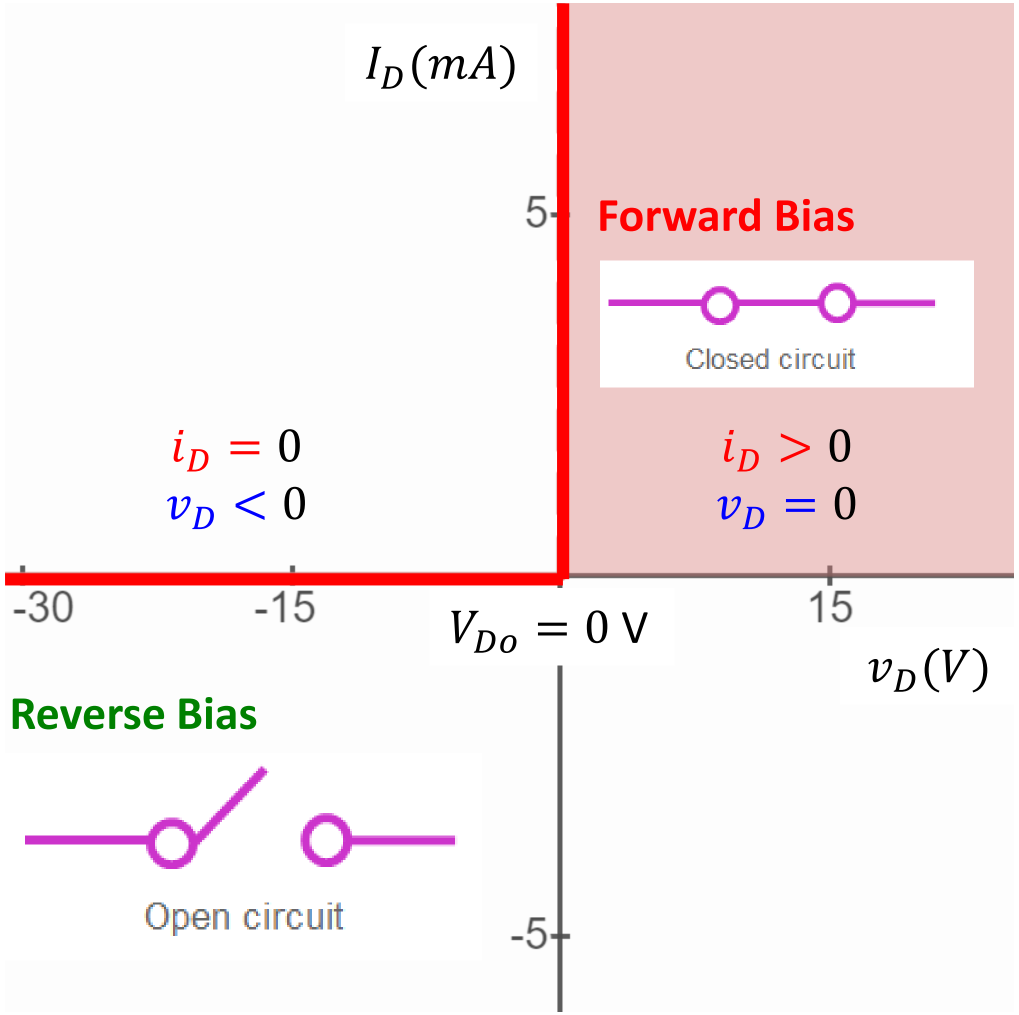
V_{Do}: Diode Cut-off voltage
----
i_D: Total current through diode (Anode to Cathode)



Diode Models

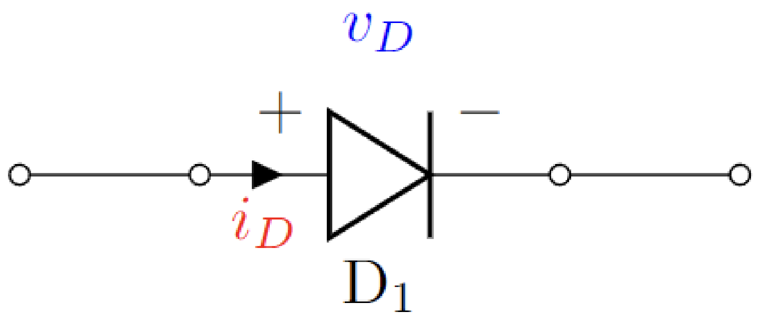
1. Ideal Diode Model:

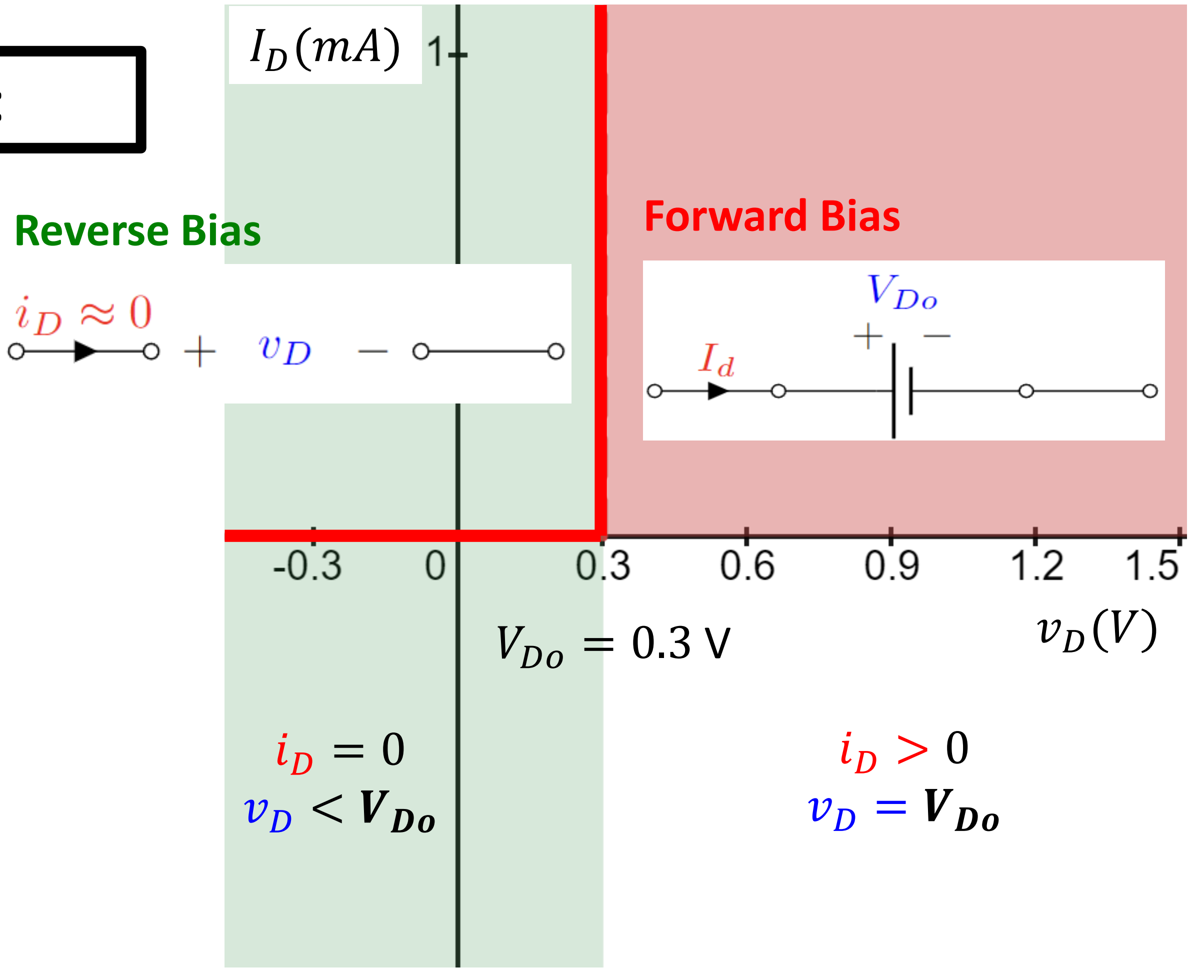




Diode Models

2. Constant Voltage Drop (CVD) Model:



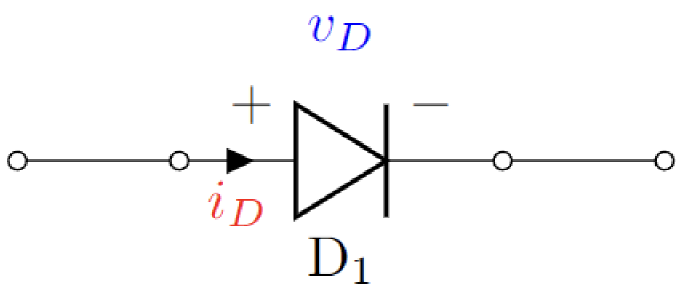


v_D: Total Voltage Across diode

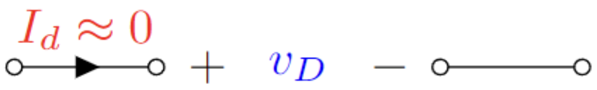
V_{Do}: Diode Cut-off voltage (0.3 V here)

Diode Models

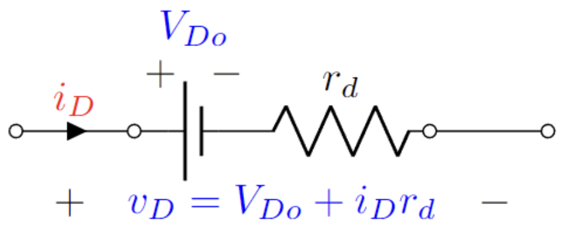
3. CVD+R Model:

