L3
part 2
sec 2
8/7/2021

ENEE2360

Analog Electronics

T2: Semiconductor Diodes and Diode Models

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Diode Operating Conditions/Modes

A diode has three operating Modes:

1) **No bias**
2) **Reverse bias** → external voltage source
3) **Forward bias**

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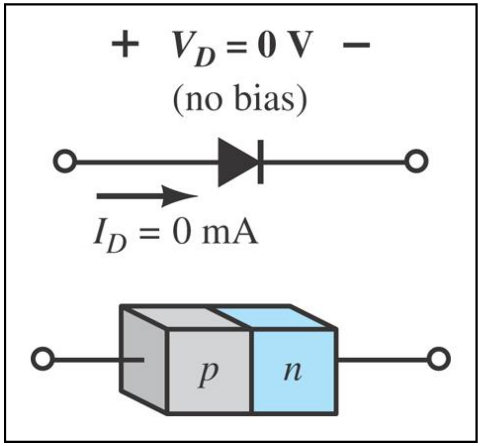
Diode Operating Modes

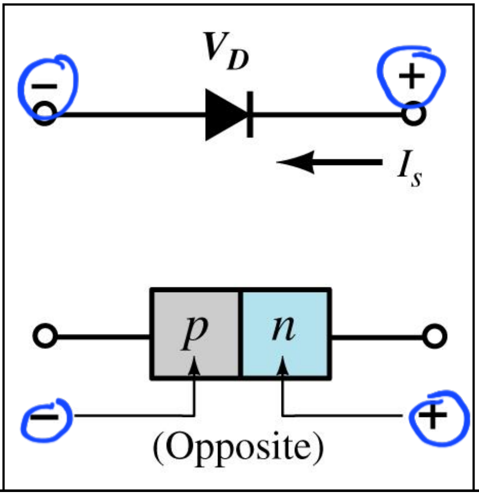
1) No Bias Condition

- No external voltage is applied: $V_D = 0$ V
- There is no diode current: $I_D = 0$ A
- Only a modest depletion region exists



2) Reverse Bias Condition

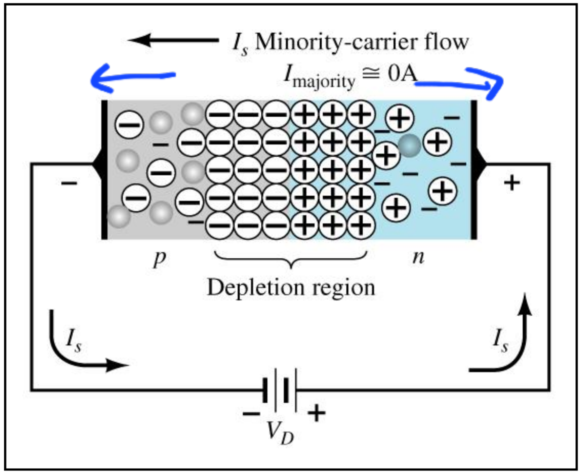
- External voltage is applied across the *p-n* junction in the opposite polarity of the *p-* and *n-*type materials.



Diode Operating Modes

Reverse Bias

- The reverse voltage causes the depletion region to widen.

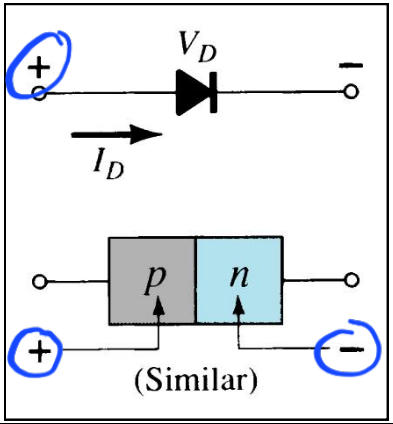


- The electrons in the *n*-type material are attracted toward the positive terminal of the voltage source.

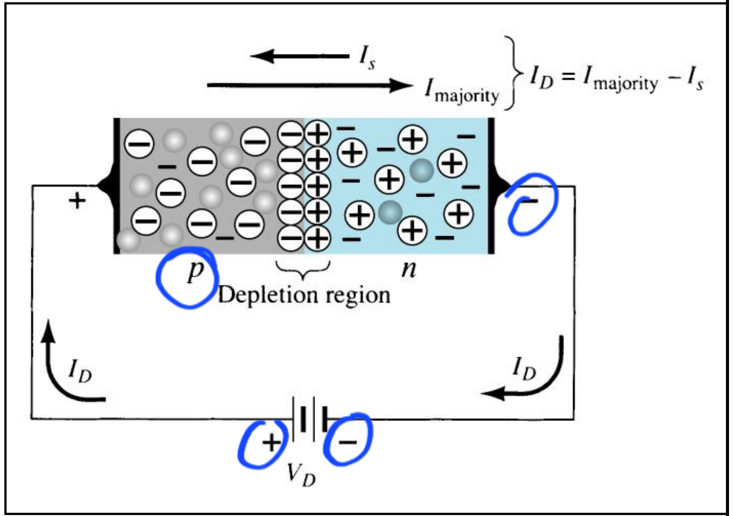
- The holes in the *p*-type material are attracted toward the negative terminal of the voltage source.

Diode Operating Modes

3) Forward Bias Condition



- External voltage is applied across the *p-n* junction in the same polarity as the *p-* and *n*-type materials.
- The forward voltage causes the depletion region to narrow.
- The electrons and holes are pushed toward the *p-n* junction.
- The electrons and holes have sufficient energy to cross the *p-n* junction.



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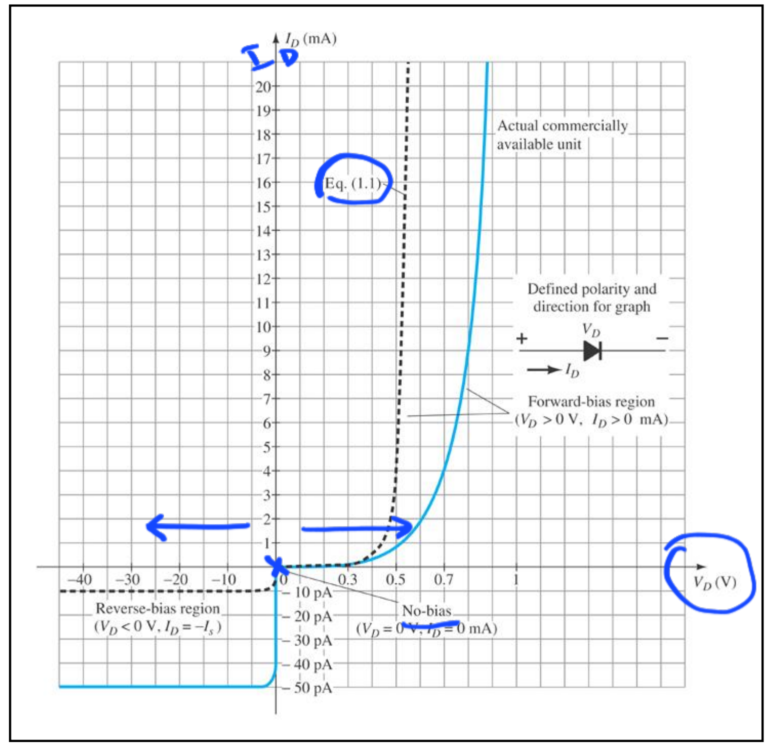
Actual Diode Characteristics

Note the regions for no bias, reverse bias, and forward bias conditions.

Carefully note the scale for each of these conditions.



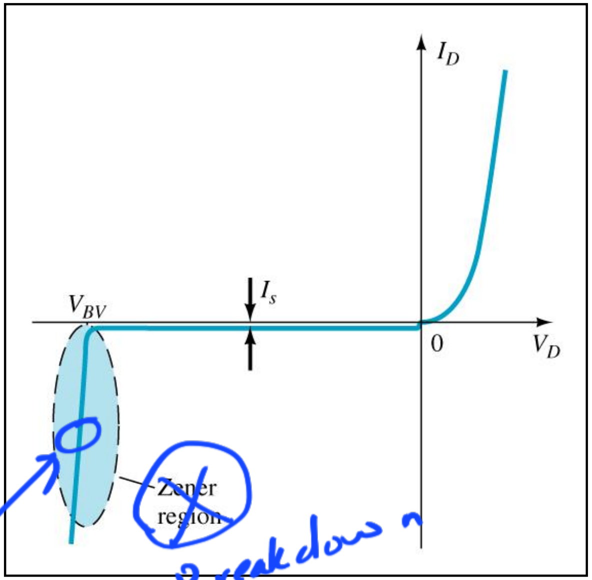
Zener Region (Breakdown Region)

The Zener region is in the diode's reverse-bias region.

At some point the reverse bias voltage is so large the diode breaks down and the reverse current increases dramatically.

The maximum reverse voltage that won't take a diode into the zener region is called the **peak inverse voltage** or **peak reverse voltage**.

