UNIT - 5

Chapter - 3

Diode Theory

3-1 Basic Ideas

3-2 The ideal diode

3-3 The second approximation

3-4 The third approximation

Introduction :

Semiconductor :

An element with electrical properties between those of a conductor and an insulator.
ex:- Silicon, Germanium.

Intrinsic Semiconductor :

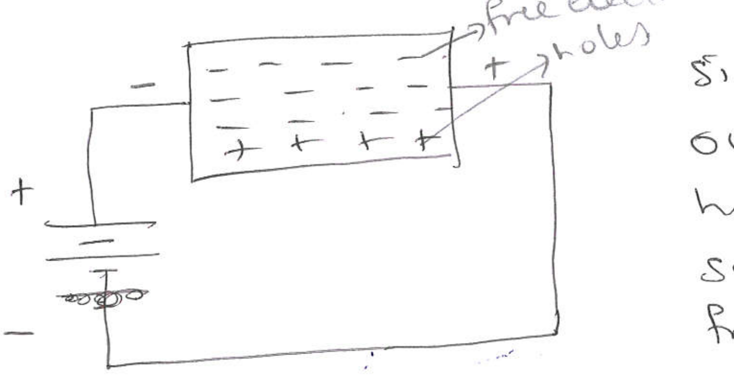
This is a pure semiconductor.

Extrinsic semiconductor :

one way to increase conductivity of a semiconductor is by doping. This means adding impurity atoms to an intrinsic crystal to alter its electrical conductivity. A doped semiconductor is called an extrinsic semiconductor.

n type semiconductor :

silicon that has been doped with a Pentavalent impurity is called an n-type semiconductor, where n stands for negative.

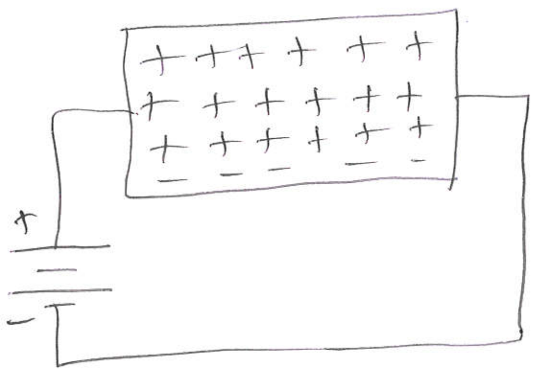


Since the free electrons outnumber the holes in an n-type semiconductor, the free electrons are called majority carriers and the holes are called minority carriers.

Because of the applied voltage, the free electrons move to the left and the holes move to the right.

P type semiconductor :

→ silicon that has been doped with a trivalent impurity is called a p-type semiconductor. where p stands for positive.



→ since holes outnumber free electrons, the holes are referred to as the majority carriers and the free electrons are known as the minority carriers.

Barrier potential :

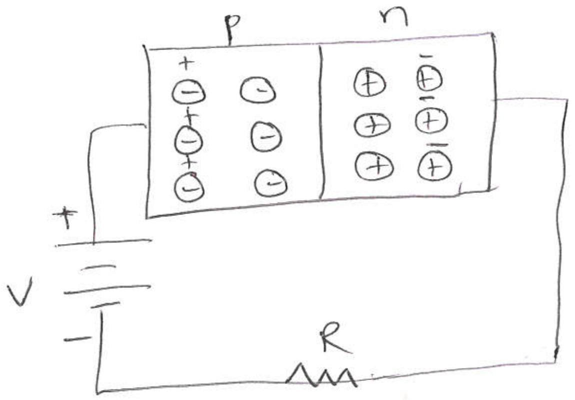
→ Each dipole has an electric field between the positive and negative ions.

→ The electric field between the ions is equivalent to a difference of potential called the barrier potential.

0.3 V → Germanium, 0.7 V → silicon.

Forward bias :

→ Diagram below shows a dc source across a diode.

