ECE3110J/VE311 Electronic Circuits

Chapter 3. Diodes and Diode Circuits

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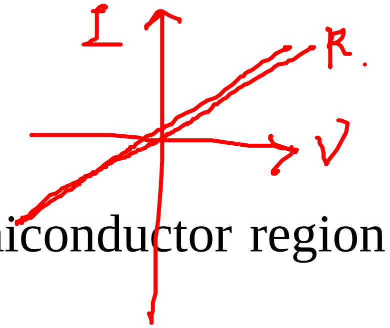
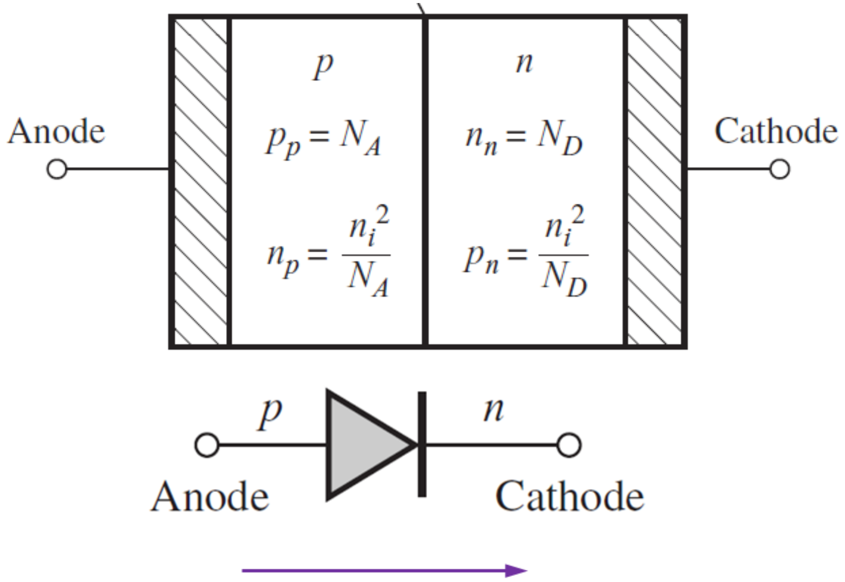
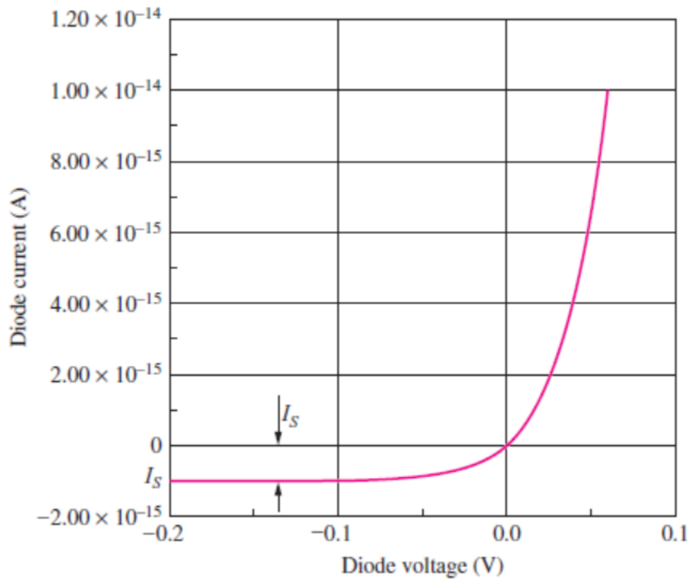
PN Junction Diode



The pn junction diode is formed by fabrication of a p-type semiconductor region in intimate contact with an n-type semiconductor region.



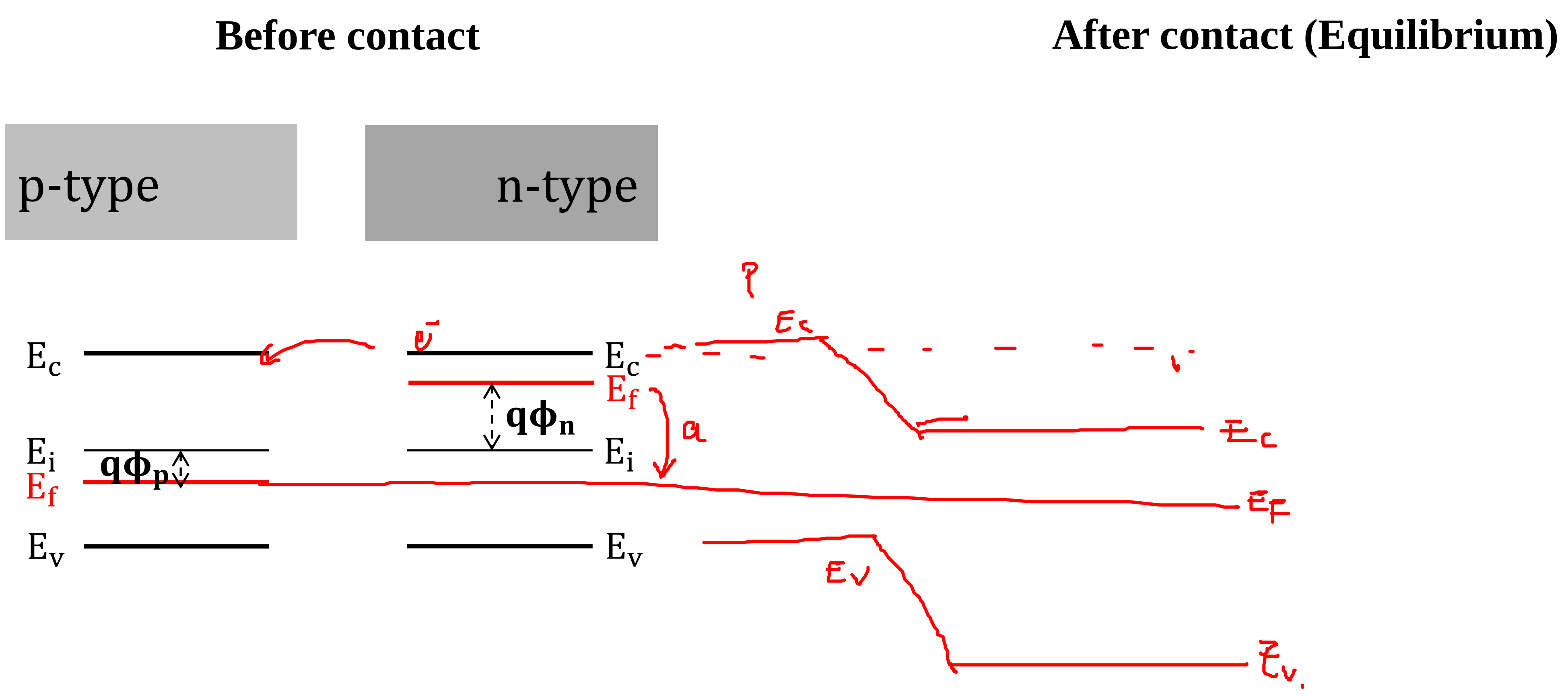
Diode current



Non-linear, or rectifying, behavior

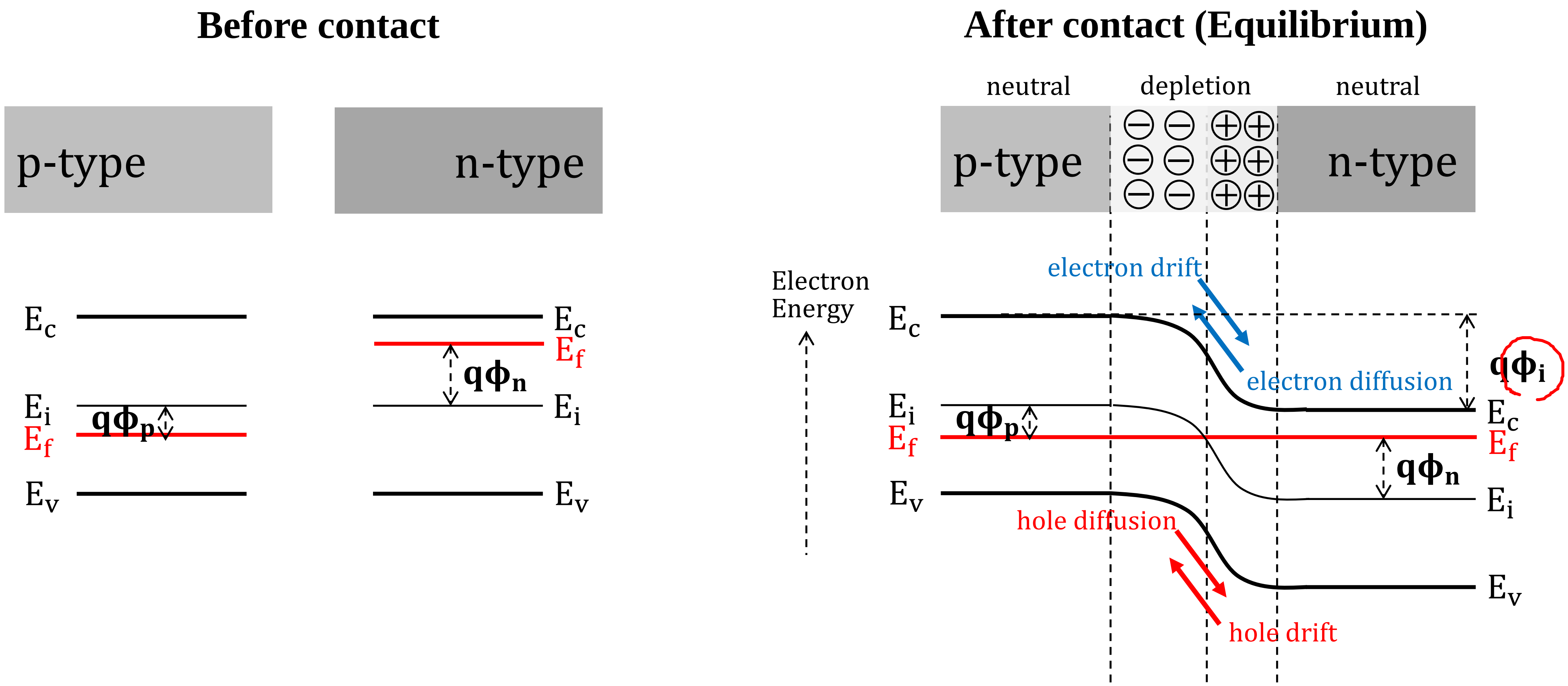
The PN diode is one of the most widely used semiconducting devices, such as components for **IC chips, solar cells, LEDs, photodetectors** etc.

*Energy Band Diagram of PN junction



Depletion region: **bands are bent** and **a field exists** that sweeps the mobile carriers, leaving behind negatively charged acceptors in the p-region and positively charged donors in the n-region.

*Energy Band Diagram of PN junction



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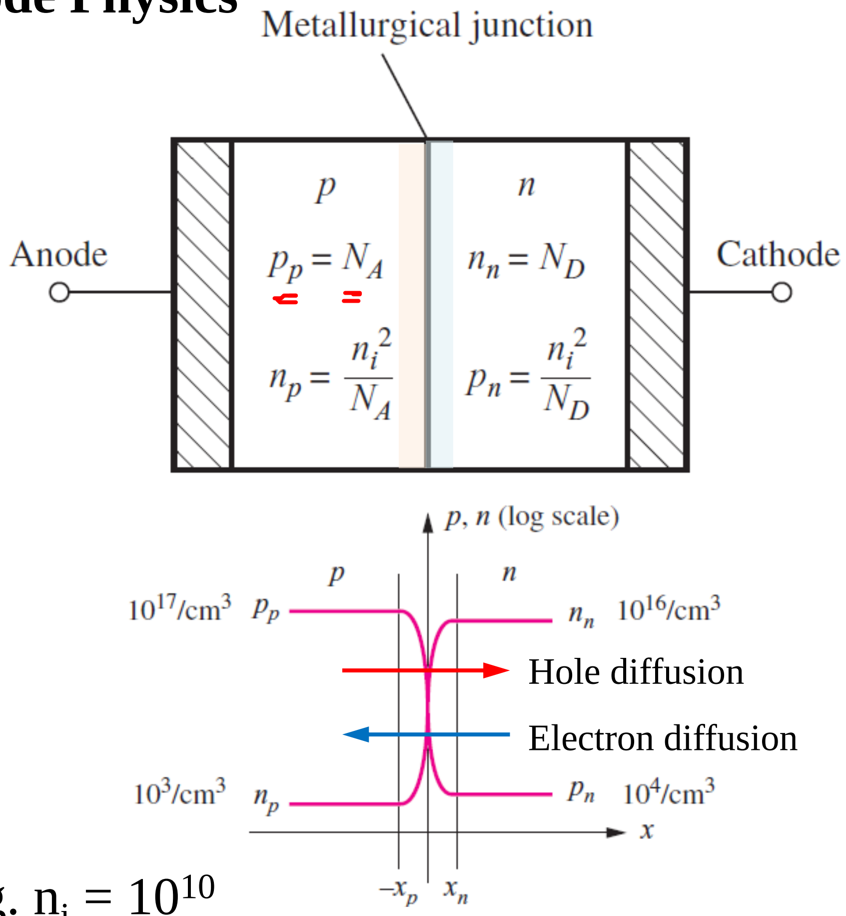
PN diode Physics



$np = n_i^2$

N-type : $n = N_D$

p in N-type $= \frac{n_i^2}{N_D}$

e.g. $n_i = 10^{10}$

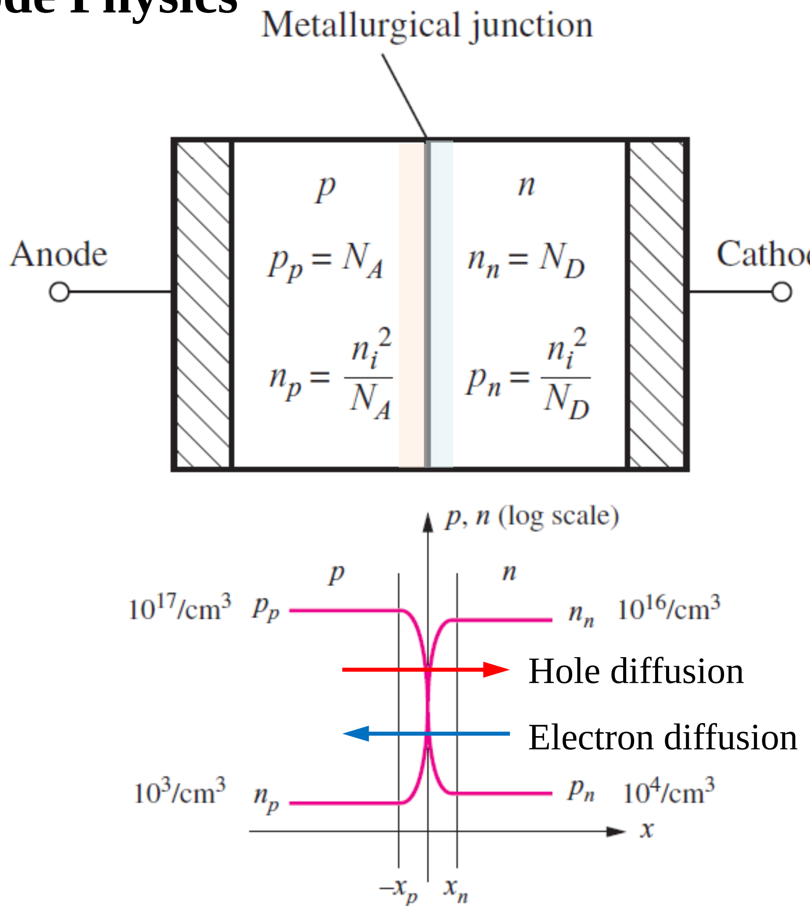
Hole in p = $p_p = 10^{17}$ cm^{-3}

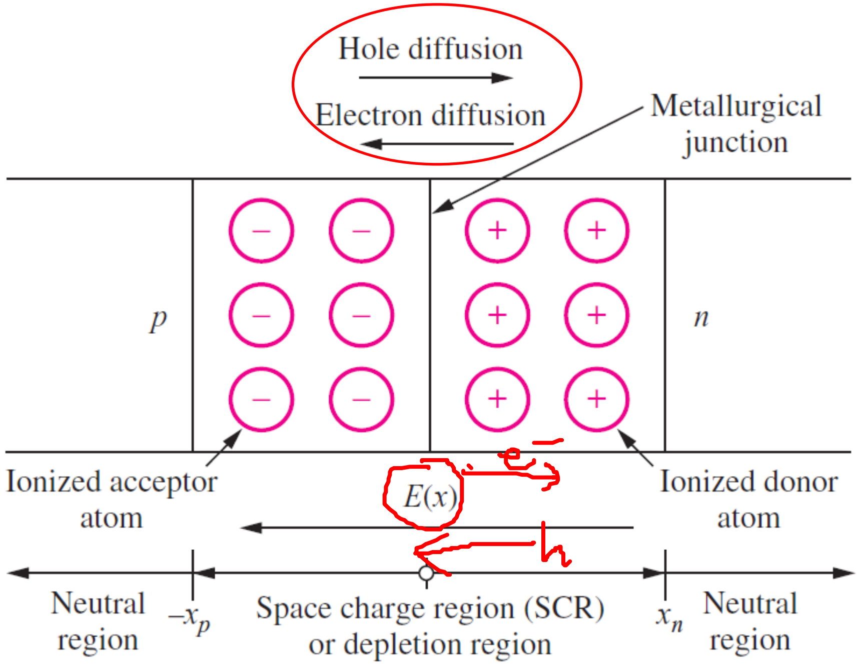
Electron in n = $n_n = 10^{16}$ cm^{-3}

Then, Hole in n = $p_n = 10^4$ cm^{-3}

Electron in p = $n_p = 10^3$ cm^{-3}

PN diode Physics

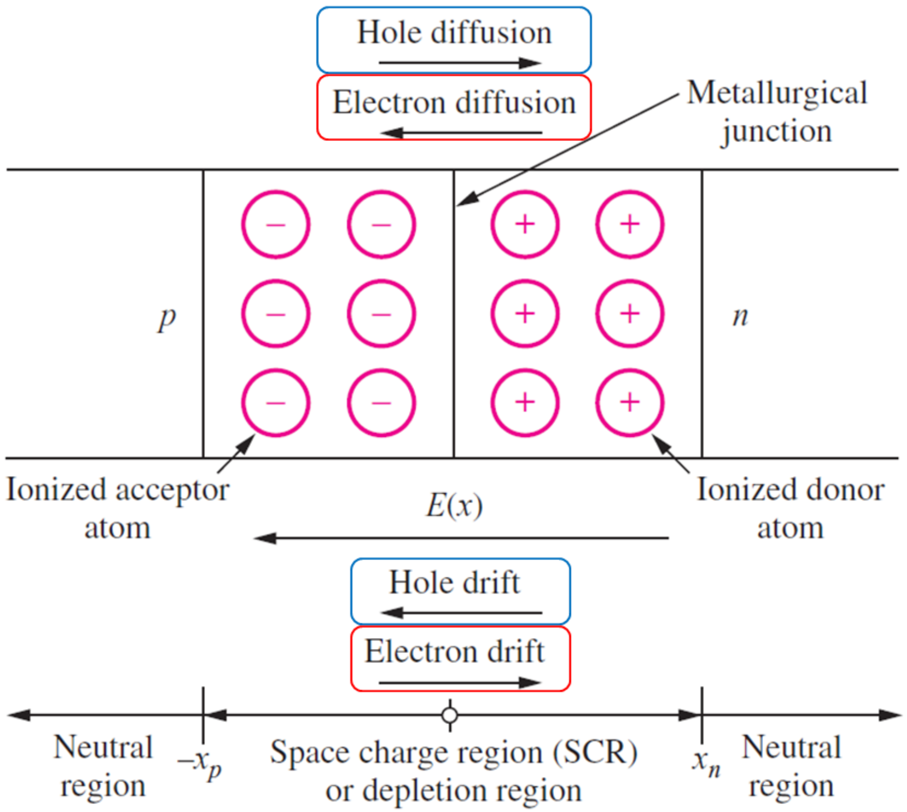




Zero current

V = 0

As a result of the diffusion of charges, immobile ionized charges (atoms) are revealed, generating an electric field, or **built-in potential**.

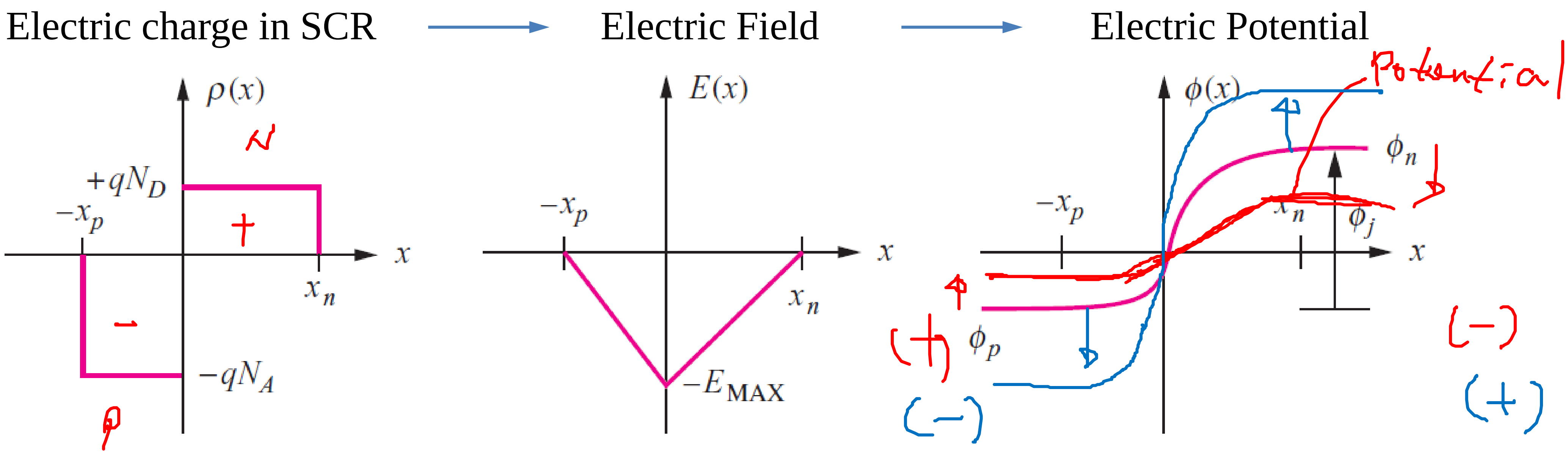


$$j_n^T = qn\mu_n E + qD_n \frac{\partial n}{\partial x} = 0$$

$$j_p^T = qp\mu_p E - qD_p \frac{\partial p}{\partial x} = 0$$

The carriers **drift in directions opposite the diffusion** of the same carrier species. Because the terminal currents must be zero, **a dynamic equilibrium** is established in the junction region. Hole diffusion is precisely balanced by hole drift, and electron diffusion is exactly balanced by electron drift.

***Built-in Potential and Depletion Width**



By solving Poisson's equations, we get Electric field E(x) and electrostatic potential Ø(x)

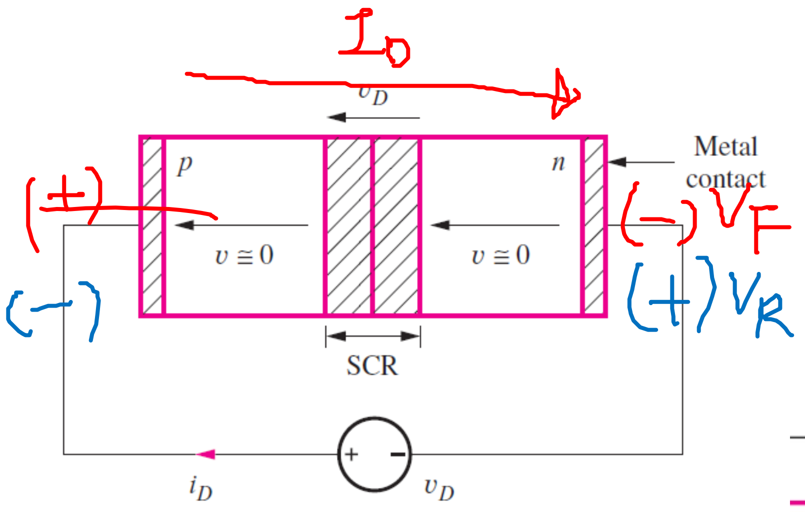
Built-in potential is V_{bi} $(=\emptyset_j) = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$ [V]

And depletion-layer width is $w_{do} = x_n + x_p = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\emptyset_j}$ [m]

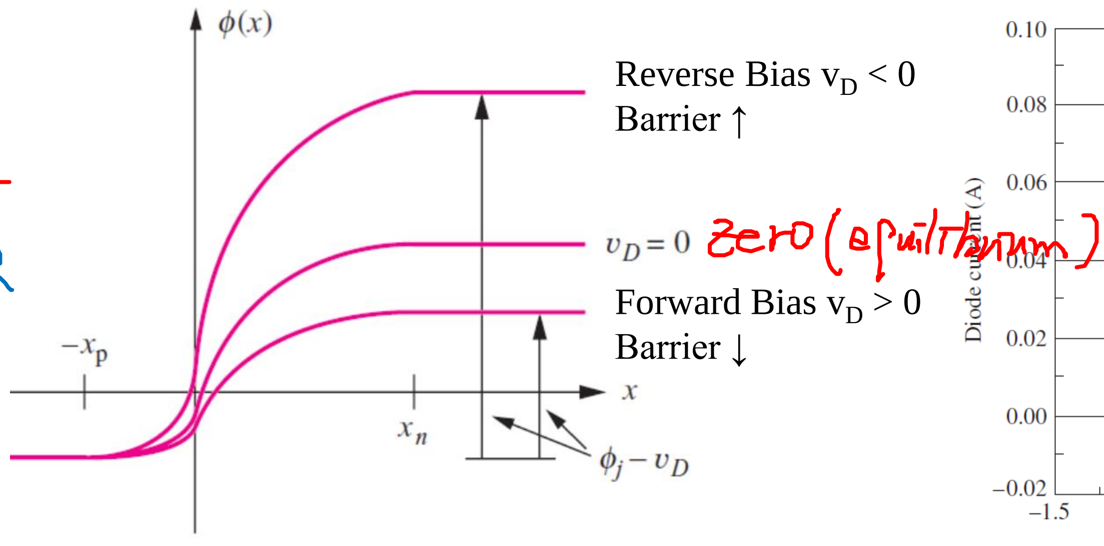
Example 3.1 Calculate the **built-in potential** for a silicon diode with $N_A = 10^{17}$ cm^{-3} on the *p*-type side and $N_D = 10^{20}$ cm^{-3} on the *n*-type side. Assume that $n_i = 10^{10}$ cm^{-3} and $V_T = 0.025$ V.

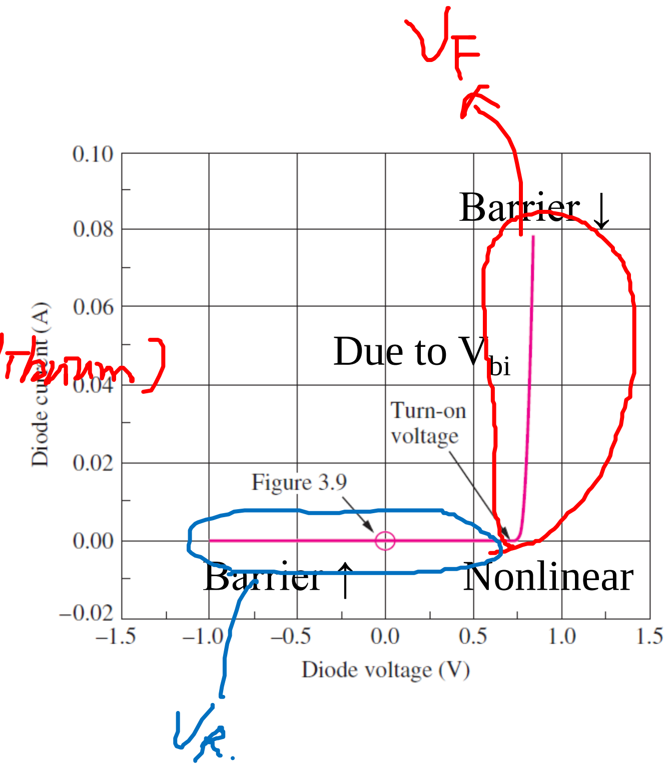
$V_{bi} = 0.979$ V

I-V Characteristics of Diode



Under Bias (Non Equilibrium)

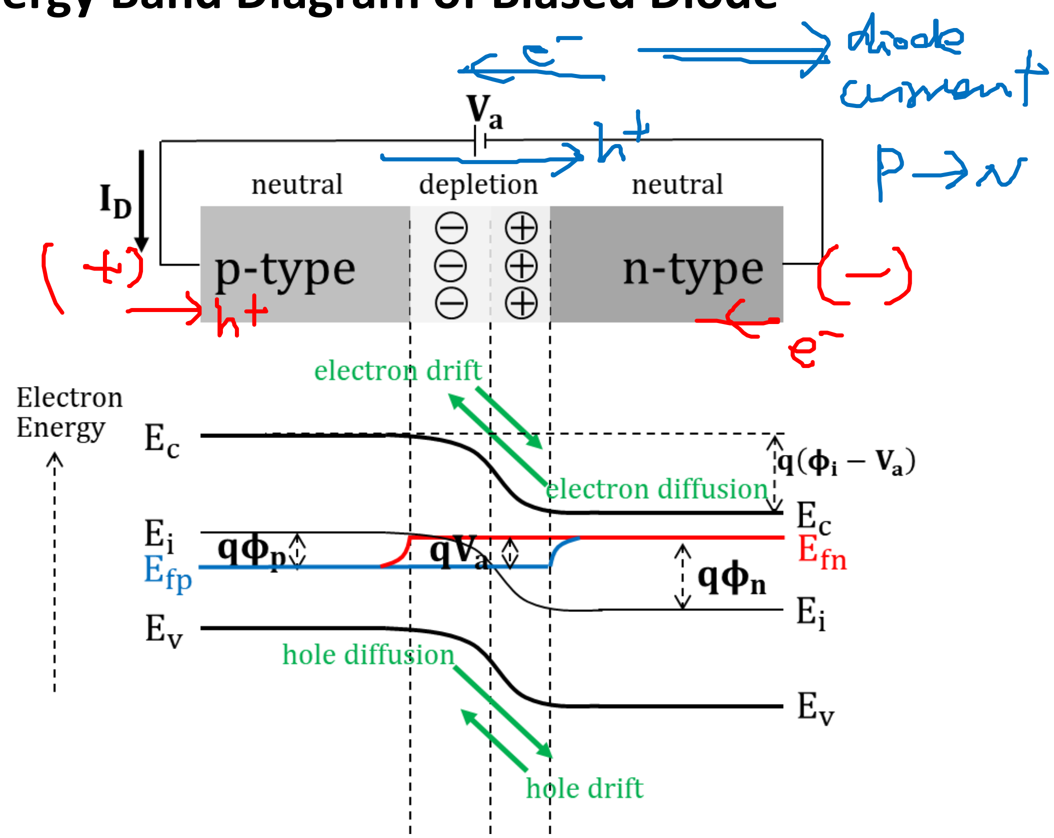


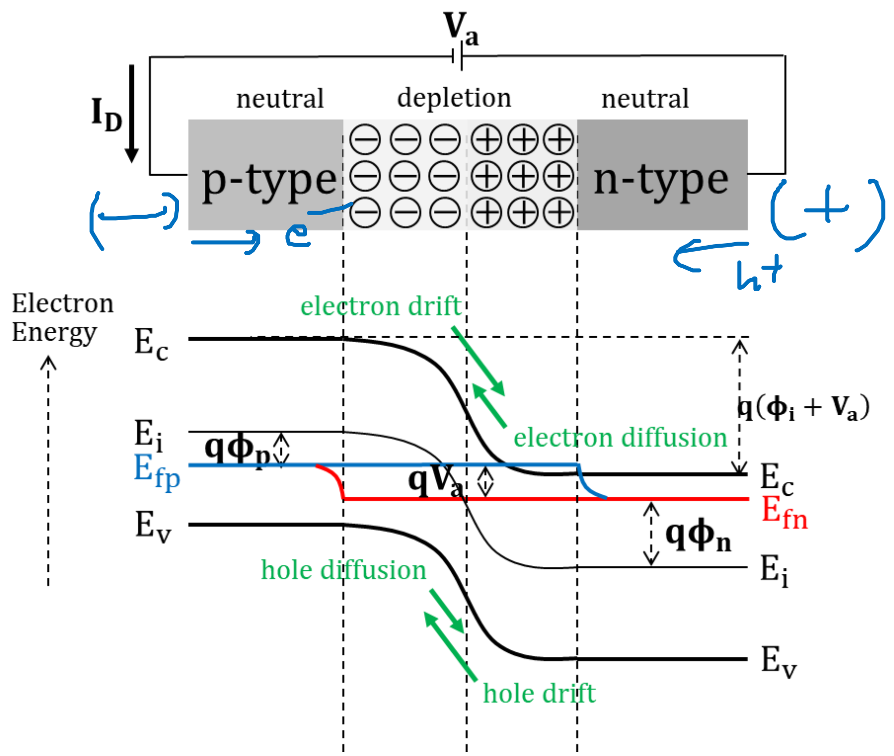


The diode permits **current to flow in one direction in a circuit**, but prevents movement of current in the opposite direction **due to the barrier, or built-in potential**. We will find that this nonlinear behavior has many useful applications in electronic circuit design.