The voltage that causes a diode to enter the zener region of operation is called the **zener voltage (V_Z) or reverse breakdown voltage (V_{BV}) .**

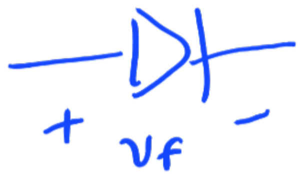


I^2R ↑, heat, damage of Diode

Forward Bias Voltage

The point at which the diode changes from no-bias condition to forward-bias condition occurs when the electrons and holes are given sufficient energy to cross the p-n junction. This energy comes from the external voltage applied across the diode.

The forward bias voltage required for a:



gallium arsenide diode ≅ 1.2 V

silicon diode ≅ 0.7 V

germanium diode ≅ 0.3 V

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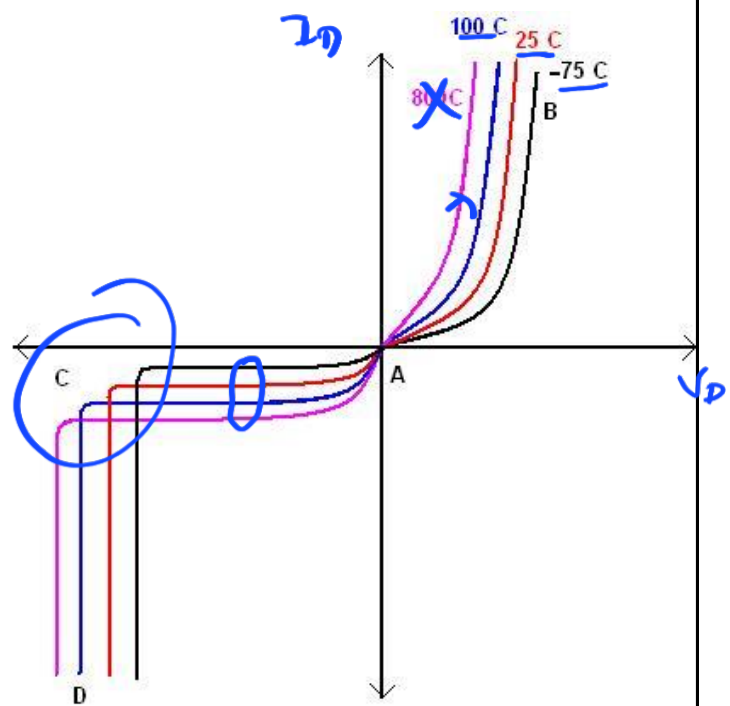
Temperature Effects

As temperature increases it adds energy to the diode.

- It reduces the required forward bias voltage for forward-bias conduction.
- It increases the amount of reverse current in the reverse-bias condition.
- It increases maximum reverse bias avalanche voltage.

$P = I^2 R$



Germanium diodes are more sensitive to temperature variations than silicon or gallium arsenide diodes.

Diode Internal Resistance

Semiconductors react differently to DC and AC currents.

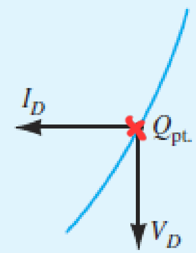
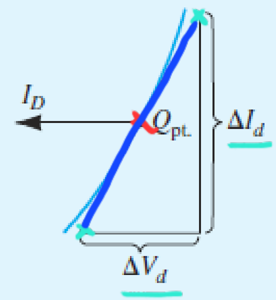
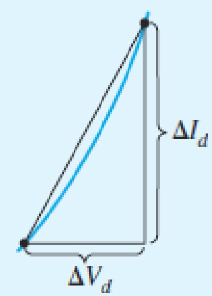
There are three types of resistance:

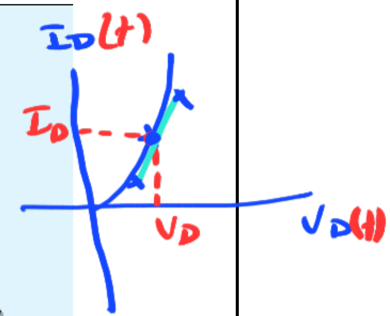
DC (static) resistance

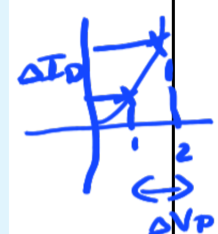
AC (dynamic) resistance

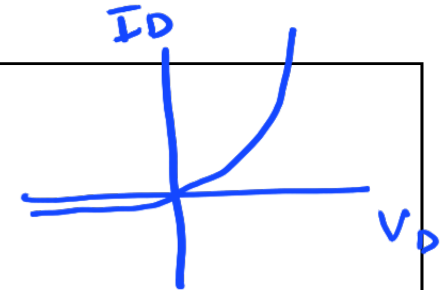
Average AC resistance

Resistance Levels

Type	Equation	Special Characteristics	Graphical Determination
DC or static	$R_D = \dfrac{V_D}{I_D}$	Defined as a point on the characteristics	
AC or dynamic	$r_d = \dfrac{\Delta V_d}{\Delta I_d} = \dfrac{26\text{ mV}}{I_D}$	Defined by a tangent line at the Q-point	
Average ac	$r_{av} = \dfrac{\Delta V_d}{\Delta I_d}\bigg\rvert_{\text{pt. to pt.}}$	Defined by a straight line between limits of operation	

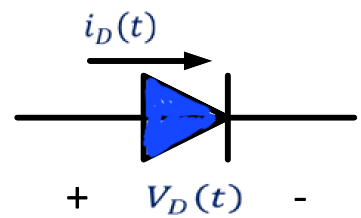






Diode Equation

$$i_D(t) = I_S\left(e^{\frac{V_D(t)}{\eta V_T}} - 1\right)$$



Is: Reverse saturation current

$Is = 10^{-12}, 10^{-14}$ A

η : eta

$1 \le \eta \le 2$

for example

$$\eta = \begin{cases} 1 \; for \; Ge \\ 2 \; for \; Si \; (small \; current) \\ 1 \; for \; Si \; (large \; current) \end{cases}$$

V_T= Thermal Voltage

$V_T = \frac{T}{11600}$;T in kelvin

At Room Temp. (25°C) T=~~300~~ 298 k

∴ V_T = 25.69 mv at Room Temp.

- The equation is a non linear equation

∴ The Diode is non linear Device

$0°C \rightarrow 273\ K$

$25°C \rightarrow 298\ K$

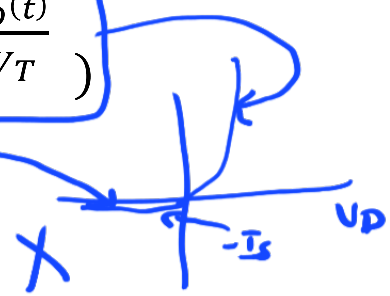
$V_T = \frac{298}{11600} \approx 25.69\ mV$

$$i_D(t) = I_S(e^{\frac{V_D(t)}{\eta V_T}} - 1)$$

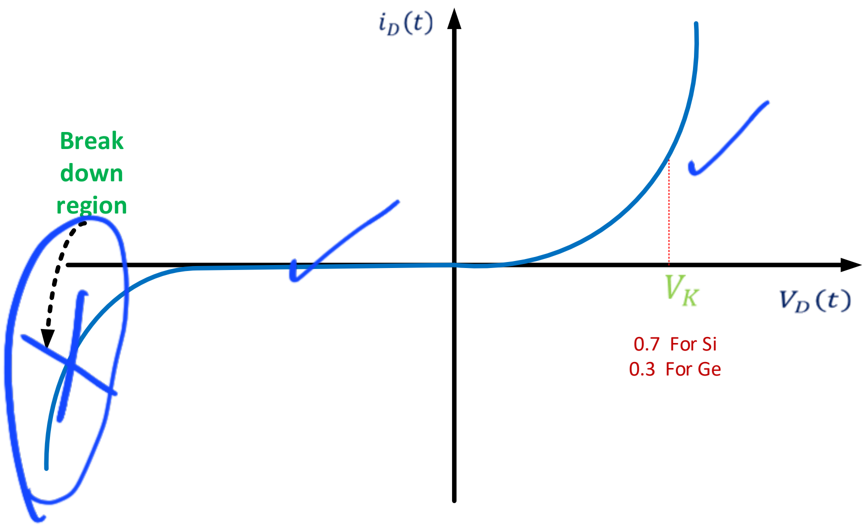
($e^{\frac{V_D(t)}{\eta V_T}} \ll 1$)

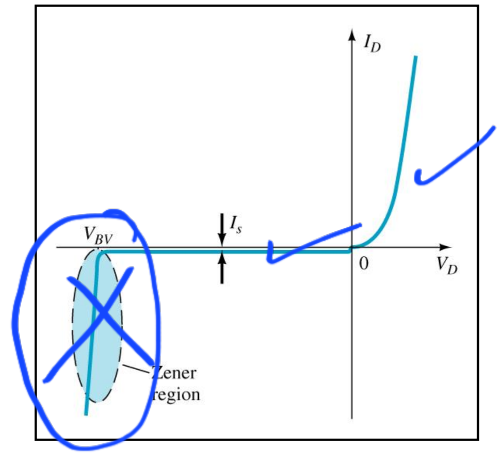
- For positive $V_D(t)$, $i_D(t) = I_S(e^{\frac{V_D(t)}{\eta V_T}})$