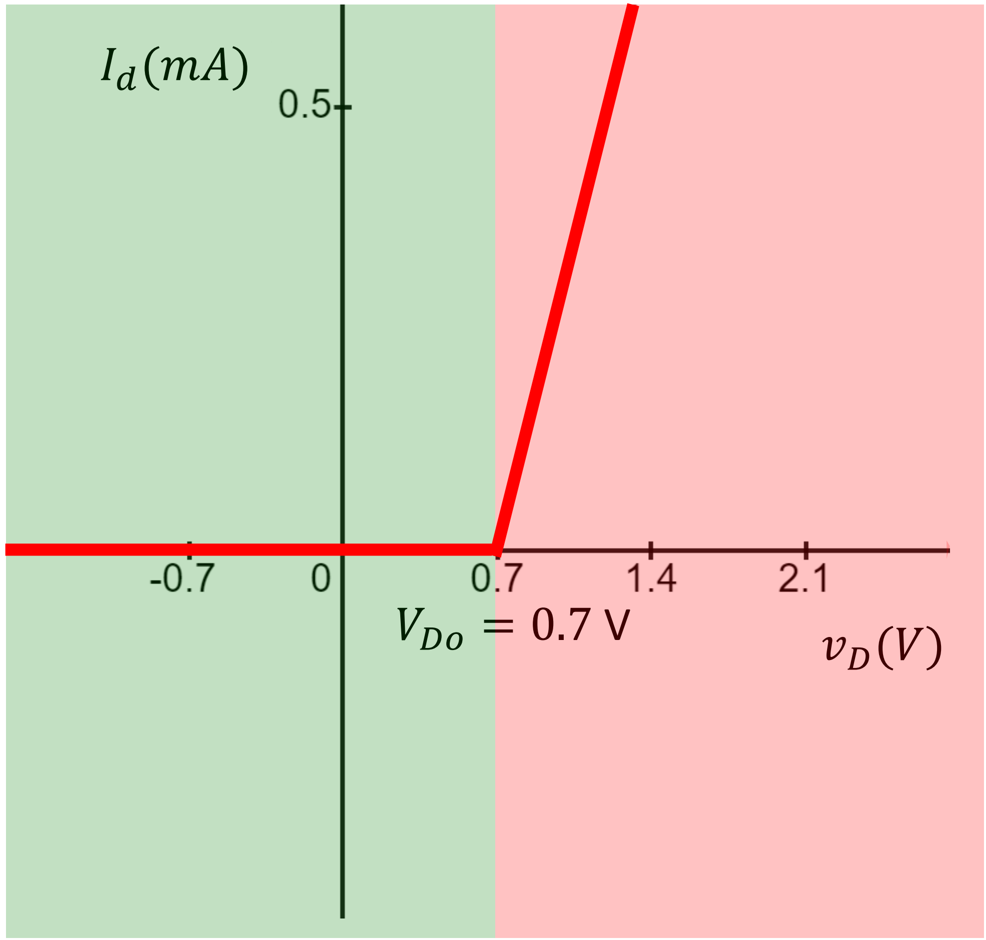


Reverse Bias



Forward Bias



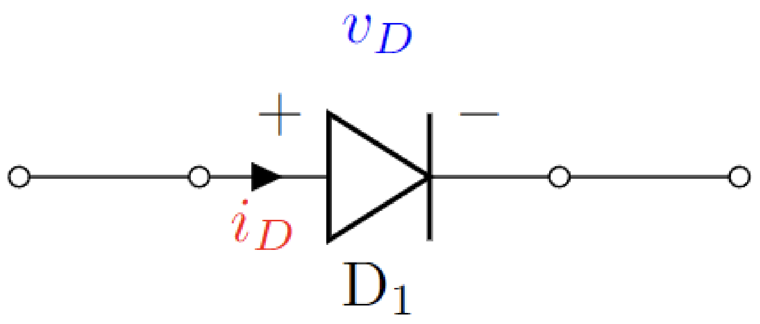


v_D: Total Voltage Across diode

V_{Do}: Diode Cut-off voltage (0.7 V)

Diode Models

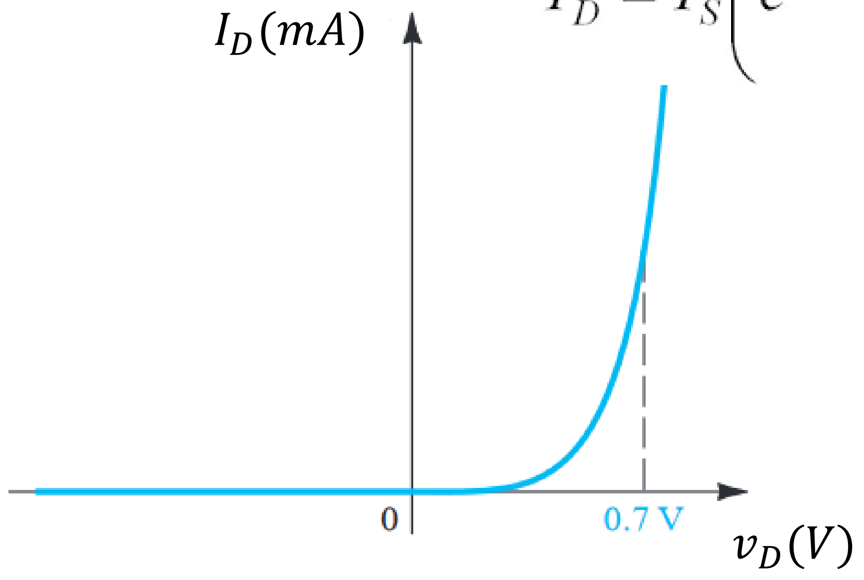
4. Shockley Diode Equation Model:



$$i_D = I_s\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right] \qquad V_T = \frac{kT}{q}$$

k = 1.38 × 10^{-23} J/K is Boltzmann's constant and q = 1.60 × 10^{-19} C is the magnitude of the electrical charge of an electron. At a temperature of 300 K, we have $V_T \simeq 26\,\mathrm{mV}$

$$I_D = I_S\left(e^{\frac{qV_D}{nkT}} - 1\right)$$



Where I_S is reverse saturation current

Solving Circuits with Diodes

- Use **Method of Assumed State**!
- Three steps:
  - **Assume**: One of the **two** operating modes (**Forward Biased** – **FB** or **Reverse Biased - RB**)

    *Correct assumptions will make solving circuit easier.
  - **Solve**: Use corresponding equation and KCL/KVL or any circuit analysis tool of your choice.
  - **Verify**: Check if the conditions of the diodes in the chosen region **(FB or RB)** are satisfied. If not, one can be sure that the other operating mode is correct.

Example Problems (Ideal Diode)

Example 1: $R_L = 2.5\ \mathbf{k\Omega}$

Assume:

Diode is in **FB:** A short circuit,

$v_d = 0\ \text{V}$

$I > 0\ \mathbf{mA}$

Solve:

$$v_O = v_{IN} = \mathbf{5\ V}$$

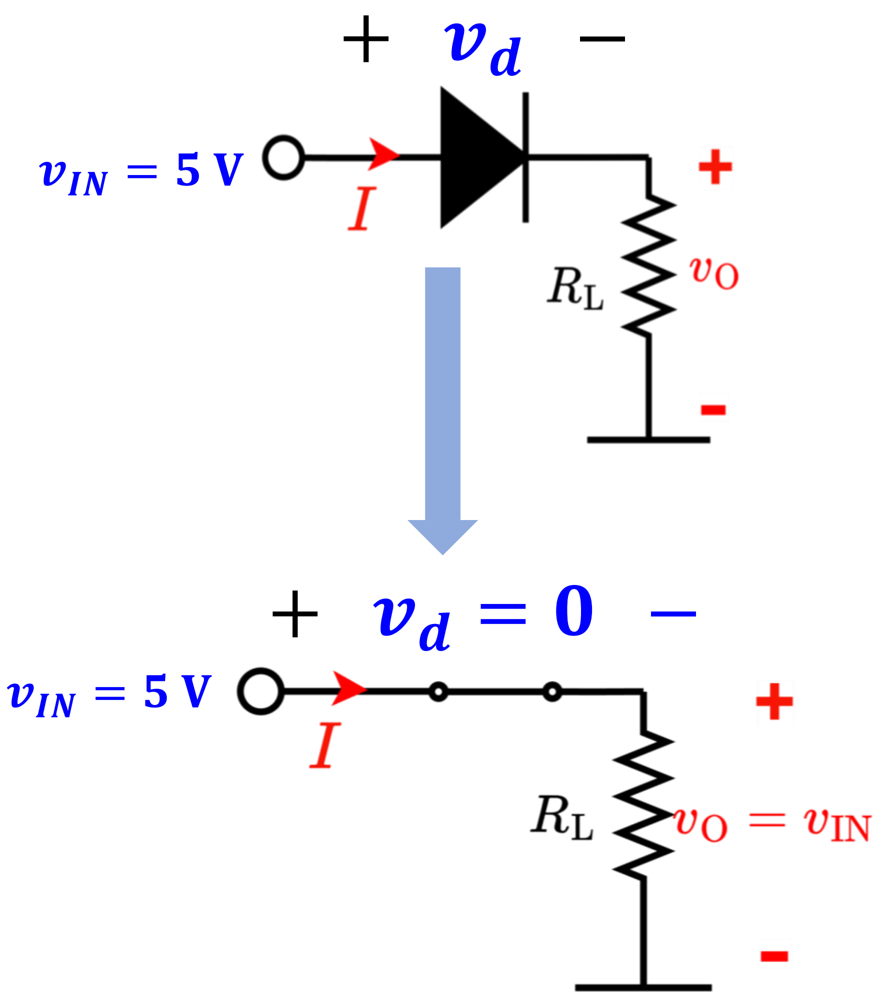
$$\boxed{v_d = v_{IN} - v_O = \mathbf{0\ V}}$$

$$I = \frac{v_O}{R_L} = \frac{5\ \text{V}}{2.5\ \text{k}\Omega} = \boxed{\mathbf{2\ mA > 0}}$$

Verify: For **FB** $\rightarrow$ $v_d = 0\ \text{V}$

$I > 0\ \mathbf{mA}$

Here, both conditions are fulfilled. **Assumption is Correct!**



Example Problems (Ideal Diode)

Example 2: $R_L = 2.5\ \mathbf{k\Omega}$

Assume:

Diode is in **FB:** A short circuit,

$$v_d = 0\ \text{V}$$
$$I > 0\ \mathbf{mA}$$

Solve:

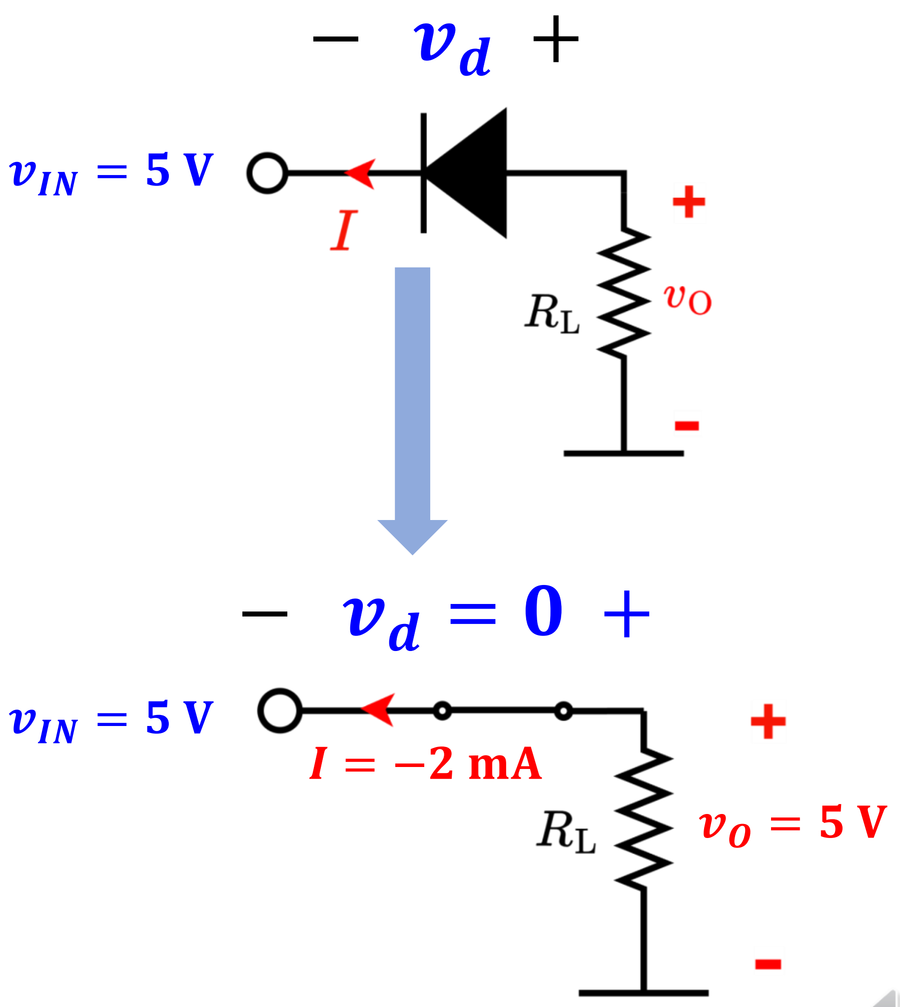
$$v_O = v_{IN} = \mathbf{5\ V}$$

$$v_d = v_O - v_{IN} = \mathbf{0\ V}$$

$$I = -\frac{v_O}{R_L} = -\frac{5\ \text{V}}{2.5\ \text{k}\Omega} = \boxed{-\mathbf{2\ mA} < \mathbf{0}}$$