- Turn-on voltage typically 0.5 to 0.7 V
- Saturation current (I_S) typically 10^{-18} to 10^{-9} A
- $kT/q = 0.025875$ V at 300 K

*Energy Band Diagram of Biased Diode





Forward Bias:

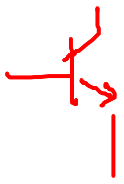
- potential difference (barrier) ↓
- depletion width ↓
- More electrons/holes diffuse
- Conducts current flow

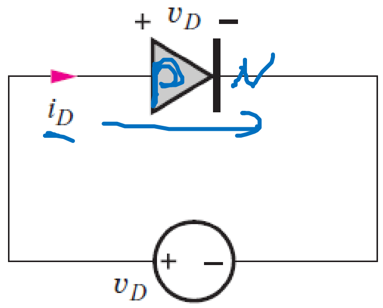
Reverse Bias:

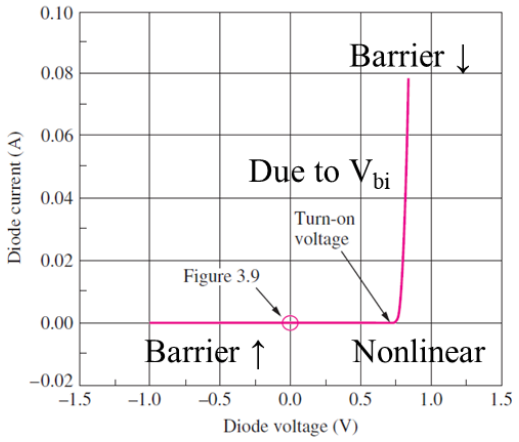
- potential difference (barrier) ↑
- depletion width ↑
- Less electrons/holes diffuse
- Blocks current flow

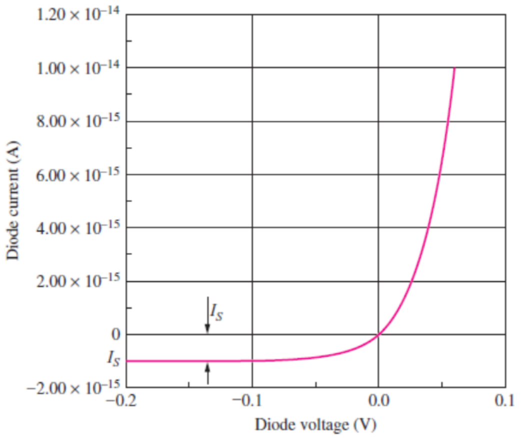
Diode Equation and Diode Under Bias

Forward bias, i.e. $v_D > 0$, **diode is on**: Current flows from P to N
Reverse bias, i.e. $v_D < 0$, **diode is off**: Current does not flow, but saturation current exists









The total current through the diode is i_D, and the voltage drop across the diode terminals is v_D.

$\mathbf{I_D = I_S\left(e^{\frac{qV_d}{kT}} - 1\right)}$ ***or*** $\boldsymbol{I_S(e^{v_D/v_T} - 1)}$ where k is Boltzmann's constant.

e.g. $v_D = 1$ V, $i_D = I_S\left(e^{v_D/v_T} - 1\right) = I_S\left(e^{1/0.025} - \cancel{1}\right)$

e.g. $v_D = -1$ V, $i_D = I_S\left(e^{v_D/v_T} - 1\right) = I_S\left(e^{\cancel{-1/0.025}} - 1\right) = I_S * (-1) \approx -I_S$

Example 3.3

(a) Calculate V_a for a silicon diode with $I_S = 0.1$ fA and I_D increasing from 300 µA to 10 mA at 300 K.

(b) Calculate I_S for a silicon diode with $I_D = 2.5$ mA and $V_a = 0.736$ V at 50°C.
Boltzmann's constant $k = 1.3806 \times 10^{-23}$ J/K
$q = 1.6 \times 10^{-19}$ C

Example 3.3

(a) Calculate V_a for a silicon diode with I_S = 0.1 fA and I_D increasing from 300 μA to 10 mA at 300 K.

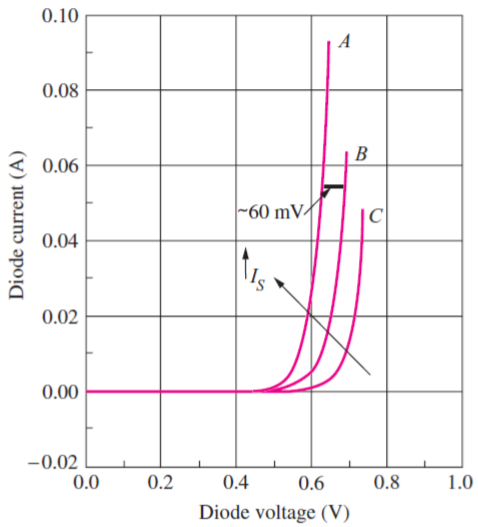
$$300 \times 10^{-6} = \left(0.1 \times 10^{-15}\right)\left(e^{\frac{V_a}{0.025}} - 1\right) \qquad V_a = 0.718\ (\mathrm{V})$$

$$10 \times 10^{-3} = \left(0.1 \times 10^{-15}\right)\left(e^{\frac{V_a}{0.025}} - 1\right) \qquad V_a = 0.806\ (\mathrm{V})$$

(b) Calculate I_S for a silicon diode with I_D = 2.5 mA and V_a = 0.736 V at 50°C.

$$2.5 \times 10^{-3} = I_S\left(e^{\frac{\left(1.6\times10^{-19}\right)\times0.736}{\left(1.38\times10^{-23}\right)(323)}} - 1\right) \quad I_S = 8.4 \times 10^{-15}\ (\mathrm{A})$$

Saturation Current I_S



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

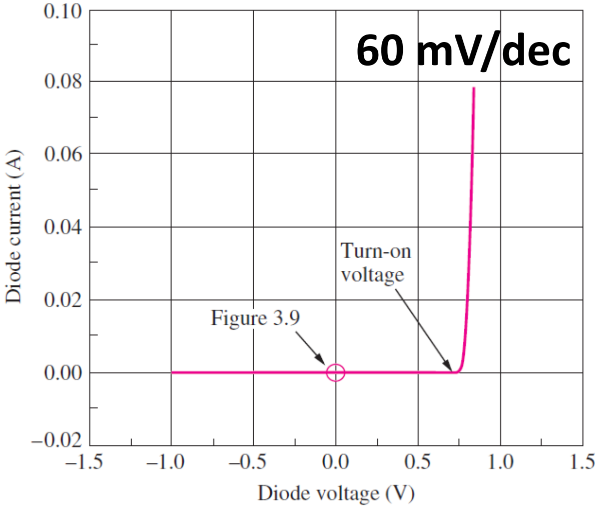
$$I_{SA} = 10^{-12}A$$

$$I_{SB} = 10^{-13}A$$

$$I_{SC} = 10^{-14}A$$

- At the same I_D, when I_S increases by 10, V_a decreases by 60 mV.
- At the same I_S, when I_D increases by 10, V_a increases by 60 mV.

1A → 10A 60mV



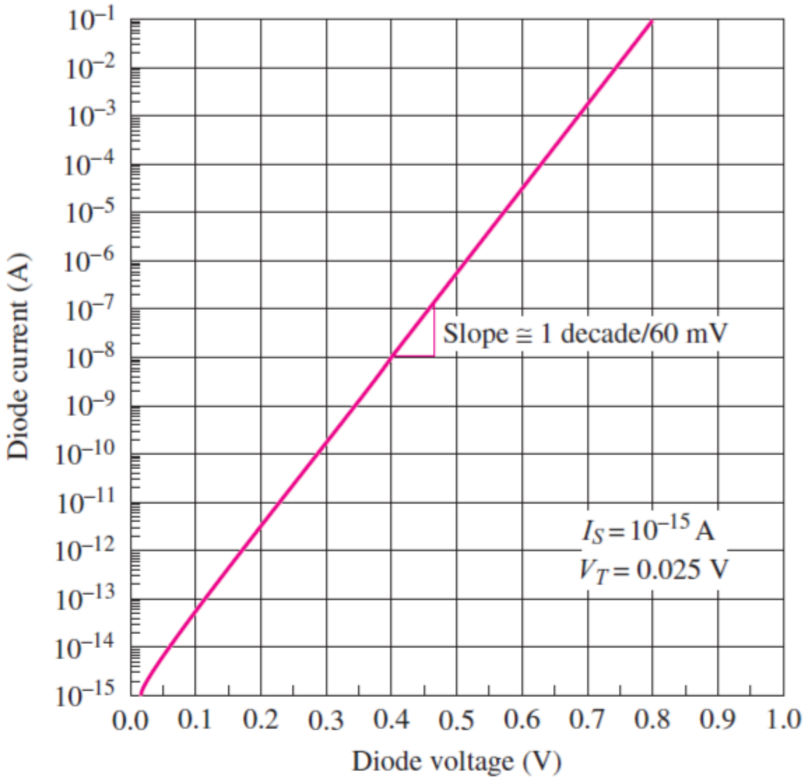
Example 3.4

Calculate the required V_a for I_D of a silicon diode to increase by a factor 10 at 300 K. Assume $I_D \gg I_S$.

$$\begin{cases} I_{D1} = I_S\left(e^{\frac{qV_{a1}}{kT}} - 1\right) \approx I_S e^{\frac{qV_{a1}}{kT}} \\ I_{D2} = I_S\left(e^{\frac{qV_{a2}}{kT}} - 1\right) \approx I_S e^{\frac{qV_{a2}}{kT}} \end{cases}$$

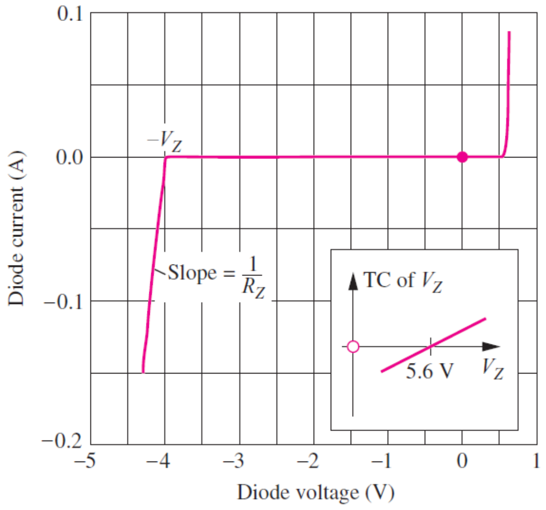
$$\frac{I_{D2}}{I_{D1}} = 10 = \frac{I_S e^{\frac{qV_{a2}}{kT}}}{I_S e^{\frac{qV_{a1}}{kT}}} = e^{\frac{V_{a2}-V_{a1}}{0.025875}}$$

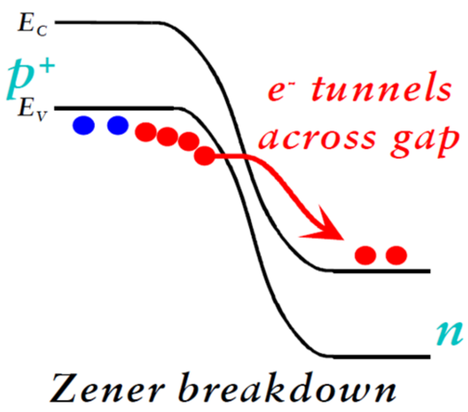
$$V_{a2} - V_{a1} = 0.025875 \times \ln 10$$
$$= 0.05958\ (V) \approx 60\ (mV)$$

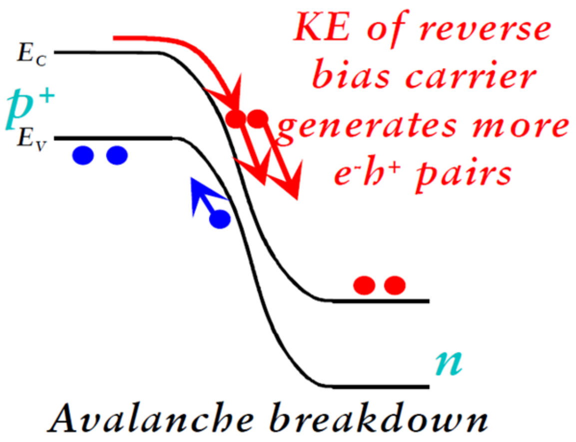


Reverse Bias Breakdown

As the reverse voltage increases, the electric field within the device grows, and the diode eventually enters the **breakdown region.** The magnitude of the voltage at which breakdown occurs is called the **breakdown voltage** $\boldsymbol{V_Z}$ of the diode.







Zener Breakdown: Large band bending means that electrons can **tunnel through** region where no free electron states exist.
Avalanche Breakdown: The kinetic energy of e- or h+ crossing the gap is sufficient to **generate e-h+ pairs** if the carrier undergoes a scattering event

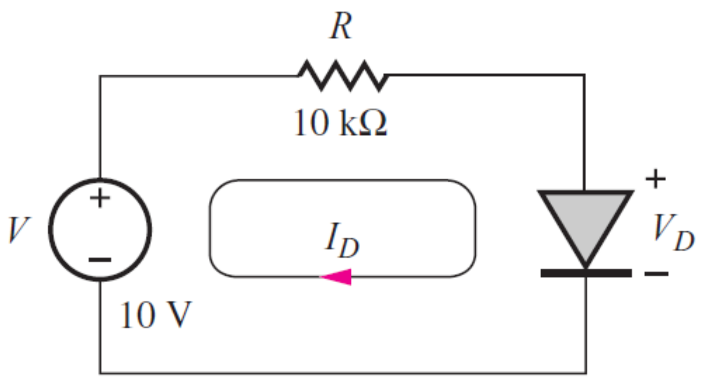
Diode Circuit Analysis

One common objective of diode circuit analysis is to find the **quiescent operating point** (Q-point), or **bias point,** for the diode. The Q-point consists of the dc current and voltage *(I_D, V_D)* that define the point of operation on the diode's *i*-*v* characteristic.

KVL :

$-V + RI_D + V_D = 0$

$V = RI_D + V_D$



$V = I_D R + V_D$

$I_D = ?$

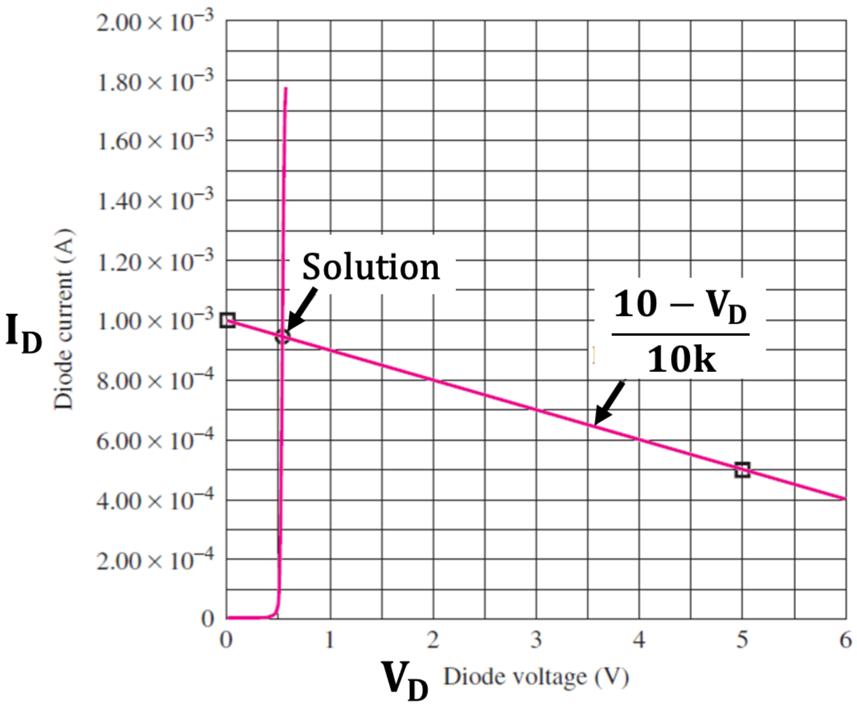
$V_D = ?$

1. **Graphical analysis**
2. **Mathematical analysis**
3. **Simplified analysis** (ideal diode)
4. **Simplified analysis** (constant voltage drop)

CVD

Graphical Analysis

A simple way is that we can use a graphical approach (**load-line analysis**) to find the simultaneous solution of $\mathbf{V = I_D R + V_D}$. The Q-point can be found by plotting the graph of the load line on the *i*-*v* characteristic for the diode. **The intersection of the two curves represents the Q-point for the diode.**

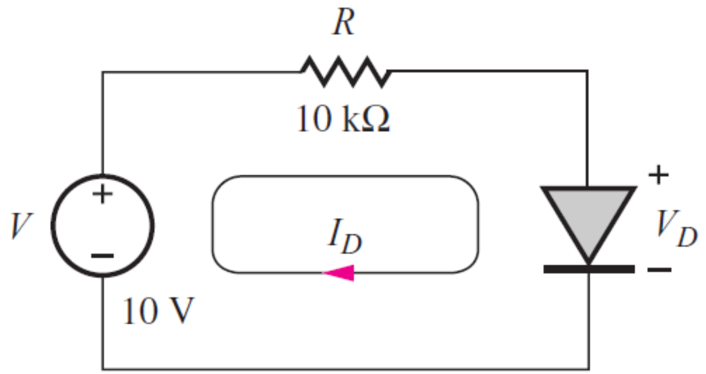


As V = 10 V and R = 10k, inserting values into the equation $V = I_D R + V_D$, we get $10 = 10\mathrm{k}I_D + V_D$

If $V_D = 0$, $I_D = 1$ mA
If $V_D = 5$ V, $I_D = 0.5$ mA
Drawing the linear line (V_D *vs* I_D), we can find the solution

$$\boldsymbol{V_D = 0.6\ \mathrm{V}}$$
$$\boldsymbol{I_D = 0.95\ \mathrm{mA}}$$

Mathematical Analysis



From the circuit $V = I_D R + V_D$

And we know the diode current equation $\mathbf{I_D = I_S\left(e^{\frac{qV_D}{kT}} - 1\right)}$

Therefore, we get $V = \left[I_S\left(e^{\frac{V_D}{V_T}} - 1\right)\right] R + V_D$

As V = 10 and R = 10k, and use a value for $I_S = 10^{-13}$

$$10 = \left[10^{-13}\left(e^{\frac{V_D}{0.025}} - 1\right)\right] 10^4 + V_D$$

Transcendental equation

Using Solver function

V_D = 0.5742 V

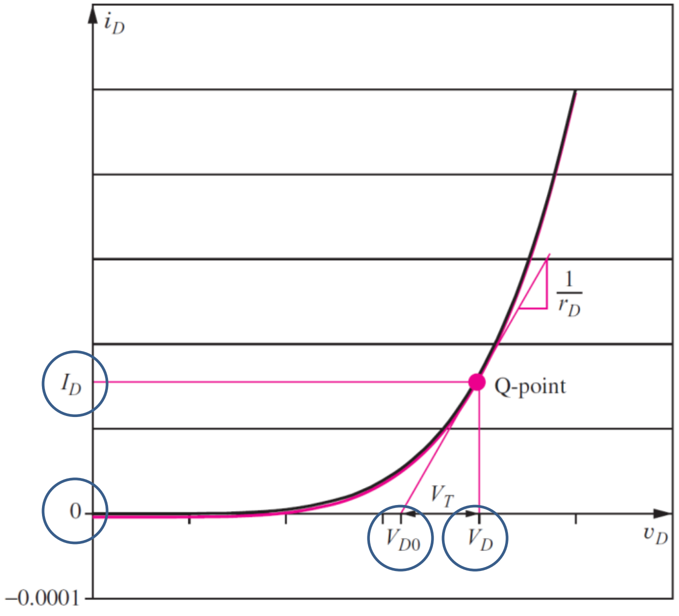
I_D = 9.438 x10^{-4} A = 0.944 mA

Or using computer software

function xd = diode(vd)

$$xd = 10 - (10^{-9}) * \left(\exp\left(\frac{vd}{0.0250}\right) - 1\right) - vd$$

Use MATLAB to plot xd as a function of vd, and find out a vd that makes xd closest to zero.

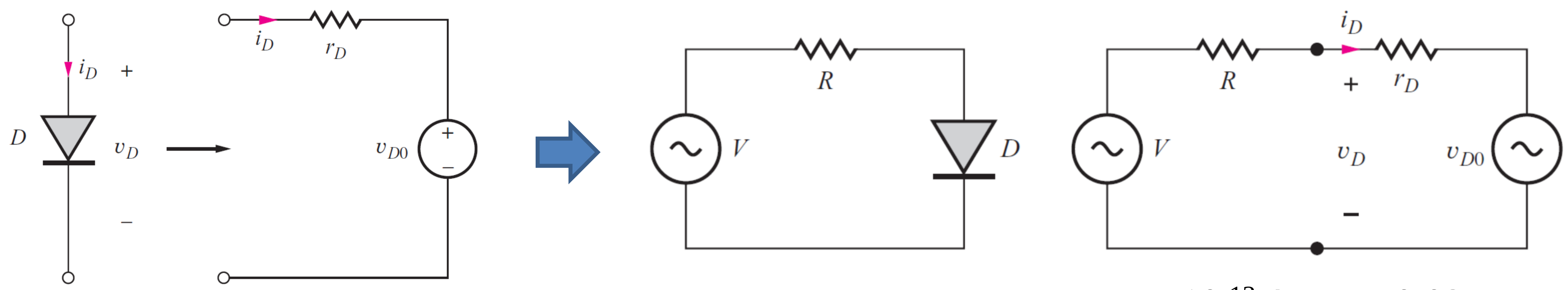


Alternatively, we can develop an iterative solution method for the diode circuit.
The slope of the diode characteristic at the operation point:

$$g_D = \left.\frac{\partial i_D}{\partial v_D}\right|_{Q-Pt} = \frac{I_S}{V_T}\exp\left(\frac{V_D}{V_T}\right) = \frac{I_D + I_S}{V_T} \cong \frac{I_D}{V_T} \quad \left(I_D = I_S\left(e^{\frac{qV_D}{kT}} - 1\right) \rightarrow I_D + I_S = I_S\exp\left({}^{V_D}/_{V_T}\right)\right)$$

$$1/\text{Slope} = 1/g_D = \boldsymbol{r_D} = \frac{\boldsymbol{V_T}}{\boldsymbol{I_D}} = \frac{\boldsymbol{V_D - V_{D0}}}{\boldsymbol{I_D - 0}} \rightarrow \boldsymbol{V_{D0} = V_D - I_D r_D} \; or \; \boldsymbol{V_T = V_D - V_{D0}}$$

From the derived equation, $\boldsymbol{V_{D0} = V_D - I_D r_D}$ *or* $\boldsymbol{V_T = V_D - V_{D0}}$, we can get a diode model

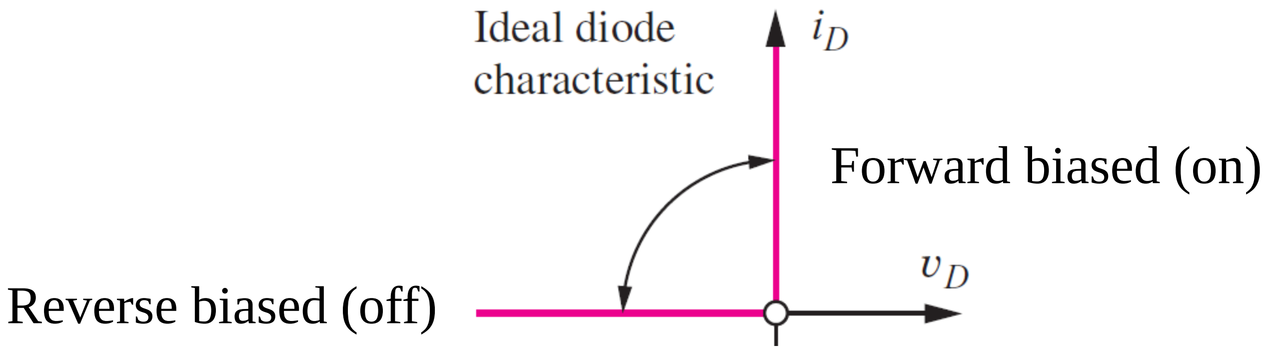


$I_S = 10^{-13}$ A, $V_T = 0.025$ V

Now we can use an iterative process to find the Q-point of the diode in the circuit.

1. Pick a starting guess for $I_D \rightarrow I_D = 10$ mA
2. Calculate the diode voltage using $V_D = V_T \ln(1 + I_D/I_S) \rightarrow V_D = 0.633$ V
3. Calculate the values of V_{D0} and $r_D \rightarrow V_{D0} = 0.608$ V, $r_D = 2.5$ ohm
4. Calculate a new estimate for I_D **from the circuit**: $I_D = (V - V_{D0})/(R + r_D) \rightarrow I_D = 9.39 \times 10^{-4}$
5. Repeat steps 2–4 until convergence is obtained.

Simplified Analysis (Ideal Diode)

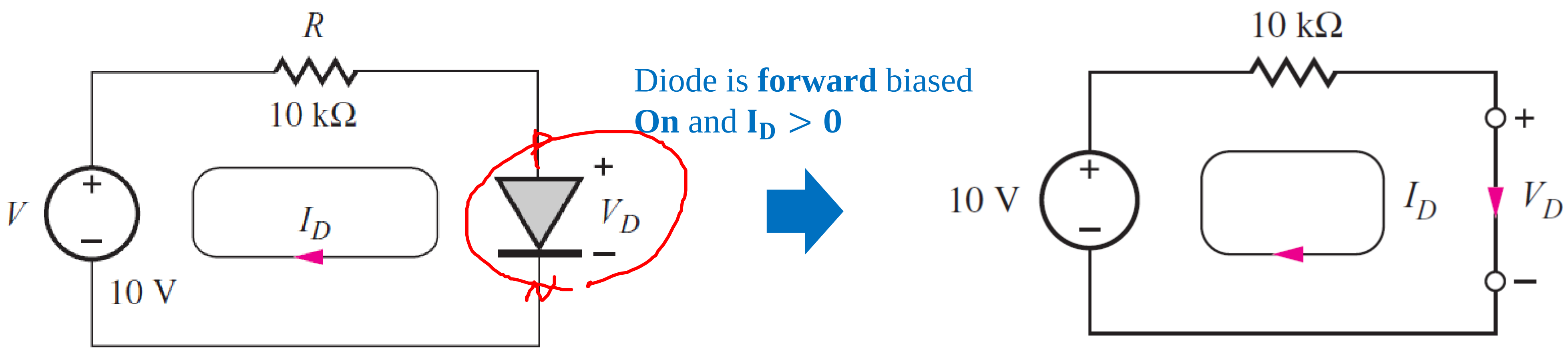


$$v_D = 0 \quad \text{for } i_D > 0$$

$$i_D = 0 \quad \text{for } v_D \leq 0$$

Though the diode i-v curve is not linear we can use **piecewise linear** approximations for the diode i-v characterization. The **ideal diode model** is the simplest model for the diode. The *i-v* characteristic for the **ideal diode consists of two straight-line segments.**

(1) Forward bias

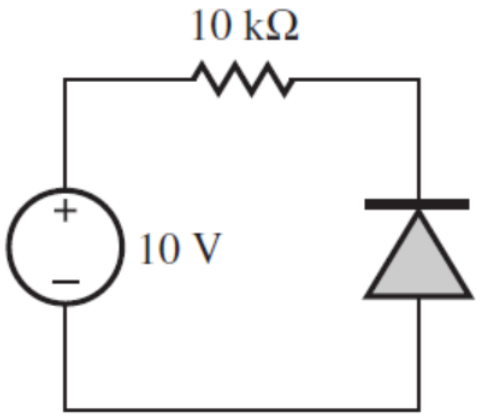


Based on the ideal diode model, we can find that the diode is forward biased and operating with a current of 1 mA as follows.

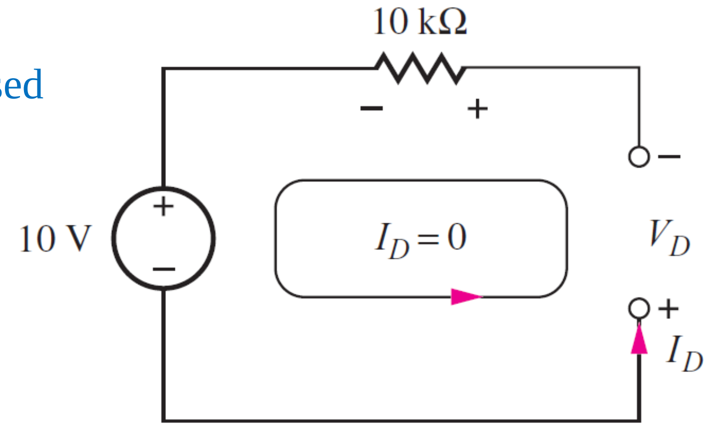
$$I_D = \frac{10\ V}{10k\Omega} = 1\ mA$$

Q-point is 0 V and 1 mA.

(2) Reverse bias



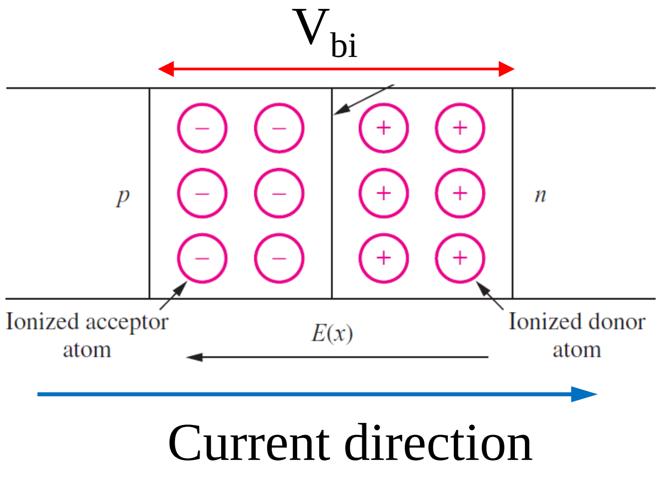
Diode is **reverse** biased
Off and $\mathbf{I_D < 0}$

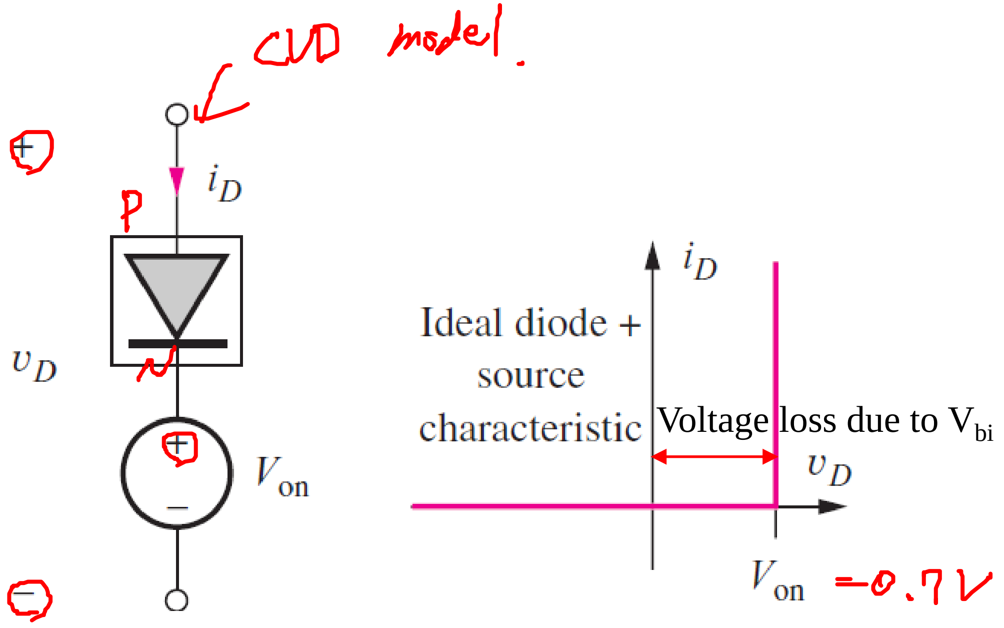


As the diode is off, the circuit is open.
$I_D = 0$ and $V_D = -10$ V

Q-point is -10 V and 0 A.