- **For negative V_D(t)** $i_D(t) = -I_S$

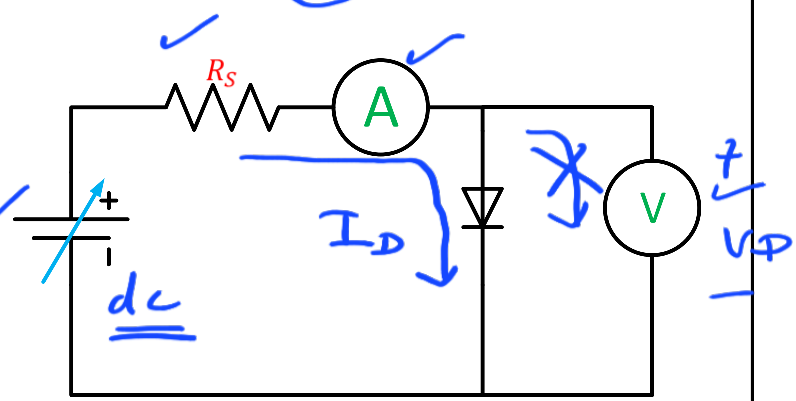


Diode V-I Characteristic curve





practical circuit to measure diode curve



Approaches to Diode Circuit Analysis

Find I_D ? V_D ?

The rectifier diode is a non linear device .

There are essentially three basic approaches to the solution of such problem :

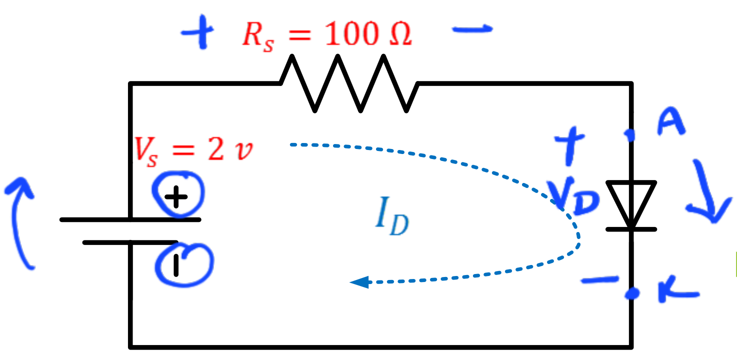
1- The use of non linear mathematics

2- The use of graphical techniques

3- The use of equivalent circuit (models)

1)The use of non linear mathematic (shown , but not required)

- For the circuit shown, find I_D and V_D



Silicon:
η=1.1
I_S= 10^{-14} A

- KVL : $V_S = R_S I_D + V_D$ ... (1)

$$I_D = I_S(e^{\frac{V_D}{\eta V_T}} - 1)$$ ... (2)

- Since the diode is forward biased , we could approximate

$$I_D = I_S(e^{\frac{V_D}{\eta V_T}})$$

$$\frac{I_D}{I_S} = e^{\frac{V_D}{\eta V_T}}$$

$$\ln \frac{I_D}{I_S} = \frac{V_D}{\eta V_T}$$

- Solving for $V_D = \eta V_T \ln \frac{I_D}{I_S}$ ...

∴ We have two equations and two unknowns

$$V_S = R_S I_D + V_D \text{ .... } 1$$

$$\mathbf{V_D = \eta\, V_T} \ln \frac{I_D}{I_S} \text{ .... } 2$$

$$\therefore \quad V_S = R_S I_D + \eta\, V_T \ln \frac{I_D}{I_S}$$

- **non linear equation**

Iterative Analysis

2) $I_D = \frac{V_S - V_D}{R_S}$

3) $V_D = \eta V_T \ln \frac{I_D}{I_S}$

1) Let V_D = 0.7v

$I_D = \frac{2-0.7}{0.1k}$ = 13 mA

V_D = 0.7882392v The error is large

$\frac{0.088}{0.7}$

2) Let V_D = 0.7882392v

I_D = 12.117608 mA

V_D = 0.7862529v The error is small

$\frac{0.0020}{0.788}$

3) Let $V_D = 0.7862529\text{v}$

$I_D = 12.137471\ \text{mA}$

$V_D = 0.7862991\ \text{V}$ The error getting smaller

4) Let $V_D = 0.7862991\ \text{V}$

$V_D = 0.786298066\ \text{V}$

$I_D = 12.137009\text{mA}$

$I_D = 12.137\ \text{mA}$

$V_D = 0.7863\text{v}$

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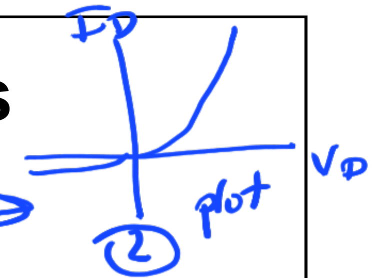
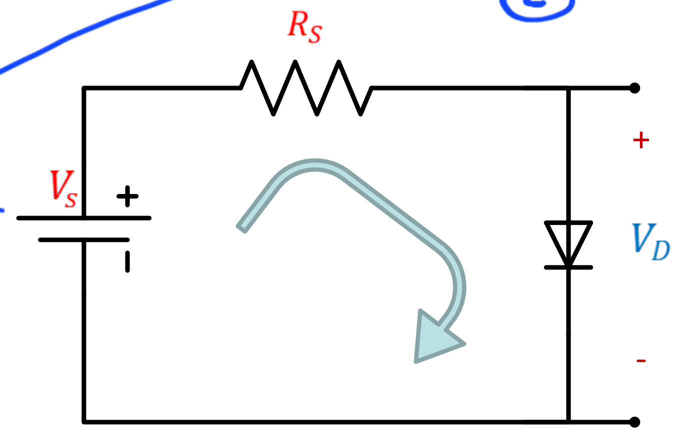
2) The use of graphical techniques

(Requires the V-I exact plot)