Verify: For **FB** $\rightarrow$ $v_d = 0\ \text{V}$, $I > 0\ \mathbf{mA}$

Here, $I < 0\ \mathbf{mA}$. **Assumption is INCORRECT!**



Example Problems (Ideal Diode)

Example 2: $R_L = 2.5\ \mathbf{k\Omega}$

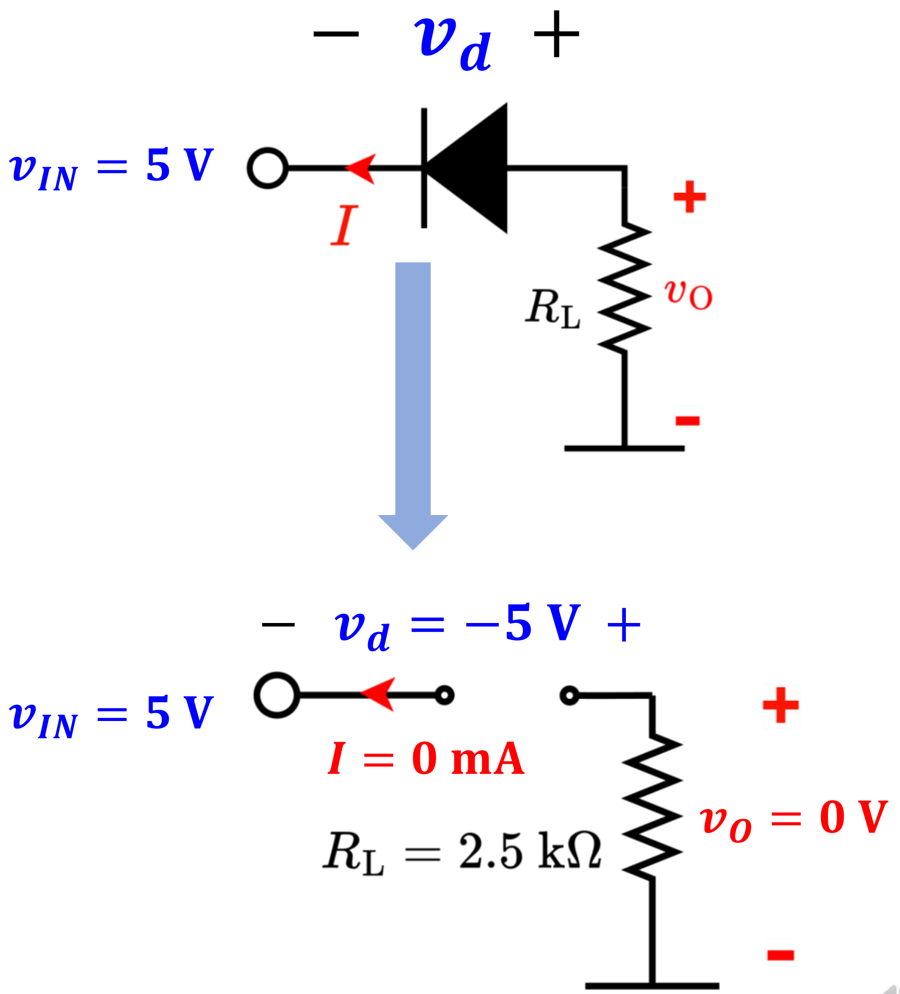
~~Assume:~~

Diode is in **RB:** An open circuit,

$$v_d < 0\ \text{V}$$
$$I = 0\ \mathbf{mA}$$

Solve:

$$v_O = \mathbf{0\ V}$$
$$v_d = v_O - v_{IN} = \mathbf{-5\ V < 0\ V}$$
$$I = 0\ \mathbf{mA}$$



Example Problems (CVD Diode)

Example 3: $R_L = 2.5\ \mathbf{k\Omega}$

Assume:

Diode is in **FB:** A constant voltage source of V_{DO} voltage,

$$v_d = V_{DO} = 0.7\ \mathbf{V}$$

$$I > 0\ \mathbf{mA}$$

Solve:

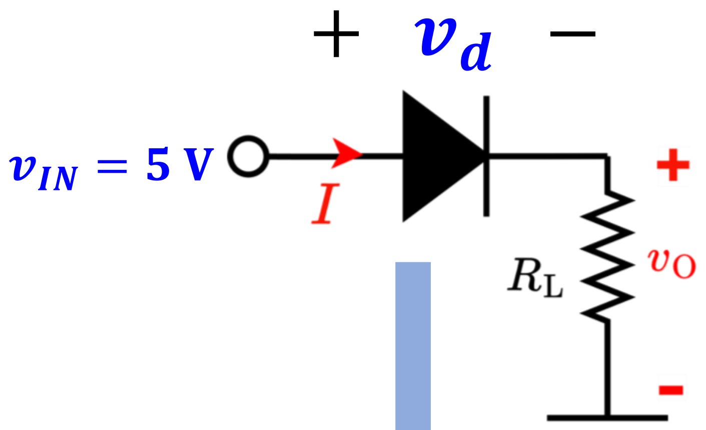
$$v_O = v_{IN} - V_{DO} = 5 - 0.7\ \mathrm{V} = 4.3\ \mathrm{V}$$

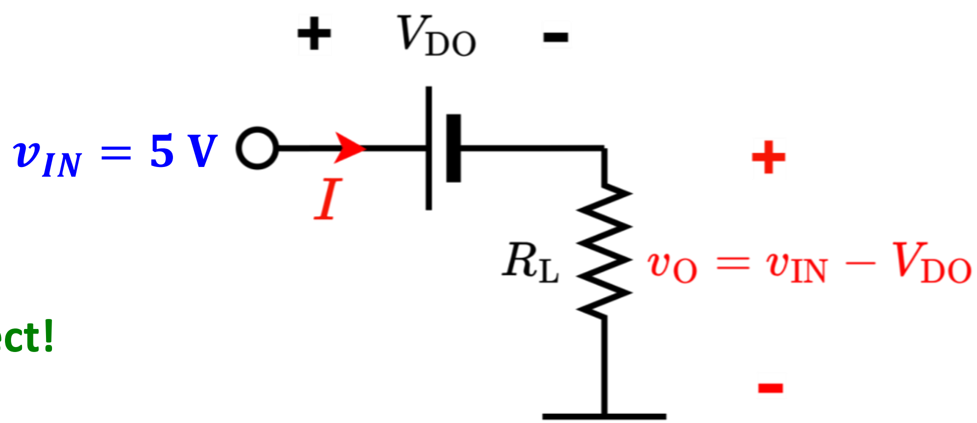
$$\boxed{v_d = V_{DO} = \mathbf{0.7\ V}}$$

$$I = \frac{v_{IN} - V_{DO}}{R_L} = \frac{4.3\ \mathrm{V}}{2.5\ \mathrm{k\Omega}} = \boxed{1.72\ \mathrm{mA} > \mathbf{0}}$$

Verify: For **FB** → $I > 0\ \mathbf{mA}$

Here, both conditions are fulfilled. **Assumption is Correct!**





Example Problems (CVD Diode)

Example 4: $R_L = 2.5\ \mathbf{k\Omega}$

Assume:

Diode is in **FB:** A **constant voltage source of** $\boldsymbol{V_{DO}}$ voltage,

$$\boldsymbol{v_d} = \boldsymbol{V_{DO}} = 0.7\ \mathbf{V}$$

$$\boldsymbol{I} > 0\ \mathbf{mA}$$

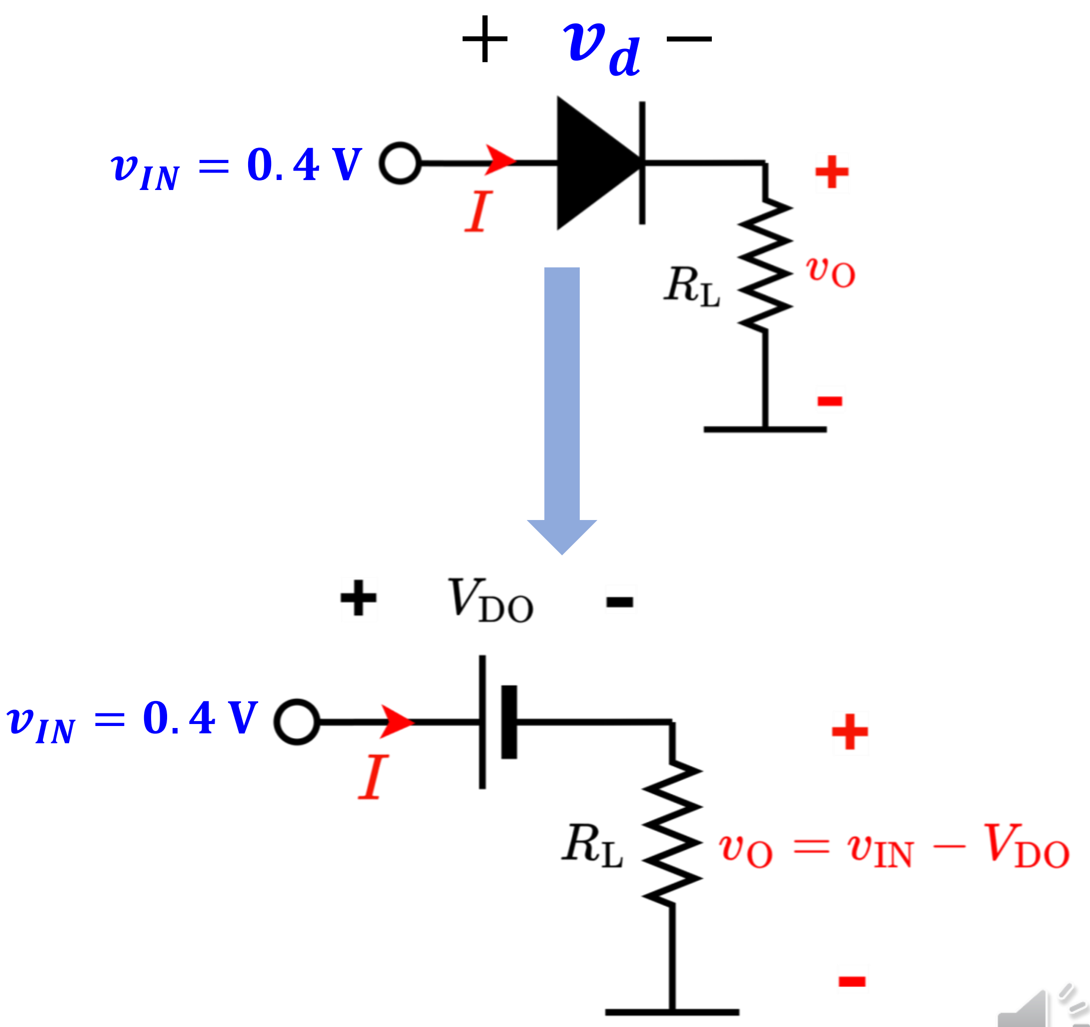
Solve:

$$\boldsymbol{v_O} = v_{IN} - V_{DO} = 0.4 - 0.7\ \mathrm{V} = -0.3\ \mathrm{V}$$

$$\boldsymbol{I} = \frac{v_O}{R_L} = \frac{-0.3\ \mathrm{V}}{2.5\ \mathrm{k\Omega}} = \boxed{-0.12\ \mathbf{mA} < \mathbf{0}}$$