Simplified Analysis (Constant Voltage Drop)

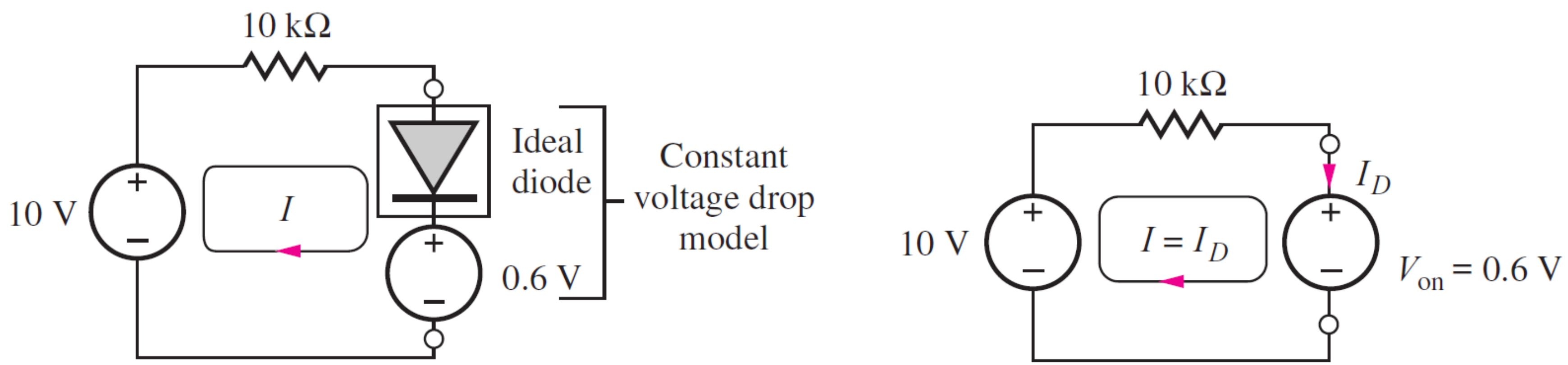




Voltage required to turn on the diode

The diode current flows when electric charges **overcome the built-in potential**, i.e. voltage loss, which can be viewed as the **turn-on voltage V_{on}** of the diode. The piecewise linear model for the diode can be improved by adding a constant voltage **V_{on}** in series with the ideal diode. This is the **constant voltage drop (CVD) model.**

We can think V_{on} as the voltage required to turn on the diode by overcoming V_{bi}.



The diode is forward biased and thus the diode is on with 0.6 V of voltage loss in the circuit.

$v_D = v_{on} = \mathbf{0.6\ V}$ and $I_D = \frac{10-0.6}{10k\Omega} = \boldsymbol{0.94\ mA}$

Thus, Q-point is 0.6 V and 0.94 mA.

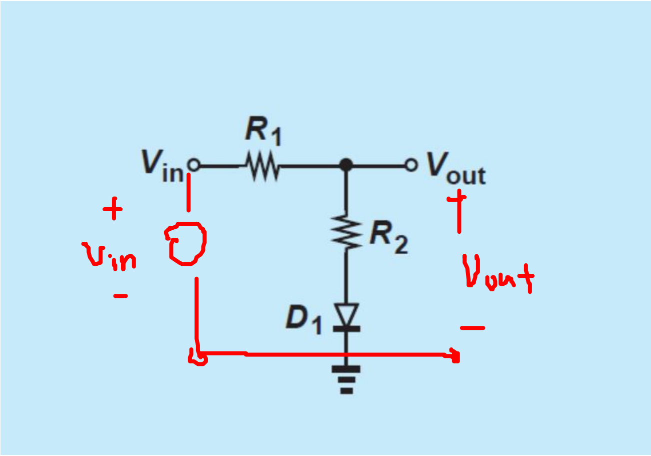
Model Comparison

	V_D	I_D
Graphical Analysis	0.6 V	0.95 mA
Mathematical Analysis	0.5742 V	0.944 mA
Ideal Diode Model	0 V	1 mA
Constant Voltage Drop Model	0.6 V	0.94 mA

We see that the current is quite insensitive to the actual choice of diode voltage. This is a result of the **exponential dependence of the diode current on voltage** as well as **the large source voltage (10 V)** in this particular circuit. Variations in V_{on} have only a small effect on the result. **However, the situation would be significantly different if the source voltage were only 1 V—Diode models consume 60% of the source voltage.**

Example 3.5

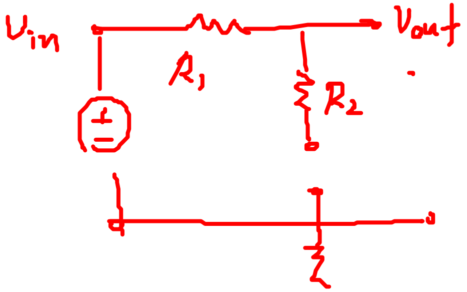
Plot the input/output characteristic of the circuit below using the **ideal model** and the **CVD model**.



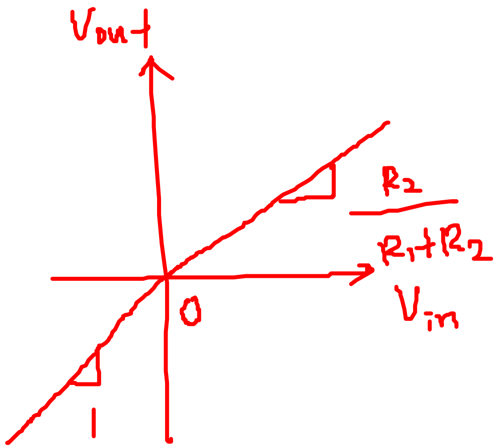
i) ideal diode model.

· diode is on $V_{in} > 0$

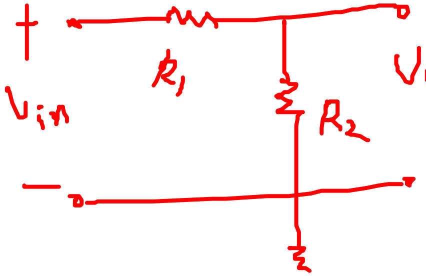
$V_{in} < 0 \Rightarrow$ diode is off



$V_{out} = V_{in}$



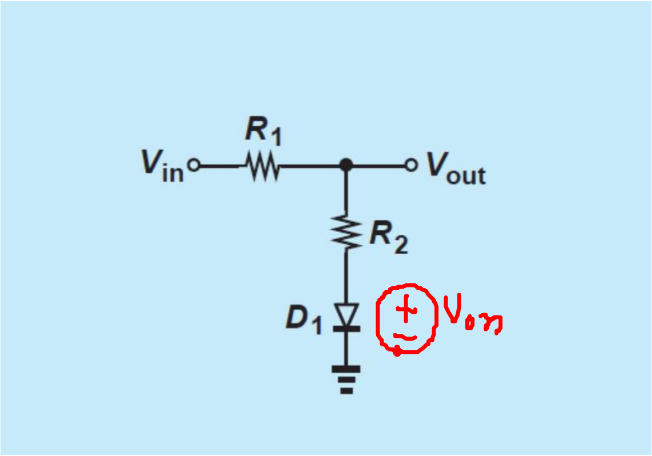
$V_{in} > 0$



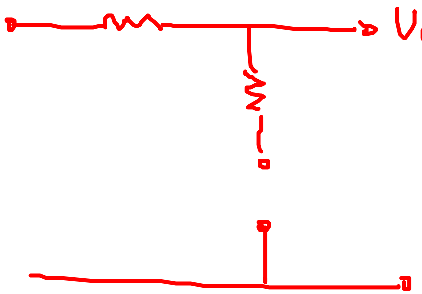
$V_{out} = \frac{R_2}{R_1+R_2} V_{in}$

Example 3.5

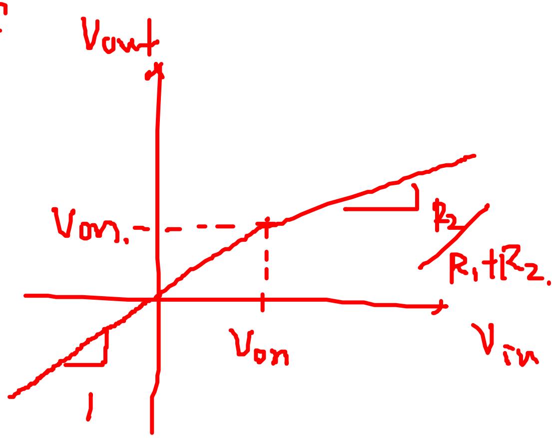
Plot the input/output characteristic of the circuit below using the **ideal model** and the **CVD model**.



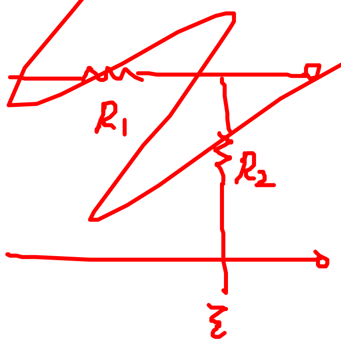
i) $V_{in} < V_{on} \Rightarrow$ diode is off



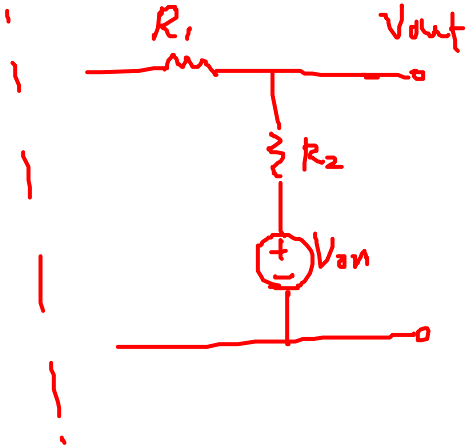
$V_{out} = V_{in}$



ii) $V_{in} > V_{on}$



$V_{out} = \frac{R_2}{R_1+R_2} V_{in}$

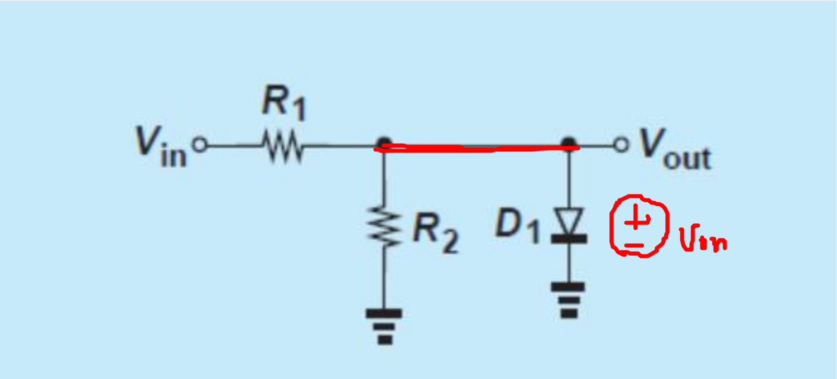


$$\frac{V_{out} - V_{in}}{R_1} + \frac{V_{out} - V_{on}}{R_2} = 0.$$

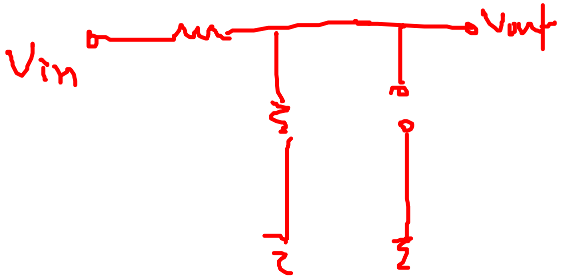
$$V_{out} = \frac{R_2}{R_1+R_2} V_{in} + \frac{R_1}{R_1+R_2} V_{on}$$

Example 3.6

Using the **CVD model**, plot the input/output characteristic of the circuit below. Note that a diode about to turn on carries zero current but sustains V_{on}.

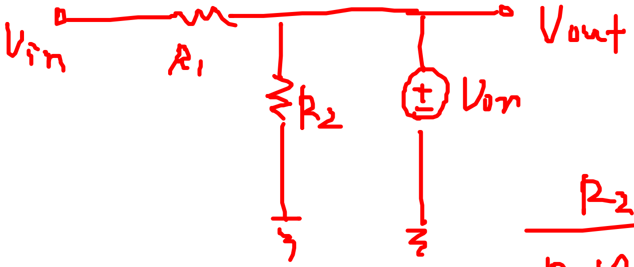


i) when the D_1 is off



$$V_{out} = \frac{R_2}{R_1+R_2} V_{in}$$

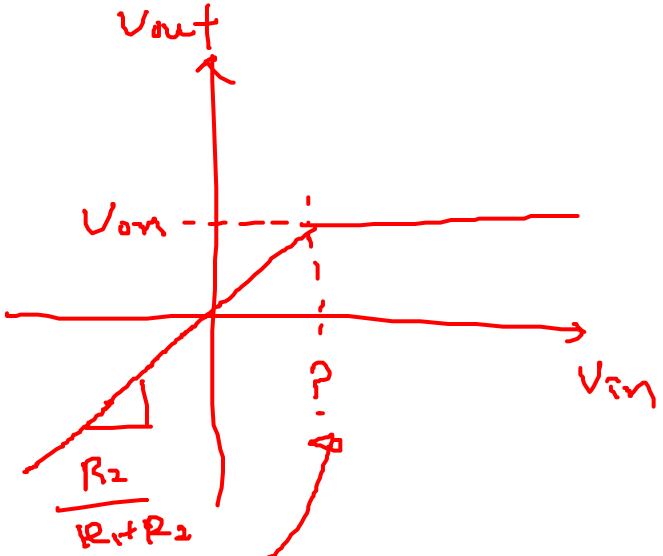
ii) when D_1 is on



$$V_{out} = V_{on}$$

$$\frac{R_2}{R_1+R_2} V_{in} = V_{on}$$

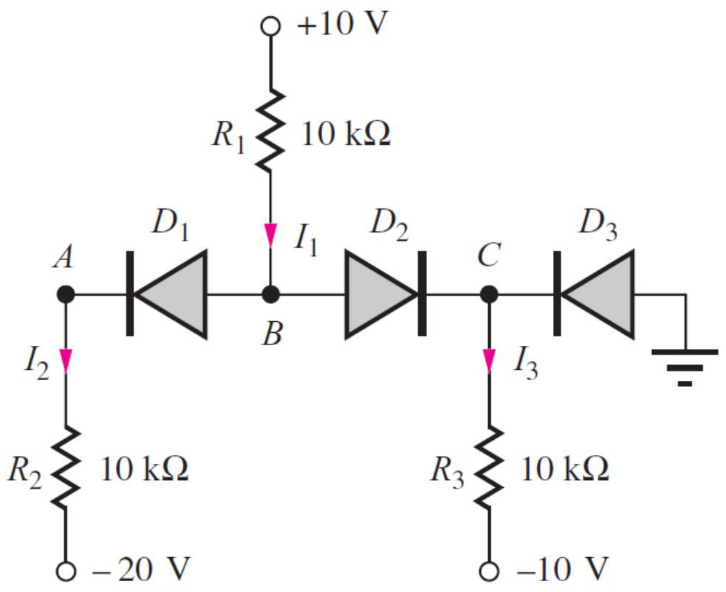
$$V_{in} = \left(1 + \frac{R_1}{R_2}\right) V_{on}$$



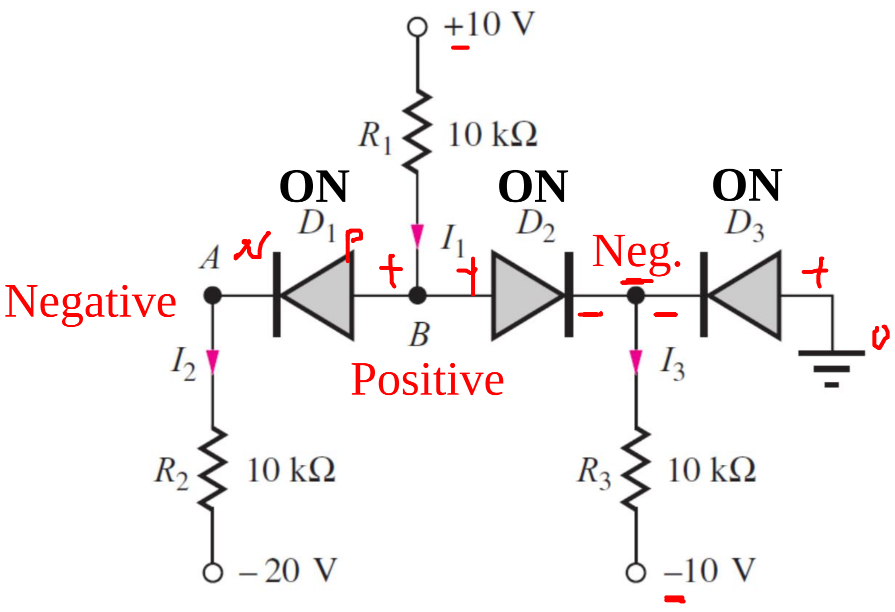
Multiple Diode Circuits

The load-line technique is applicable only to **single-diode circuits**, and the mathematical model or numerical iteration technique becomes **much more complex** for circuits with more than one nonlinear element. We will see **a multiple diode circuit** from the example below.

Example. Use constant voltage drop model ($V_{on} = 0.6$ V) to calculate V_D and I_D of each diode.

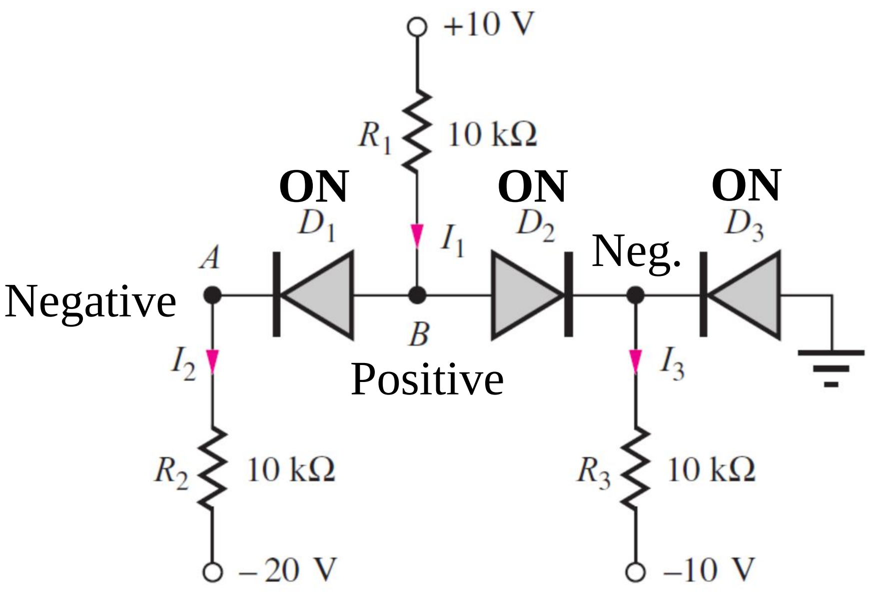


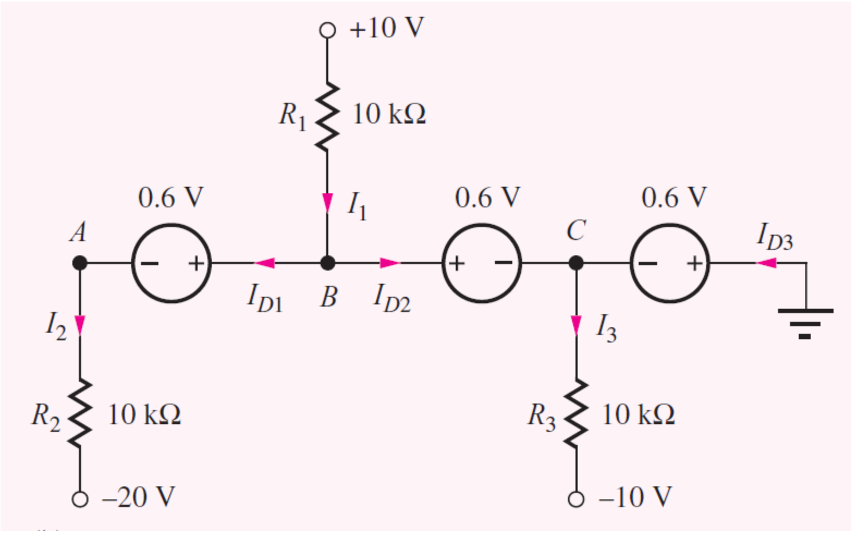
Example 3.7 Use constant voltage drop model ($V_{on} = 0.6$ V) to calculate V_D and I_D of each diode.



1. By simply reading voltages at diodes nodes, we assume that all diodes are on (Left)

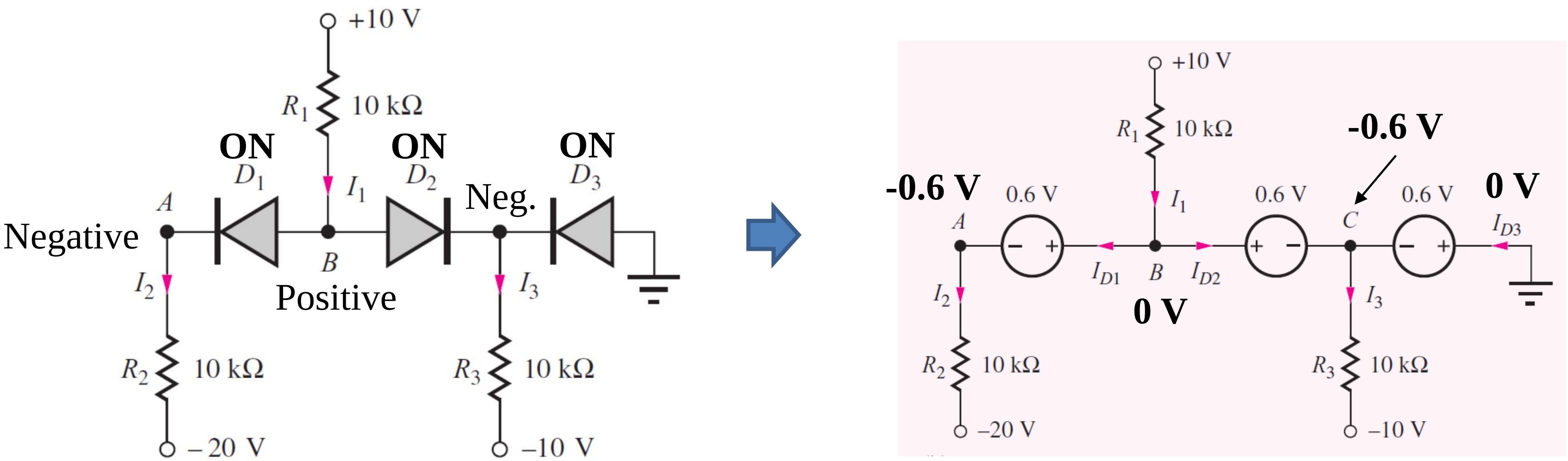
Example 3.7 Use constant voltage drop model ($V_{on} = 0.6$ V) to calculate V_D and I_D of each diode.





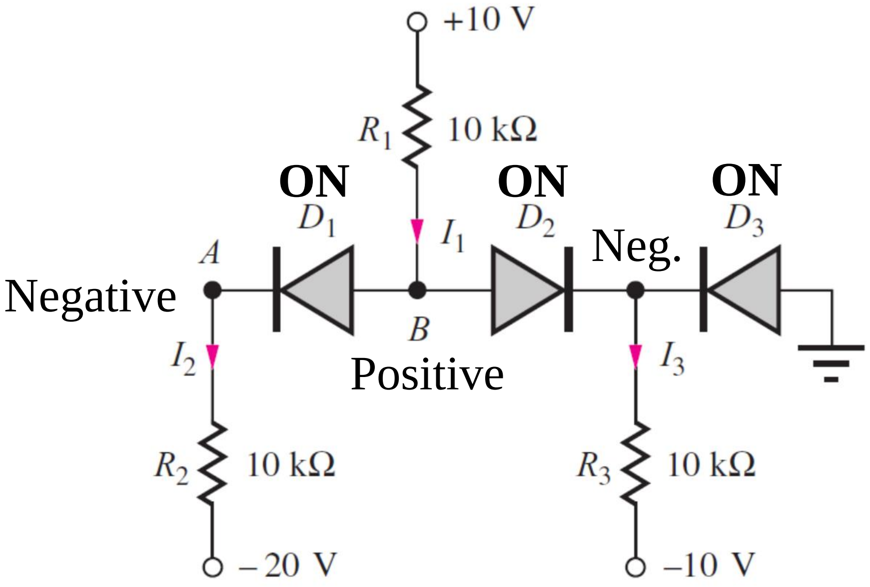
1. By simply reading voltages at diodes nodes, we assume that all diodes are on (Left)
2. Change the diode symbols in the circuit into CVD (Right)

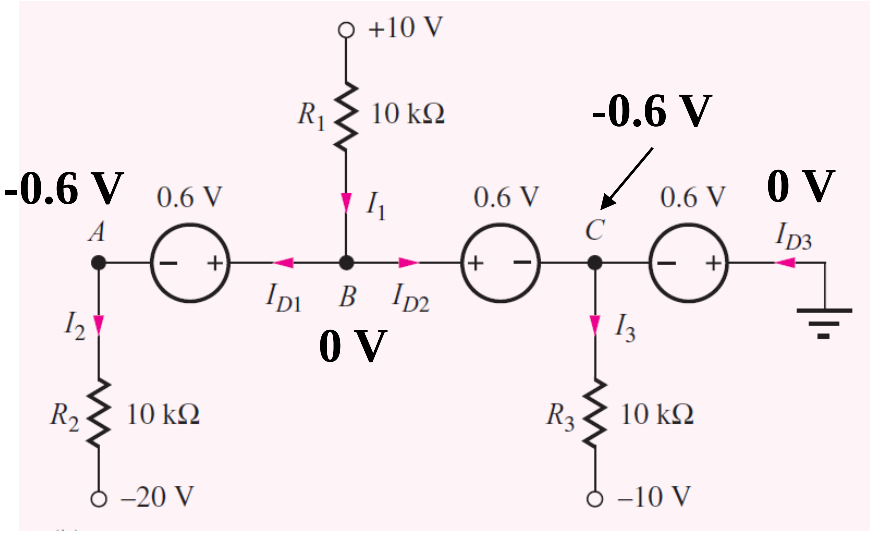
Example 3.7 Use constant voltage drop model ($V_{on} = 0.6$ V) to calculate V_D and I_D of each diode.



1. By simply reading voltages at diodes nodes, we assume that all diodes are on (Left)
2. Change the diode symbols in the circuit into CVD (Right)
3. Read node voltages at A, B, and C for each diode (Right)

Example 3.7 Use constant voltage drop model ($V_{on} = 0.6$ V) to calculate V_D and I_D of each diode.



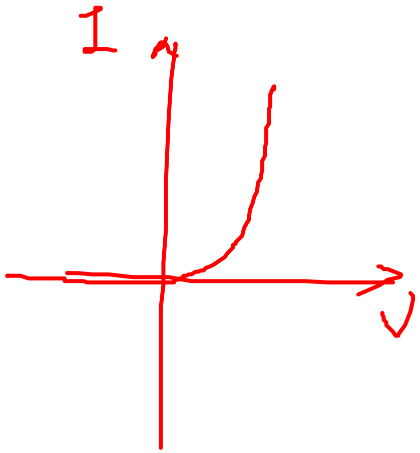


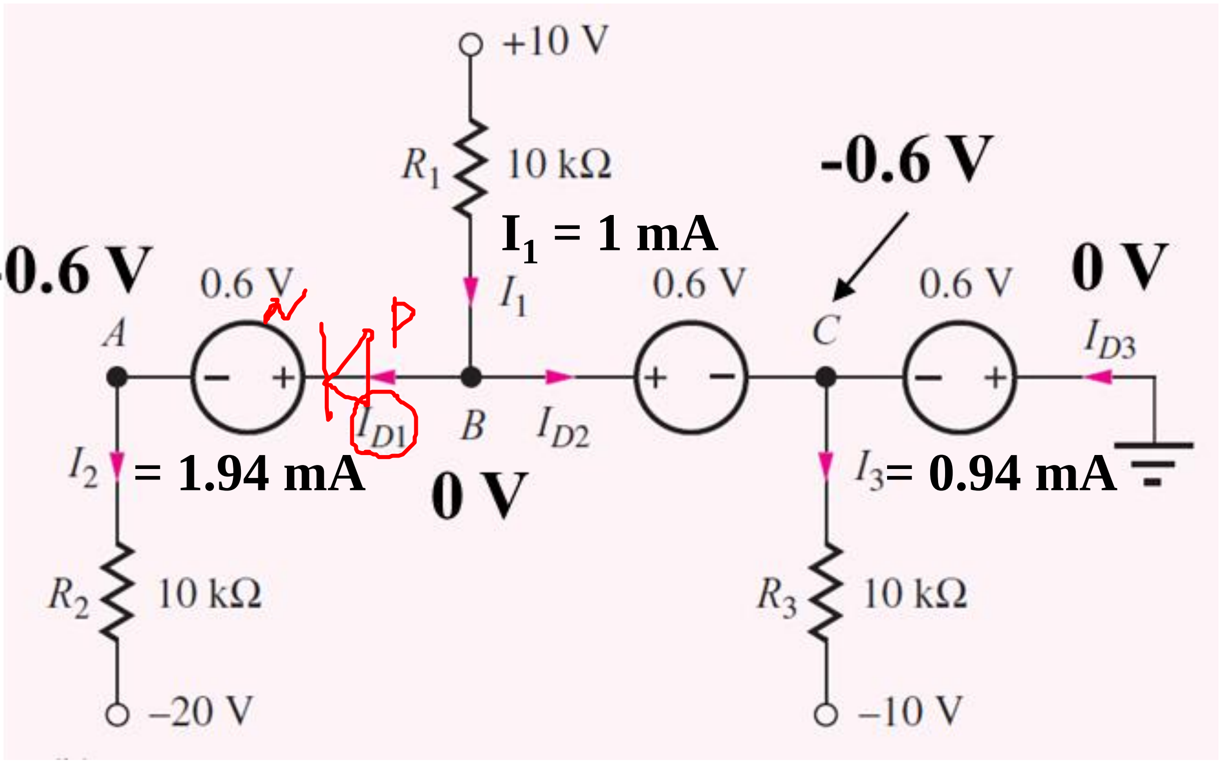
1. By simply reading voltages at diodes nodes, we assume that all diodes are on (Left)
2. Change the diode symbols in the circuit into CVD (Right)
3. Read node voltages at A, B, and C for each diode (Right)

From the circuit, we can calculate currents I_1, I_2, and I_3:

$$I_1 = \frac{10 - 0}{10}\,\frac{\text{V}}{\text{k}\Omega} = 1\,\text{mA} \qquad I_2 = \frac{-0.6 - (-20)}{10}\,\frac{\text{V}}{\text{k}\Omega} = 1.94\,\text{mA}$$

$$I_3 = \frac{-0.6 - (-10)}{10}\,\frac{\text{V}}{\text{k}\Omega} = 0.94\,\text{mA}$$





Positive → Diode is on

→ does not make sense

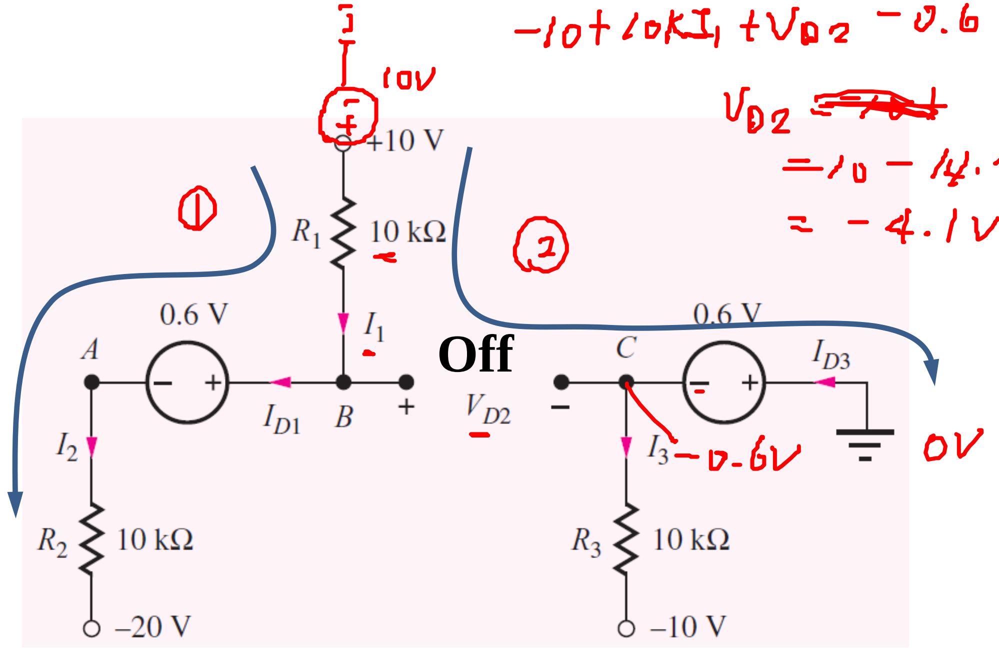
From the circuit,

$I_{D1} = I_2$ and thus I_{D1} = 1.94 mA → **Forward current and thus Diode D_1 is ON**

$I_1 = I_{D1} + I_{D2}$ and thus I_{D2} = -0.94 mA → **I_{D2} is negative meaning that Diode D_2 is OFF.**

$I_3 = I_{D2} + I_{D3}$ and thus I_{D3} = 1.86 mA → **Forward current and thus Diode D_3 is ON.**

We assumed that all the diodes are **On**, but we found that **D_2 is OFF.**



$\nearrow$ 1.47mA

$-10 + 10kI_1 + V_{D2} - 0.6 = 0$

$V_{D2} = 10 - 14.7 + 0.6$

$= -4.1V$

1

By KVL, -10 V + 10k*I_1 + 0.6 + 10k*I_2 -20 = 0 where $I_1 = I_{D1} = I_2$

$$I_{D1} = \frac{29.4}{20}\frac{\text{V}}{\text{k}\Omega} = 1.47\,\text{mA}$$

$$I_{D3} = I_3 = \frac{-0.6-(-10)}{10}\frac{\text{V}}{\text{k}\Omega} = 0.940\,\text{mA}$$

2

Voltage across D_2 is given by $V_{D2} = 10 - 10k{*}I_1 - (-0.6) = 10 - 14.7 + 0.6 =$ **$-4.10V < 0$**

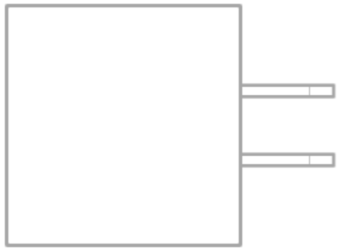
$\Rightarrow$ D_2 is off

Half-Wave Rectifier Circuit

The basic rectifier circuit converts an ac voltage to a pulsating dc voltage. A filter is added to eliminate the ac components of the waveform and produce a nearly constant dc voltage output. In fact, majority of electronic circuits are powered by a dc source, usually based on some form of rectifier.