$V_S = R_S I_D + V_D$ 1

$I_D = I_S\left(e^{\frac{V_D}{\eta V_T}} - 1\right)$ 2



- Using equation 1

$$I_D = -\frac{1}{R_S}V_D + \frac{V_S}{R_S}$$

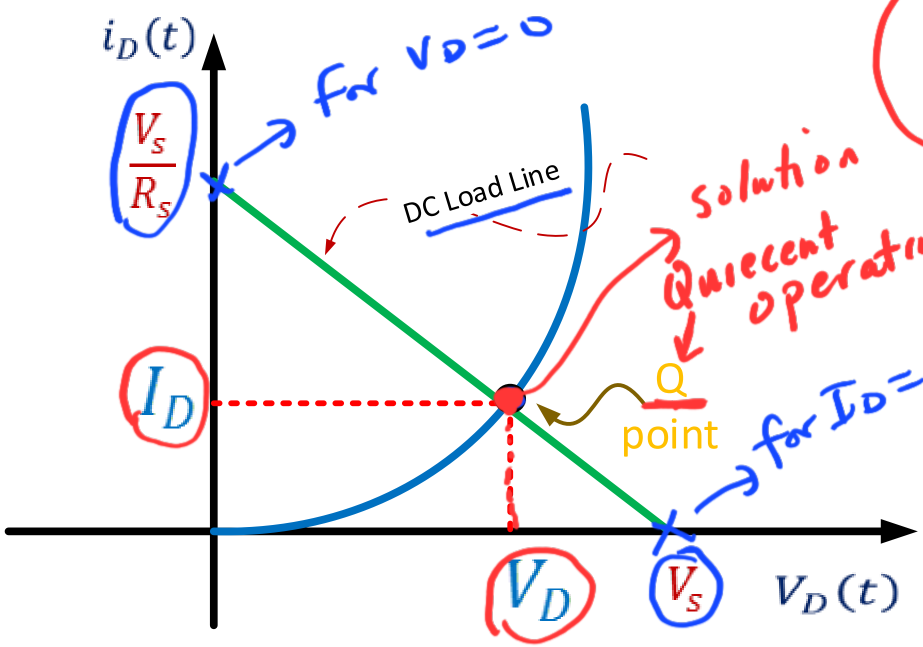
$I_D = f(V_D)$ ... plot

$I_D = \frac{V_S - V_D}{R_S} = \frac{V_S}{R_S} - \frac{V_D}{R_S}$

$I_D = f(V_S)$

$I_D = -\frac{1}{R_S}V_D + V_S/R_S$

Drawing the two equations



$$I_D = -\frac{1}{R_S}V_D + \frac{V_S}{R_S}$$

straight line

$y = ax + b$

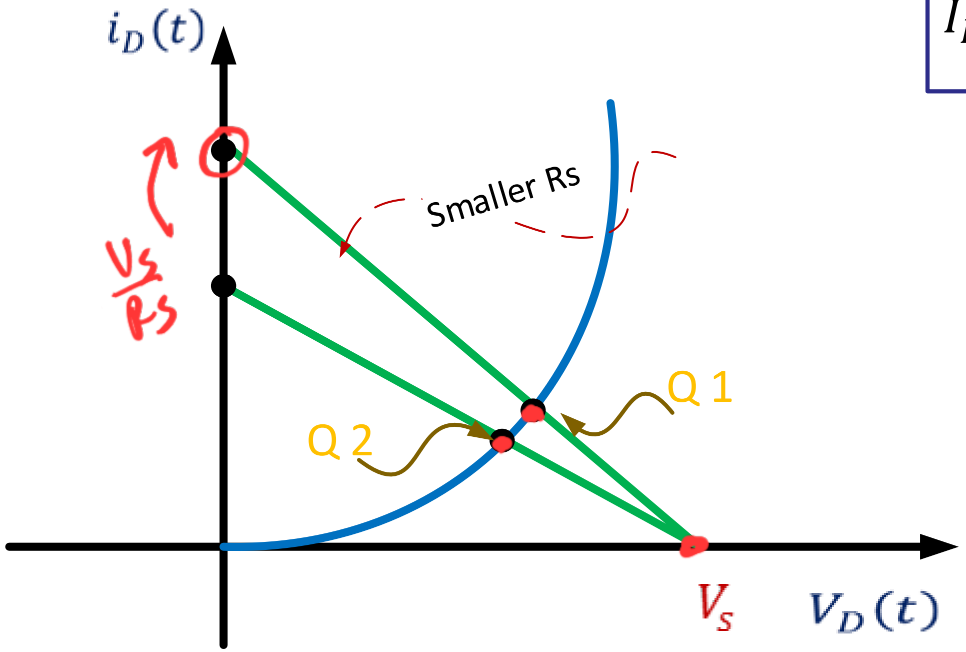
$y = I_D,\ x = V_D$

$a = -\frac{1}{R_S},\ b = \frac{V_S}{R_S}$

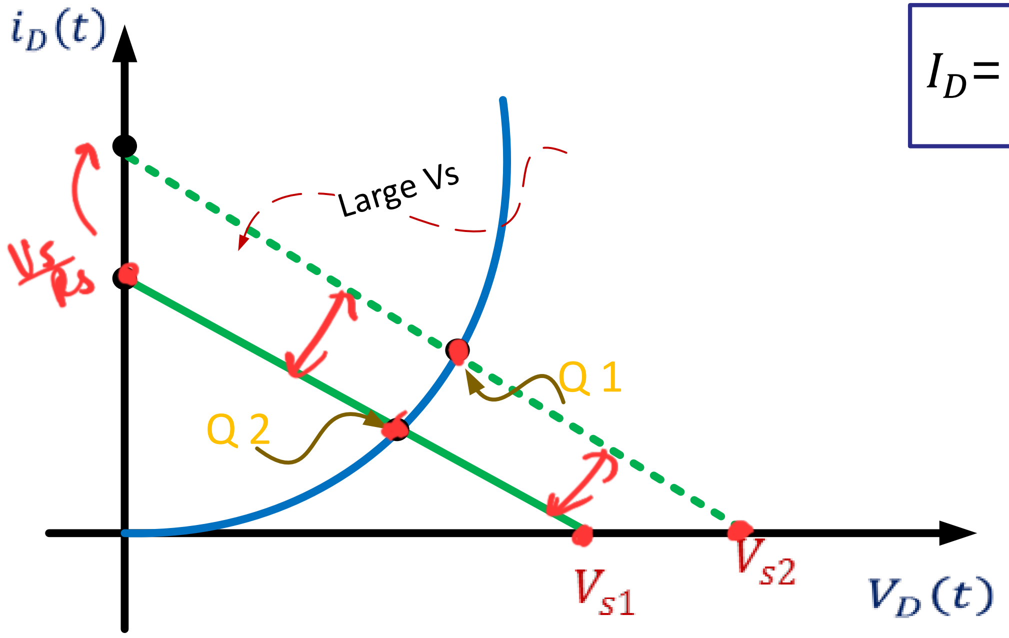
- $Q_{point} = (V_{DQ}, I_{DQ}) = Q_{uiescent\ point}$

The effect of Rs on the Qpoint

$$I_D = -\frac{1}{R_S} V_D + \frac{V_S}{R_S}$$



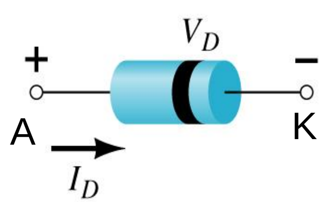
The effect of Vs on Qpoint

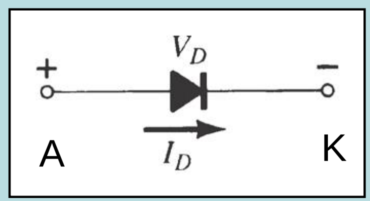


$$I_D = -\frac{1}{R_S}V_D + \frac{V_S}{R_S}$$

Diode (Models)

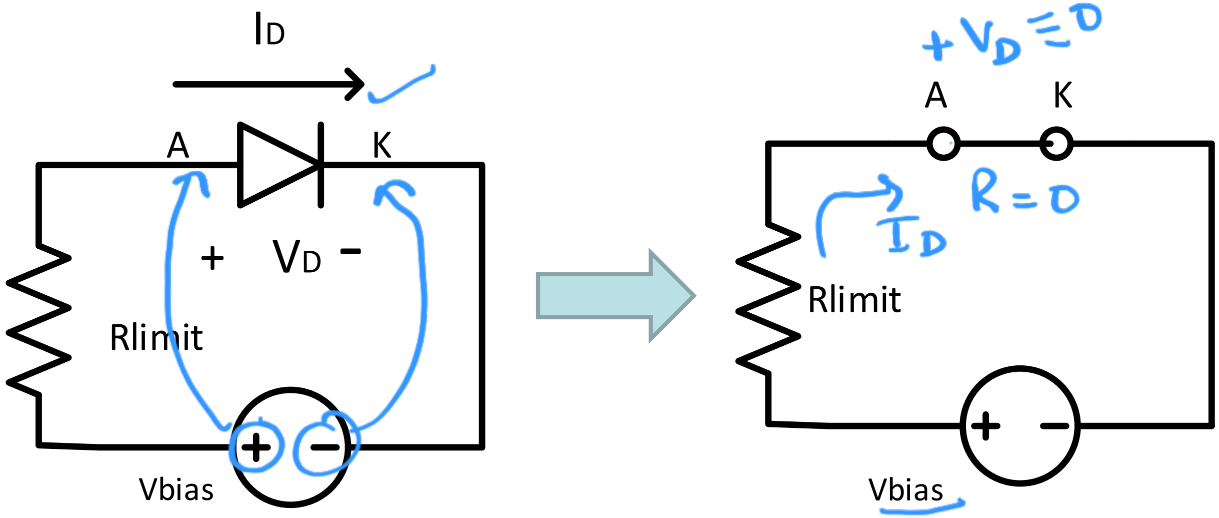
1) Ideal Diode Model
2) Simplified/piecewise/ knee model
3) Complete diode model