Verify: For **FB** $\rightarrow$ $\boldsymbol{I} > 0\ \mathbf{mA}$

Here, $\boldsymbol{I} < 0\ \mathbf{mA}$. **Assumption is INCORRECT!**



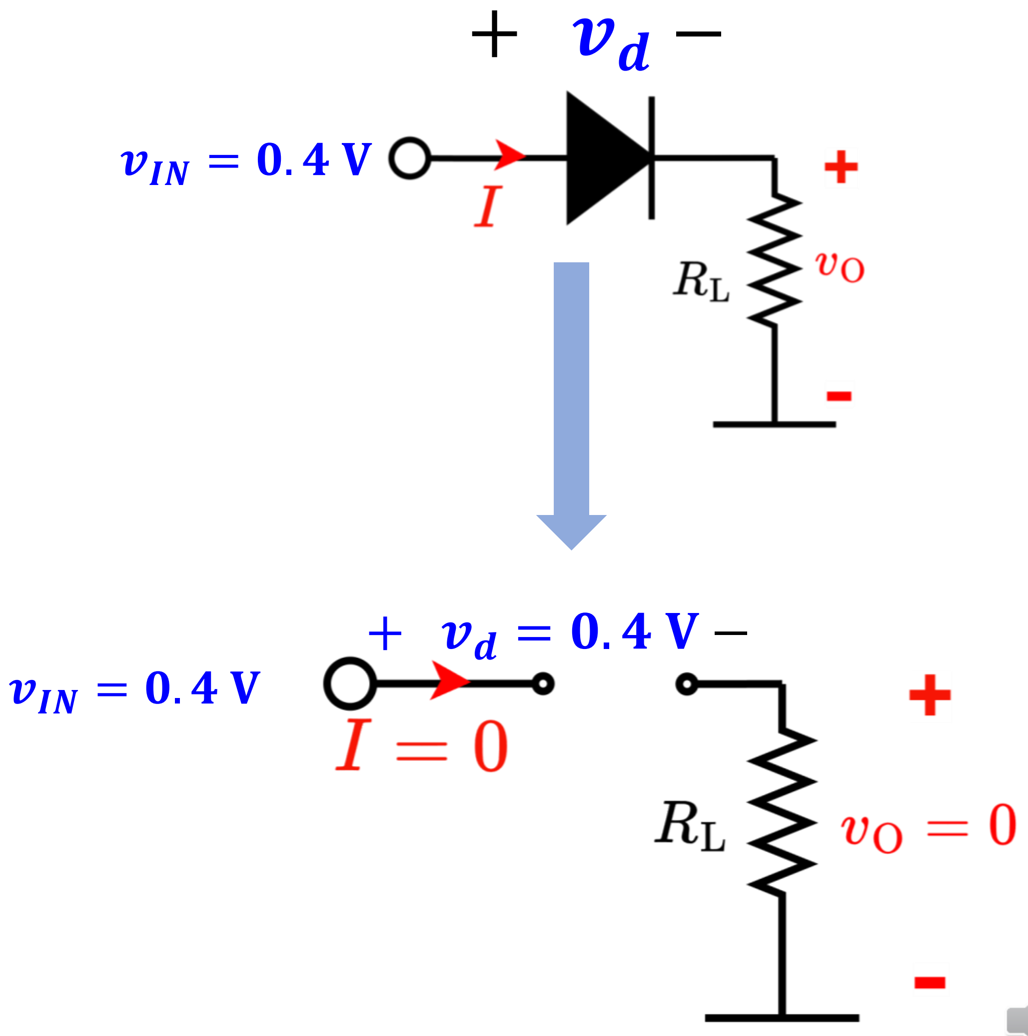
Example Problems (Ideal Diode)

Example 4: $R_L = 2.5\ \mathbf{k\Omega}$

~~**Assume:**~~

Diode is in **RB:** An open circuit,

$$v_d < V_{DO} = 0.7\ \text{V}$$
$$I = 0\ \mathbf{mA}$$



Solve:

$$I = 0\ \mathbf{mA}$$

$$v_O = \mathbf{0\ V}$$

$$v_d = v_{IN} - v_O = \mathbf{0.4\ V < 0.7\ V}$$

Example Problems (CVD+R Diode)

Example 5: $R_L = 2.5\ \mathbf{k\Omega}$, $\boldsymbol{V_{DO} = 0.7\ \mathrm{V},\ r_d = 50\ \Omega}$

Assume:

Diode is in **FB:** A constant voltage drop in series with a resistor,

$$V_{DO} = 0.7\ \mathrm{V},\quad r_d = 50\ \Omega$$

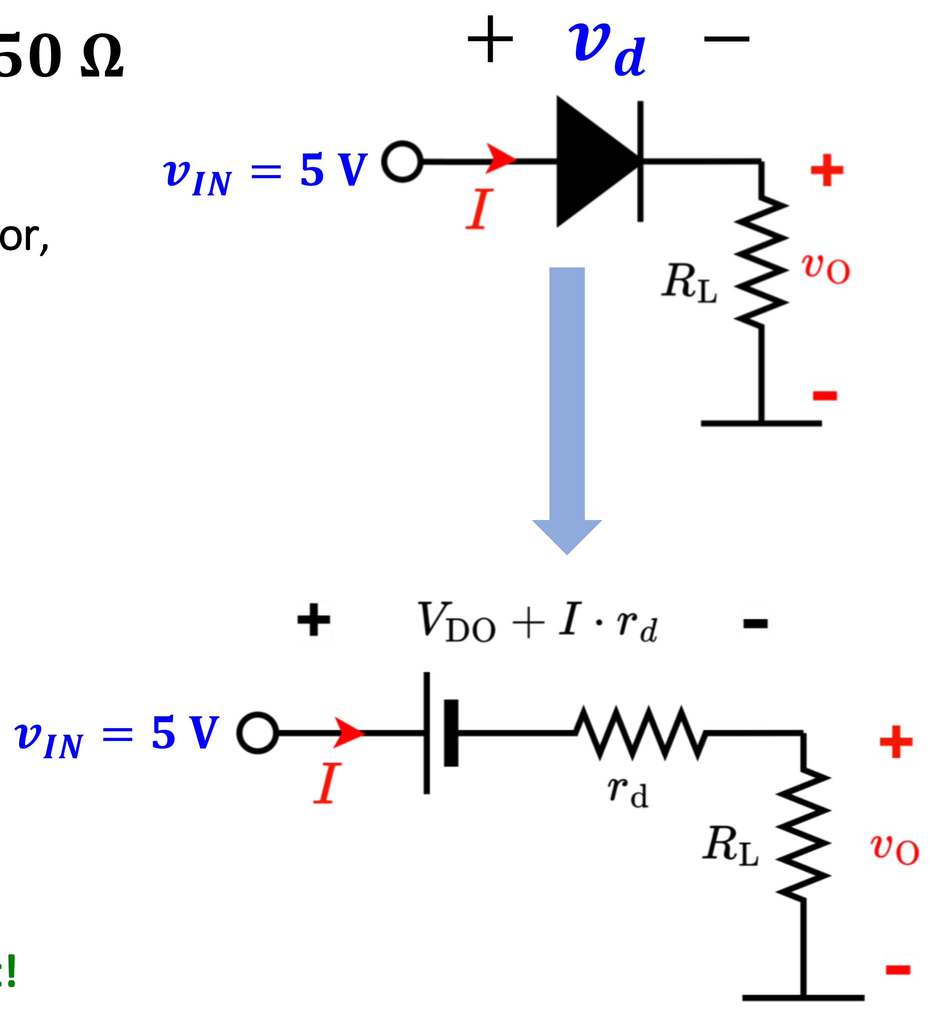
$$\boldsymbol{v_d} = V_{DO} + I r_d$$

$$\boldsymbol{I} > 0\ \mathbf{mA}$$

Solve:

$$\boldsymbol{I} = \frac{v_O - V_{DO}}{R_L + r_d} = \frac{4.3\ \mathrm{V}}{2.5\ \mathrm{k\Omega} + 0.05\ \mathrm{k\Omega}} \boxed{= 1.70\ \mathrm{mA}}$$

$$\boldsymbol{v_O} = \boldsymbol{I} R_L = 1.70 \times 2.5\ \mathrm{V} = \mathbf{4.25\ V}$$

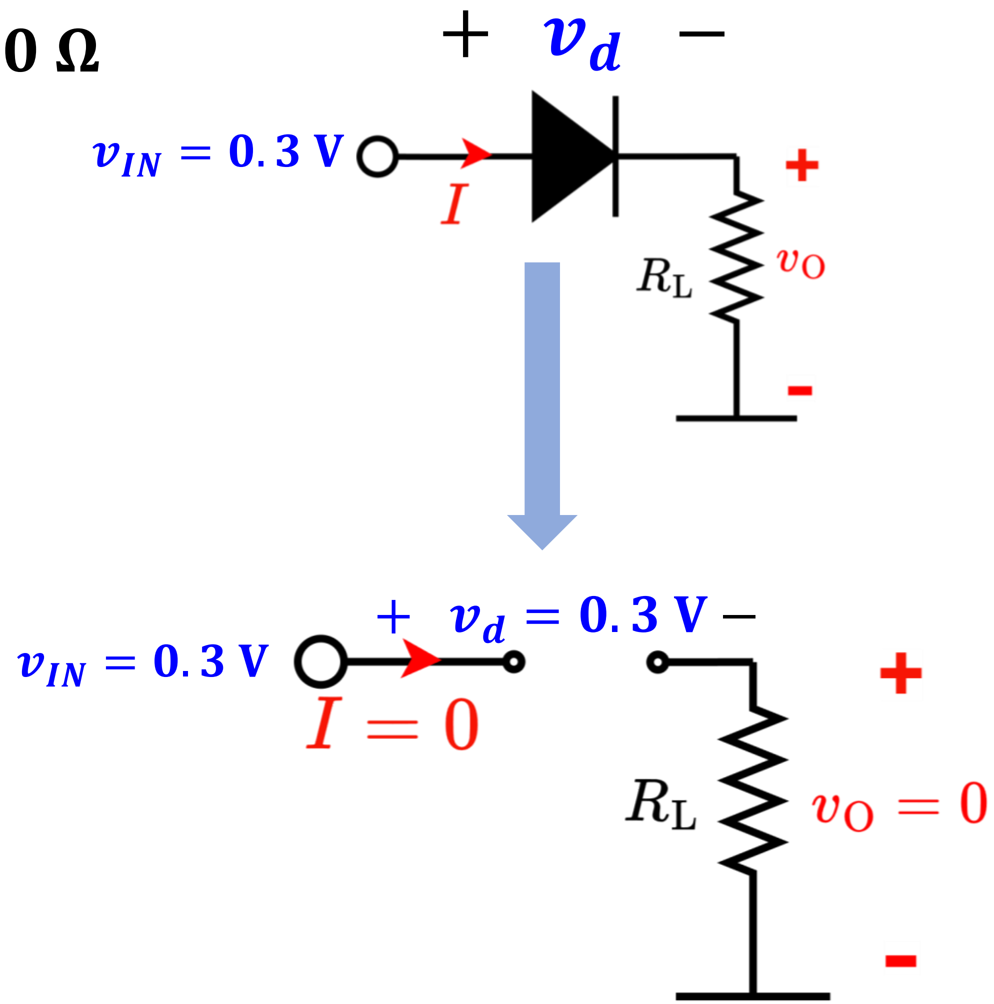


Verify: For **FB** → $\boldsymbol{I} > 0\ \mathbf{mA}$

Here, the condition is fulfilled. **Assumption is Correct!**

Example Problems (CVD+R Diode)