Input Voltage	**240 Volts (AC)**
Wattage	65 watts
Output Voltage	**19.5 Volts (DC)**
Power Source	Corded Electric
Current Rating	3.34 Amps
Frequency Range	60 hertz

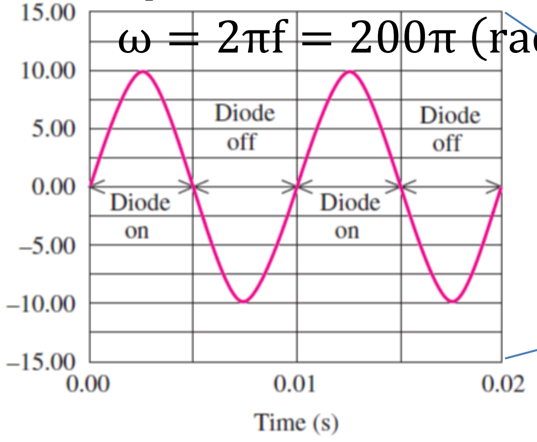
Frequency: 50 to 60 Hz, single phase
Line Voltage: **100 to 240 VAC**
Output Voltage/Current: **9 VDC/2.2 A**
Minimum Power Output: 20 W

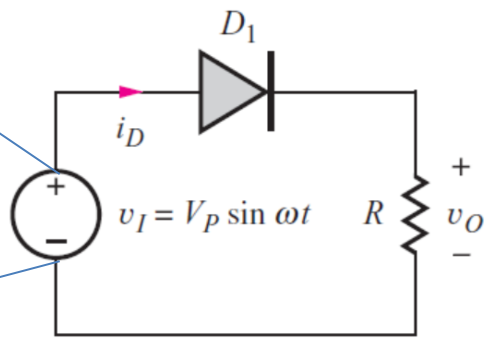


Half-wave rectifier with resistor load

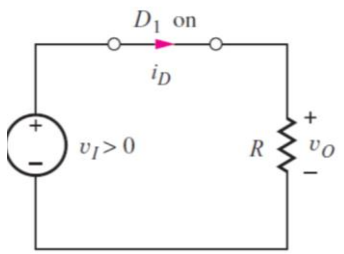
$V_P = 10$ V

$\omega = 2\pi f = 200\pi$ (rad/sec)

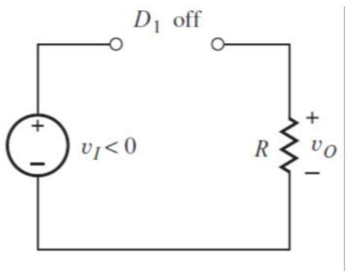




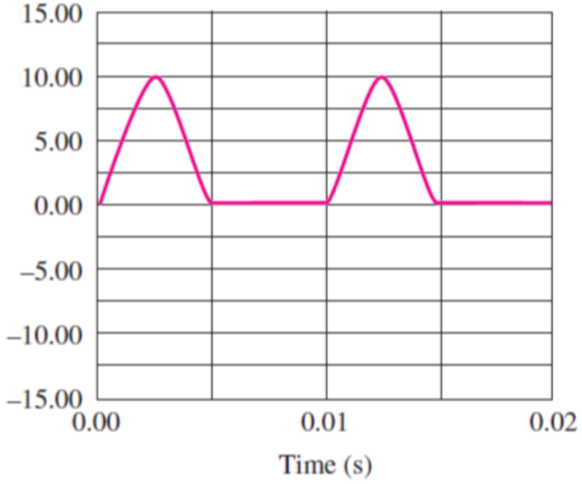
$V_I > 0$, D_1 is on



$V_I < 0$, D_1 is off

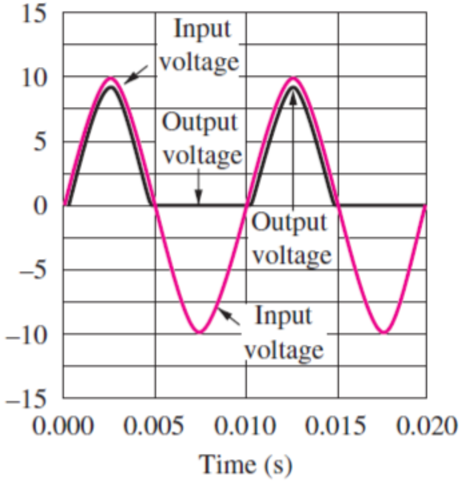


If $V_{on} = 0$ V, $V_O = V_I$



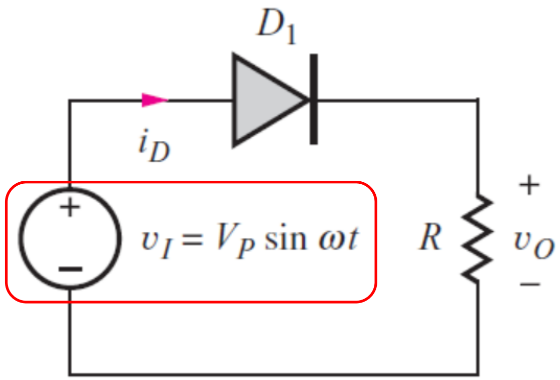
v_o is not DC.

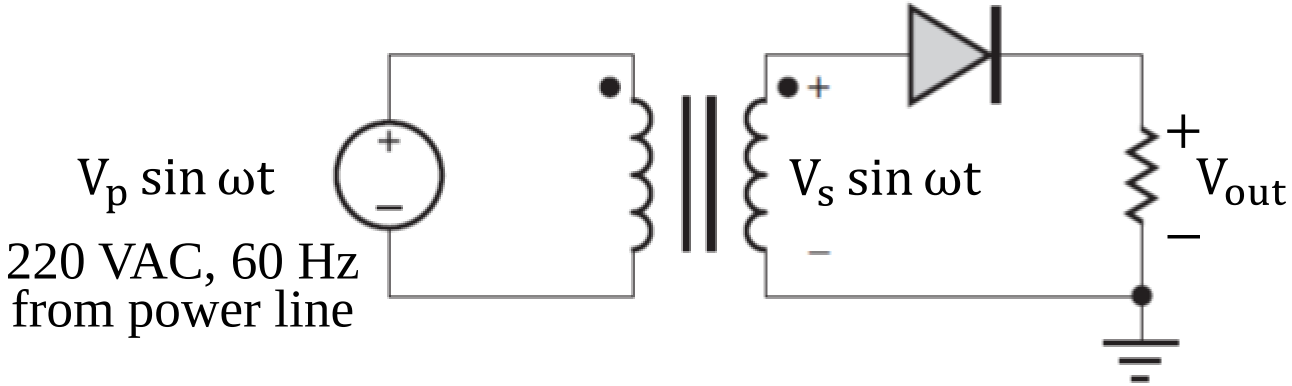
If $V_{on} = 0.7$ V, $V_O = V_P \sin \omega t - V_{on}$



v_o is not DC.

***Transformer**



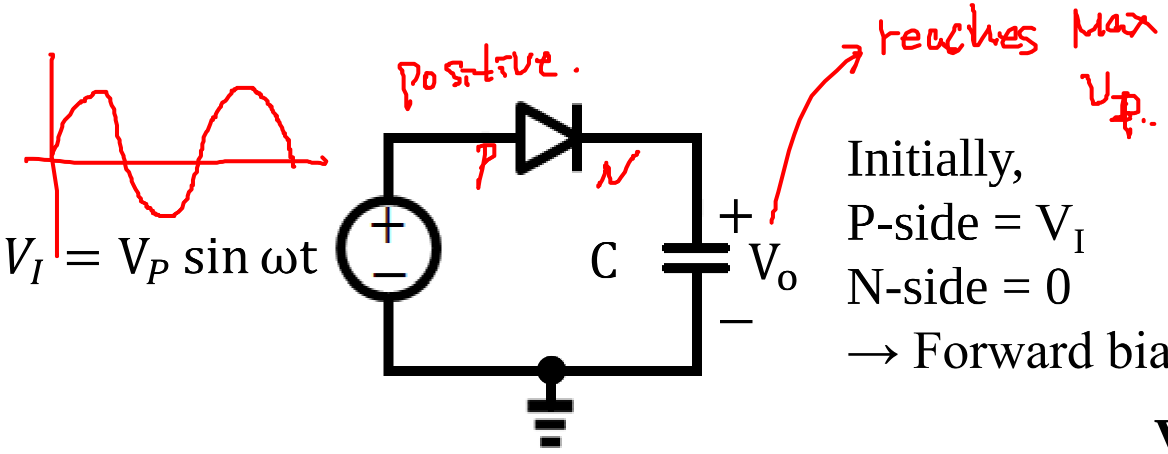


The output of an ideal transformer can be represented as an ideal voltage source, and thus the ideal voltage shown in the circuit is a transformer circuit above unless otherwise stated.

The transformer can step the voltage up or down depending on the application. Also, it enhances safety by providing isolation from the power line.

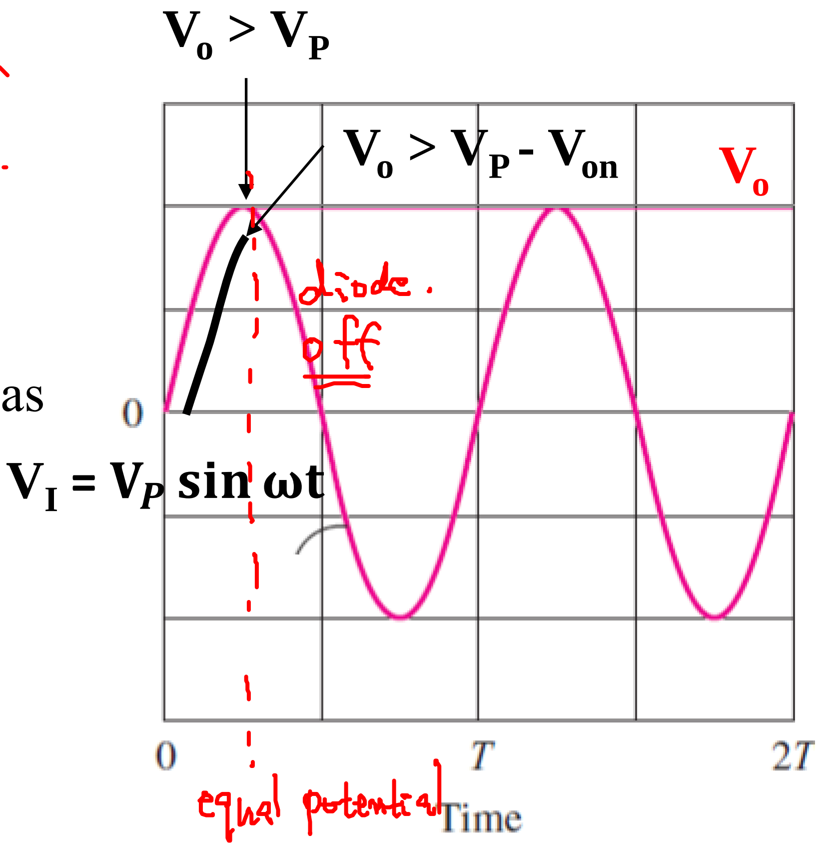
Half-Wave Rectifier with RC Load

To understand operation of the rectifier filter, we first consider operation of the peak-detector circuit consisting of the input source, diode, and capacitor. The cap was initially discharged $V_o(0) = 0$ V



Initially,
P-side = V_I
N-side = 0
→ Forward bias

No path for cap discharge when diode is off



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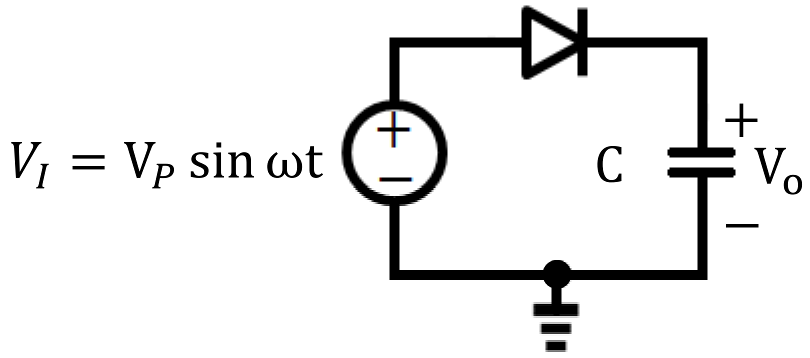
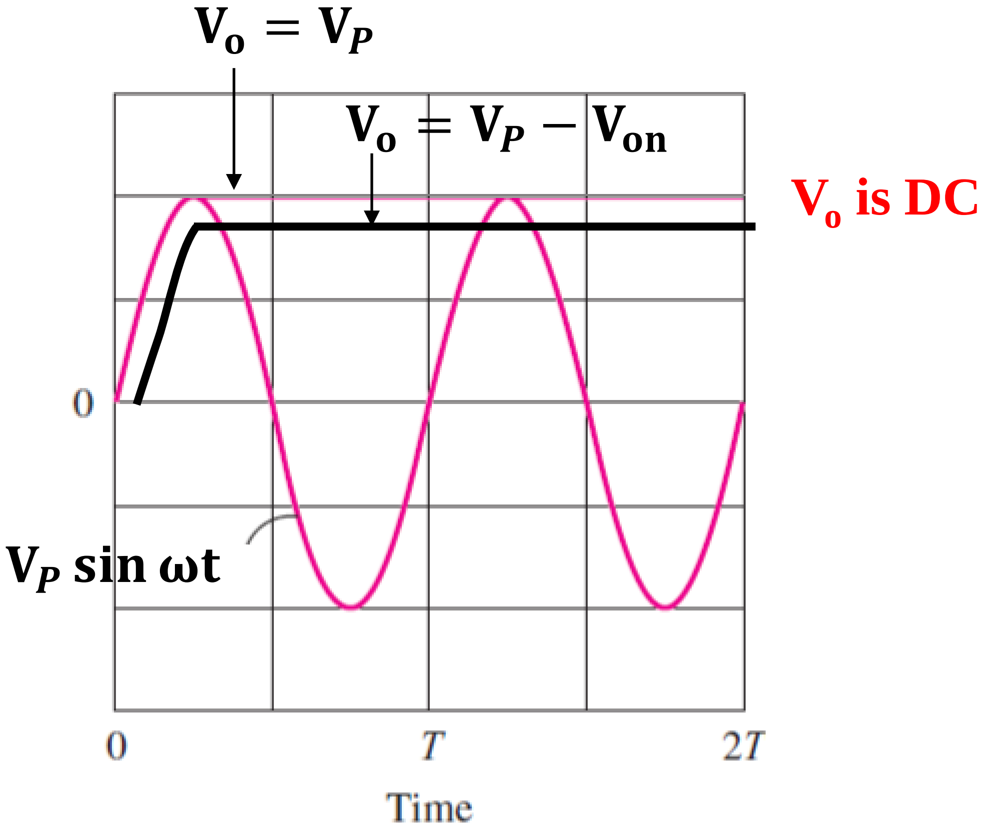
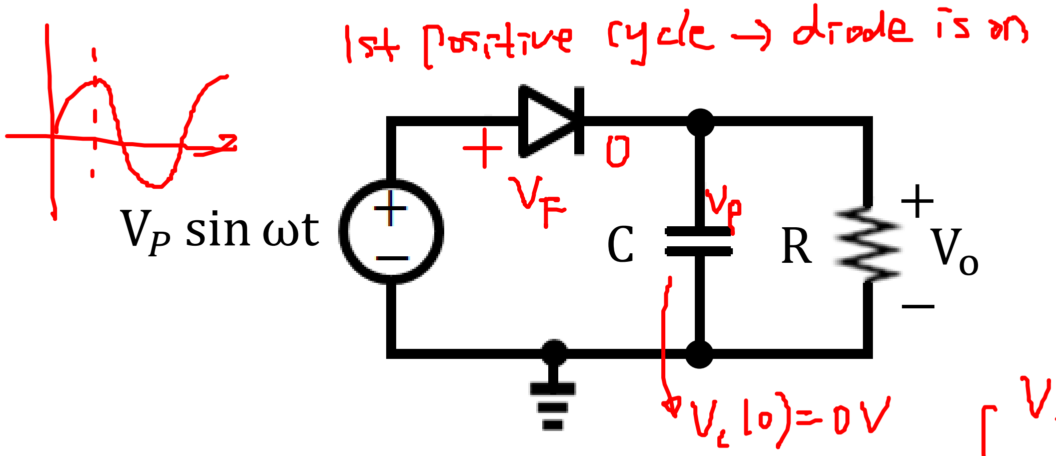
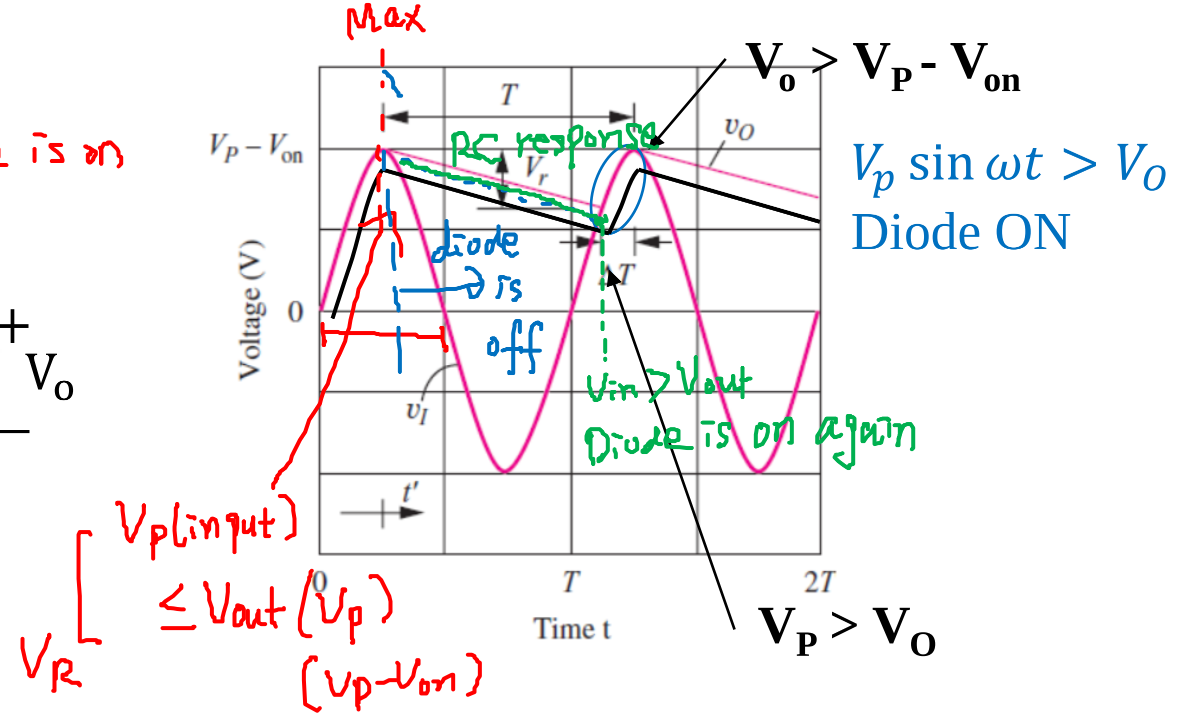


No path for cap discharge when diode is off



By connecting a load R to the peak-detector circuit, now we provide power to the load R, meaning that **there is a path available to discharge the capacitor** during the time the diode is not conducting.





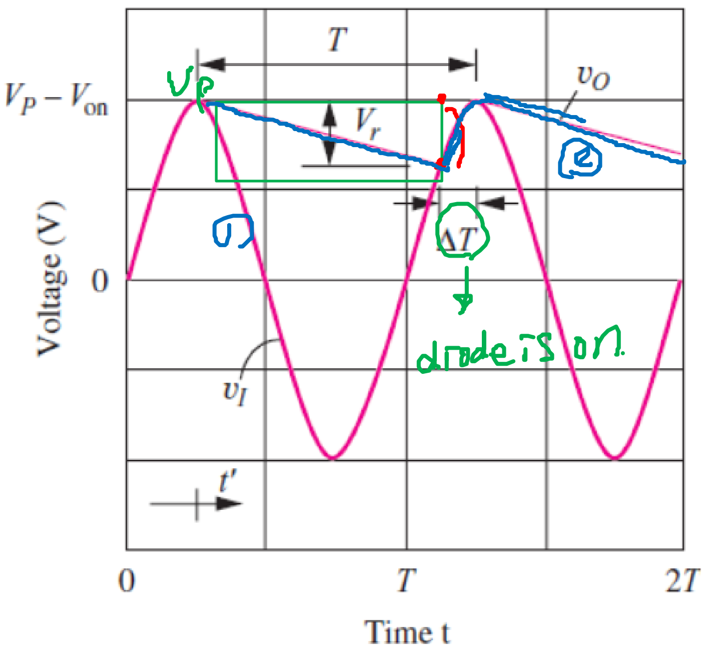
The output voltage is no longer constant, but has **a ripple voltage V_r**. Also, the **diode only conducts for a short time ΔT** during each cycle. We are interested in three parameters:

(1) Ripple voltage V_r

(2) Conduction interval ΔT

(3) Conduction angle $\theta_c = \omega \Delta T$

Ripple Voltage



Recall VE215, **a RC response** without a source (discharge period) is

$$\boxed{v_o(t) = (V_P - V_{on})\exp\left(-\frac{t}{RC}\right)} \quad \cancel{\text{for } t' = \left(t - \frac{T}{4}\right) \geq 0}$$

Ripple voltage V_r can be described as

$$\boldsymbol{V_r = Peak\ point\ - RC\ response}$$

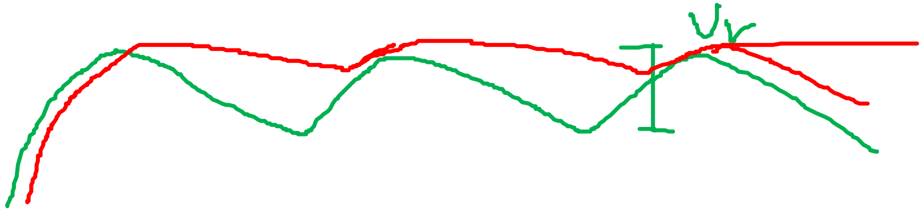
$$= (V_P - V_{on}) - v_o(t)$$

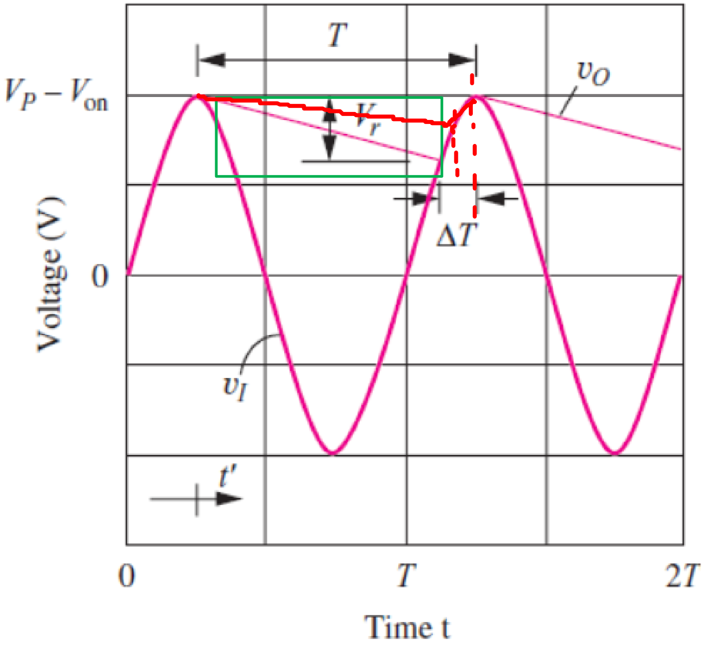
$$= (V_P - V_{on})\left[1 - \exp\left(-\frac{T - \Delta T}{RC}\right)\right]$$

When diode is off, i.e. RC response

Discharging period

Ripple Voltage





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Ripple voltage V_r can be described as

$$\boldsymbol{V_r = Peak\ point\ - RC\ response}$$
$$= (V_P - V_{on}) - v_o(t)$$
$$= (V_P - V_{on})\left[1 - \exp\left(-\frac{T - \Delta T}{RC}\right)\right]$$

When diode is off, i.e. RC response

Discharging period

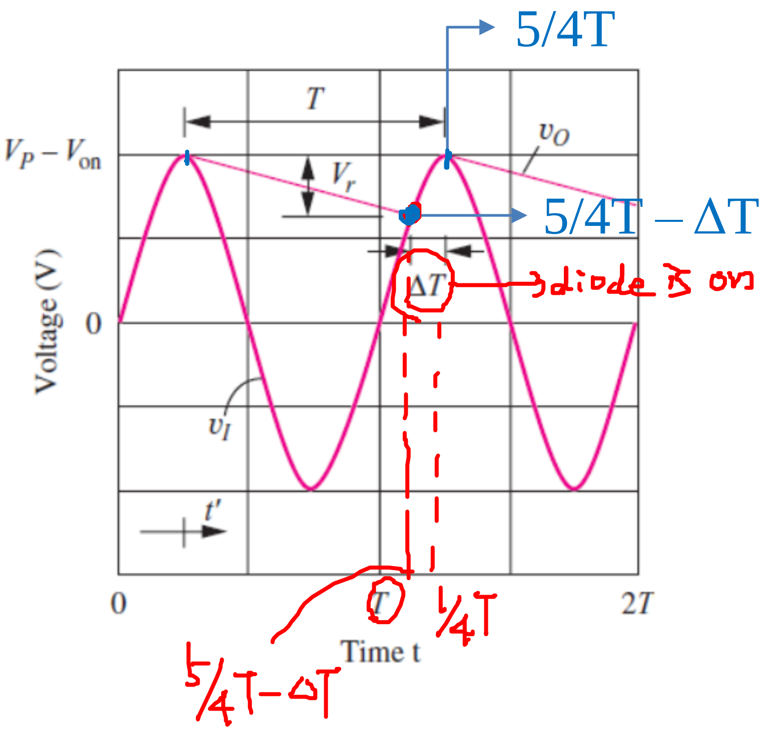
By Taylor series, $e^{-x} = 1 - x$, **ripple voltage V_r** becomes

$V_r = (V_P - V_{on})\left[1 - \left(1 - \frac{T - \Delta T}{RC}\right)\right]$, and to attain stable DC V_r needs to be minimized.

From the graph above, we can see that if $\Delta T \ll T$, V_r becomes smaller.