Ideal Diode Model

- 1) if the diode is forward biased ==> diode is replaced by short circuit

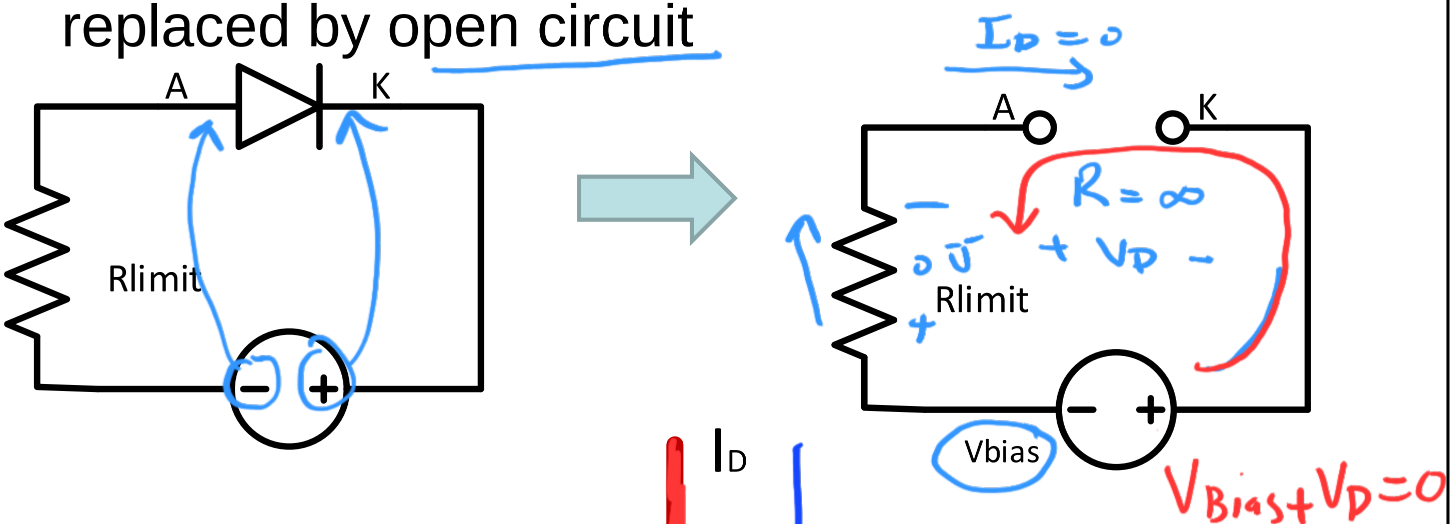


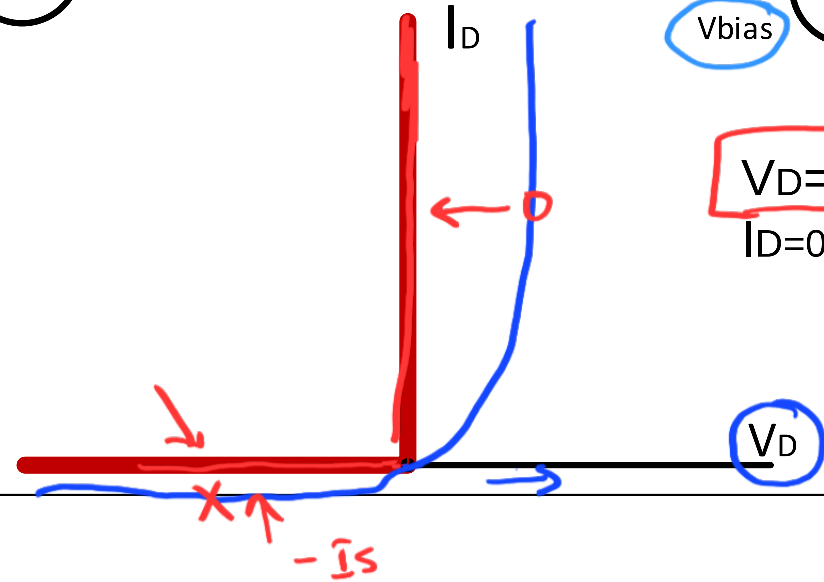
$V_D=0$

$I_D=Vbias/Rlimit$

Ideal Diode Model

- 2) if the diode is Reverse biased ==> diode is replaced by open circuit





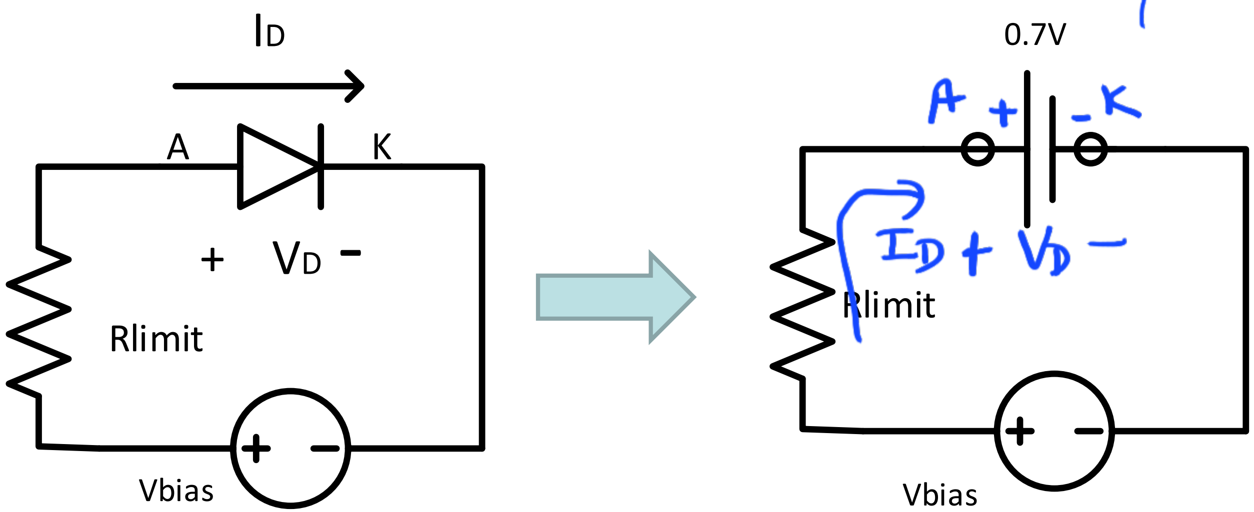
$V_D = -V_{bias}$

$I_D = 0$

Simplified / knee model

Practical

- 1) if the diode is forward biased ==> diode is replaced by a 0.7V battery (for Si)



VD=0.7 V

ID=(Vbias-0.7)/Rlimit

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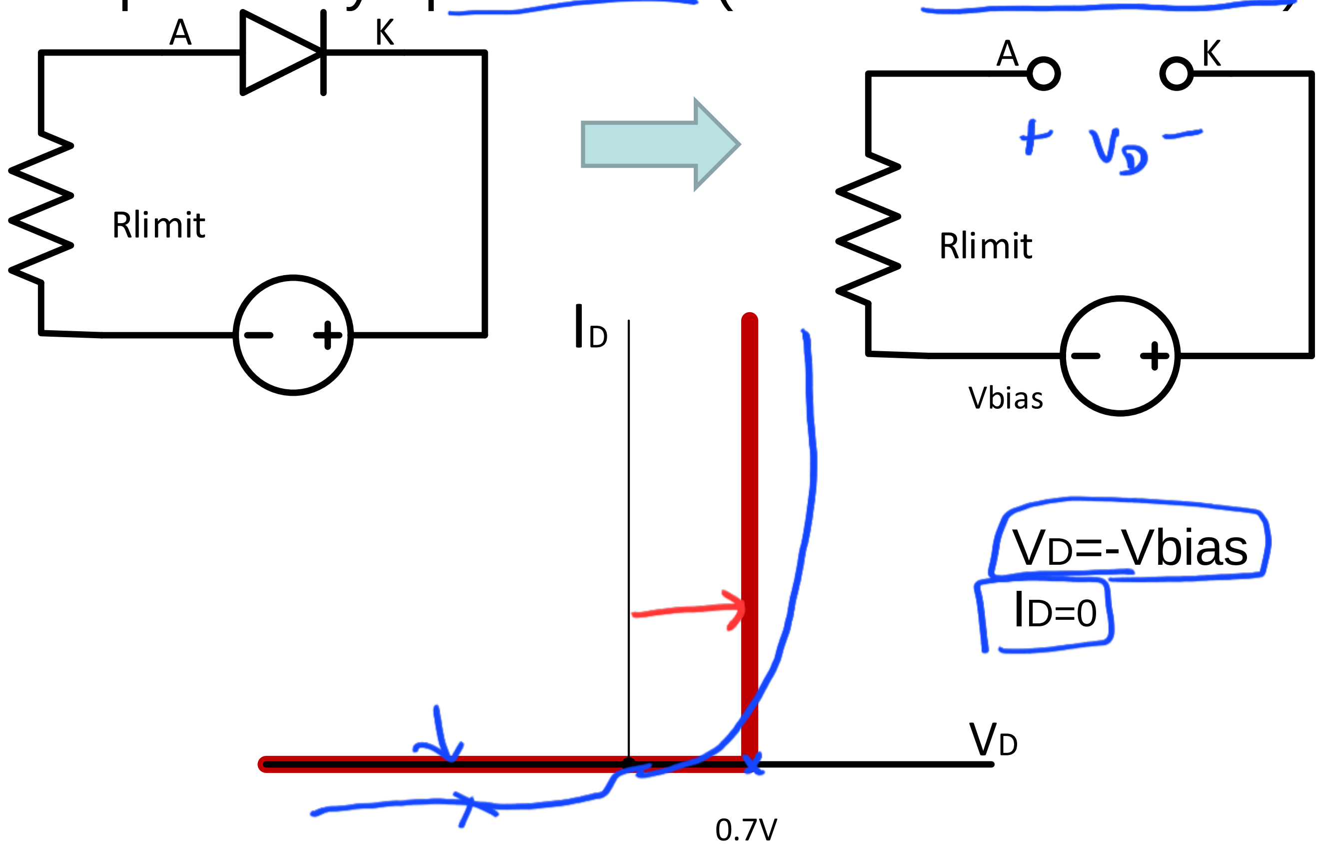
Simplified/ knee model

- 2) if the diode is Reverse biased ==> diode is replaced by open circuit (same as ideal model)