Example 6: $R_L = 2.5\ \mathbf{k\Omega}$, $\boldsymbol{V_{DO} = 0.7\ \mathrm{V}}$, $\boldsymbol{r_d = 50\ \Omega}$



Assume:

Diode is in **RB:** An open circuit,

$$v_d < V_{DO}$$
$$I = 0\ \mathrm{mA}$$

Solve:

$$v_O = 0\ \mathrm{V}$$

$$v_d = v_{IN} - v_O \boxed{= 0.3\ \mathrm{V}}$$

Verify: For **FB** → $v_d < V_{DO}$

Here, the condition is fulfilled. **Assumption is Correct!**

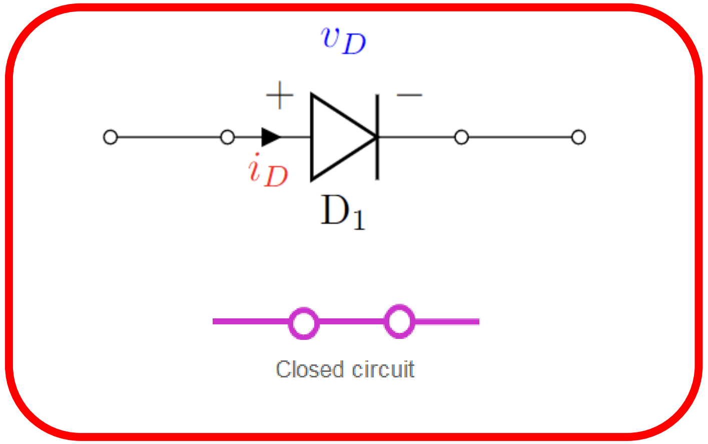
Diode Models: Summary

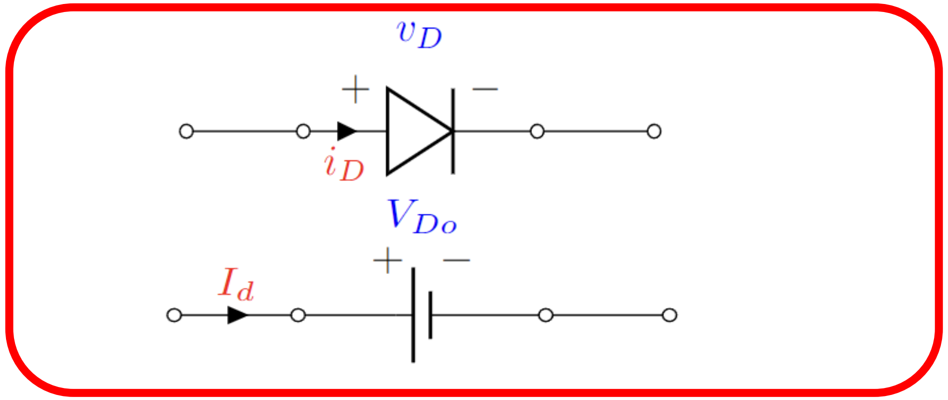
Ideal Diode

CVD Diode

$i_D > 0$

Forward Bias

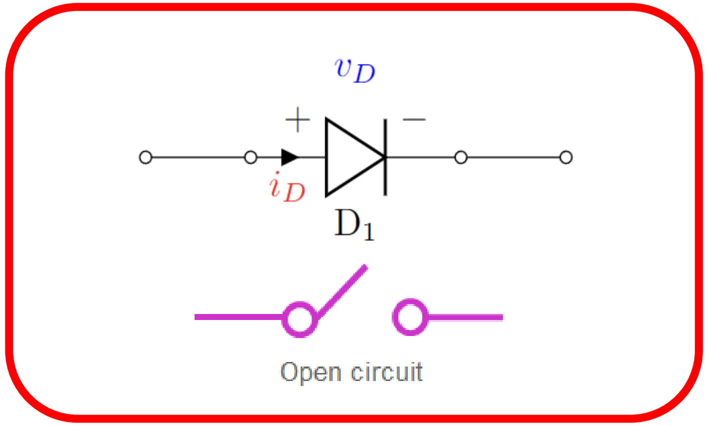


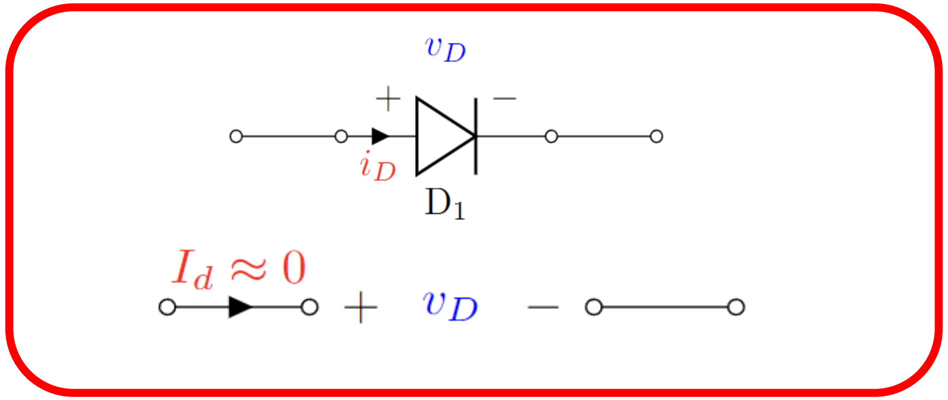


$v_D < V_{DO}$

$i_D = 0$

Reverse Bias



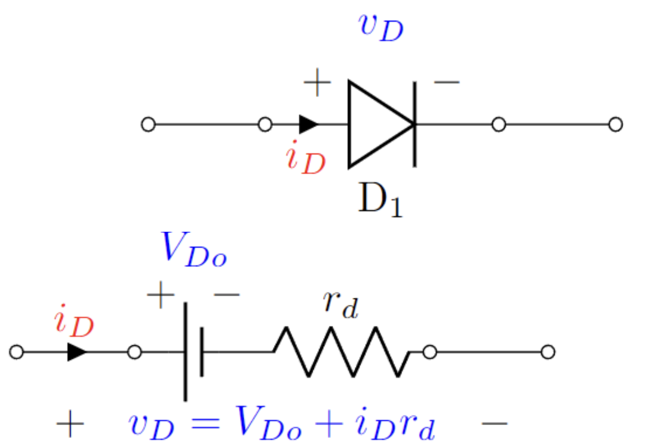


Diode Models: Summary

CVD+R Diode

$$i_D > 0$$

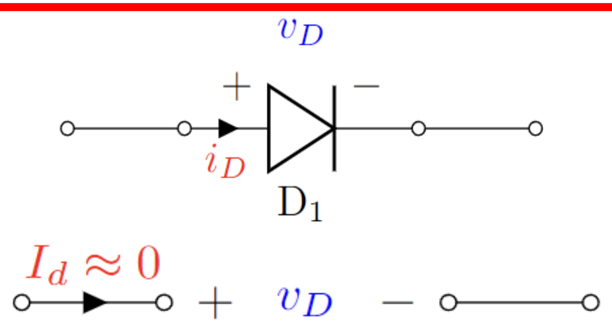
Forward Bias



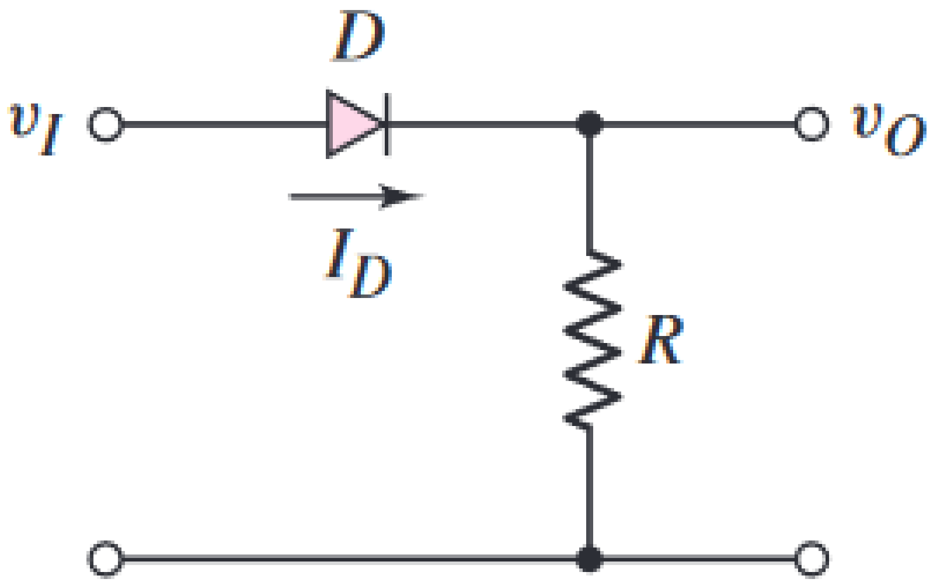
$$v_D < V_{DO}$$

$$i_D = 0$$

Reverse Bias

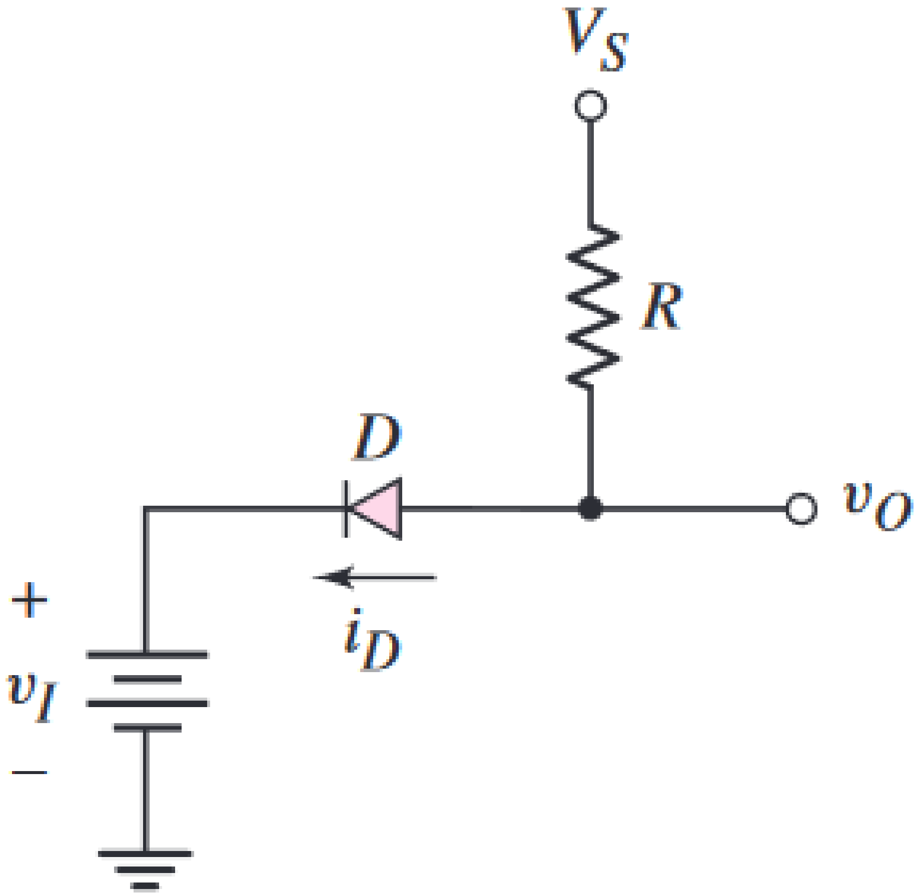


Solving Circuits with diodes (7)