Thus, finally, $\boldsymbol{V_r = \frac{(V_P - V_{on})}{R}\frac{T}{C}}$

Conduction angle and interval



At 5/4T – ΔT, the input voltage (V_P – V_{on}) just exceeds the output voltage (V_O). **Diode is ON**.

$$\Theta = \omega t = 2\pi f \cdot t = \frac{2\pi}{T}\left(\frac{5}{4}T - \Delta T\right) = \frac{5\pi}{2} - \theta_C \; as \; \theta_C = \omega \Delta T$$

At 5/4T – ΔT, **Input sine wave – V_{on} = (Peak of Sine wave – V_{on}) – V_r**

$$V_P \sin\left[\omega\left(\frac{5T}{4} - \Delta T\right)\right] - \cancel{V_{on}} = (V_P - \cancel{V_{on}}) - V_r$$

$$\longrightarrow V_P \sin\left(\frac{5\pi}{2} - \theta_c\right) - V_{on} = (V_P - V_{on}) - V_r$$

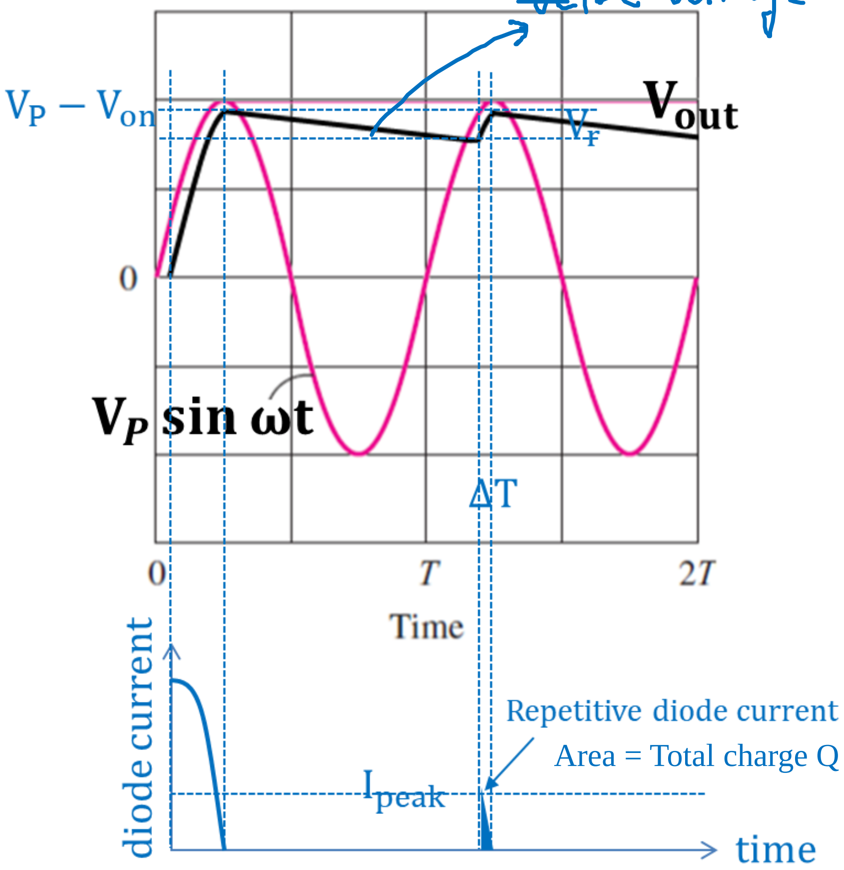
Thus, the equation becomes $V_P \cos\theta_c = V_P - V_r$ $\longrightarrow \cos\theta_c = \frac{V_P - V_r}{V_P} \cong 1 - \frac{\theta_c{}^2}{2}$ if θ_c is very small

$$\boldsymbol{\theta_c = \sqrt{\frac{2V_r}{V_P}}} \qquad \boldsymbol{\Delta T = \frac{\theta_c}{\omega} = \frac{1}{\omega}\sqrt{\frac{2V_r}{V_P}}}$$

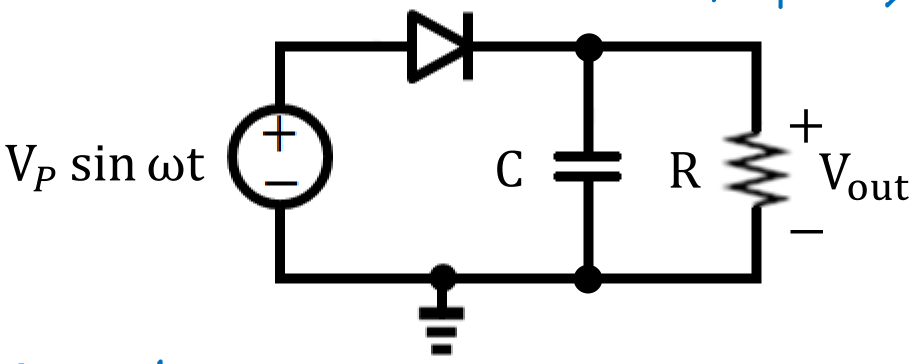
Diode ~~C~~urrent I_{peak}.

Diode current flows for only a very small fraction of the period T. **The capacitor is charged during ΔT and is discharged during $T - \Delta T$.**

+DC voltage



dc current = V_{DC}/R.



$Q = I \times t.$

$I = Q/t.$

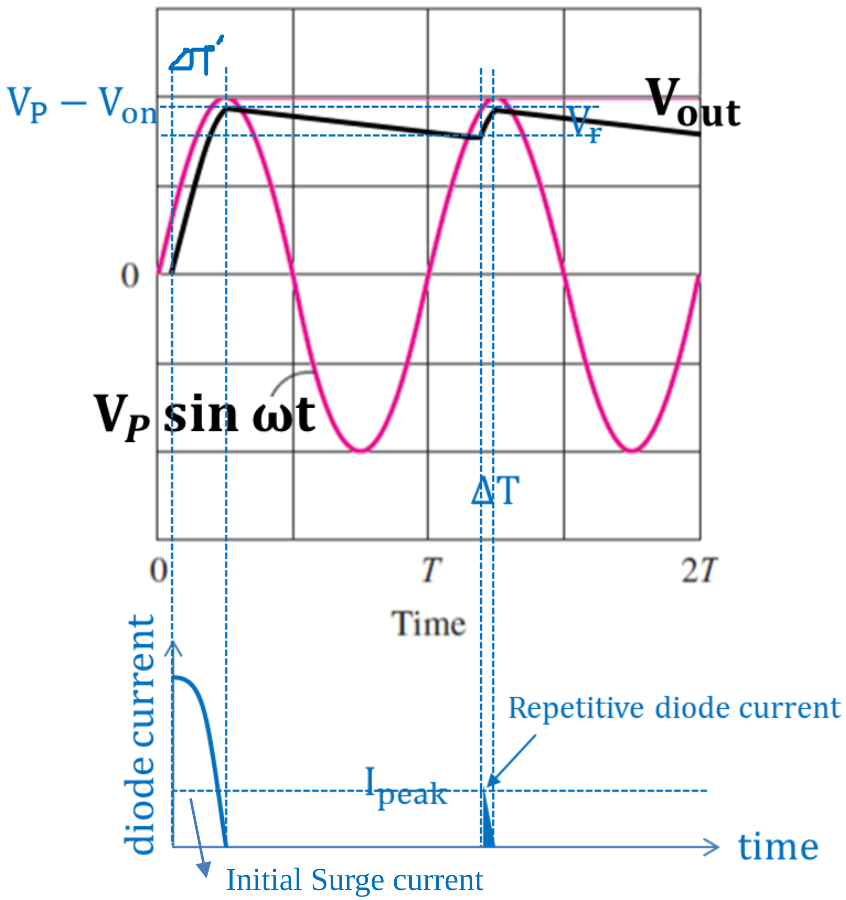
$$Q \cong \frac{I_{peak}\Delta T}{2} = I_{dc}(T - \cancel{\Delta T}) \cong I_{dc}T$$

$$where\ I_{dc} = \frac{V_p - V_{on}}{R}$$

$$\rightarrow \mathbf{I_{peak}} = \frac{\mathbf{2I_{dc}T}}{\mathbf{\Delta T}}$$

Surge Current

At the first cycle, the capacitor is completely discharged (as we assumed), and therefore, there will be a larger current through the diode. During charging period ($\Delta T'$), almost all diode current goes to C.



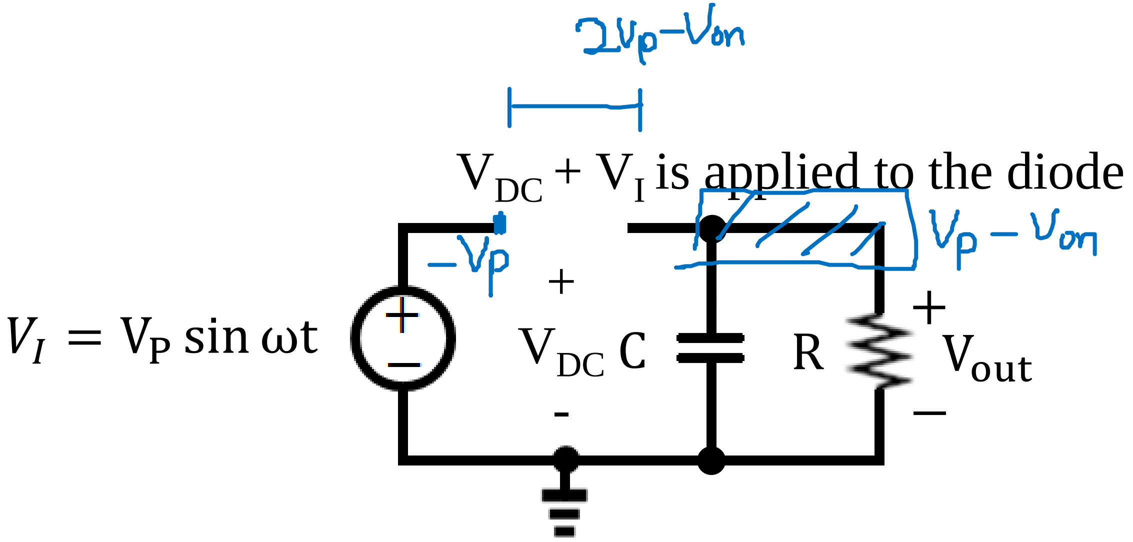
$$I_{surge} = i_d(t) = C\frac{d(V_P \sin \omega t - V_{on})}{dt} = \omega C V_P \cos \omega t \Big|_{t=0}$$

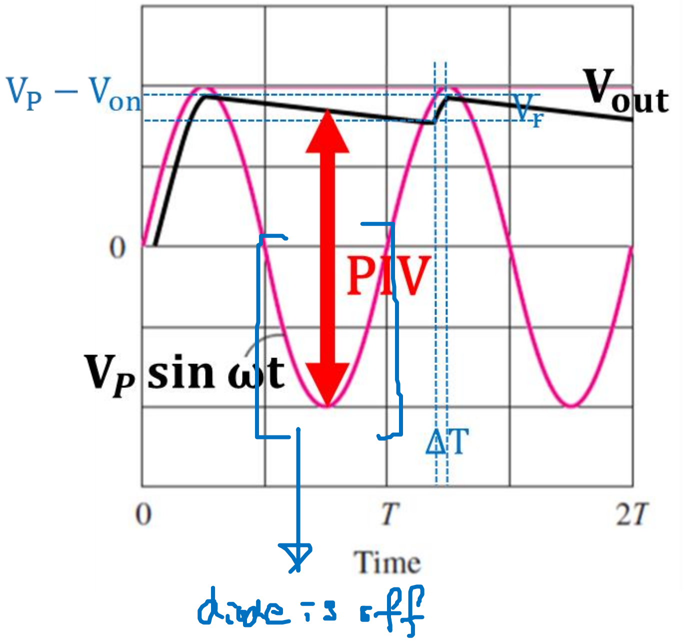
$$i_c = c\frac{dV}{dt}$$

$$= \omega C V_P$$

Peak Inverse Voltage (PIV)

The breakdown voltage rating of the diodes is called the peak-inverse-voltage (VIP). If V_r is very small, the diode must be able to withstand a large negative peak voltage.





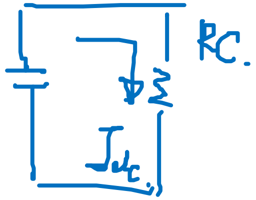
$$\textbf{Peak-inverse-voltage (PIV)} \geq \boldsymbol{V_{DC} + V_I = V_P - V_{on} + V_P \cong 2V_P - V_{on}}$$

If the diode PIV is smaller than $\mathbf{2V_P - V_{on}}$, the diode breaks down.

Example 3.8 Find the value of the dc output voltage, dc output current, ripple voltage, conduction interval, conduction angle and diode peak current for a half-wave rectifier driven from a transformer having a secondary voltage of 12.6 V_{rms} (60 Hz) with R = 15 Ω and C = 25,000 μF. Assume V_{on} = 1 V.

$V_p = 12.6\sqrt{2} = 17.82\ V.$ $V_{dc} = V_p - V_{on} = 16.82V.$ $I_{dc} = \frac{16.82}{15} = 1.12A.$

DC like = DC.



$$V_R = \frac{V_{dc}T}{RC} = \frac{16.82/60}{15 \times 25000 \times 10^{-6}} = 0.747V.$$

$\theta_c = 0.29$ rad

Example 3.8 Find the value of the dc output voltage, dc output current, ripple voltage, conduction interval, conduction angle and diode peak current for a half-wave rectifier driven from a transformer having a secondary voltage of 12.6 V_{rms} (60 Hz) with R = 15 Ω and C = 25,000 μF. Assume V_{on} = 1 V.

$$V_{dc} = 12.6\sqrt{2} - 1 = 16.8\ (V)$$

$$I_{dc} = \frac{16.8}{15} = 1.12\ (A)$$

$$V_r \cong V_{dc}\frac{T}{RC} = 16.8\frac{\frac{1}{60}}{15 \times 25000 \times 10^{-6}} = 0.747\ (V)$$

$$\theta_c \cong \sqrt{\frac{2V_r}{V_P}} = \sqrt{\frac{2 \times 0.747}{12.6 \times \sqrt{2}}} = 0.29\ (rad)\ \text{or}\ 16.6^{\circ}$$

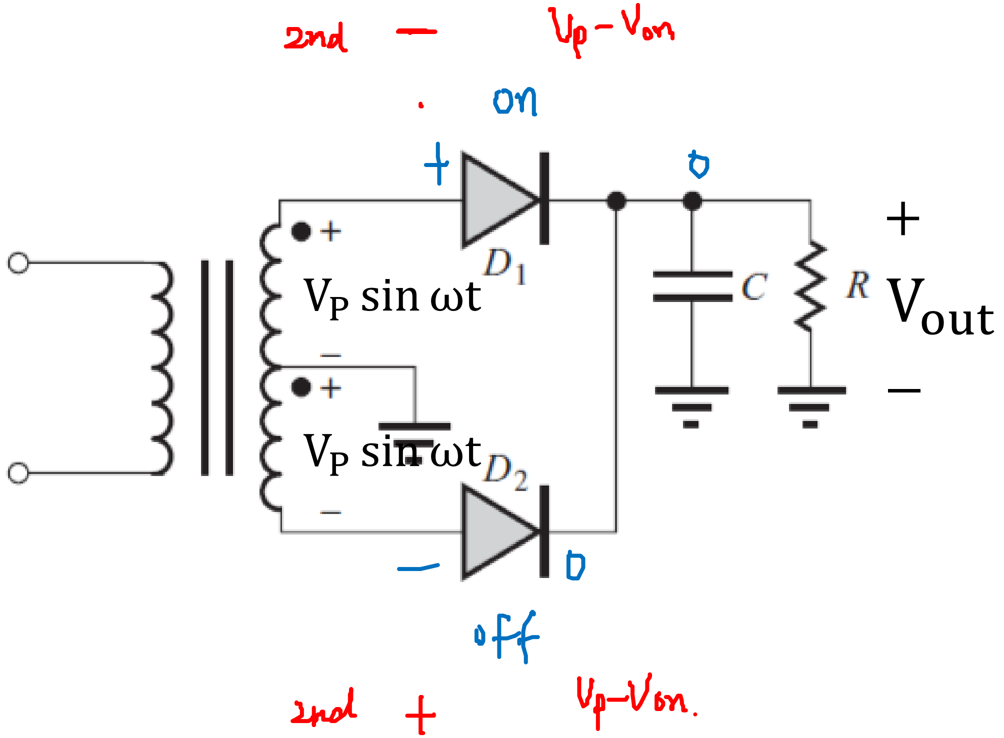
$$\Delta T \cong \frac{\theta_c}{\omega} = \frac{0.29}{2\pi \times 60} = 7.69 \times 10^{-4}\ (sec)$$

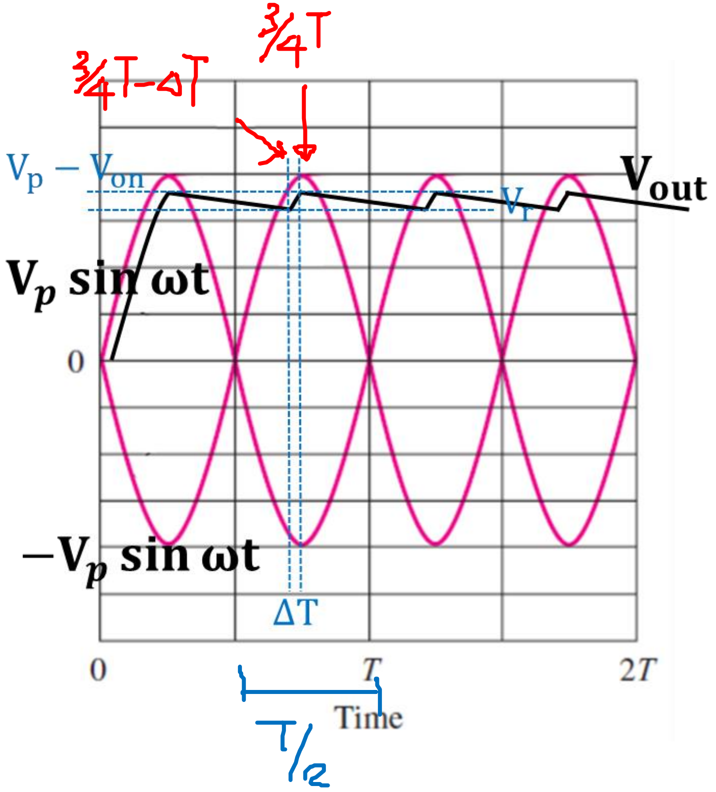
$$I_{peak} = \frac{2 \times 1.12 \times \frac{1}{60}}{7.69 \times 10^{-4}} = 48.6\ (A)$$

- Make sure all assumptions are valid.
- Since R is small (15 Ω), C needs to be large (25,000 μF) to maintain a low V_r.
- The diode must be able to handle these repetitively high peak currents.

Full-Wave Rectifier

Full-wave rectifier circuits cut the capacitor discharge time in half and offer the advantage of requiring only one-half the filter capacitance to achieve a given ripple voltage.

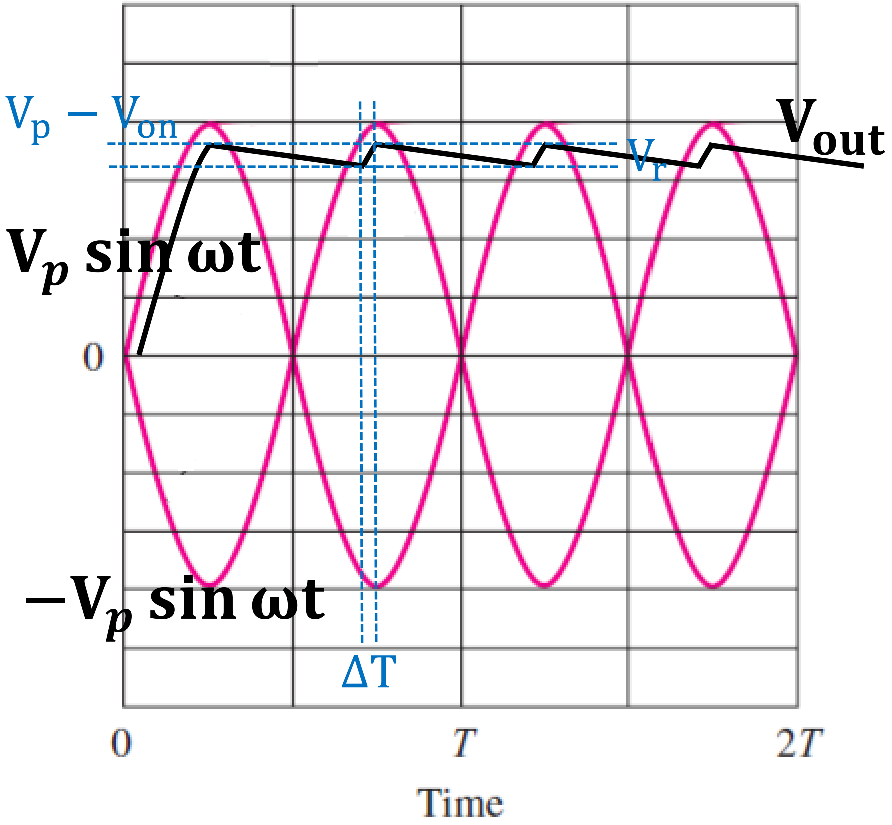




When $v_I > 0$, D_1 will be functioning as a half-wave rectifier, and D_2 will be off.
When $v_I < 0$, D_2 will be functioning as a half-wave rectifier, and D_1 will be off.

Ripple Voltage

An analysis similar to that for the half-wave rectifier yields the same formulas for dc output voltage, ripple voltage, and ΔT, except that the **discharge interval is T/2** rather than T.



$$V_{dc} = \mathbf{V_p - V_{on}}$$

$$I_{dc} = \frac{V_{dc}}{R}$$

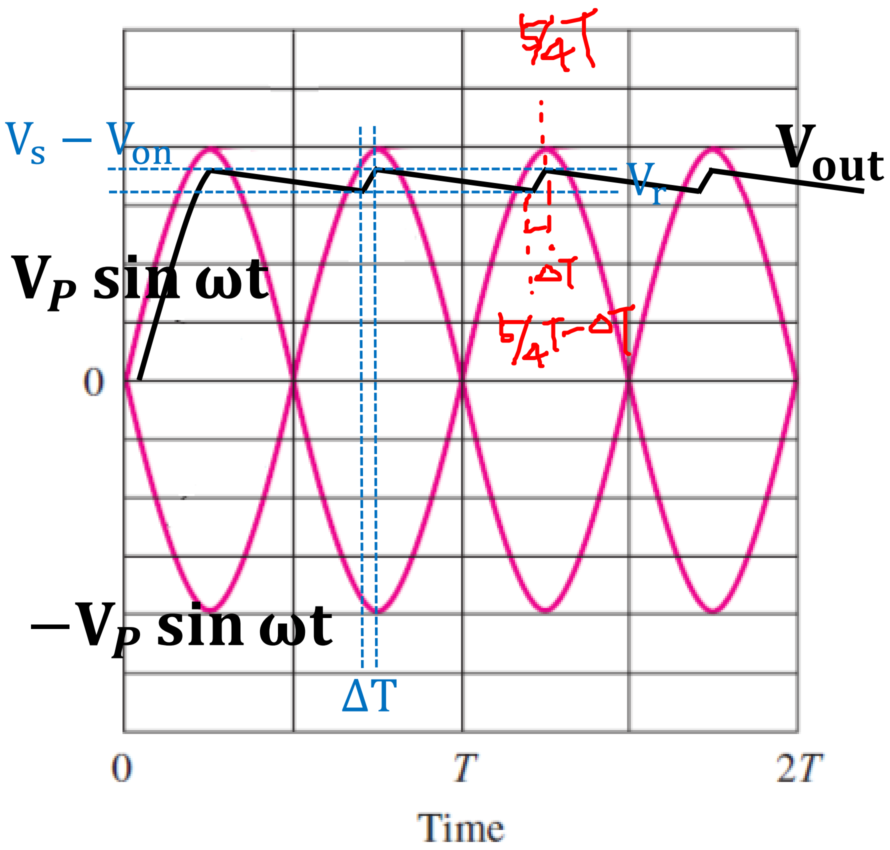
diode is off

$$\mathbf{V_r} = (V_P - V_{on})\left(1 - e^{-\frac{T/2-\Delta T}{RC}}\right)$$

$$\cong (V_P - V_{on})\left(\frac{T/2 - \Delta T}{RC}\right)$$

$$\cong \mathbf{(V_P - V_{on})\left(\frac{T}{2RC}\right)} \quad if\,\Delta T \ll \frac{T}{2}$$

Conduction angle and interval



In a negative cycle

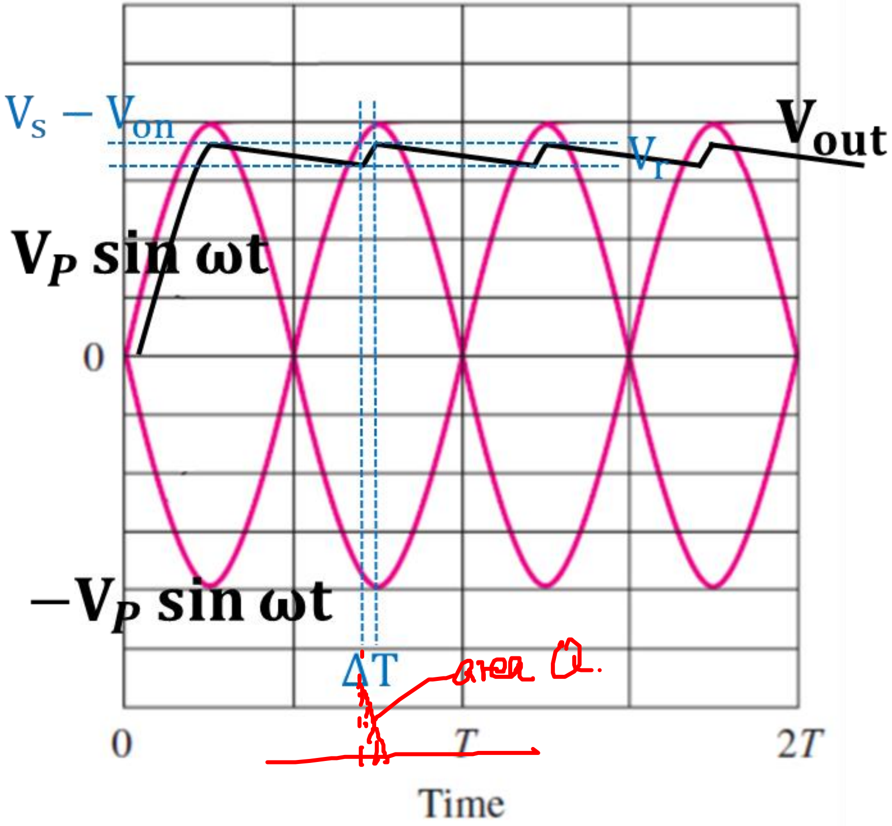
$$-V_P \sin\left[\omega\left(\frac{3T}{4} - \Delta T\right)\right] - V_{on} = (V_P - V_{on}) - V_r$$

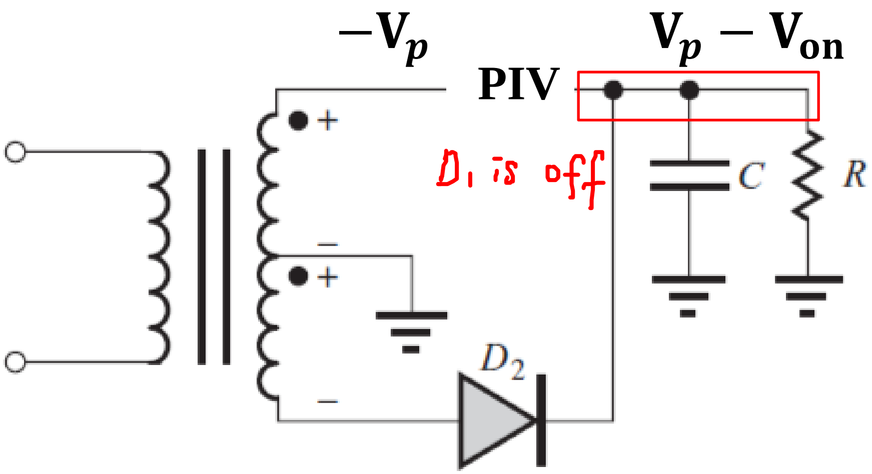
$$-V_P \sin\left(\frac{3\pi}{2} - \theta_c\right) - V_{on} = (V_P - V_{on}) - V_r$$

$$V_P \cos\theta_c = V_P - V_r$$

$$\cos\theta_c = \frac{V_P - V_r}{V_P} \cong 1 - \frac{\theta_c^{\ 2}}{2} \quad \textit{if } \theta_c \textit{ very small}$$

$$\boxed{\boldsymbol{\theta_c = \sqrt{\frac{2V_r}{V_P}}}} \qquad \boxed{\boldsymbol{\Delta T = \frac{\theta_c}{\omega} = \frac{1}{\omega}\sqrt{\frac{2V_r}{V_P}}}}$$





on period.

$$Q \cong \frac{I_{peak}\Delta T}{2} = I_{dc}\underbrace{\left(\frac{T}{2} - \cancel{\Delta T}\right)}_{\text{off period}} \cong I_{dc}\frac{T}{2}$$

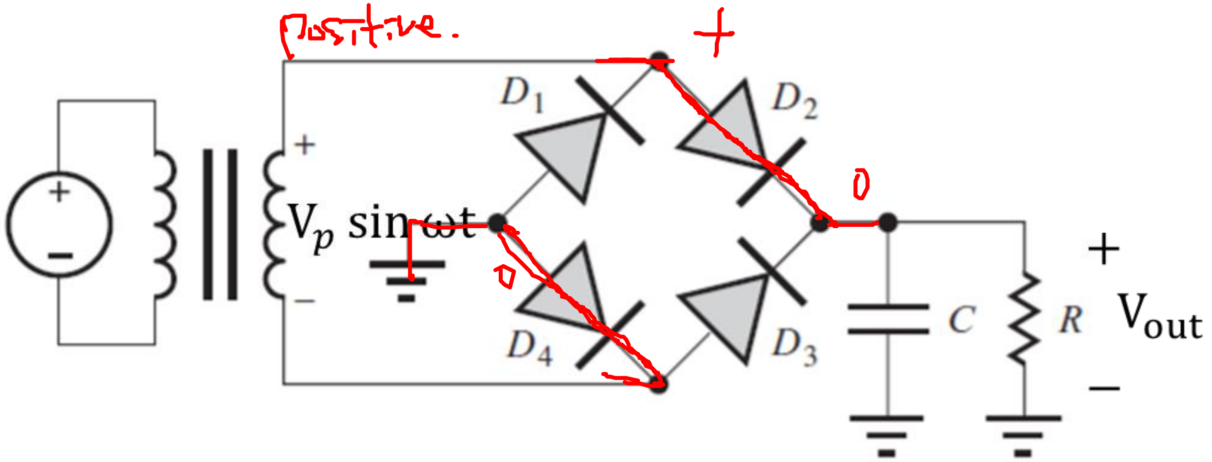
$$I_{peak} = \frac{I_{dc}T}{\Delta T}$$

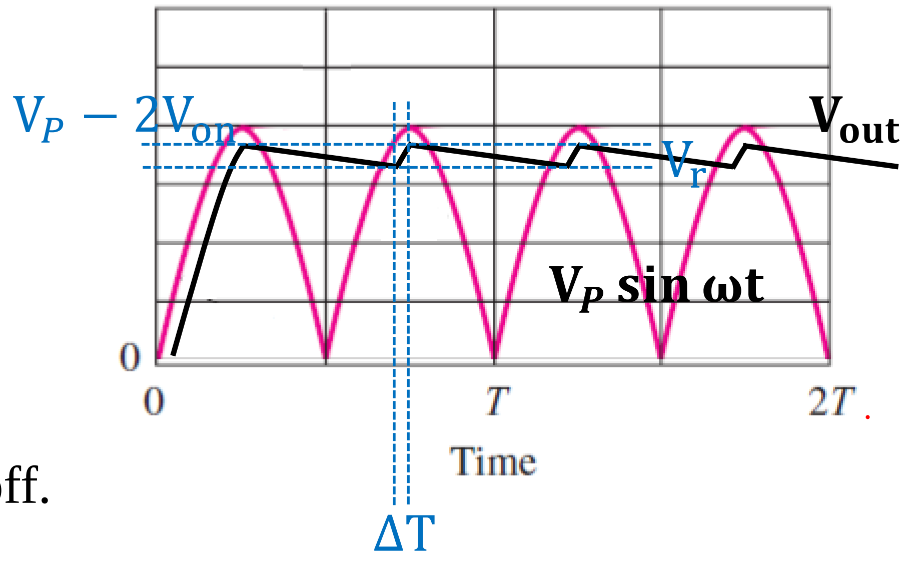
const.

$$I_{surge} = \omega C V_P \text{ (at } t = 0) \Big|_{t=0}$$

$$PIV = 2V_P - \cancel{V_{on}} \cong 2V_P$$

Full-Wave Bridge Rectifier





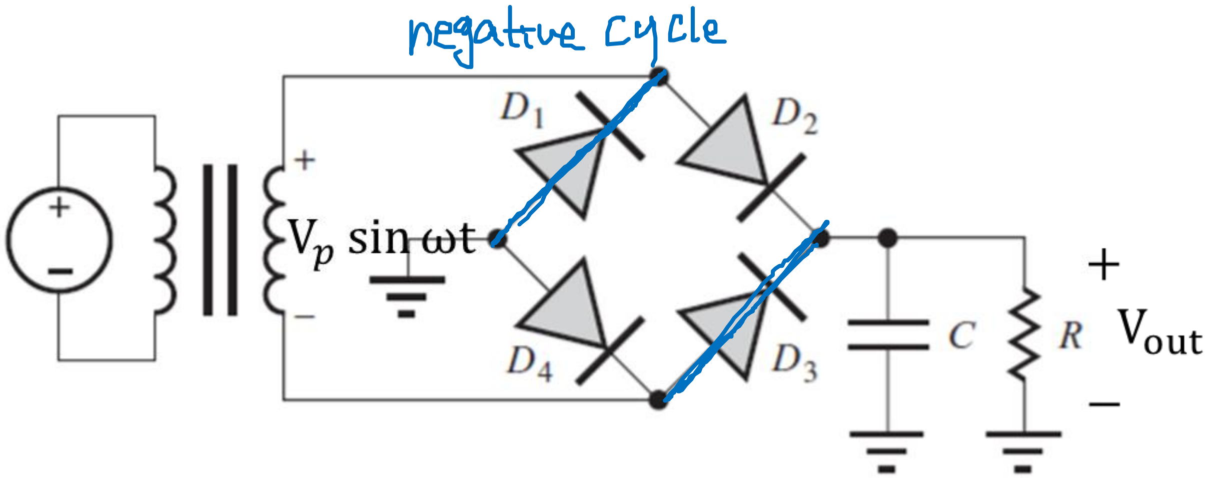
For $v_I > 0$, D_2 and D_4 will be on and D_1 and D_3 will be off.