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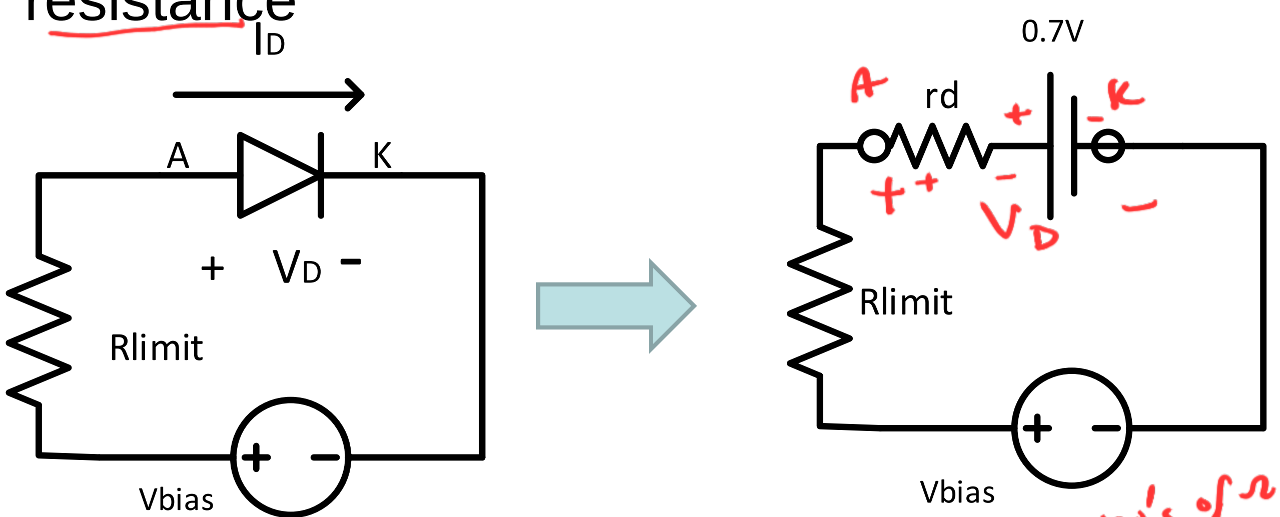
Complete Diode model

- 1) if the diode is forward biased ==> diode is replaced by a 0.7V battery and forward dynamic resistance

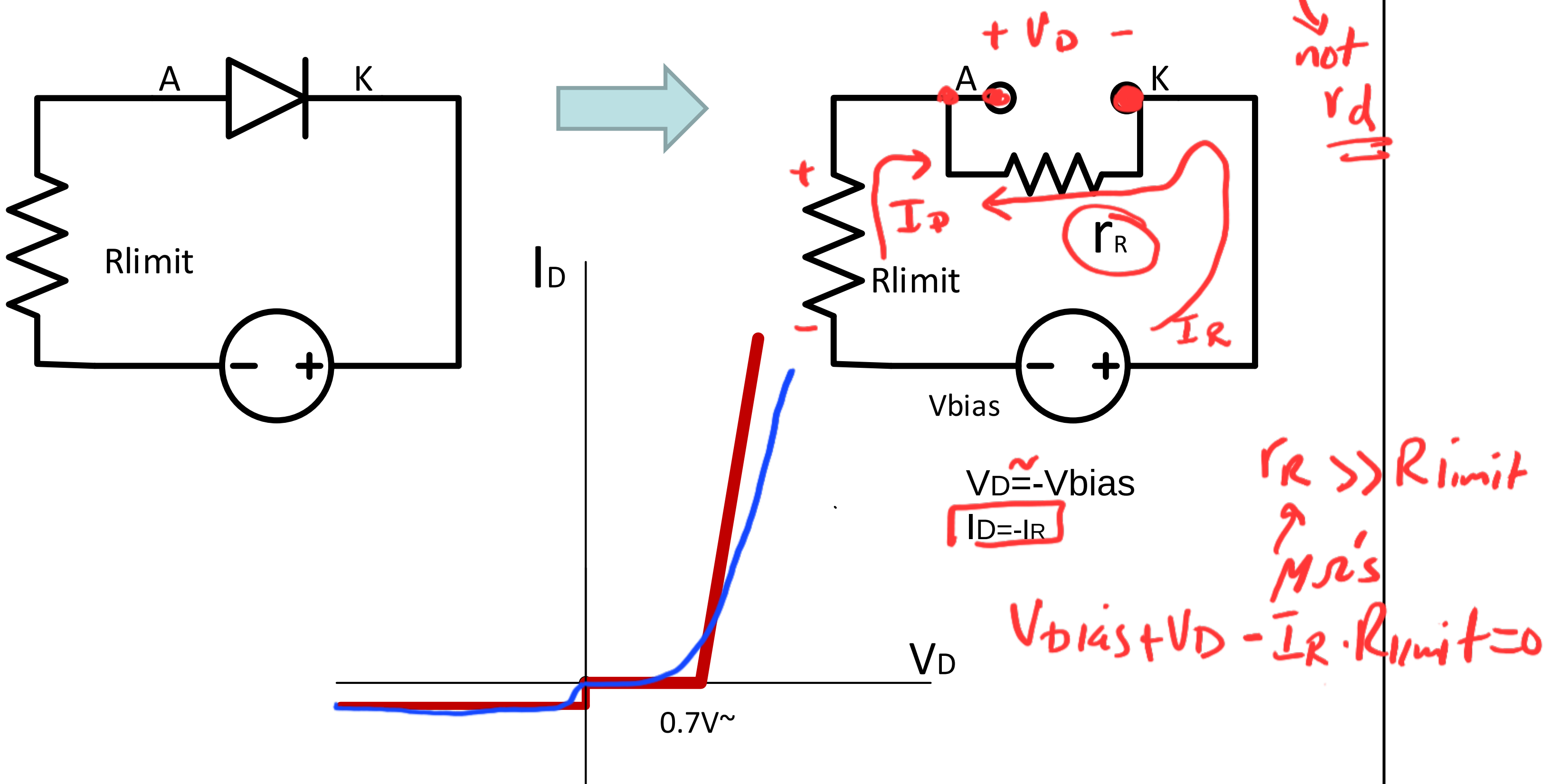


$V_D = 0.7 + I_D \cdot rd$

$I_D = (Vbias - 0.7)/(Rlimit + rd)$

Complete Diode model

- 2) if the diode is Reverse biased ==> diode is replaced by open circuit // to reverse resistance r_R

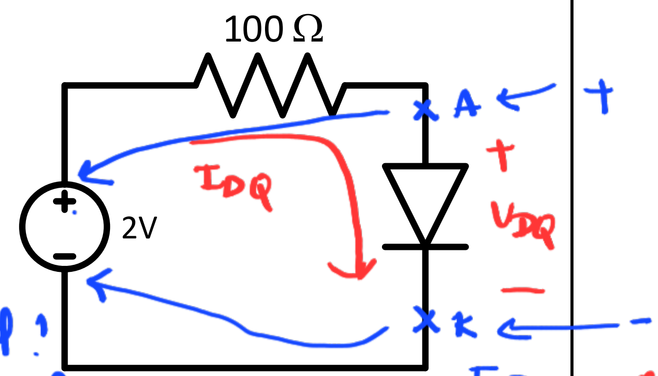


End of L3 8/7/2021

Diode Model
Ideal Practical Complete

Start of L4
13/7/2021

Example:



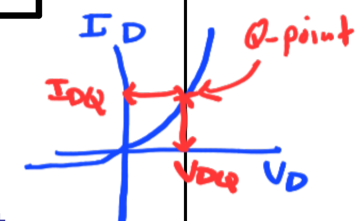
Find the Q-point (I_{DQ} and V_{DQ})

a) Use ideal diode model

b) Use practical diode model

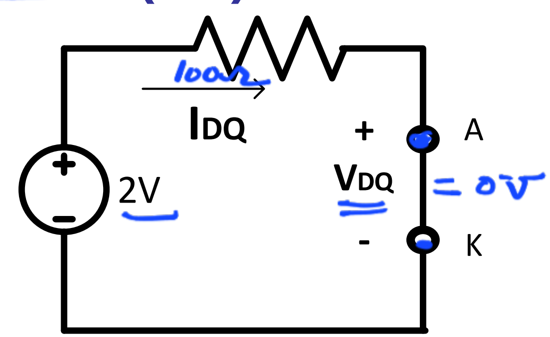
c) Use exact model X

Forward Biased ≡ ON
Reverse " ≡ off



Solution

a) Since VA > VK , diode is forward biased (ON) ==> it can be replaced by a short circuit



$V_{DQ}=V_{AK}=0$ V ✓

$I_{DQ}= 2V/100\ \Omega=20$ mA ✓

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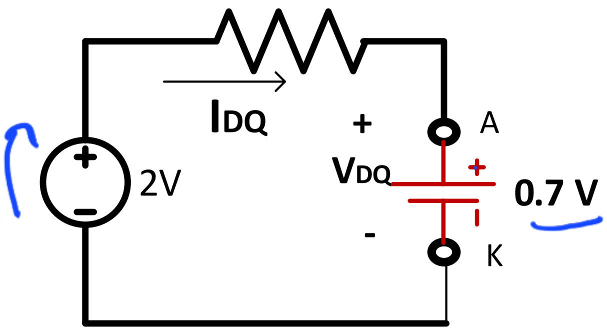
b) When using practical model , diode is replaced by a 0.7 V battery