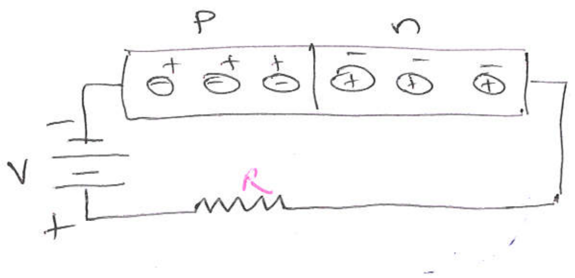


→ The negative source terminal is connected to the n-type material & the positive terminal is connected to the p-type material.

Reverse bias :

-ve battery terminal → P side

+ve battery terminal → n side



3.1 Basic ideas

→ An ordinary ~~diode~~ resistor is a linear device because the graph of its current versus voltage is a straight line.

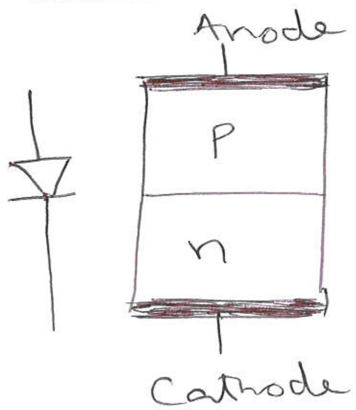
→ A diode is a non linear device because the graph of its current versus voltage is not a straight line.

→ The reason is the barrier potential.

→ when the diode voltage is less than the barrier potential, the diode current is small.

→ when diode voltage exceeds the barrier potential, the diode current increases rapidly.

Schematic symbol



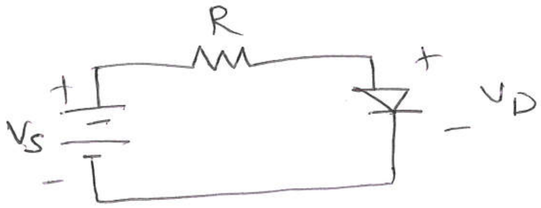
P side → Anode

n side → cathode

→ The diode symbol looks like an arrow that points from the p side to the n side, from anode to cathode

Basic diode circuit :

→ Figure below shows a diode circuit.



→ In the above circuit the diode is forward biased.

→ The positive battery terminal drives the p side through a resistor, and the negative battery terminal is connected to the n side.

→ The circuit is trying to push holes & free electrons towards the junction.

The Forward Region :

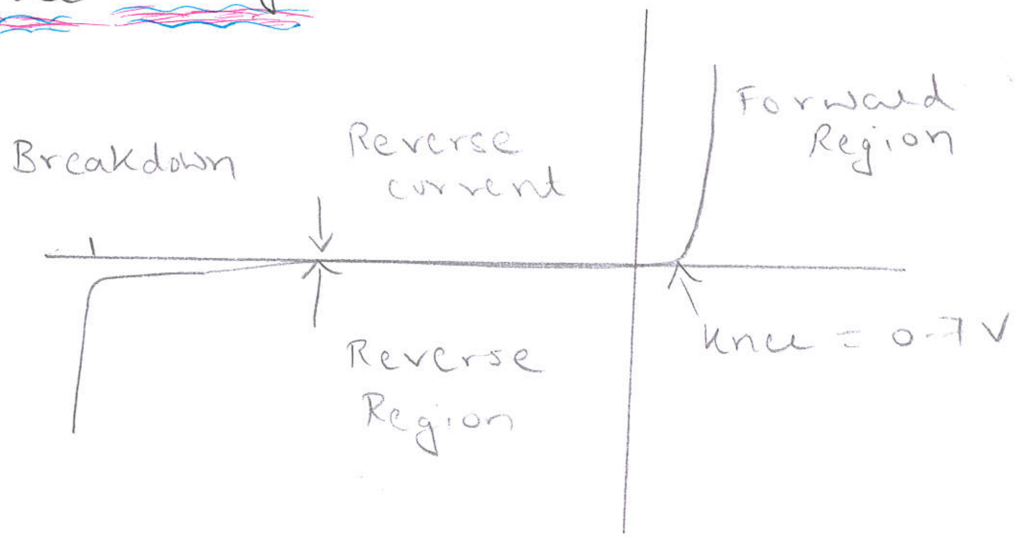
→ For the above circuit we can measure the current and the voltage for the diode.