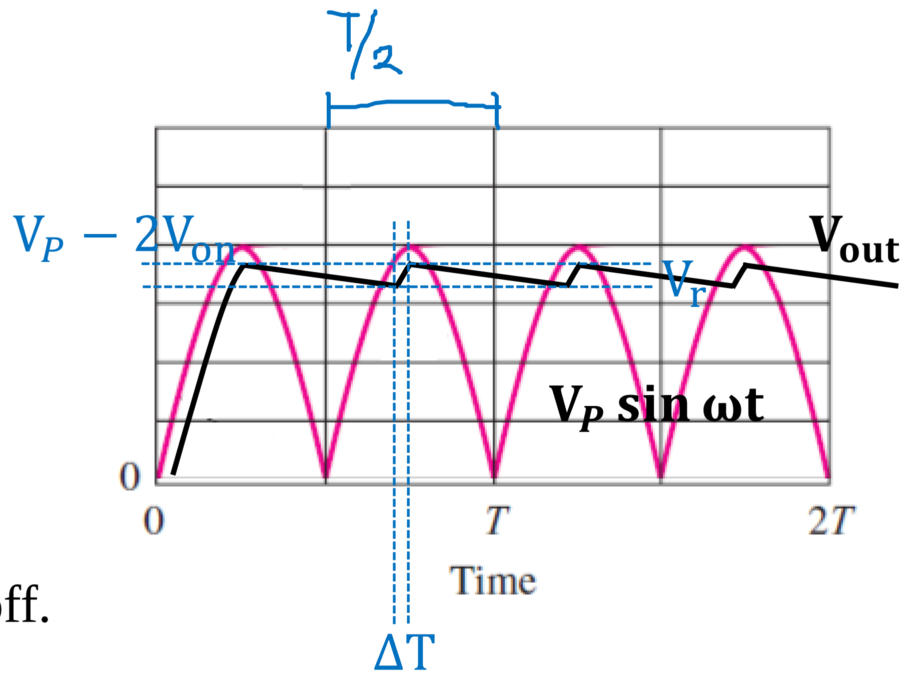
$$V_{dc} = \mathbf{V_P - 2V_{on}}$$

$$I_{dc} = \frac{V_{dc}}{R}$$

$$\mathbf{V_r} = (V_P - 2V_{on})\left(1 - e^{-\frac{T/2-\Delta T}{RC}}\right) \cong (V_P - 2V_{on})\left(\frac{T/2 - \Delta T}{RC}\right) \quad if \left(\frac{T}{2} - \Delta T\right) \ll RC$$

$$\cong (\mathbf{V_P - 2V_{on}})\left(\frac{\mathbf{T}}{\mathbf{2RC}}\right) \quad if\ \Delta T \ll \frac{T}{2}$$





↳ Charging period

discharging period = T/2 − ΔT

For $v_I < 0$, D_1 and D_3 will be on and D_2 and D_4 will be off.

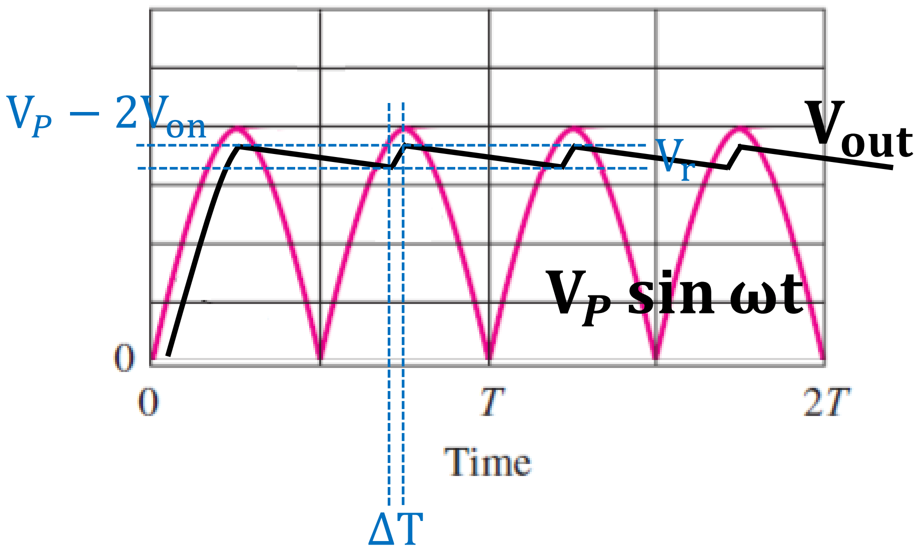
$$V_{dc} = \mathbf{V_P - 2V_{on}}$$

$$I_{dc} = \frac{V_{dc}}{R}$$

$$\mathbf{V_r} = (V_P - 2V_{on})\left(1 - e^{-\frac{T/2-\Delta T}{RC}}\right) \cong (V_P - 2V_{on})\left(\frac{T/2-\Delta T}{RC}\right) \quad if \left(\frac{T}{2} - \Delta T\right) \ll RC$$

$$\cong \mathbf{(V_P - 2V_{on})}\left(\frac{\mathbf{T}}{\mathbf{2RC}}\right) \quad if\ \Delta T \ll \frac{T}{2}$$

Conduction angle and interval



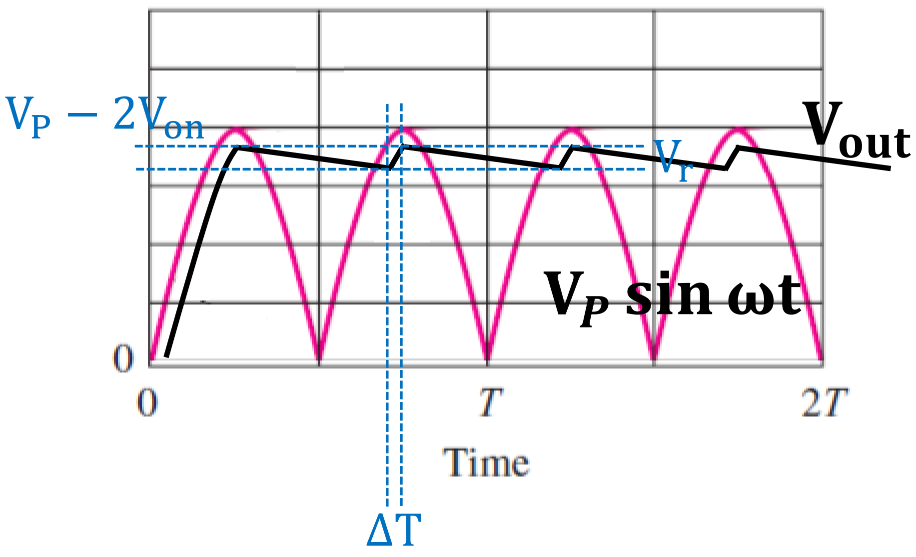
$$-V_P \sin\left[\omega\left(\frac{3T}{4} - \Delta T\right)\right] - 2V_{on} = (V_P - 2V_{on}) - V_r$$

$$-V_P \sin\left(\frac{3\pi}{2} - \theta_c\right) - 2V_{on} = (V_P - 2V_{on}) - V_r$$

$$V_P \cos\theta_c = V_s - V_r$$

$$\cos\theta_c = \frac{V_P - V_r}{V_s} \cong 1 - \frac{\theta_c{}^2}{2} \quad \textit{if } \theta_c \textit{ very small}$$

$$\boxed{\theta_c = \sqrt{\frac{2V_r}{V_P}}} \qquad \boxed{\Delta T = \frac{\theta_c}{\omega} = \frac{1}{\omega}\sqrt{\frac{2V_r}{V_P}}}$$

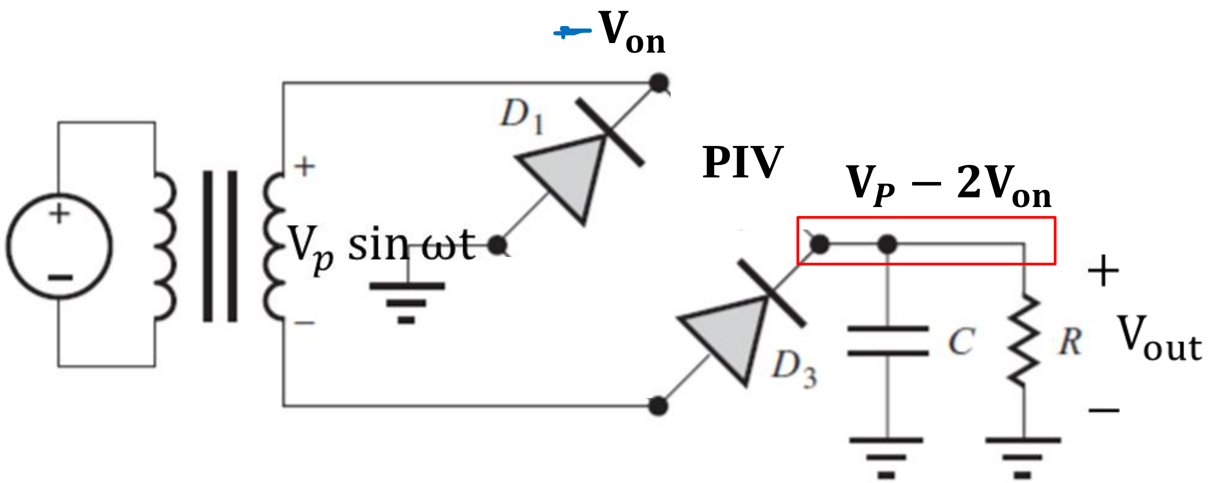


$$Q \cong \frac{I_{peak}\Delta T}{2} = I_{dc}\left(\frac{T}{2} - \Delta T\right) \cong I_{dc}\frac{T}{2}$$

$$\mathbf{I_{peak} = \frac{I_{dc}T}{\Delta T}}$$

$$\mathbf{I_{surge} = \omega C V_P \text{ (at } t = 0)}$$

$$\mathbf{PIV = V_P - V_{on} \cong V_P}$$

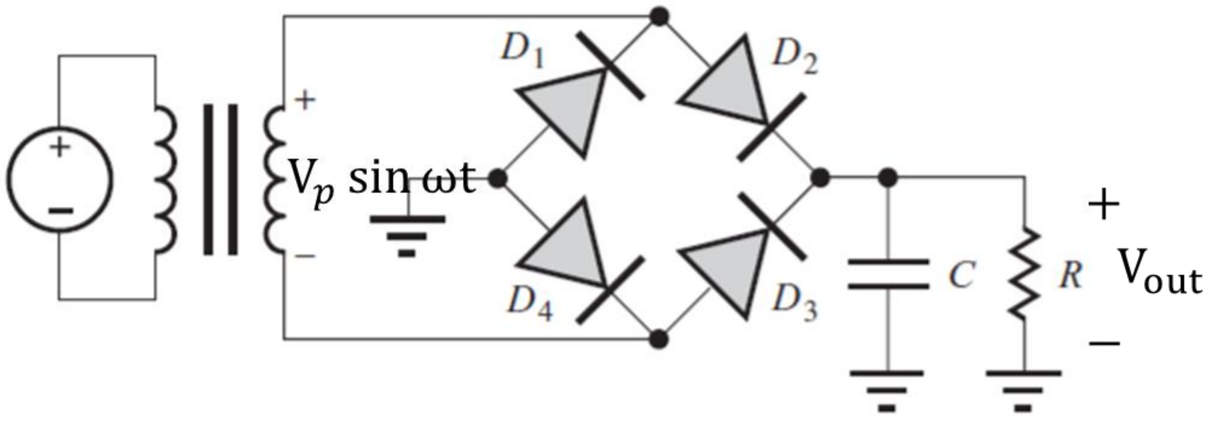


Example 3.9 Design a full-wave bridge rectifier to provide a dc output voltage 15 V with no more than 1 percent ripple at a load current of 2A. ($V_{on} = 1\ V, T = 1/60\ \sec$)

$V_{dc} = 15\ (V)$

$V_r < 0.15\ (V)$

$I_{dc} = 2\ (A)$



Example 3.9 Design a full-wave bridge rectifier to provide a dc output voltage 15 V with no more than 1 percent ripple at a load current of 2A. ($V_{on} = 1\text{ V}, T = 1/60\text{ sec}$)

$$V_{dc} = 15\ (V)$$

$$V_r < 0.15\ (V)$$

$$I_{dc} = 2\ (A)$$

$$\text{Load resistance} = 15/2 = 7.5\ (\Omega)$$

$$\text{The required transformer voltage } V_P = 15 + 2 = \mathbf{17\ (V)\ or\ \frac{17}{\sqrt{2}}\ (V_{rms})}$$

$$V_r \cong (V_P - 2V_{on})\left(\frac{T}{2RC}\right) = 15\left(\frac{1}{2 \times 60 \times 7.5 \times C}\right) = 0.15 \Rightarrow \mathbf{C = 0.111\ (F)}$$

$$\Delta T = \frac{1}{\omega}\sqrt{\frac{2V_r}{V_P}} = \frac{1}{2\pi \times 60}\sqrt{\frac{2 \times 0.15}{17}} = \mathbf{0.352 \times 10^{-3}\ (sec)}$$

$$I_{peak} = \frac{I_{dc}T}{\Delta T} = \frac{2 \times \frac{1}{60}}{0.352 \times 10^{-3}} = \mathbf{94.7\ (A)}$$

$$I_{surge} = \omega C V_P = 2\pi \times 60 \times 0.111 \times 17 = \mathbf{711\ (A)}$$

Make sure the diodes can handle these large currents

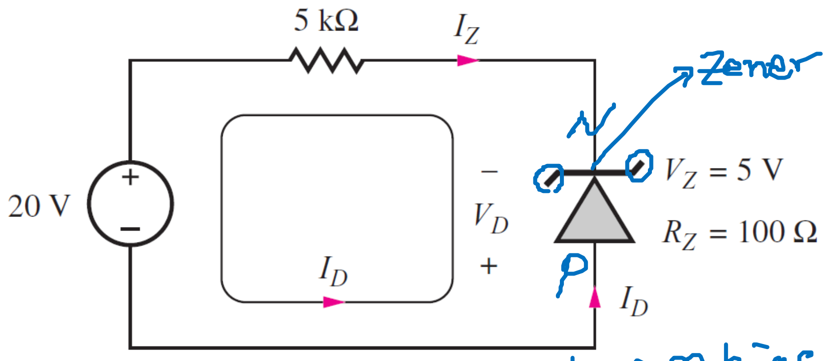
Diodes (Zener) in Breakdown Region

Reverse breakdown is actually a highly useful region of operation for the diode. The reverse **breakdown voltage is nearly independent of current** and can be used as either **a voltage regulator or voltage reference**. Thus, it is important to understand the analysis of diodes operating in reverse breakdown.

diode $p \to n : I_D$

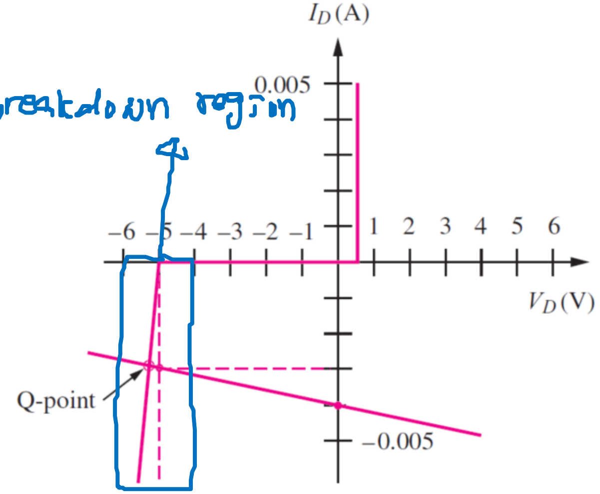
I_Z opposite to I_D.

Load-line analysis



Zener → on in a breakdown region

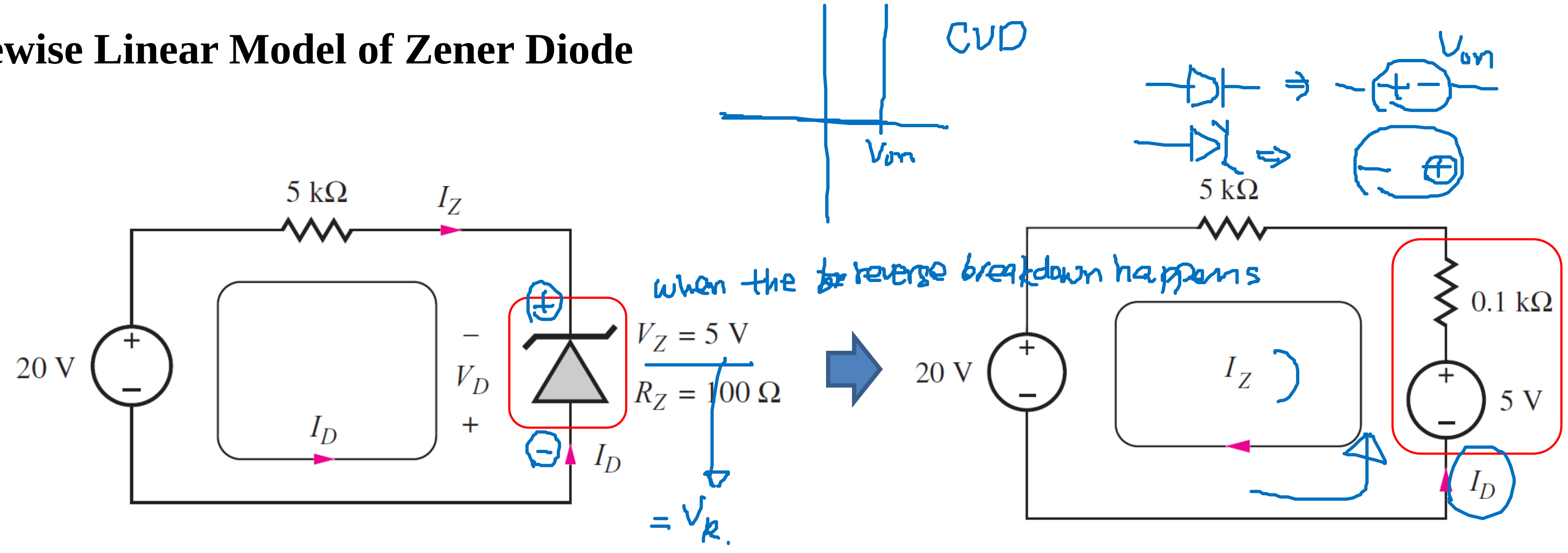
reverse bias



By KVL using I_D, $V_D + 5k \times I_D + 20 = 0$
If $V_D = 0$ V, $I_D = -4$ mA
If $V_D = -5$ V, $I_D = -3$ mA

We can find Q-point at -5.2 V and -2.9 mA

Piecewise Linear Model of Zener Diode



$-5 + 0.1k I_D + 20 = 0$

$I_D = -2.94mA$

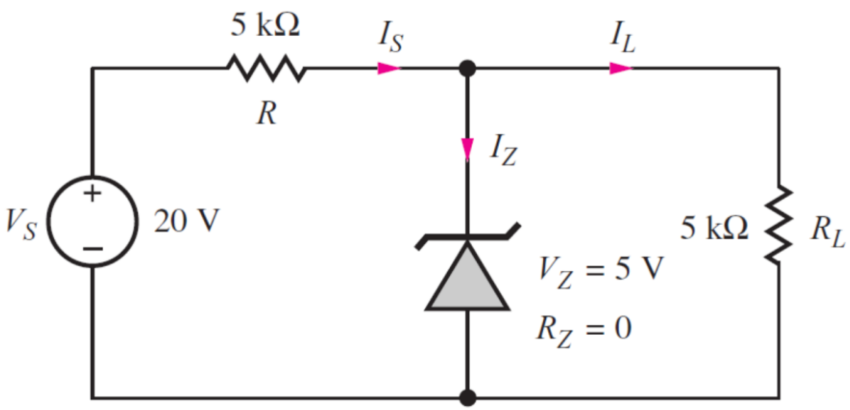
Replace the Zener diode with the piecewise linear model.

By taking KVL from the circuit, $-20 + 5k\times I_Z + 0.1k\times I_Z + 5 = 0$
We get $I_Z = 2.94$ mA

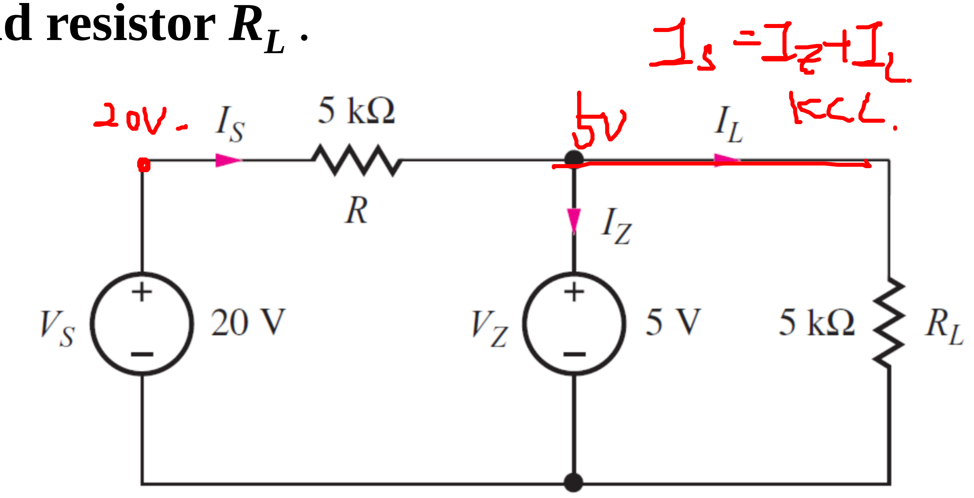
$I_Z > 0$ or $I_D < 0$, the solution is consistent with our assumption of Zener breakdown operation.

Voltage Regulator Using Zener Diode ($R_Z = 0$)

A useful application of the Zener diode is as a **voltage regulator.** The function of the Zener diode is to maintain **a constant voltage across load resistor R_L** .



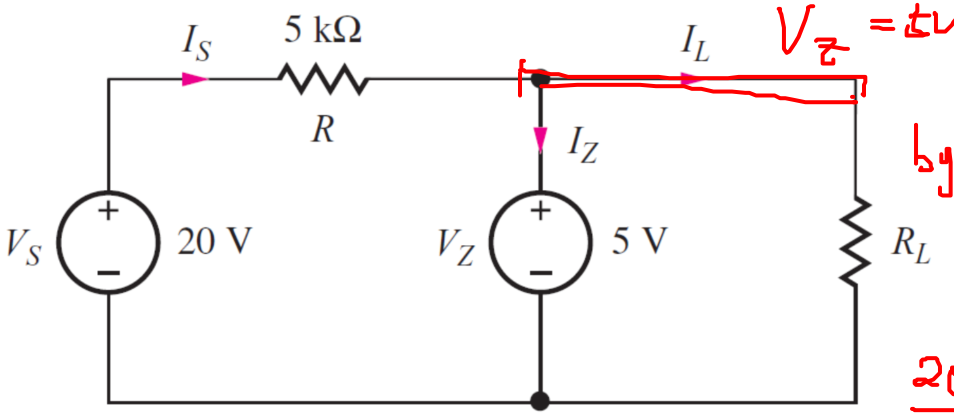
$I_Z > 0$



By KCL, $\quad I_Z = I_S - I_L = \dfrac{20-5}{5k} - \dfrac{5}{5k} = 2\ \text{mA} > 0$

From the circuit, we can see that **a constant voltage (5 V) appears across R_L** as long as the Zener diode operates in reverse breakdown region (**I_Z > 0**).

Minimum R_L required for reverse breakdown to happen



$V_Z = 5V$

by KCL

$I_S = I_Z + I_L.$

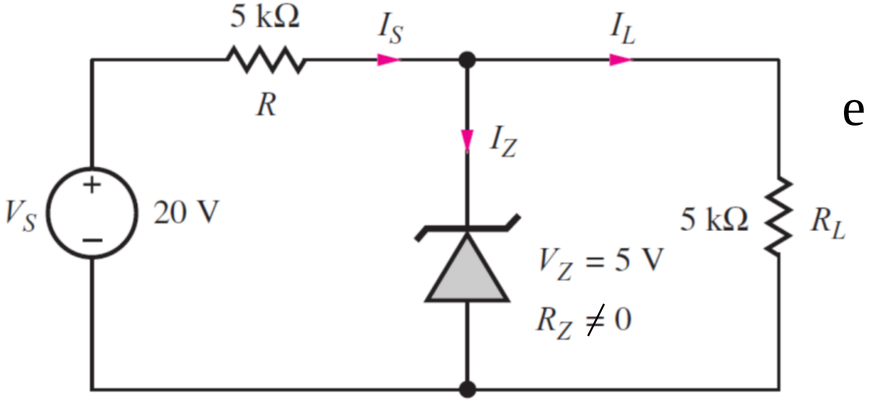
$$\frac{20-5}{5k} = I_Z + \frac{5-0}{R_L}.$$

$I_Z > 0.$

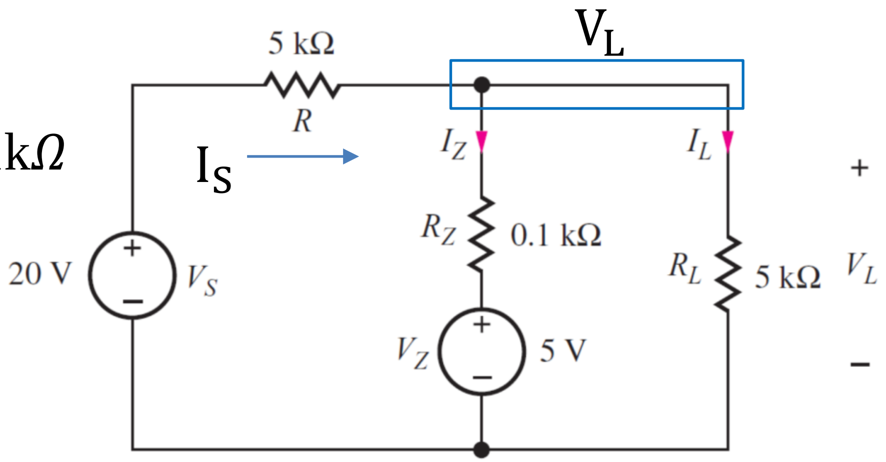
By KCL, $\quad I_Z = I_S - I_L = \dfrac{20-5}{5k} - \dfrac{5}{R_L} > 0 \qquad R_L > 1.67\ k\Omega$

Therefore, ***$R_{L,min}$* is 1.67 kΩ**

Voltage Regulator Using Zener Diode ($R_Z \neq 0$)



e.g. $R_Z = 0.1k\Omega$



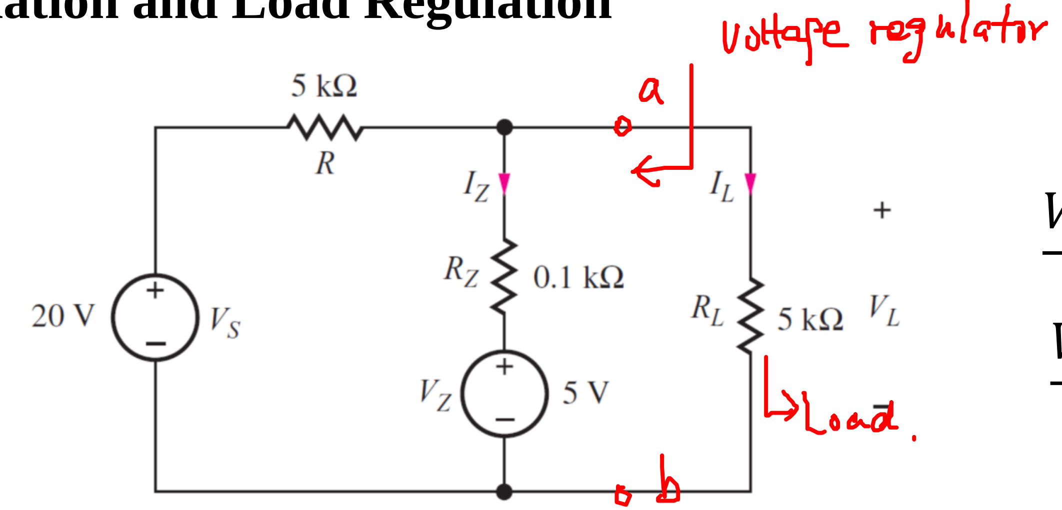
By KCL, $I_S - I_L = I_Z$ or $I_S = I_Z + I_L$

$$\frac{20 - V_L}{5k} = \frac{V_L - 5}{0.1k} + \frac{V_L}{5k}$$

$$\rightarrow V_L = 5.1923 \text{ V}$$

$$\rightarrow I_Z = \frac{5.19 - 5}{0.1k} = 1.9 \text{ mA} > 0$$

Line Regulation and Load Regulation



$$\frac{V_L - V_S}{R} + \frac{V_L - V_Z}{R_Z} + \frac{V_L}{R_L} = 0$$

$$\frac{V_L - V_S}{R} + \frac{V_L - V_Z}{R_Z} + I_L = 0$$

Line Regulation: how sensitive the output voltage (V_L) is to input voltage (V_S) changes when $R_L = \infty$

$$\text{Line Regulation} = \frac{dV_L}{dV_S} = \frac{R_Z}{R + R_Z}$$

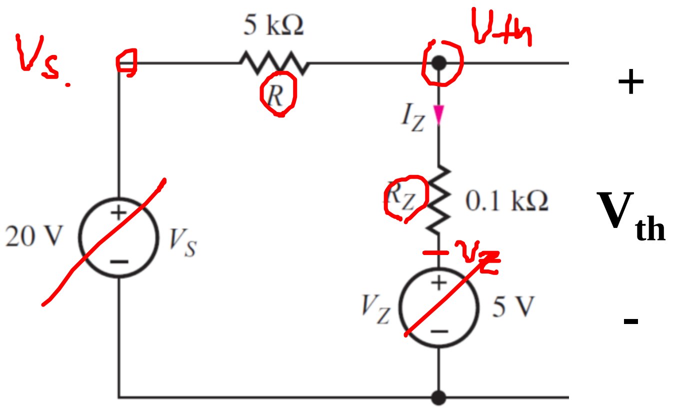
e.g. The circuit above has $\frac{0.1k}{5k+0.1k} = 19.6\ \text{mV/V}$

Load Regulation: output impedance of the voltage regulator, or **Thevenin equivalent resistance** looking back into the regulator from the load terminals.

$$\text{Load Regulation} = \frac{dV_L}{dI_L} = R \parallel R_Z$$

e.g. The circuit above has $5k \parallel 0.1k = 98\ \Omega$

Load Regulation: output impedance of the voltage regulator, or **Thevenin equivalent resistance** looking back into the regulator from the load terminals.