If $v_I = 5\text{ V}$ and $V_{DO} = 0.7\text{ V}$, find $\boldsymbol{v_O}$

Solving Circuits with diodes (7)

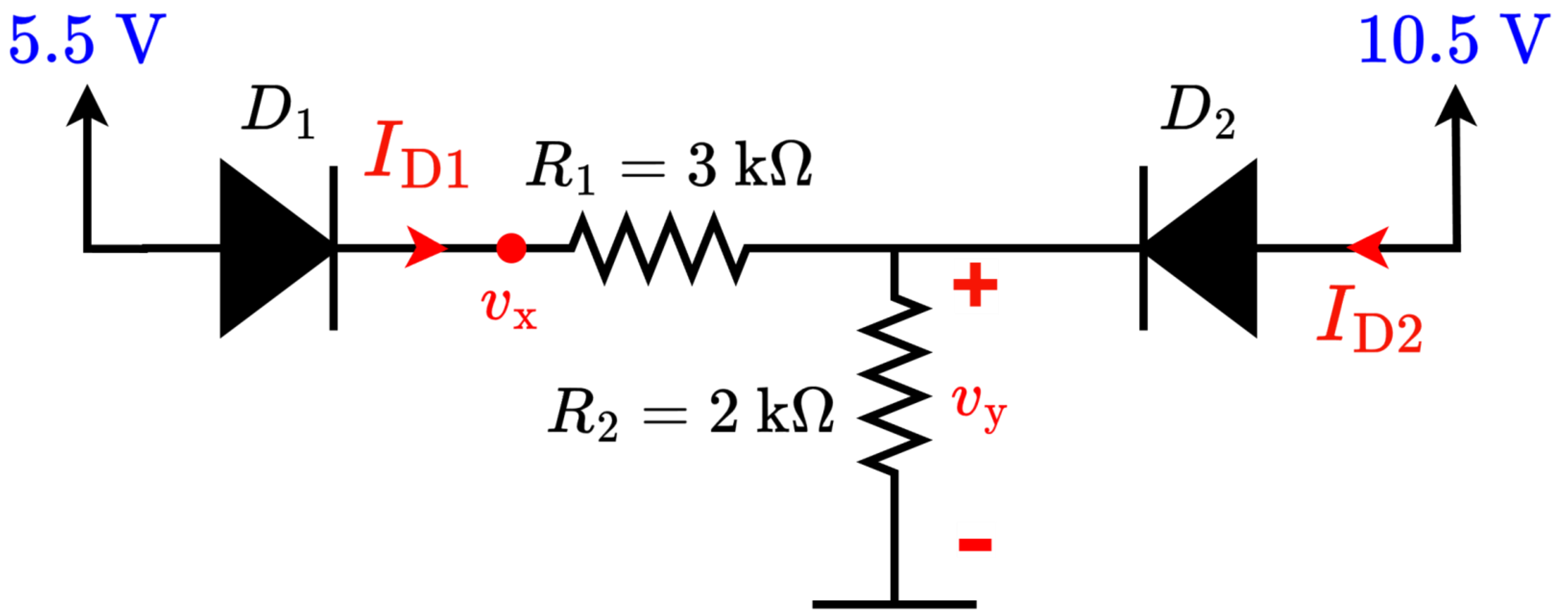


i) If $v_I = 5\text{ V}$, $V_S = 10\text{ V}$ and $V_{DO} = 0.7\text{ V}$, find $\boldsymbol{v_O}$

ii) If $v_I = 11\text{ V}$, $V_S = 10\text{ V}$ and $V_{DO} = 0.7\text{ V}$, find $\boldsymbol{v_O}$

iii) If $v_I = 0\text{ V}$, $V_S = 10\text{ V}$ and $V_{DO} = 0.7\text{ V}$, find $\boldsymbol{v_O}$

Solving Circuits with diodes (9)

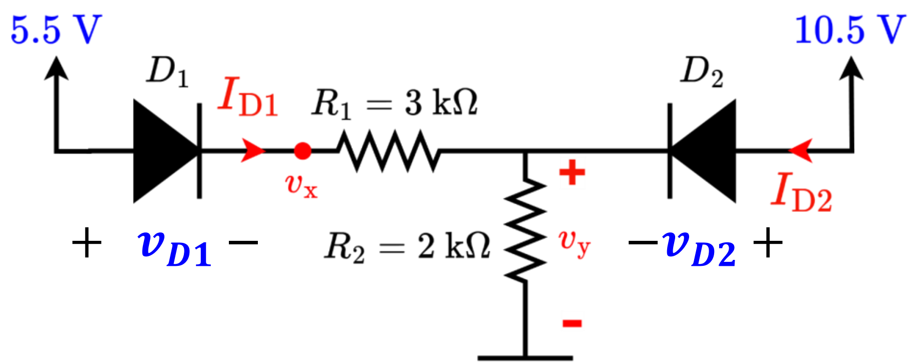


Example 9: Analyze the circuit to find I_{D1}, I_{D2}, v_x and v_y. Consider $\boldsymbol{V_{DO} = 0.5\ V}$.
[Validate Assumptions]

Solving Circuits with diodes (9)

Example 9: Analyze the circuit to find I_{D1}, I_{D2}, v_x and v_y. Consider $\boldsymbol{V_{DO} = 0.5\ V}$.

[Validate Assumptions]



Assume:

D1, D2 are in **FB:** A **constant voltage source of** V_{DO} voltage,

$v_{D1} = 0.5\ \mathbf{V}$, || $v_{D2} = 0.5\ \mathbf{V}$

$I_{D1} > 0\ \mathbf{mA}$, || $I_{D2} > 0\ \mathbf{mA}$

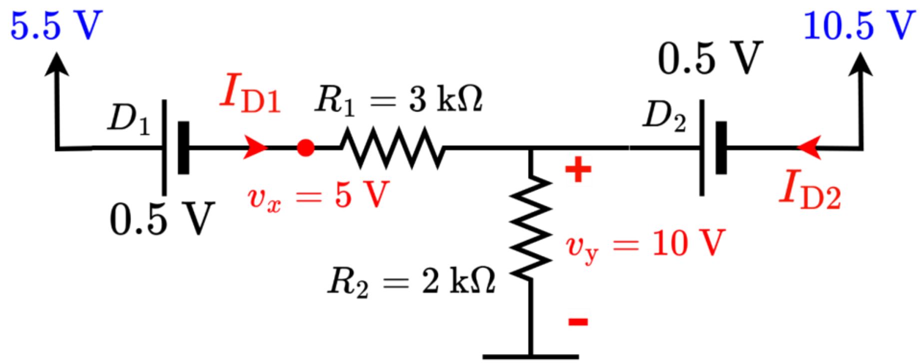
Solve:

$$v_x = 5.5 - v_{D1} = 5\ \mathbf{V}$$

$$v_y = 10.5 - v_{D2} = 10\ \mathbf{V}$$

$$I_{D1} = \frac{v_x - v_y}{R_1} = \frac{-5\ \mathrm{V}}{3\ \mathrm{k}\Omega} \boxed{= -1.66\ \mathbf{mA} < \mathbf{0}}$$

$$I_{D2} = \frac{v_y}{R_1} - I_{D1} = \frac{10}{2} - \frac{-5}{3} \boxed{= \frac{20}{3}\ \mathbf{mA} > \mathbf{0}}$$



Verify: $I_{D1} > 0\ \mathbf{mA}$, || $I_{D2} > 0\ \mathbf{mA}$

Here, $I_{D1} < 0\ \mathbf{mA}$. **Assumption is INCORRECT!**

Solving Circuits with diodes (9)

Example 9: Analyze the circuit to find I_{D1}, I_{D2}, v_x and v_y. Consider $\boldsymbol{V_{DO} = 0.5\ V}$.

[Validate Assumptions]

Assume:

D1 in RB		D2 are in FB
$I_{D1} = 0\ \mathbf{mA}$,	||	$v_{D2} = 0.5\ \mathbf{V}$
$v_{D1} < 0.5\ \mathbf{V}$,	||	$I_{D2} > 0\ \mathbf{mA}$

Solve:

$$v_y = 10.5 - v_{D2} = 10\ \mathbf{V}$$

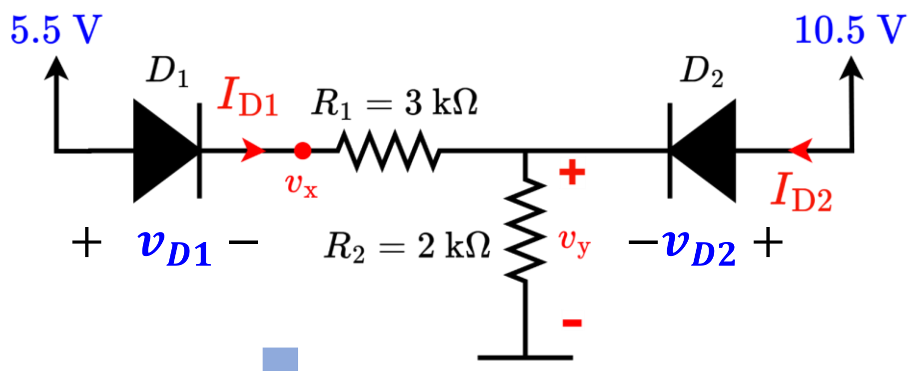
$$v_x = v_y = \mathbf{10\ V}, \text{as } I_{D1} = 0$$