→ when the diode is forward biased, there is no significant current until the diode voltage is greater than the barrier potential.

→ on the other hand, when the diode is reverse biased, there is almost no reverse current until the diode voltage reaches the breakdown voltage.

→ Then, avalanche produces a large reverse current, destroying the diode.

Knee voltage :



→ In the forward region, the voltage at which the current starts to increase rapidly is called the knee voltage of the diode.

→ The knee voltage equals the barrier Potential.

→ Analysis of diode circuits usually comes down to determining whether the diode voltage is more or less than the knee voltage.

→ If it's more, the diode conducts easily.

→ If it's less, the diode conducts poorly.

→ we define the knee voltage of a silicon diode as $V_k \approx 0.7\,V$

→ For germanium diode $V_k \approx 0.3\,V$

Bulk Resistence :

→ Above the knee voltage, the diode current increases rapidly.

→ This means that small increase in the diode voltage causes large increase in diode current.

→ In other words, if the p and n regions were two seperate pieces of semiconductor, each would have a resistance that you could measure with an ohmmeter, the same as an ordinary resistor.

→ The sum of the ohmic resistances is called the bulk resisstnce of the diode.

→ It is defined as $R_B = R_p + R_N$

→ The bulk resistence depends on the size of the p and n regions, and how heavily doped they are.

→ often the bulk resistence is less than 1Ω

maximum DC forward current.

→ If the current in a diode is too large, the excessive heat can destroy the diode.

→ For this reason, a manufacturer's data sheet specifies the maximum current a diode can safely handle without shortening its life or degrading its characteristics.

→ The maximum forward current is one of the maximum ratings given on a data sheet

→ This current may be listed as Imax, $I_F(max)$, I_o etc depending on the manufacturer.

→ For instance a 1N456 has a maximum forward current rating of 135 mA.

→ This means that it can safely handle a continuous forward current of 135 mA.

Power Dissipation :

→ You can calculate the power dissipation of a diode the same way as you do for a resistor.

→ It equals the product of diode voltage and current.

$$P_D = I_D V_D$$

→ The power rating is the maximum power the diode can safely dissipate without shortening its life or degrading its properties.

$$P_{max} = V_{max} I_{max}.$$

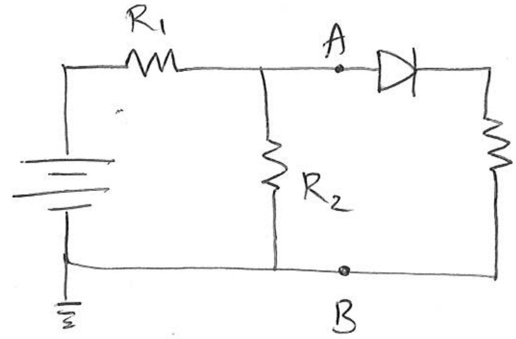
Ex :- max. voltage $V_{max} = 1V$

current $= 2A$

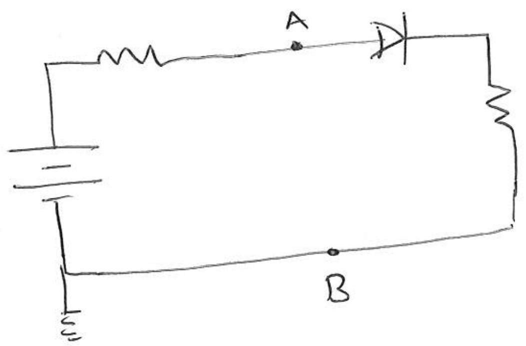
Power rating $= 2W$.

Example 3.1 :

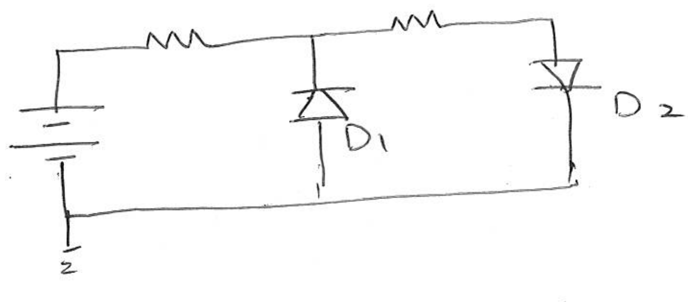
Is the diode forward biased / reverse biased.