Voltage Regulator

Recall, VE215..

$$\frac{V_{Th}-V_S}{R}+\frac{V_{Th}-V_Z}{R_Z}=0 \rightarrow V_{Th}=\frac{R_Z V_S + R V_Z}{R_Z+R}$$

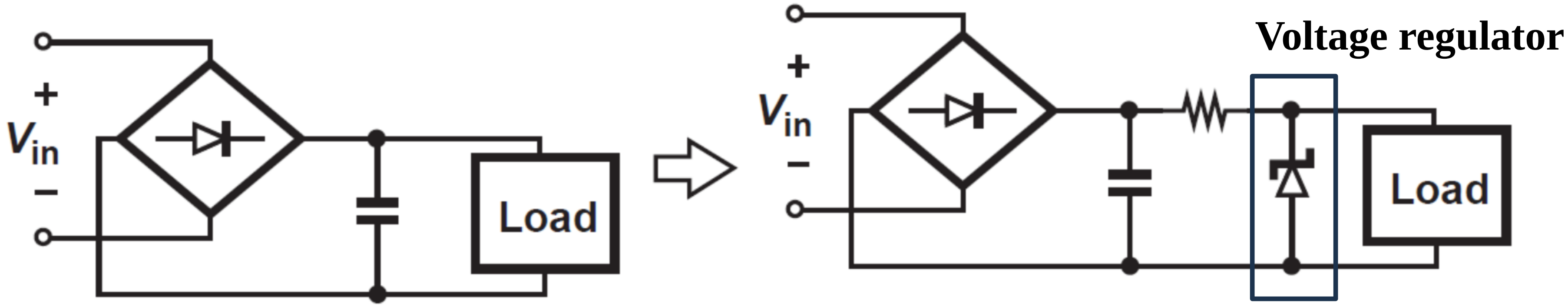
$$R_{Th}=R \parallel R_Z$$

Numerical Test: $\mathrm{V_S}=20\ \mathrm{V},\ \mathrm{R}=5\ \mathrm{k\Omega},\ \mathrm{R_Z}=0.1\ \mathrm{k\Omega},\ \mathrm{V_Z}=5\mathrm{V},\ \mathrm{R_L}=5\ \mathrm{k\Omega}$

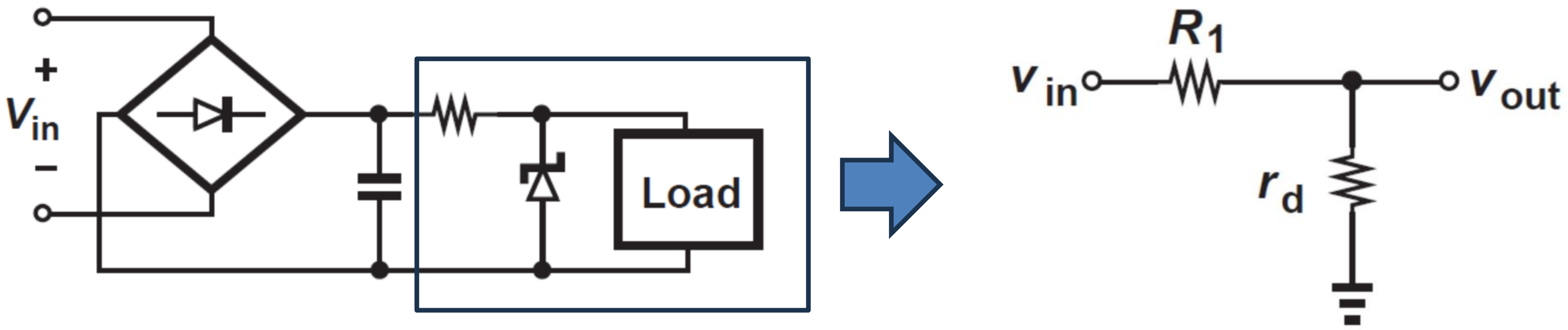
$$\mathrm{V_{th}}=5+\frac{20-5}{5\mathrm{k}+0.1\mathrm{k}}0.1\mathrm{k}=5.2941\ (\mathrm{V})$$

$$\mathrm{V_L}=\mathrm{V_{Th}}\frac{\mathrm{R_L}}{(R_{Th}=\mathrm{R}\|\mathrm{R_Z})+\mathrm{R_L}}=5.2941\times\frac{5k}{\frac{5k\times 0.1k}{5k+0.1k}+5k}=5.1923\ (V)$$

Voltage Regulation with Rectifier



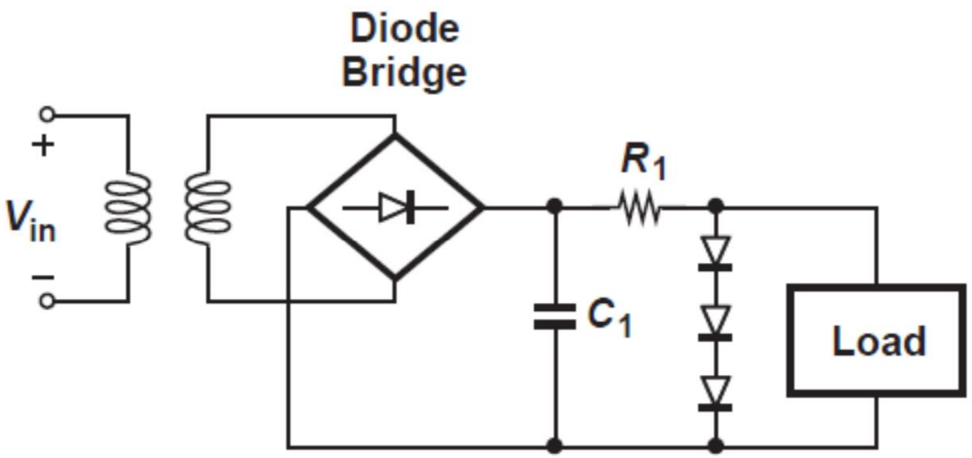
The adaptor circuit studied above generally proves inadequate. Due to the significant variation of the line voltage, the peak amplitude produced by the transformer and hence the dc output vary considerably. Therefore, the rectifying circuit is often followed by a “voltage regulator” so as to provide **a constant output**.



A regulator circuit employs a Zener diode which is operated in the reverse breakdown region. Therefore, the Zener diode exhibits a small-signal resistance, providing a relatively constant output despite input variations if $r_D \ll R_1$ as

$$v_{out} = \frac{r_D}{r_D + R_1} v_{in}$$

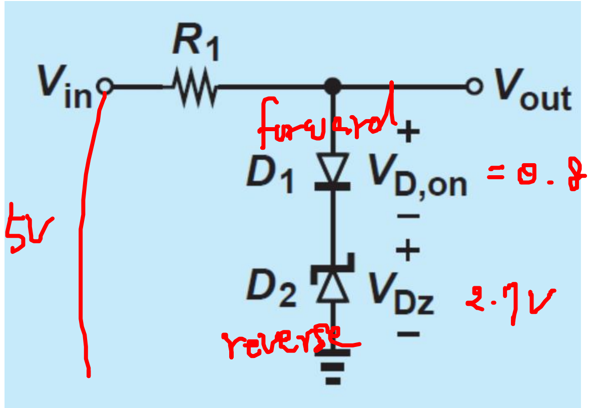
The Zener regulator below nonetheless has the same drawback, namely, **poor stability if the load current varies significantly**.



Our brief study of regulators thus far reveals two important aspects of their design: (1) the stability of the **output with respect to input variations**, i.e. Line Regulation defined as $\Delta V_{out}/\Delta V_{in}$, and (2) the stability of the **output with respect to load current variations**, i.e. Load Regulation defined as defined as $\Delta V_{out}/\Delta I_L$.

Example 3.10. In the circuit, V_{in} has a nominal value of 5 V, R_1 = 100 Ω, and D_2 has a reverse breakdown of 2.7 V and a small-signal resistance of 5 Ω. Assuming $V_{D,on} \approx 0.8$ V for D_1, determine the line and load regulation of the circuit. The small-signal resistance of D_1 can be found by taking V_T/I_D.

what is I_D = ?



$R_D = V_T/I_D = 0.025/15mA = 1.67\Omega.$

$V_T = 0.025 \sim 0.026$

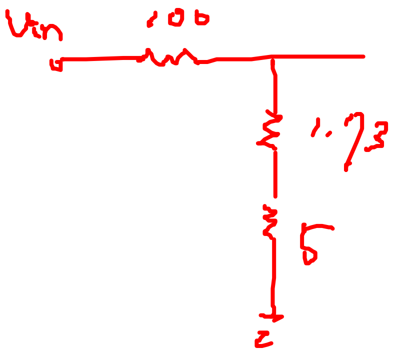
if 0.026

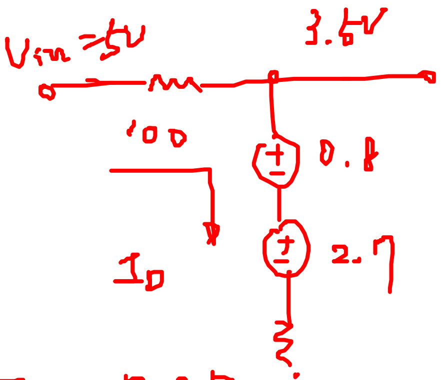
I_D = 1mA

0.08A

$R_D = 1.73\Omega.$

$R_Z = 5\Omega.$ ⇒



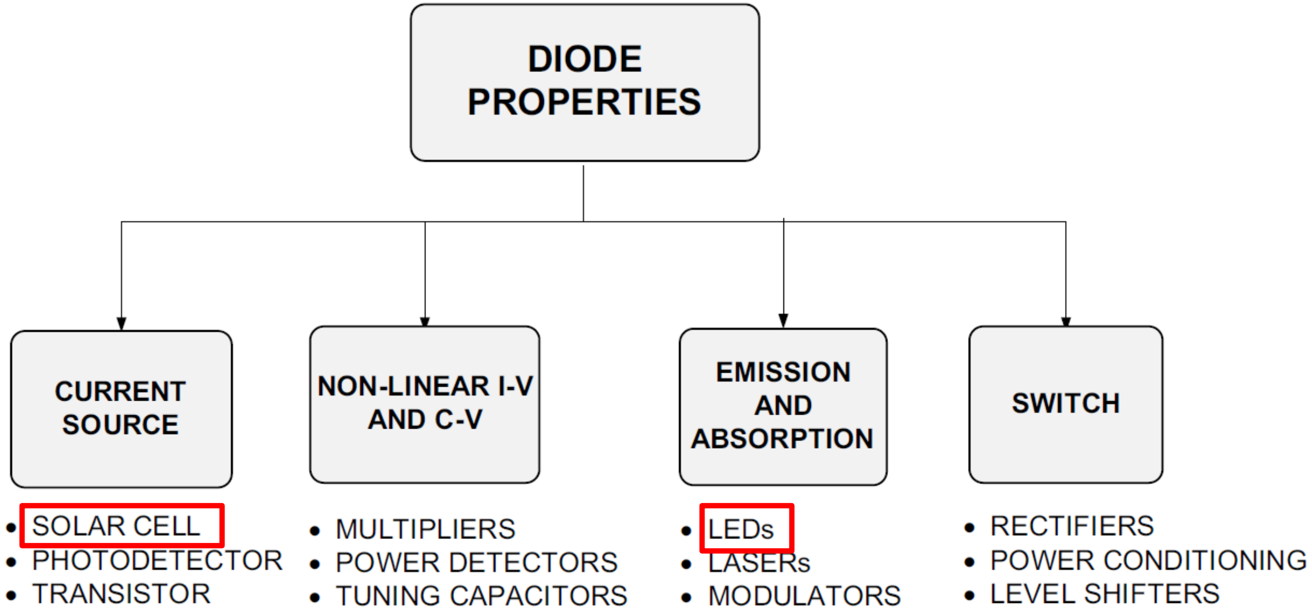


$I_D = \frac{5-3.5}{100} = 15mA$

line regulation = $\frac{R_D+R_Z}{R+R_D+R_Z}$

load regulation = $R \,\|\, (R_D+R_Z)$

*(Opto)electronics based on diodes



Electrons can interact with light through the following fundamental mechanisms:
(1) light absorption → **Solar cells**
(2) spontaneous light emission → **Light-emitting diode (LED)**

A common name for these devices is *optoelectronic* devices or *photonic* devices.

Nobel prize in Semiconductors and (opto)electronics

nobelprize.org

In 1956, Nobel Prize in Physics in for **discovery of the transistor effect**
…
In 2000, Nobel Prize in Physics in for **developing semiconductor heterostructures**
In 2014, Nobel Prize in Physics for **the invention of efficient blue light-emitting diodes**

The Nobel Prize in Physics 1973
Leo Esaki and Ivar Giaever “for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively”

The Nobel Prize in Physics 1986
Ernst Ruska “for his fundamental work in electron optics, and for the design of the first electron microscope”
Gerd Binnig and Heinrich Rohrer“ for their design of the scanning tunneling microscope”

The Nobel Prize in Physics 1987
J. Georg Bednorz and K. Alexander Müller “for their important break-through in the discovery of superconductivity in ceramic materials”

The Nobel Prize in Physics 2009
Charles Kuen Kao “for groundbreaking achievements concerning the transmission of light in fibers for optical communication”
Willard S. Boyle and George E. Smith “for the invention of an imaging semiconductor circuit – the CCD sensor”

The Nobel Prize in Physics 2010
Andre Geim and Konstantin Novoselov “for groundbreaking experiments regarding the two-dimensional material graphene”

and more..

https://www.nobelprize.org/prizes/lists/all-nobel-prizes-in-physics/

Solar spectrum and light absorption

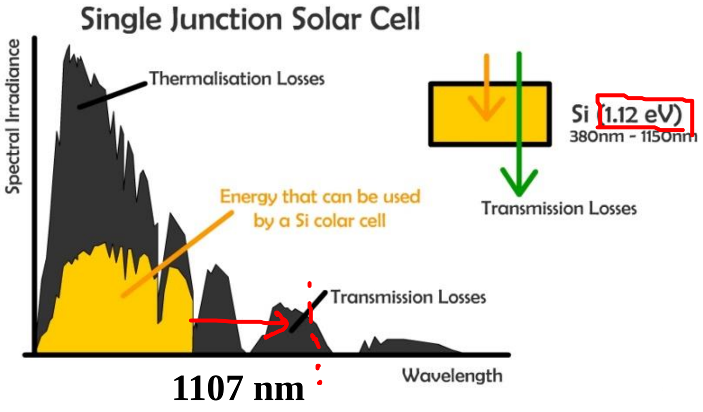
A semiconductor material with a bandgap of E_g can absorb the light energy higher than its bandgap. Thus, if we know the bandgap we can determine a cutoff wavelength.

$$By\ \boldsymbol{E} = \boldsymbol{h\nu}\ and\ \boldsymbol{\lambda} = \frac{\boldsymbol{c}}{\boldsymbol{\nu}}$$

$$\lambda_c = \frac{hc}{E_g} = \frac{1240}{E_g}$$

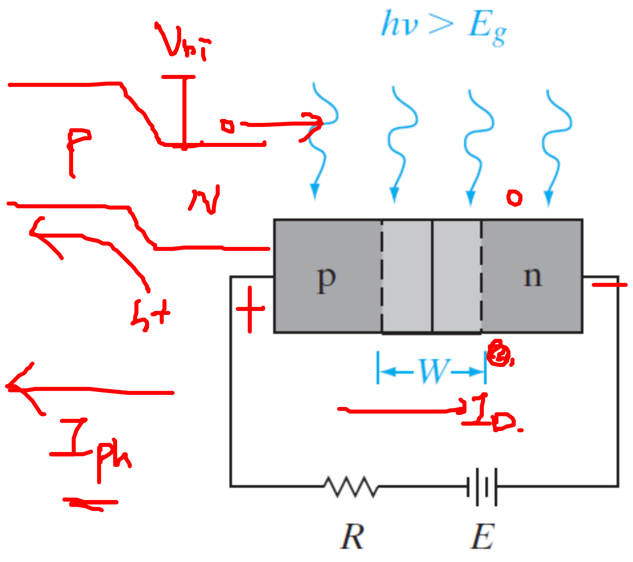
Where,
h = Planck Constant = 4.14 x 10^-15 eV*s
c = Speed of Light = 3 x 10^17 nm/s
Eg = Energy Gap in eV
λ_c = Cutoff Wavelength in nm

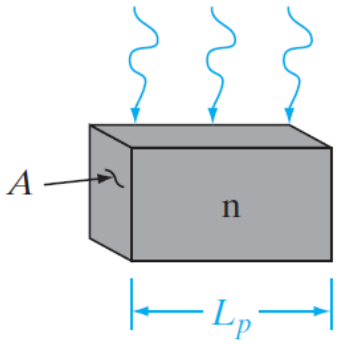
λ = 620 nm   E = 2 eV.



The photon energy *hv* is used to destroy a covalent bond, liberating an electron and creating a hole. The existing electric field (V_{bi}) sweeps the generated electron and hole away, creating the photocurrent → Solar cells

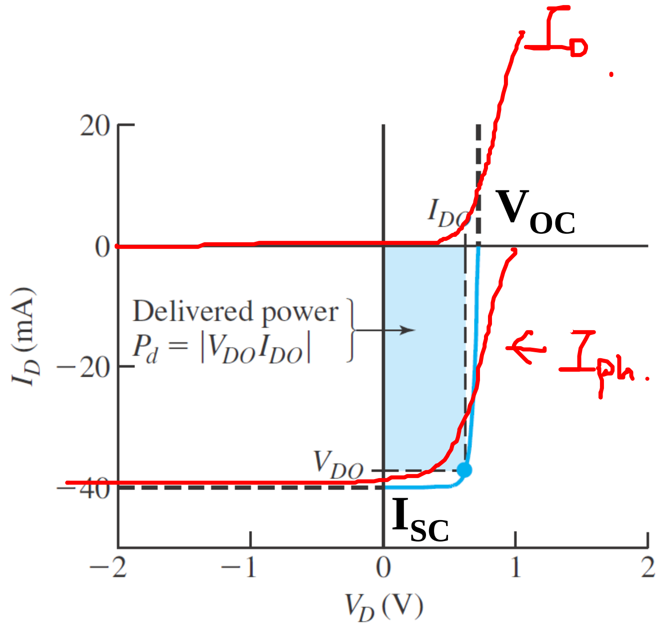
Solar cells





$\delta p_{op} = g_{op} \tau_p$

$I_{op} = q A L_p g_{op}$



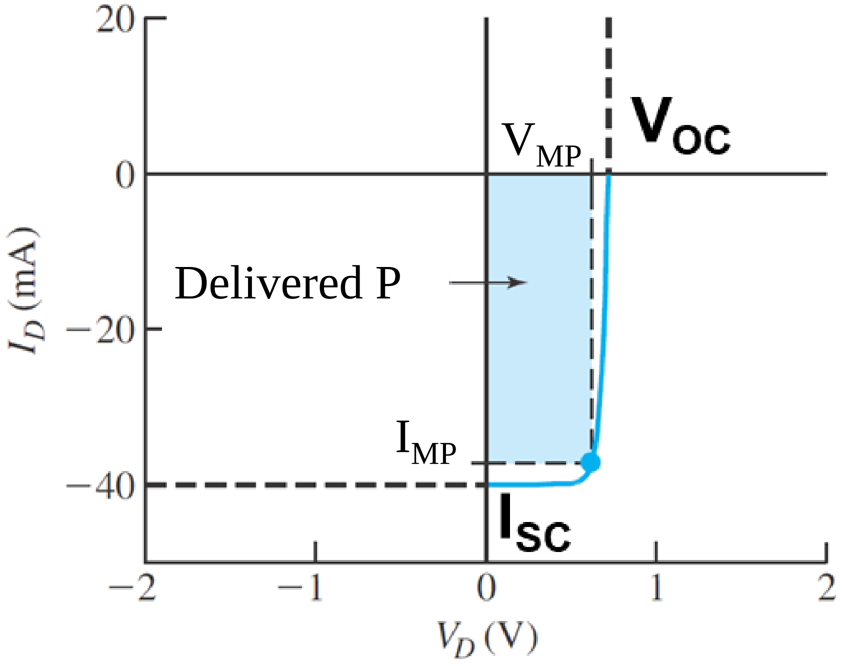
The junction is uniformly illuminated by photons with **hν > E$_g$**, an added generation rate g_{op} (electron-hole pair > cm^3/s) participates in this current.

The total diode current is

$$I = I_{th}(e^{qV/kT} - 1) - I_{op}$$

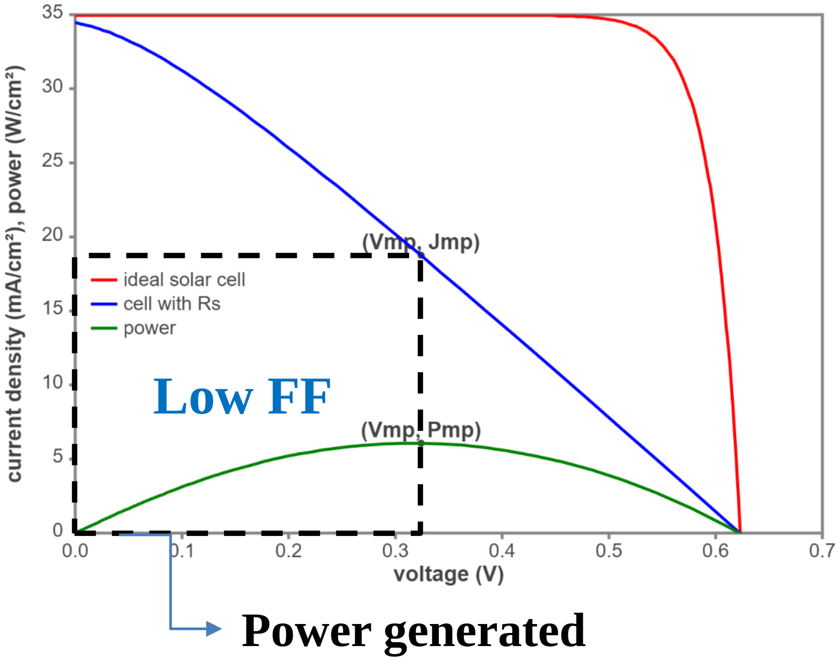
$$I = qA\left(\frac{L_p}{\tau_p}p_n + \frac{L_n}{\tau_n}n_p\right)(e^{qV/kT} - 1) - qAg_{op}(L_p + L_n + W)$$

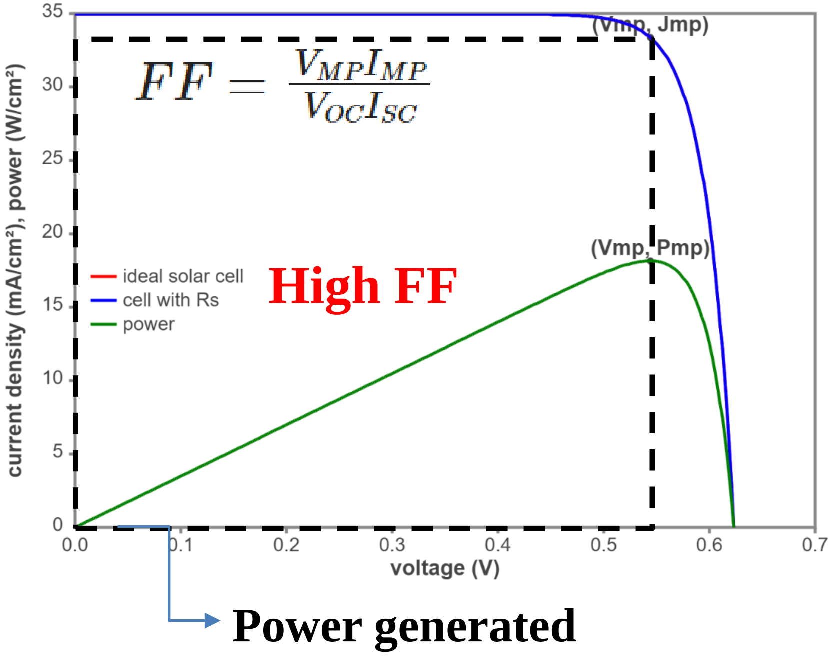
Photovoltaics Figure of Merit



(1) **I_{SC}:** The current through the solar cell when the voltage across the solar cell is zero.
(2) **V_{OC}:** The maximum voltage available from a solar cell (V_{OC} = E_g – some voltage losses). Bandgap determines V_{OC}.

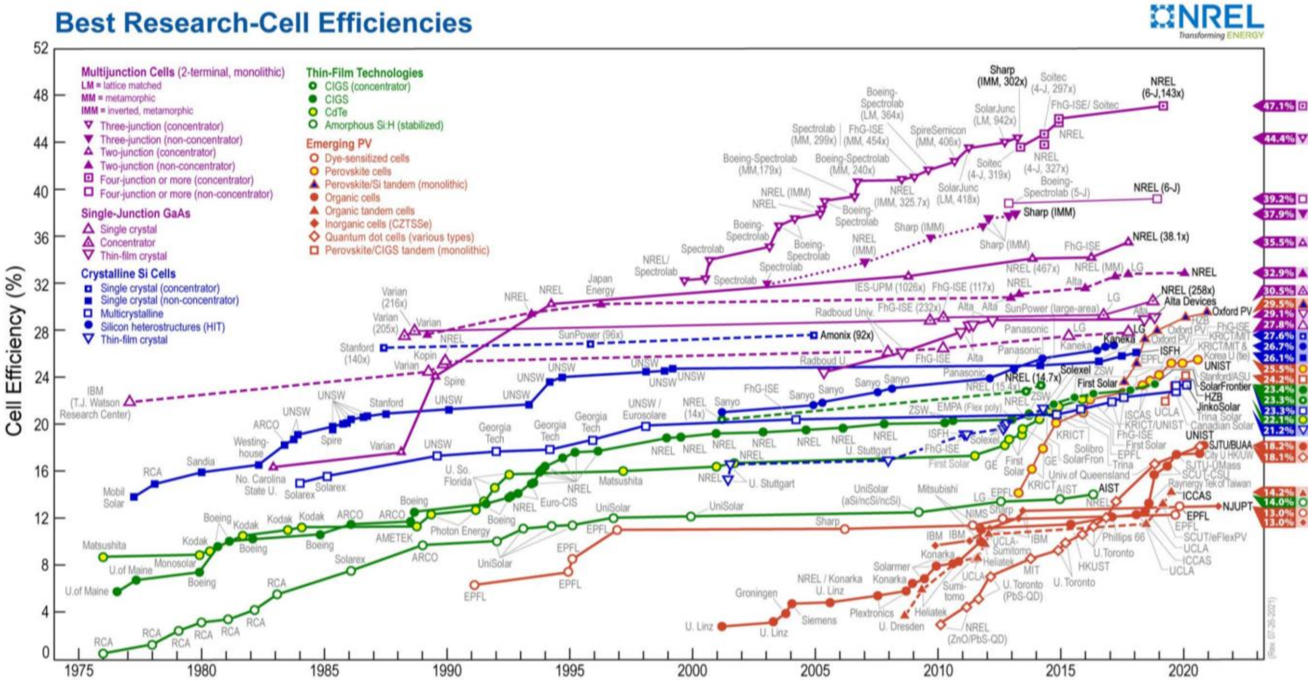
Photovoltaics Figure of Merit





(3) FF: the area of the largest rectangle which will fit in the IV curve.

Photovoltaics Figure of Merit

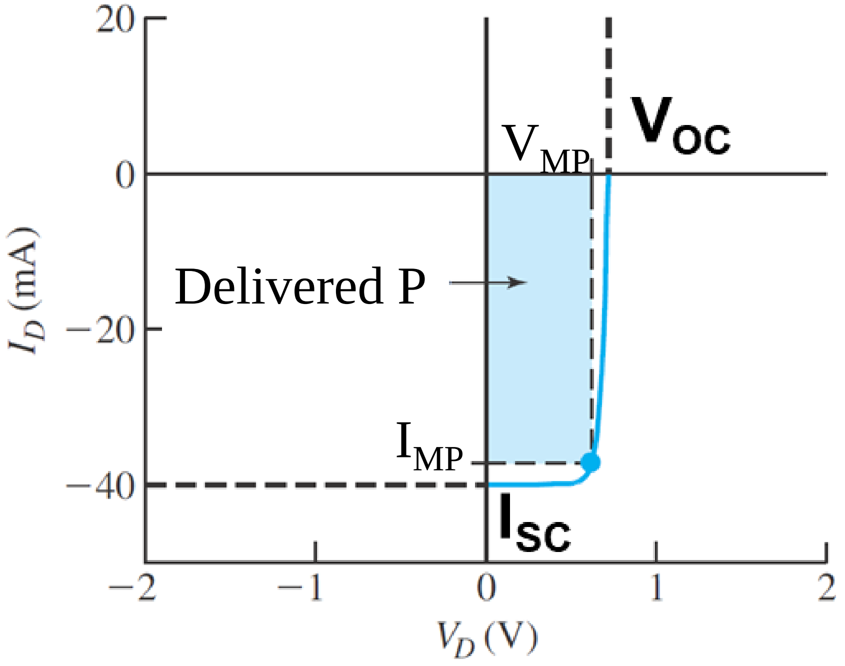


$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}}$$

V_{OC}: open circuit voltage
I_{SC}: short circuit current
FF: fill factor
P_{in}: input power (1 sun, 100 mW/cm^2)

(4) PCE: The ratio of energy output from the solar cell to input energy from the sun.

Photovoltaics Figure of Merit

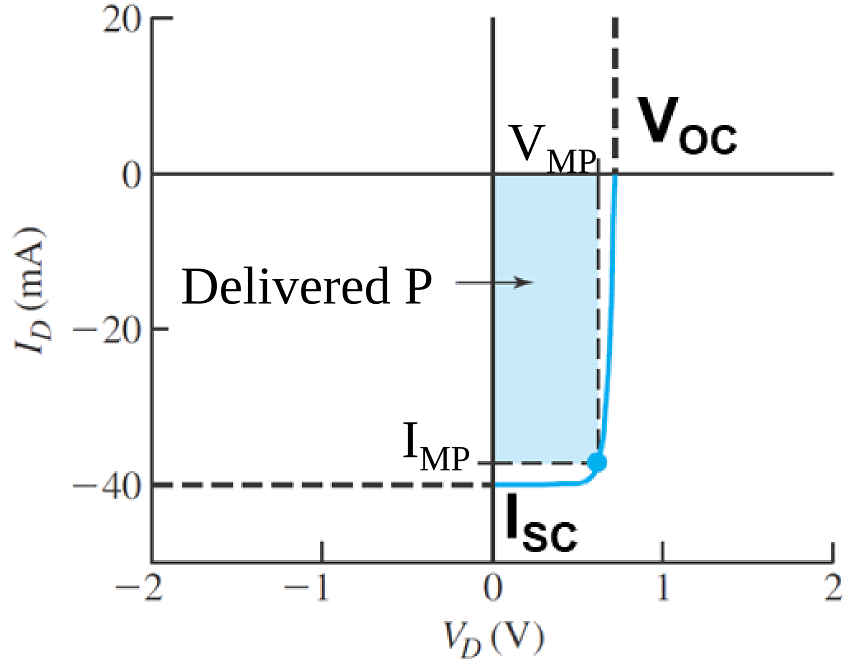


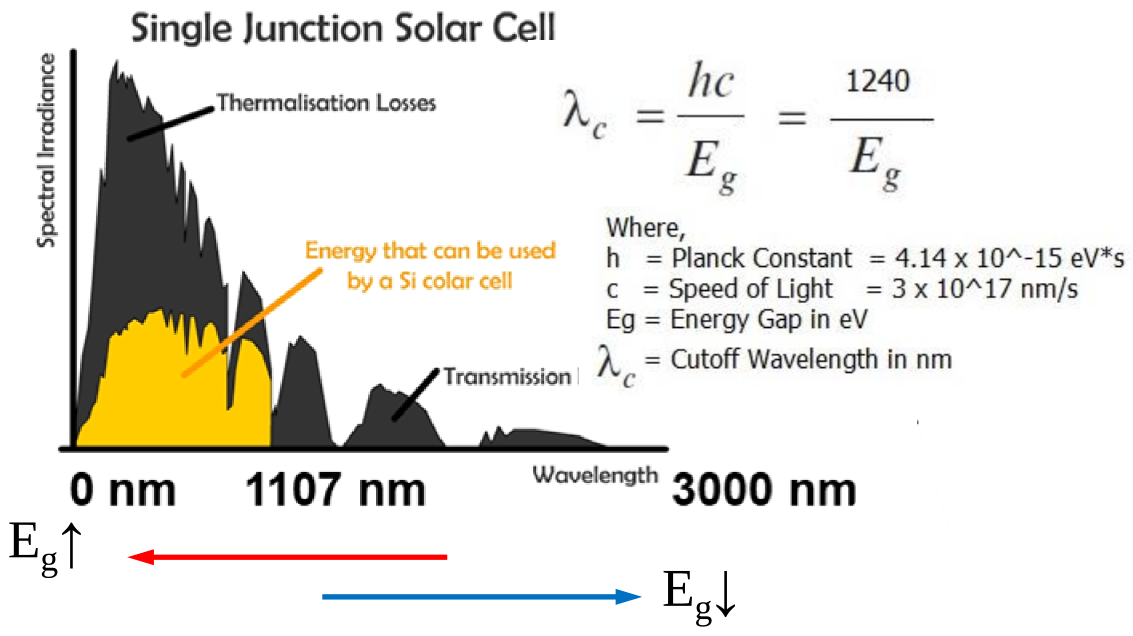
How to increase both V_{OC} and I_{SC}?