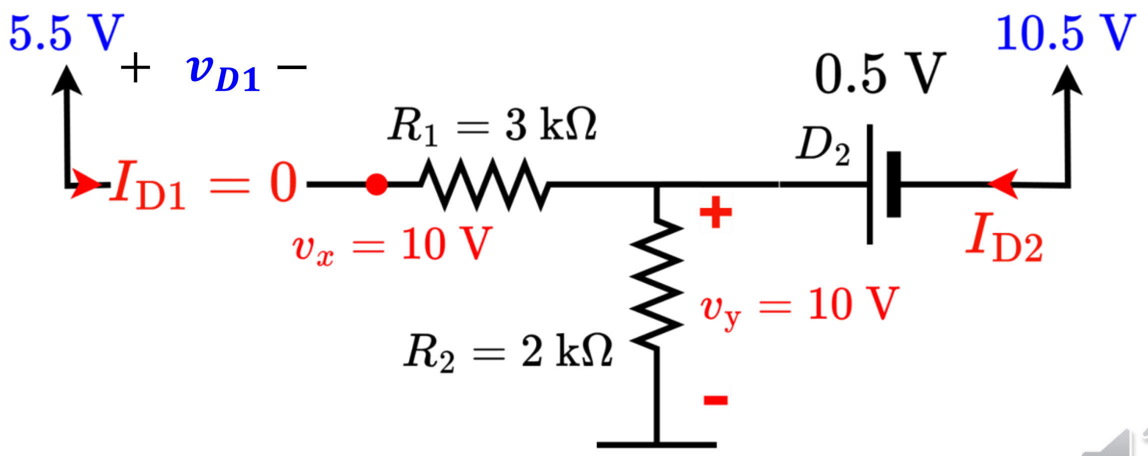
$$v_{D1} = 5.5 - v_x \boxed{= -4.5\ \mathbf{V} < 0.5\ \mathbf{V}}$$

$$I_{D2} = \frac{v_y}{R_1} = \frac{10}{2} = \boxed{5\ \mathbf{mA} > 0}$$

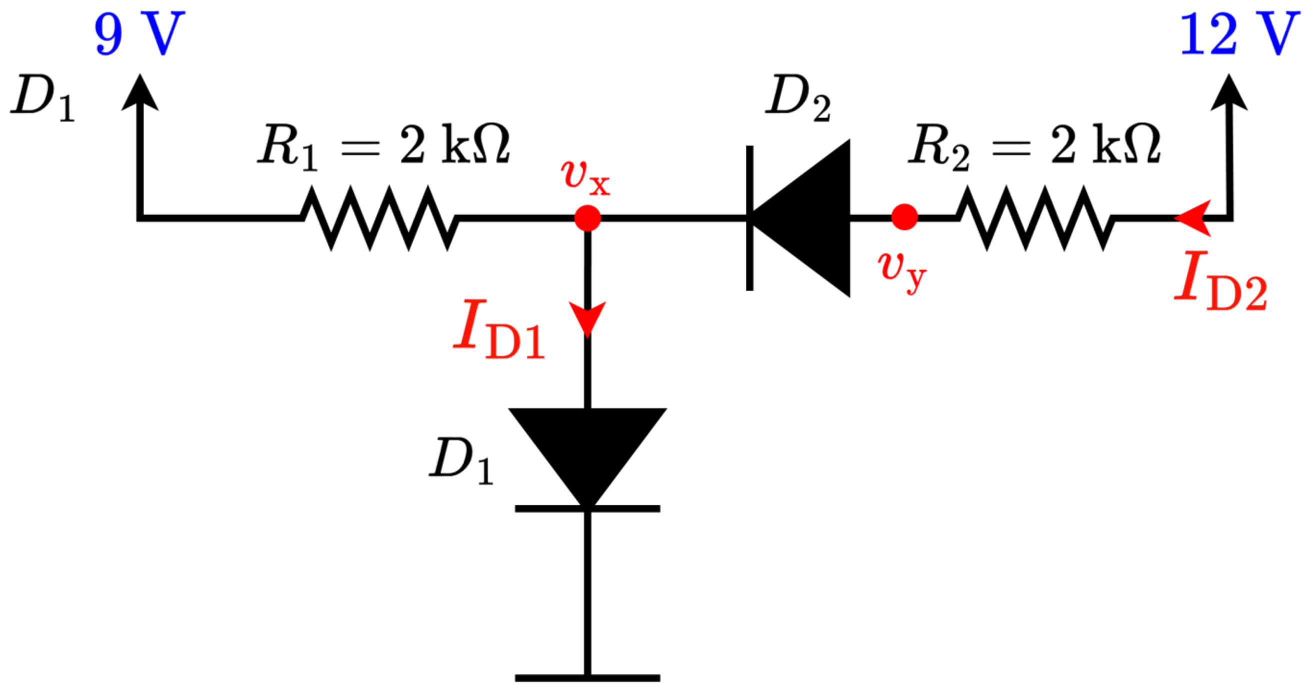
Verify: $v_{D1} < 0.5\ \mathbf{V}$, || $I_{D2} > 0\ \mathbf{mA}$

Assumption is Correct!





Solving Circuits with diodes (10)



Example 10: Analyze the circuit to find I_{D1}, I_{D2}, v_x and v_y. Consider $\boldsymbol{V_{DO} = 1\ \text{V}}$. **[Validate Assumptions].** Are the diodes consuming power or delivering power?

Solving Circuits with diodes (10)

Example 10: Analyze the circuit to find I_{D1}, I_{D2}, v_x and v_y. Consider $\boldsymbol{V_{DO} = 1\ \mathrm{V}}$. [Validate Assumptions]. Are the diodes consuming power or delivering power?

Assume:

D1, D2 are in **FB**: A **constant voltage source of** $\boldsymbol{V_{DO}}$ voltage,

$\boldsymbol{v_{D1}} = 1\ \mathbf{V}$, || $\boldsymbol{v_{D2}} = 1\ \mathbf{V}$

$\boldsymbol{I_{D1}} > 0\ \mathbf{mA}$, || $\boldsymbol{I_{D2}} > 0\ \mathbf{mA}$

Solve:

$$\boldsymbol{v_x} = \boldsymbol{v_{D1}} = 1\ \mathbf{V}$$

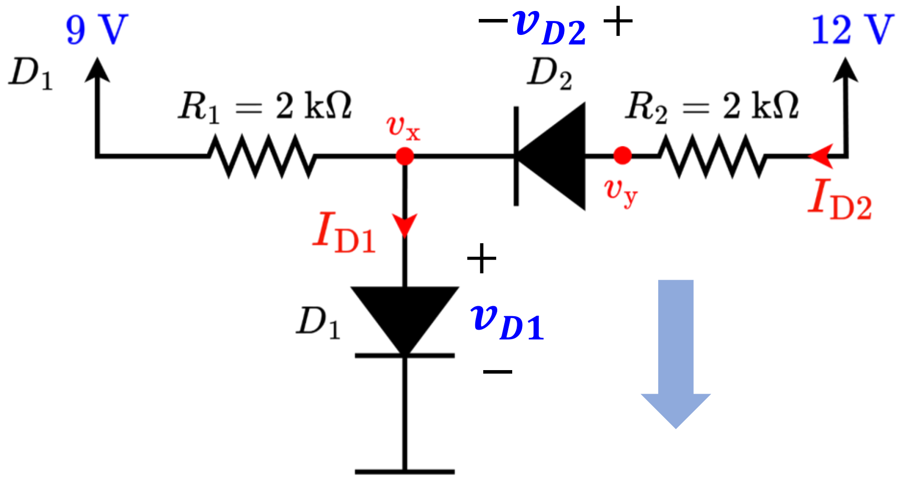
$$\boldsymbol{v_y} = \boldsymbol{v_x} + \boldsymbol{v_{D2}} = 2\ \mathbf{V}$$

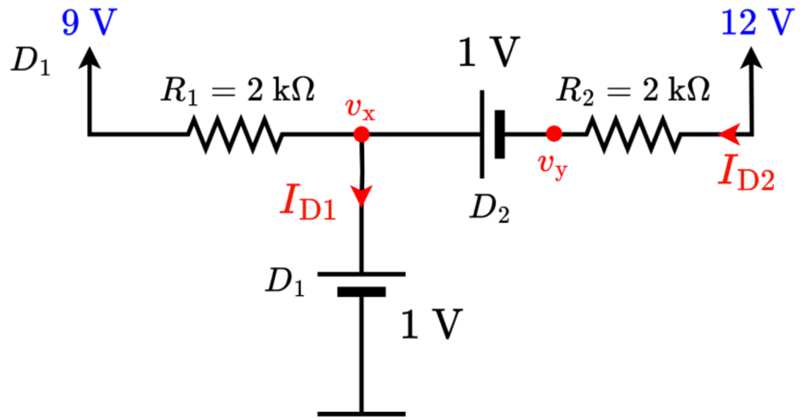
$$\boldsymbol{I_{D2}} = \frac{\mathbf{12} - \boldsymbol{v_y}}{R_2} = \frac{10}{2} \boxed{= 5\ \mathbf{mA} > \mathbf{0}}$$

$$\boldsymbol{I_{D1}} = \boldsymbol{I_{D2}} + \frac{\mathbf{9} - \boldsymbol{v_x}}{R_1} = 5 + \frac{8}{2} \boxed{= 9\ \mathbf{mA} > \mathbf{0}}$$

Verify: $\boldsymbol{I_{D1}} > 0\ \mathbf{mA}$, || $\boldsymbol{I_{D2}} > 0\ \mathbf{mA}$

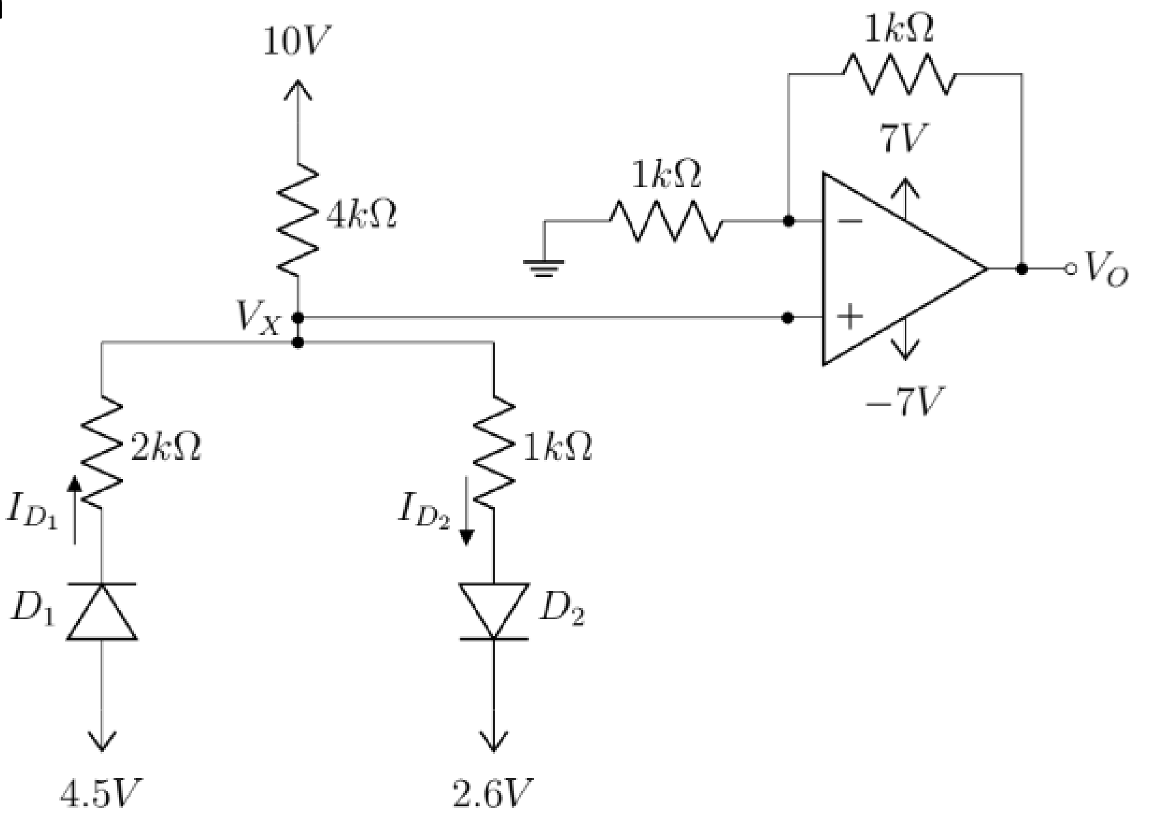
Assumption is Correct!