$V_{DQ} = V_{AK} = 0.7\ V$

$I_{DQ} = (2-0.7)/100 = 13\ mA$



c) Exact solution yields

$V_{DQ} = V_{AK} = 0.786\ V$

$I_{DQ} = 12.14\ mA$

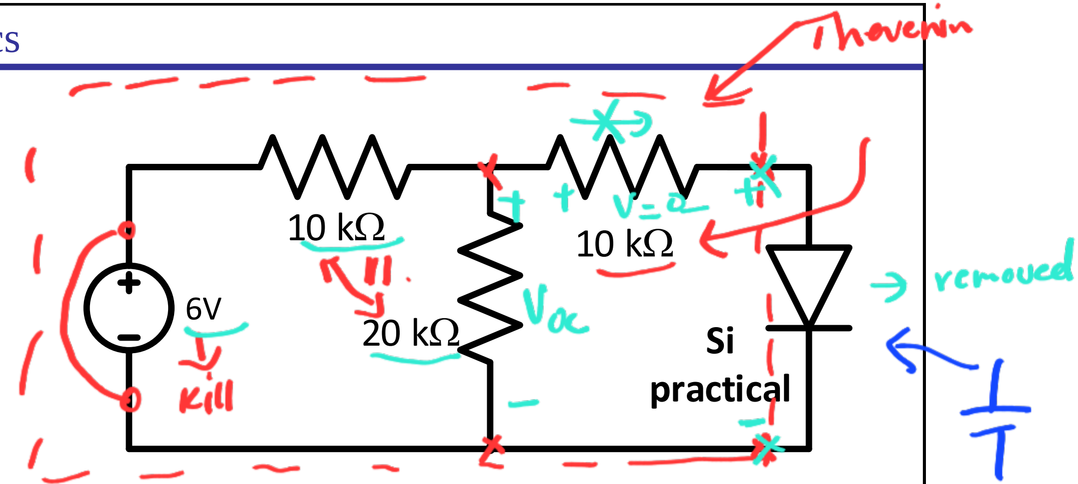
≈ 0.7 V

Note: If applied voltage is much higher than VAK (at least 10 times) , then ideal diode model is recommended

Example:

Find the Q-point

(I_{DQ} and V_{DQ})



Solution

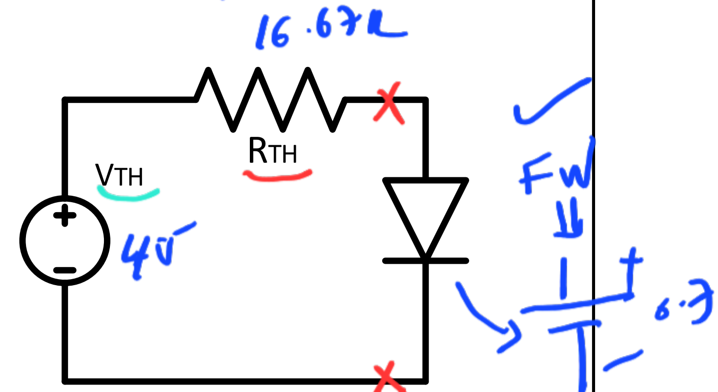
It is better to convert the two loop circuit to a single loop circuit by finding Thevenin's equivalent circuit

V_{TH}=6V. 20k/(20k+10k)=4 V

R_{TH}=(10k+(20k//10k))=16.67 kΩ

V_{DQ}=V_{AK}=0.7 V

I_{DQ}= (4-0.7)/16.67 kΩ = 0.198 mA



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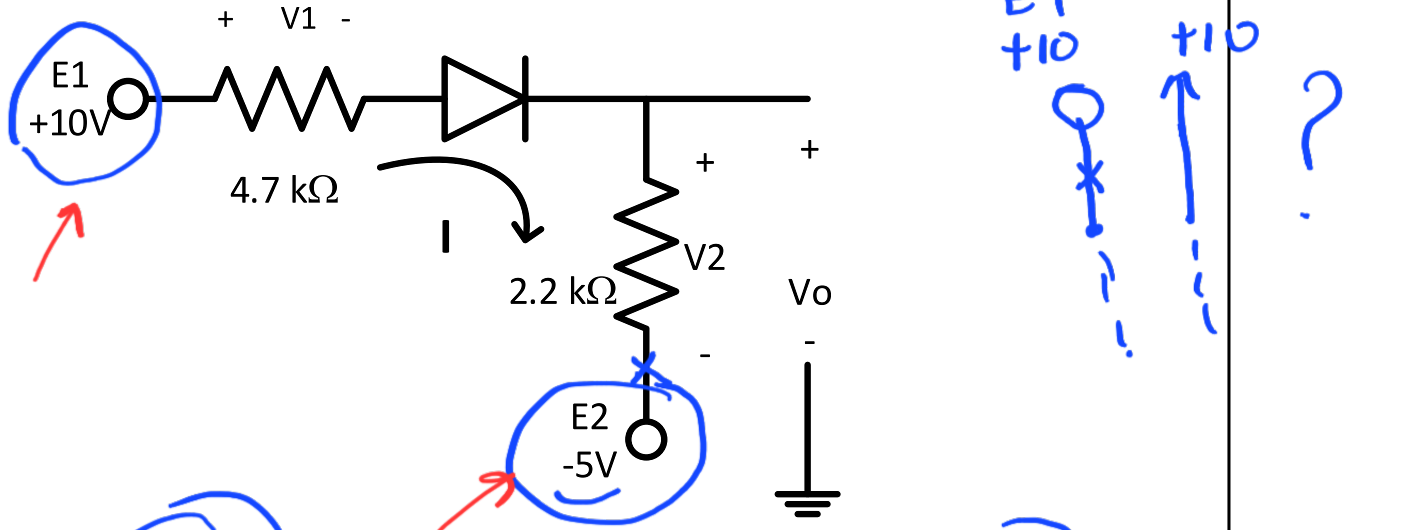
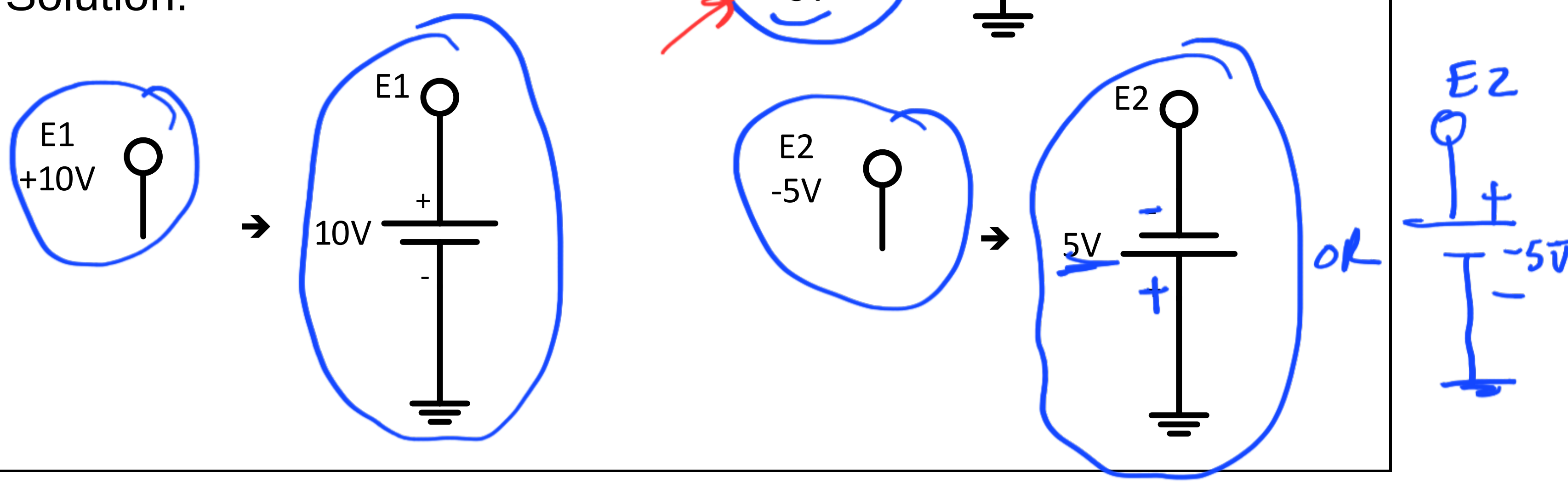
Example: **Find I,V1,V and Vo (use simplified model)**



Solution:



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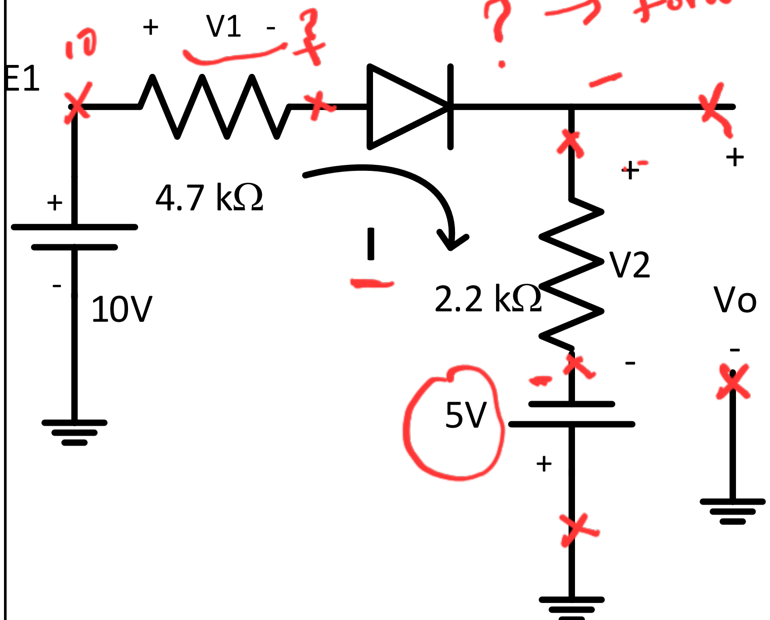
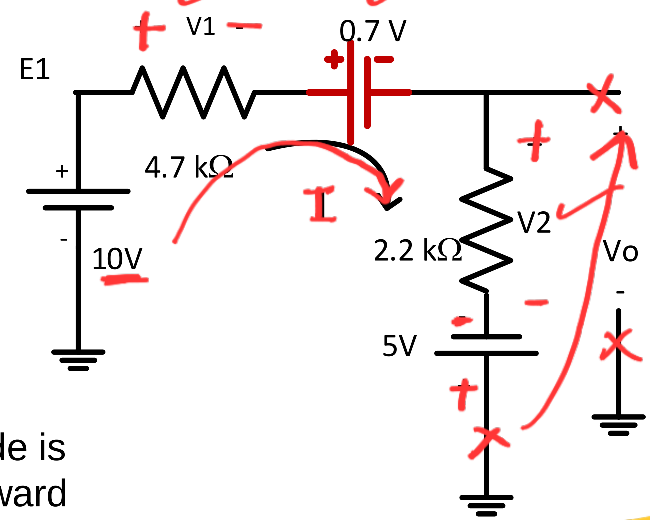


==>
Diode is Forward biased



Since VA > VK

$10+5 = I \cdot 4.7k + 0.7 + I \cdot 2.2k$

$I = \frac{15 - 0.7}{6.9k} = 2.07mA$

I=(10+5-0.7)V/(4.7+2.2) kΩ
=2.07 mA

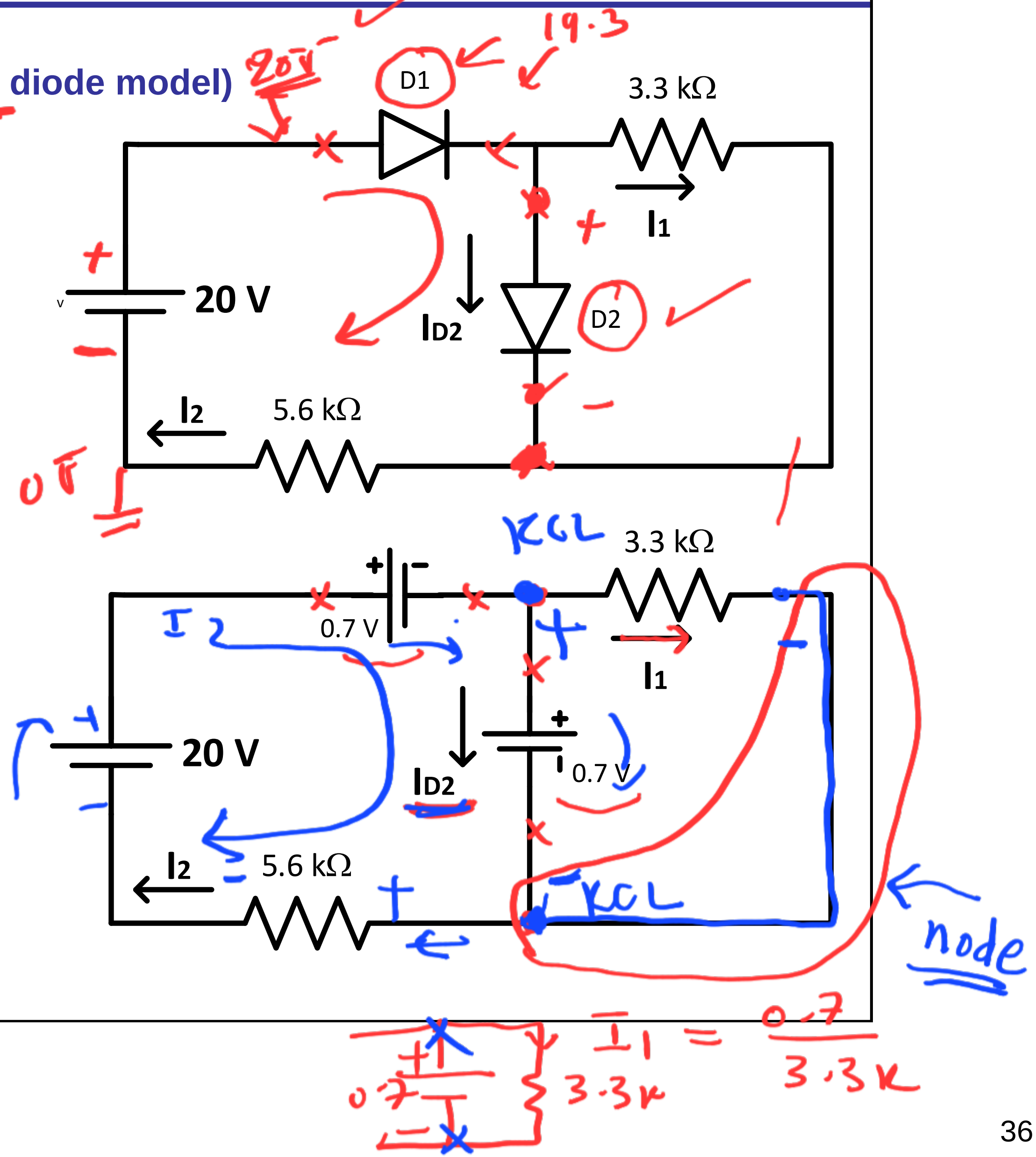
V1=I . R1= 9.73 V
$= 2.07m \times 4.7k$

V2=I . R2= 4.55 V
$= 2.07m \times 2.2k$

Vo= V2- 5 = -0.45 V

ENEE236 – Analog Electronics

Find I_1, I_2, I_{D2} (use practical diode model)



Solution:

Applied voltage is suitable for forward biasing both diodes

$I_1 = 0.7\ \text{V}/3.3\ \text{k}\Omega$

$= 0.212\ \text{mA}$

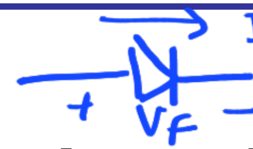
$I_2 = (20-0.7-0.7)/5.6\ \text{k}\Omega$

$= 3.32\ \text{mA}$

$I_2 = I_1 + I_{D2}$

$I_{D2} = I_2 - I_1 = 3.32 - 0.212$

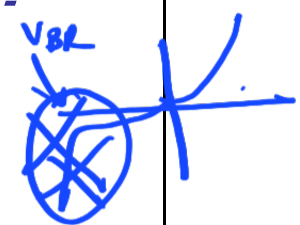
$= 3.11\ \text{mA}$



Power
$P_D = V_F \cdot I_F$
1N 4002

Diode Specification Sheets

Diode data sheets contain standard information, making cross-matching of diodes for replacement or design easier.



1. **Forward Voltage (V_F) at a specified current and temperature**
2. **Maximum forward current (I_F) at a specified temperature**
3. **Reverse voltage rating, PIV or PRV or $V_{(BR)}$, at a specified temperature** (peak inverse voltage; reverse)
4. **Maximum power dissipation at a specified temperature**
5. Reverse saturation current (I_R) at a specified voltage and temperature
6. Capacitance levels
7. Reverse recovery time, t_{rr}
8. Operating temperature range

Other Types of Diodes

There are several types of diodes besides the standard *p-n* junction diode. Three of the more common are:

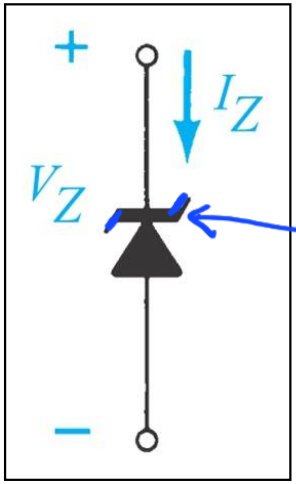
Zener diodes

Light-emitting diodes

Zener Diode (explained in L6) T5

A **Zener diode** is one that is designed to safely operate in its zener region; i.e., biased at the Zener voltage (V_Z).

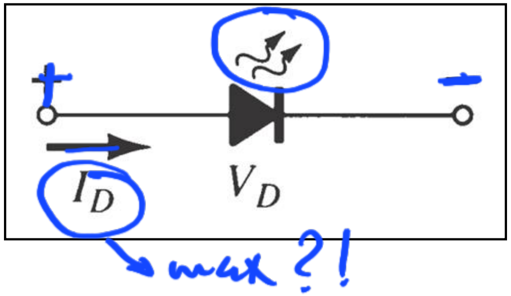
Common zener diode voltage ratings are between 1.8 V and 200 V



The **Zener diode** is used mainly **for voltage regulation**, details will be discussed later

Light-Emitting Diode (LED)

An **LED** emits light when it is forward biased, which can be in the infrared or visible spectrum.



The forward bias voltage is usually in the range of 2 V to 3 V.

End of J3

L4 - part 1

13/7/2021