① 

The voltage across R_2 is positive ; therefore the circuit is trying to push current in the easy direction of flow.
∴ Diode → Forward biased.

② 

The DC source is trying to push the current in easy direction of flow.
Diode → Forward biased.

③ 

Diode D1
→ Reverse biased

Diode D2
→ Forward biased.

Example 3.2 :

A diode has power rating of 5W. If the diode voltage is 1.2 V and the diode current is 1.75A, what is the power dissipation ? will the diode be destroyed.

$$P_D = (1.2\,V)(1.75\,A) = 2.1\,W$$

less than power rating

so the diode will not be destroyed.

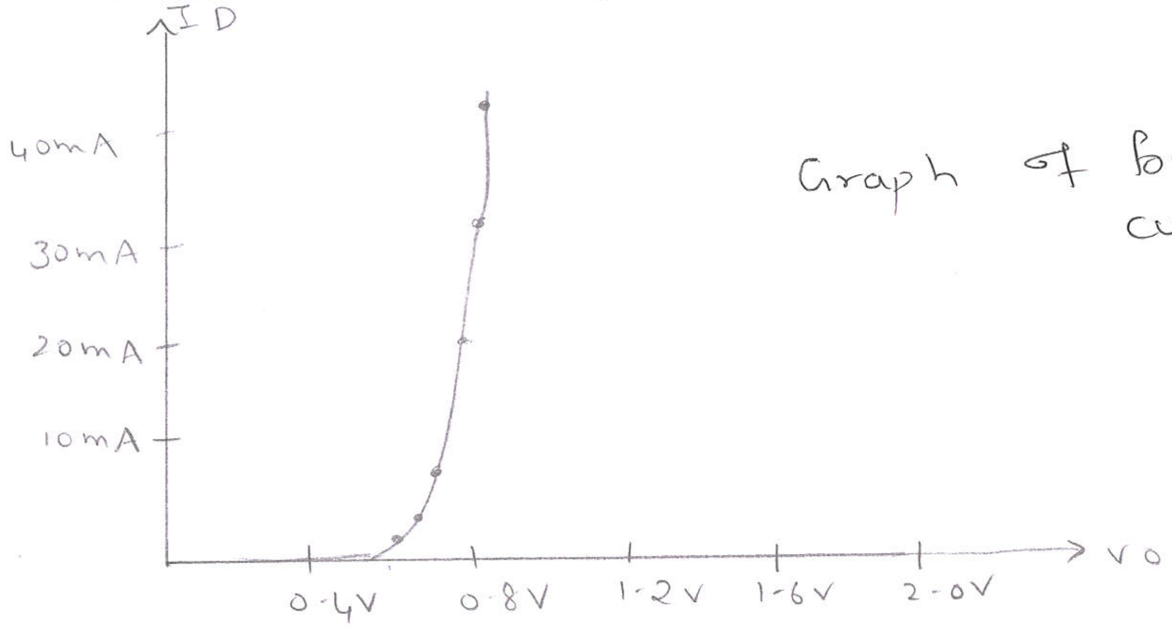
Practice problem 3.2

What is the diode's power dissipation if the diode voltage is 1.1 V and the diode current is 2 A?

$$(1.1\,V)(2\,A) = 2.2\,W.$$

3.2 The ideal Diode

→ Figure below shows a detailed graph of the forward region of a diode.



Graph of forward current.

→ Diode current I_D versus diode voltage V_D.

→ The current is approximately zero until the diode voltage approaches the barrier potential.

→ somewhere in the vicinity of 0.6 to 0.7 V the diode current increases.

→ When the diode voltage is greater than 0.8 V, the diode current is significant and the graph is almost linear.

→ Depending on how a diode is doped and its physical size, it may differ from other diodes in its maximum forward current, power rating and other characteristics.

→ If we need an exact solution, we would have to use the graph of the particular diode.

→ Although the exact current and voltage points will differ from one diode to the next, the graph of an diode is similar to the graph.

→ All silicon diodes have a knee voltage of approximately 0.7 V.