(1) **I_{SC}:** The current through the solar cell when the voltage across the solar cell is zero.

(2) **V_{OC}:** The maximum voltage available from a solar cell (V_{OC} = E_g – some voltage losses). Bandgap determines V_{OC}.

Trade-off between V_{OC} and I_{SC}



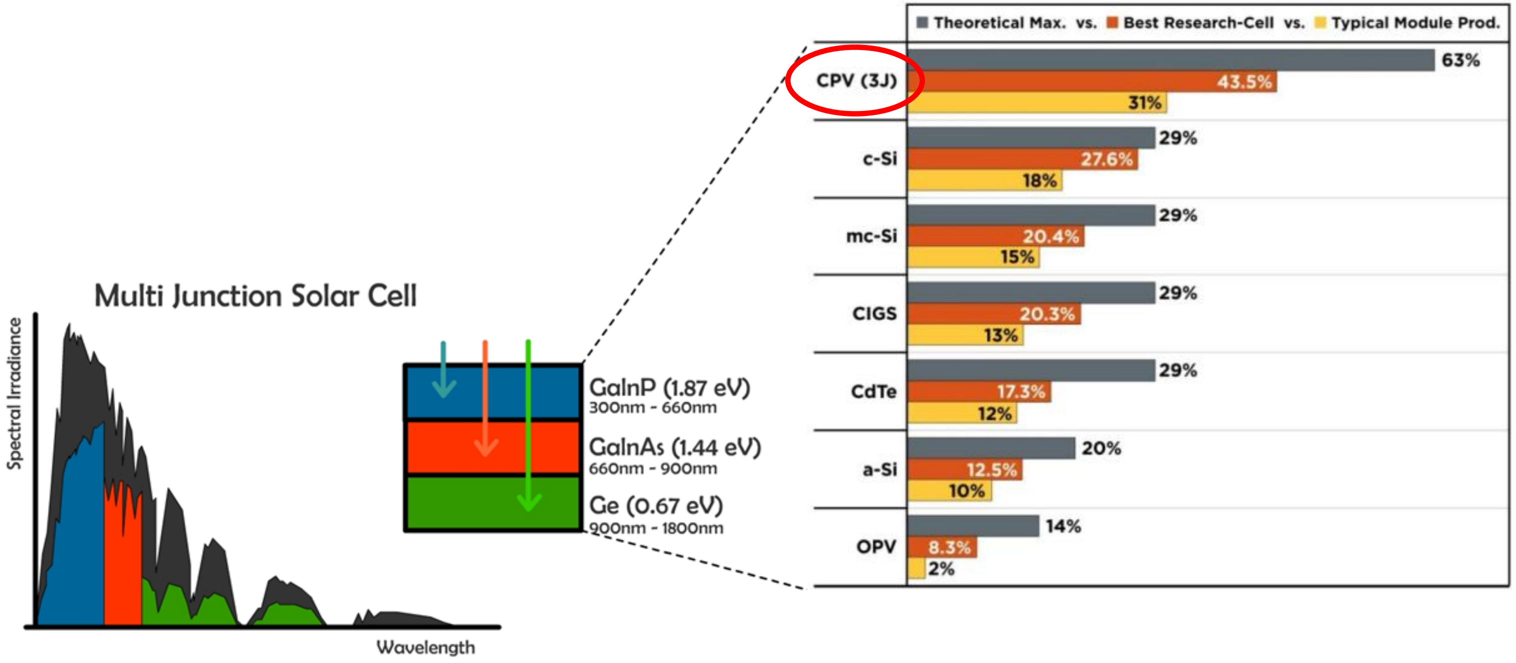


Bandgap determines (1) V_{OC} and (2) light absorption (I_{SC})

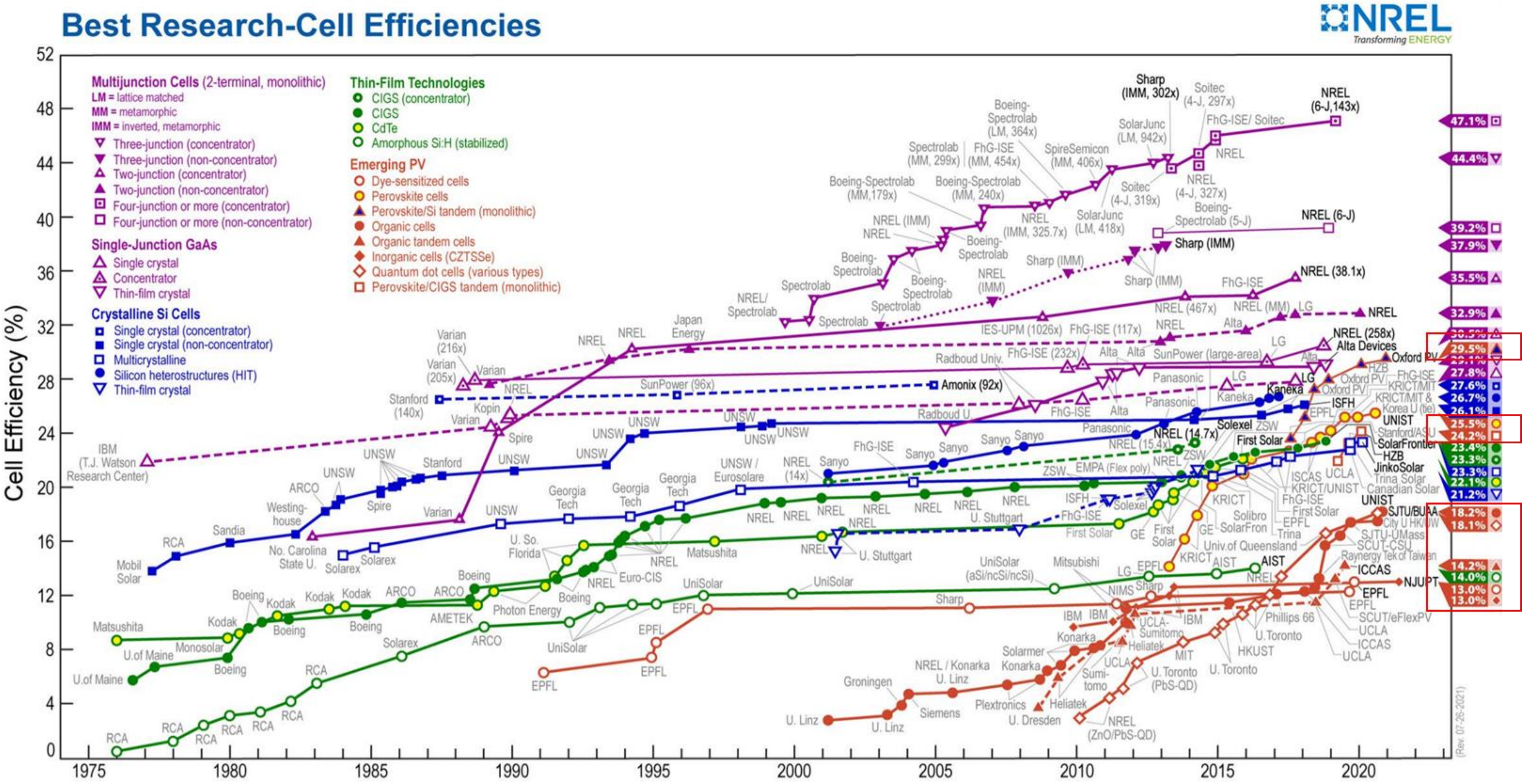
Semiconductor with a larger bandgap: $V_{OC}\uparrow$, $I_{SC}\downarrow$

Semiconductor with a smaller bandgap: $V_{OC}\downarrow$, $I_{SC}\uparrow$

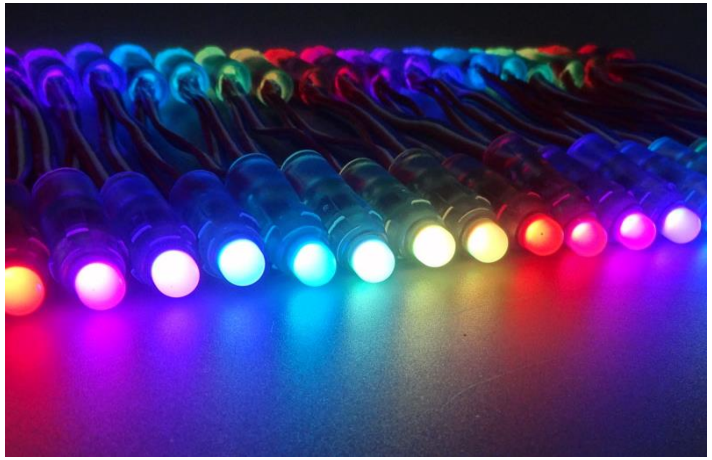
Solar spectrum and light absorption



Tandem/ Multiple junction structure
→ Increase both V_{OC} and I_{SC}

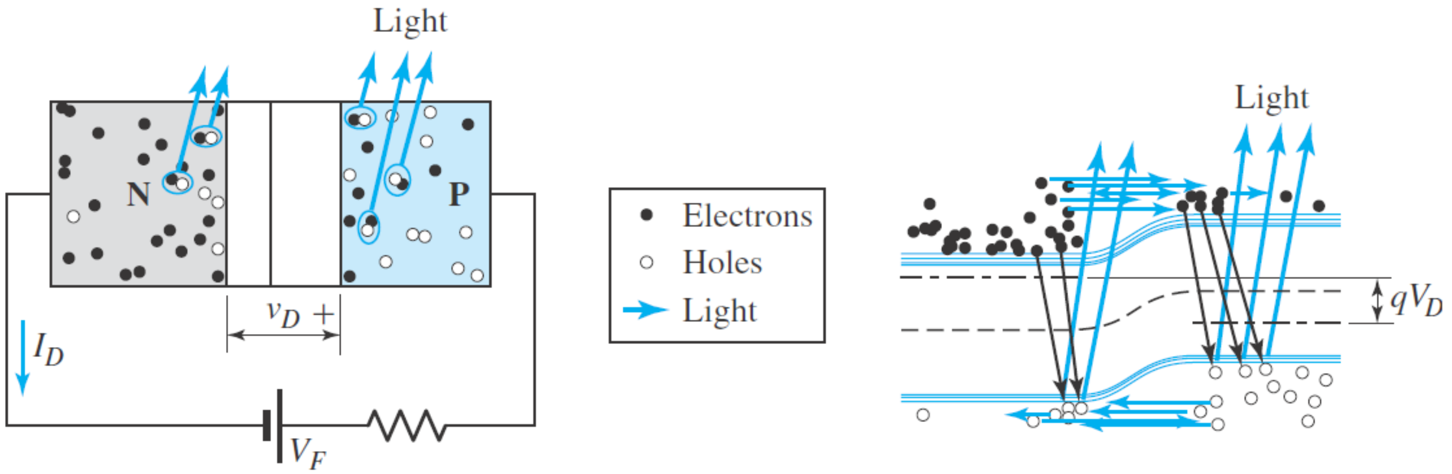

Best Research-Cell Efficiencies
NREL
Transforming ENERGY
Cell Efficiency (%)
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells
Perovskite/Si tandem (monolithic)
Organic cells
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells (various types)
Perovskite/CIGS tandem (monolithic)
47.1%
44.4%
39.2%
37.9%
35.5%
32.9%
29.5%
27.8%
27.6%
26.7%
26.1%
25.5%
24.2%
23.4%
23.3%
23.3%
22.1%
21.2%
18.2%
18.1%
14.2%
14.0%
13.0%
13.0%
(Rev. 07-26-2021)

Light emission



- **Photoluminescence** (**PL**) is light emission from any form of matter after the **absorption of photons**.
- **Electroluminescence** (**EL**) is an optical and electrical phenomenon in which a material emits light in response to **an electric current.**

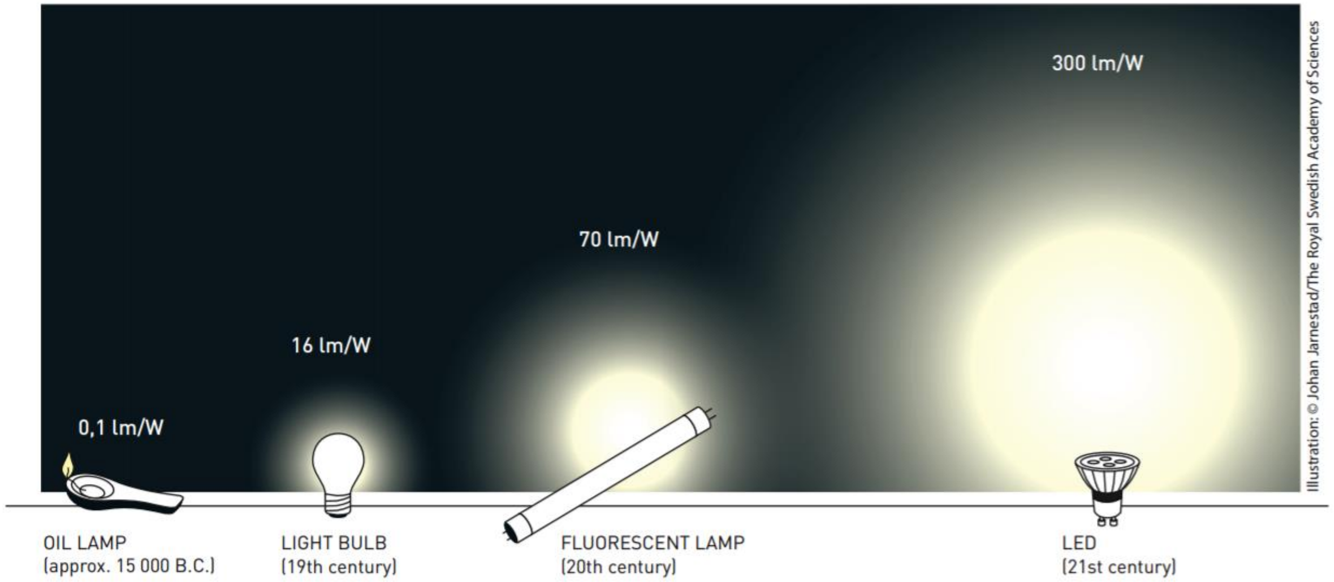
Energy saving technology - Light-emitting diodes



Forward bias → reduced barrier

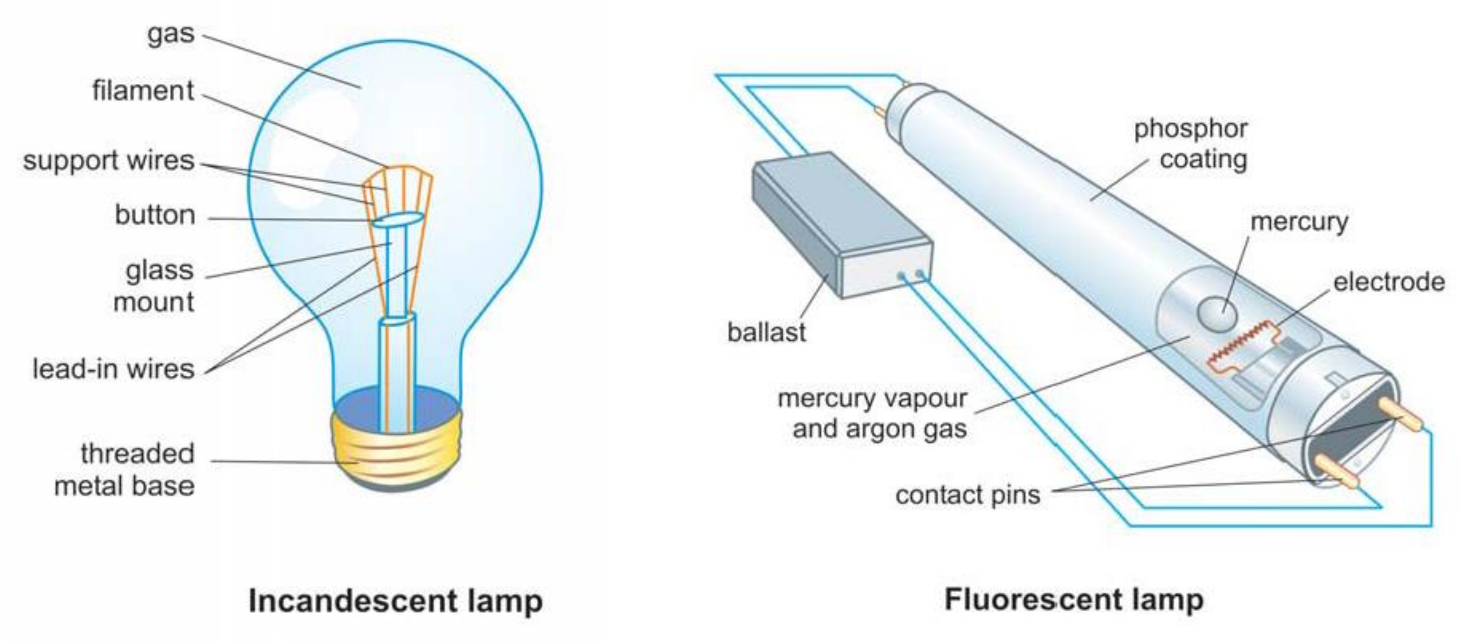
A **light-emitting diode** (**LED**) is a semiconductor light source that emits light when current flows through it. Electrons in the semiconductor recombine with holes, releasing energy in the form of photons.

Converting Energy into Light



(1) Light emitting diodes: **electricity is directly converted into light particles**, photons.
(2) Other light sources: **most of the electricity is converted to heat and only a small amount into light**.

- in *incandescent bulbs and halogen lamps*, electric current is used to heat a wire filament, making it glow.
- *in fluorescent lamps*, a gas discharge is produced creating both heat and light.



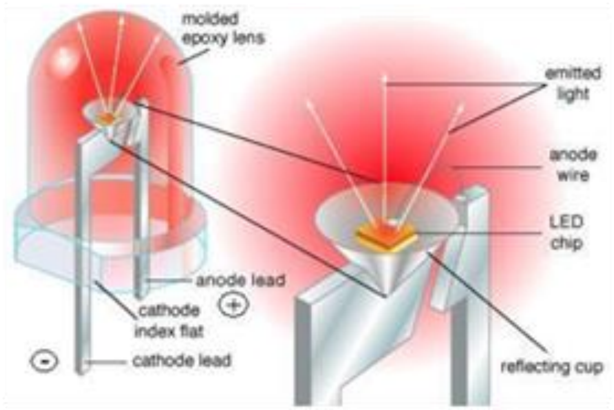
Resonance, **20**, 605–616 (2015)

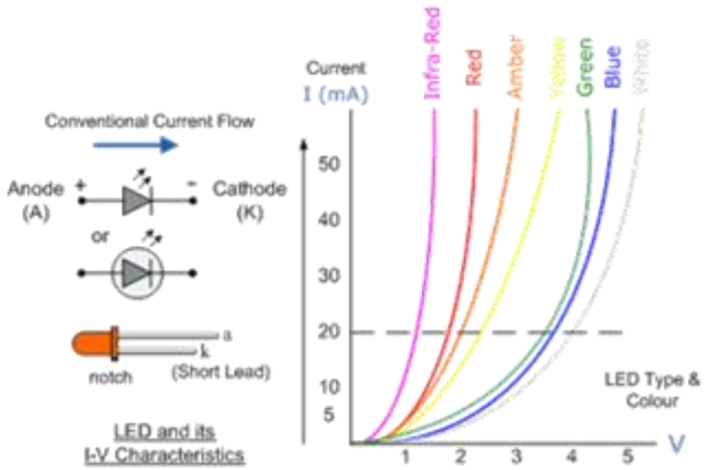
The incandescent lamp is based on the emission of photons through the heating up of an electric-current conducting filament. The incandescent bulb produces only about **16 lm/W** (an oil lamp produces **0.1 lm/W**), as the rest of the energy is lost in the form of heat.

The fluorescent lamp, producing light and heat through a gas discharge, the energy efficiency improved to **70 lm/W**. However, these lamps are quite large and have safety concerns as the lamp is subject to breakdown due to overheating and fluorescent lamps use mercury as the discharge element.

White LED lamps emit a bright white light and are long-lasting and energy-efficient. The most recent record is just over **300 lm/W.**

One fourth of world electricity consumption is used for lighting purposes
→ LEDs save a lot of resources on the Earth.

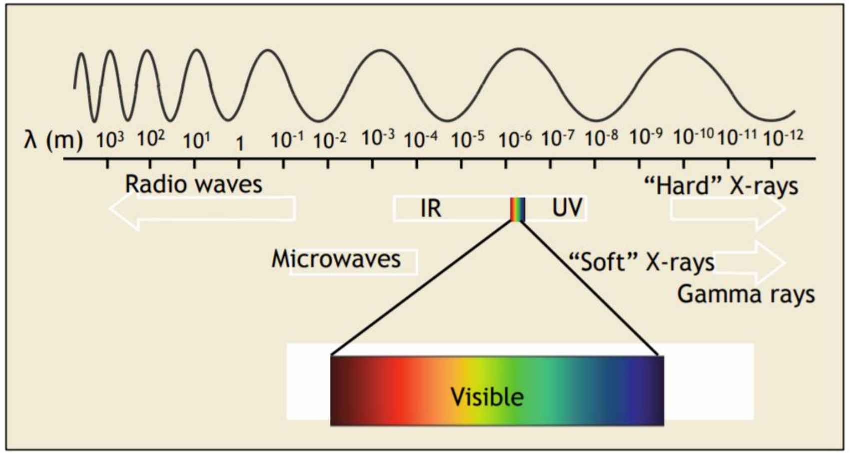


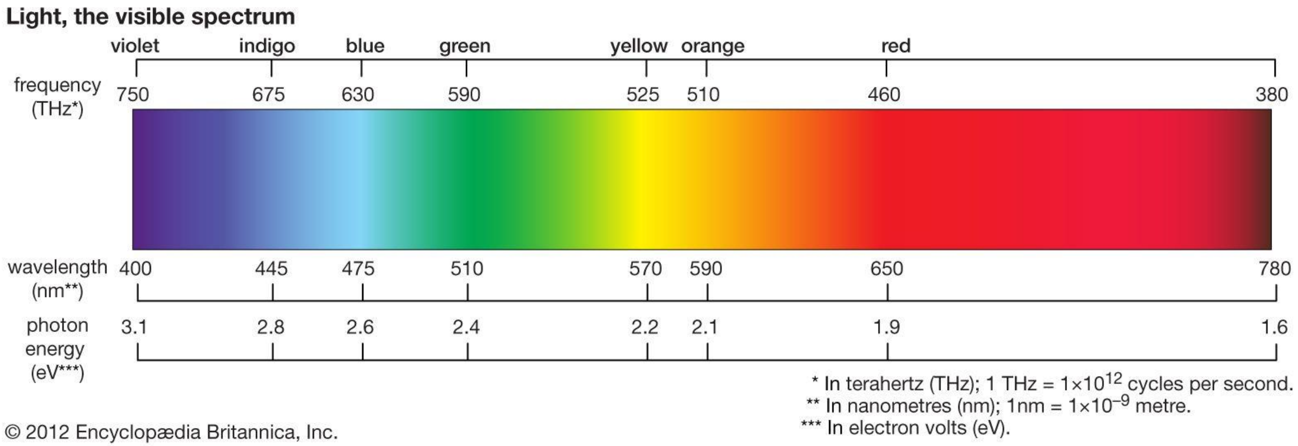


https://wiki.analog.com/university/courses/eps/diode-curves

Incandescent light bulbs lit the 20th century; the 21st century will be lit by LED lamps.

How to make different colors





$E_g \leftrightarrow$ Wavelength $\leftrightarrow$ Color

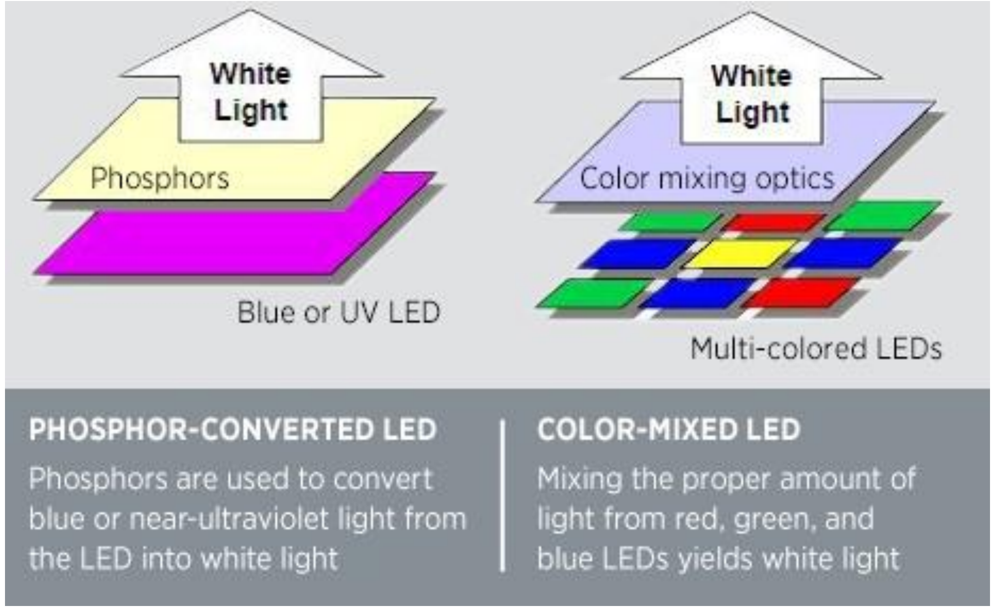
$$\lambda_c = \frac{hc}{E_g} = \frac{1240}{E_g}$$

Where,
h = Planck Constant = 4.14 x 10^-15 eV*s
c = Speed of Light = 3 x 10^17 nm/s
Eg = Energy Gap in eV
λ_c = Cutoff Wavelength in nm

e.g. Green light: Wavelength is 525 nm. E_g is 2.36 eV.
Blue light: Wavelength is 425 nm. E_g is 2.92 eV.

How to make the white light

Different from visible light, white light is the mixture of various light sources.

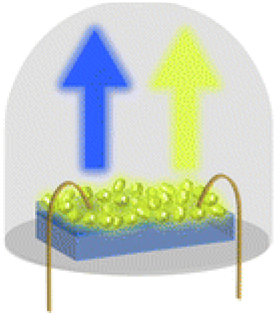


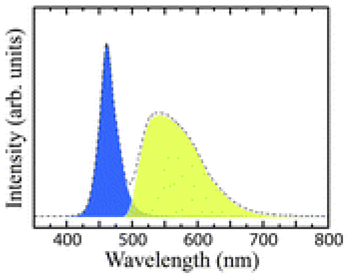
https://www.energy.gov/eere/ssl/led-basics

White light can be created in two different ways.
(1) Wavelength conversion, such as by using **phosphors**.
(2) Emit **R, G, and B colors simultaneously.**

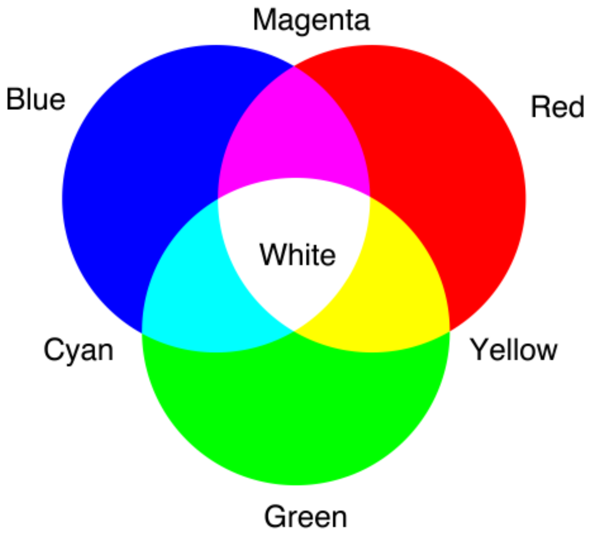
(1) Wavelength Conversion

B+Y → White



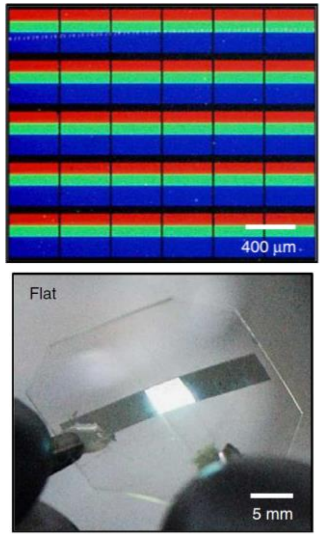


Topics in Current Chemistry, 374, 21 (2016)

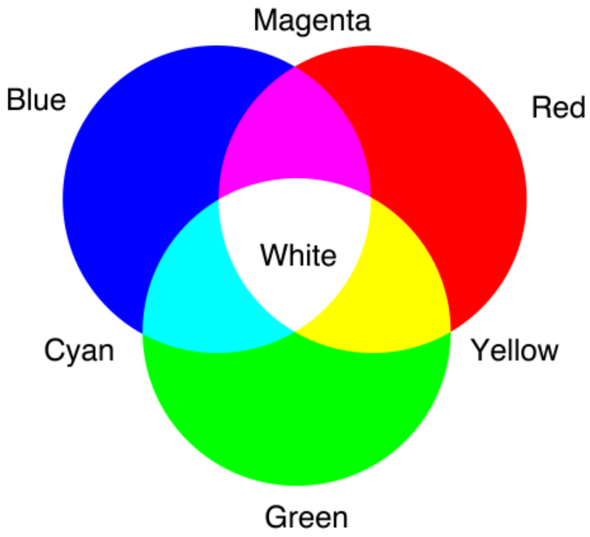


Using a blue LED, the yellow phosphor absorbs blue light and emit yellow light. The remaining blue light is mixed with the yellow light, **resulting in white light**.

(2) Mixed-color white light

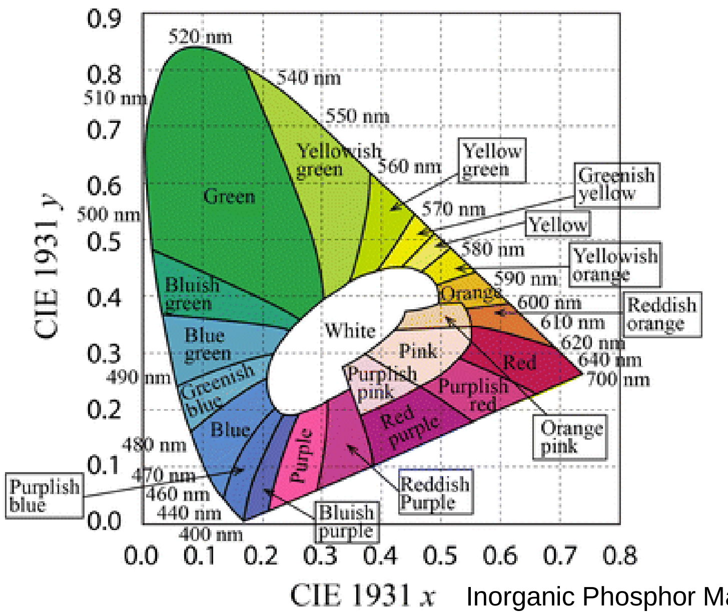


Nature Communications, 6, 7149 (2015)



Properly patterning/ mixing the amount of RGB output, we can achieve white light emission in the LED.

The Nobel Prize in Physics 2014



Inorganic Phosphor Materials for Lighting,
Topics in Current Chemistry, 374, 21 (2016)

Red and green light-emitting diodes have been with us for almost half a century, **but blue light was needed to really revolutionize lighting technology**.

Only the triad of red, green and blue can produce the **white light** that illuminates the world for us. Despite the high stakes and great efforts undertaken in the research community as well as in industry, **blue light remained a challenge for three decades**. **Using blue LEDs, white light can be created in a new way**.