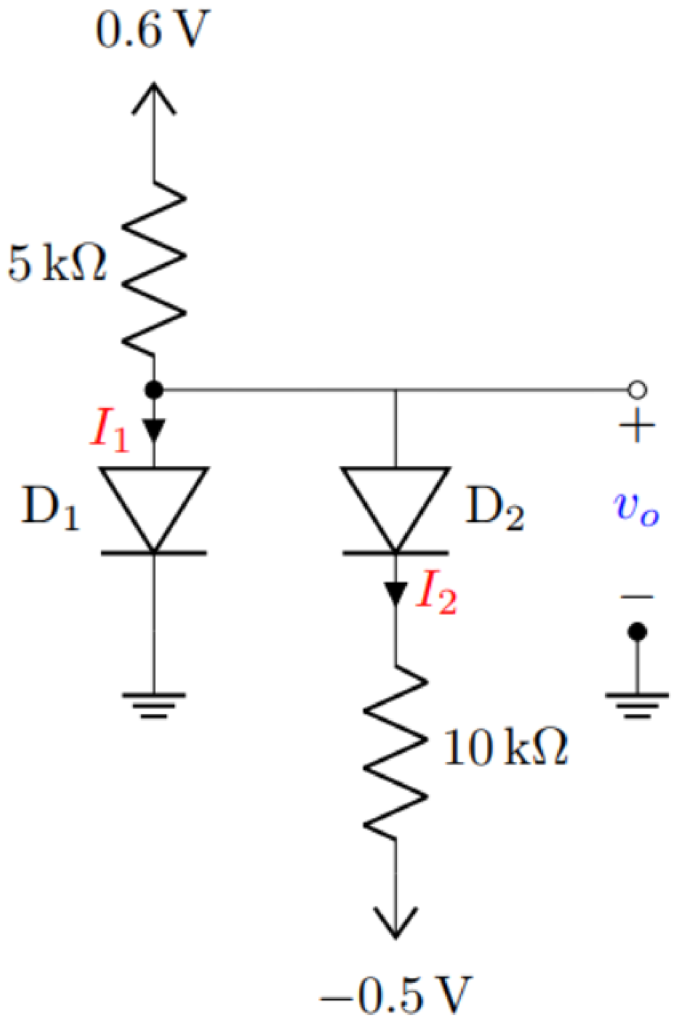
Solving Circuits with diodes (11)

Consider the following circuit with an ideal OP-Amp an
two diodes. The Diode D_1 and D_2 have V_{Do} of 0.5V and 0.6V respectively.



a) State the equivalent circuit model of an ideal diode in reverse bias.
b) Analyze the circuit and calculate V_x, I_{D1} and I_{D2}. Use method of assumed states. You must validate your assumption.
c) Determine the output voltage V_o .

Solving Circuits with diodes (12)



Analyze the circuit to find I_1, I_2, and $\boldsymbol{v_O}$ for

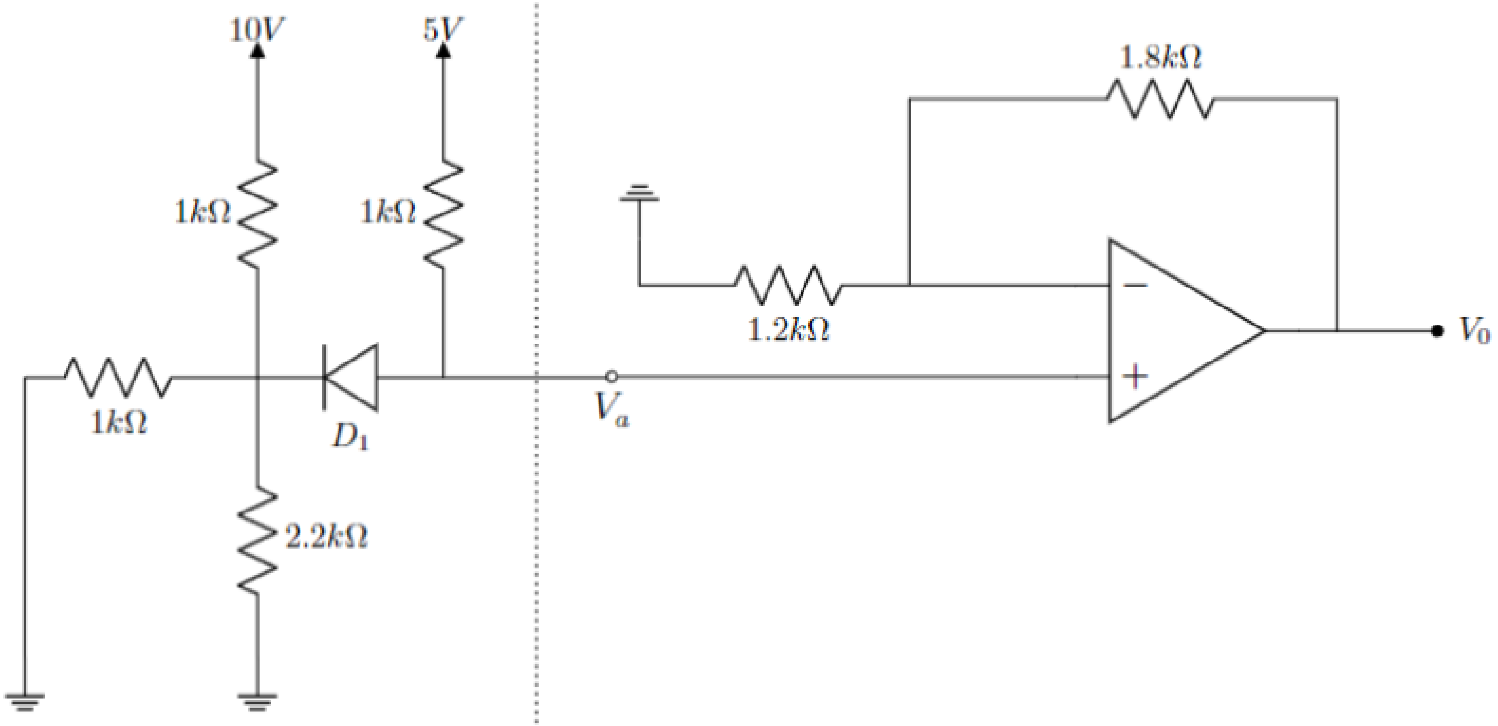
i. Assuming all diodes as ideal

ii. Consider $\boldsymbol{V_{D1} = 0.5\ \mathrm{V}}$ and $\boldsymbol{V_{D2} = 0.7\ \mathrm{V}}$. **(CVD model)**

iii. Consider $\boldsymbol{V_{DO} = 0.6\ \mathrm{V}}$ and $\boldsymbol{r_d = 50\ \Omega}$. **(CVD+R model)**

[Validate Assumptions]

Solving Circuits with diodes (13)



The saturation voltages of the Op-Amp are given as- $V^{+}_{sat} = +\ 10V$ and $V^{-}_{sat} = -\ 10V$. The forward voltage drop of the diode, V_D is $0.7V$.

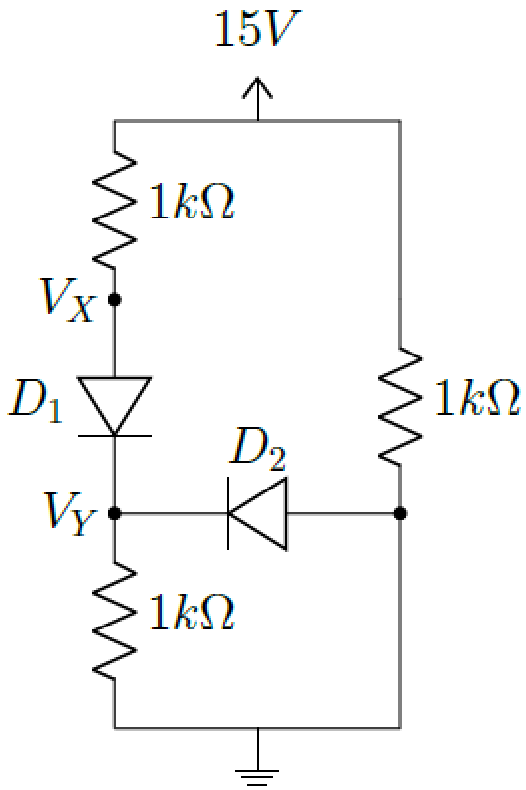
(a) **Determine** the operating mode diode, D_1. Verify your assumption with necessary calculations.

(b) **Calculate** the voltage at - (i) node 'Va', (ii) non-inverting terminal of the Op-Amp, (iii) inverting terminal of the Op-Amp.

(c) Find out the output voltage, Vo of the Op-Amp.

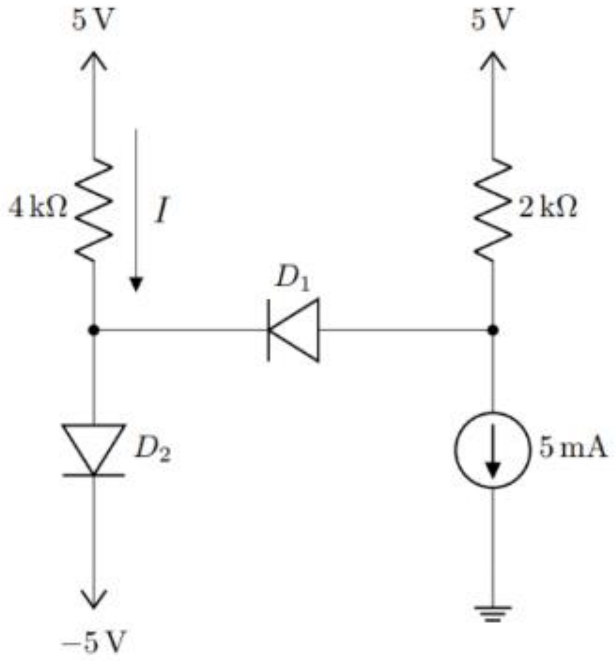
Solving Circuits with diodes (14)

Analyze the circuit to calculate V_X, V_Y, I_{D1} and I_{D2} using the method of assumed states. You must validate your assumptions. Use V_{DO} = 0.7V for both diodes.



Solving Circuits with diodes (15)

Determine I for the circuit shown below using CVD model (with V_{DO} = 0.7V



Thank You!