→ Most of the time we donot need an exact solution.

→ This is why we can and should use approximations for a diode.

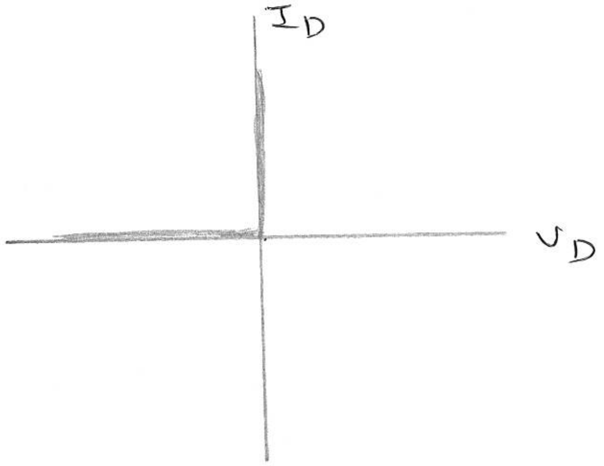
→ A diode in most basic terms conducts well in the forward direction & poorly in the reverse direction.

→ Ideally a diode acts like a perfect conductor (zero resistence) when forward biased and like a perfect insulator (infinite resistence) when reverse biased.

→ Figure below shows the current voltage graph of an ideal diode.

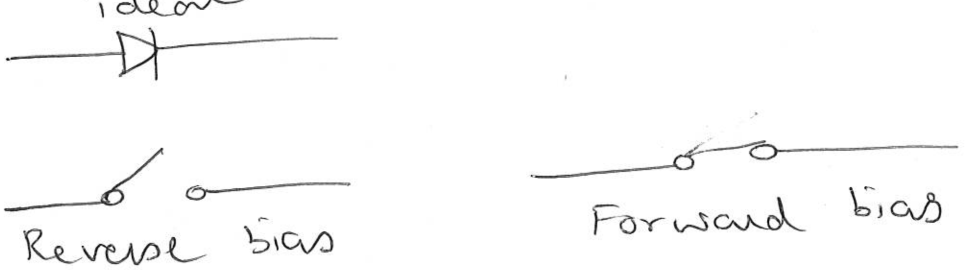
→ It echoes what we just said: zero resistance when forward biased and infinite resistance when reverse biased.

→ It is impossible ~~to~~ to build such a device, but this is what manufacturers would produce if they could.



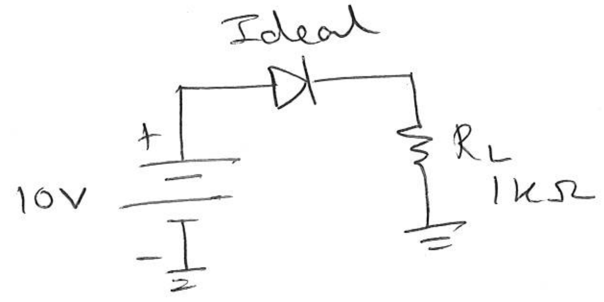
→ An ordinary switch has zero resistance when closed and infinite resistance when open.

→ Therefore, an ideal diode acts like a switch that closes when forward biased and opens when reverse biased.



Example 3.3 :

use the ideal diode to calculate the load voltage and load current in fig below.



$V_L = 10V$

with ohm's, the load current is

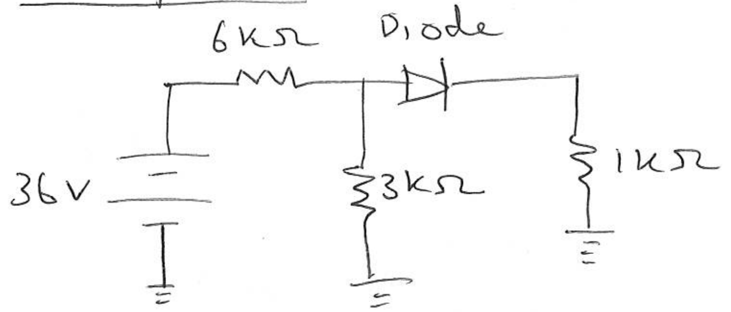
$$I_L = \frac{10V}{1k\Omega} = 10mA.$$

Practice problem :

Find the ideal load current if the source voltage is 5V

$V_L = 5V$ $\quad I_L = \frac{5V}{1k\Omega} = 5mA$

Example 3.4 :



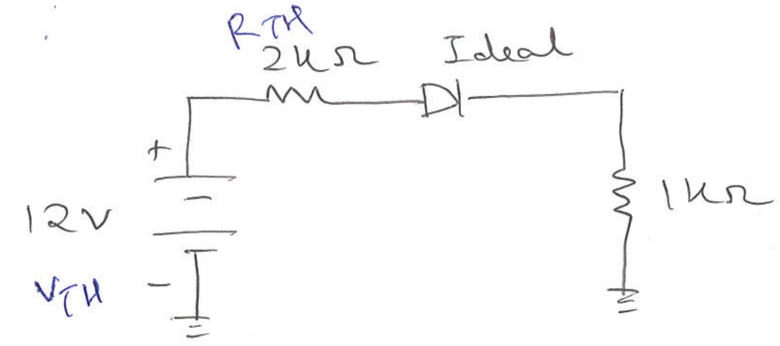
$6k\Omega$ & $3k\Omega$ are in parallel when we see from the diode back towards the source.

$$R_{Th} = \frac{6 \times 3}{6+3} = 2k\Omega$$

$$I_{TH} = \frac{36V}{9k\Omega} = 4mA$$

— current flowing through $3k\Omega = 4mA$.

$V_{TH} = 12V \ (3k\Omega \times 4mA)$



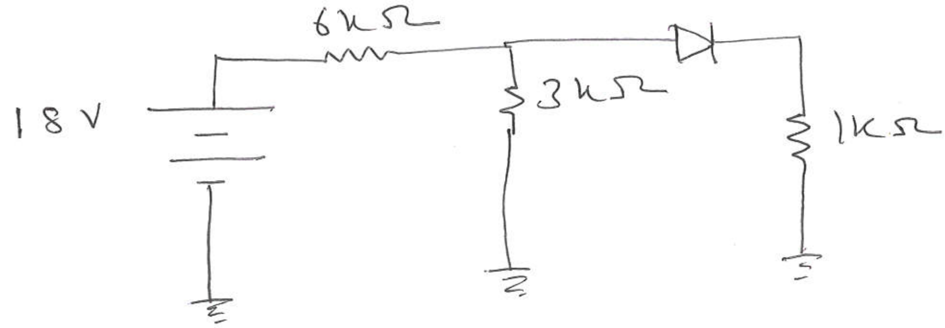
$$I_L = \frac{12\,V}{3\,k\Omega} = 4\,mA$$

$3\,k\Omega$ ← ($2k\Omega + 1k\Omega$) in series

$$V_L = (4\,mA)(1\,k\Omega) = 4\,V.$$

Practice problem 3-4

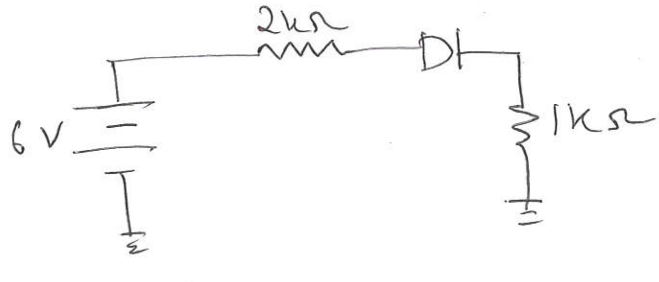
36V source → 18 V and solve for the load voltage & load current



$$\frac{18\,V}{9\,k\Omega} = 2\,mA = I_{TH}$$

$$R_{TH} = \frac{6 \times 3}{6 + 3} = 2\,k\Omega$$

$$V_{TH} = 2\,mA \times 3\,k\Omega = 6\,V$$



$$I_L = \frac{V_S}{R} = \frac{6\,V}{3\,k\Omega} = 2\,mA$$

R ← (1+2 in series)

$$V_L = (2\,mA)(1\,k\Omega)$$
$$= 2\,V$$

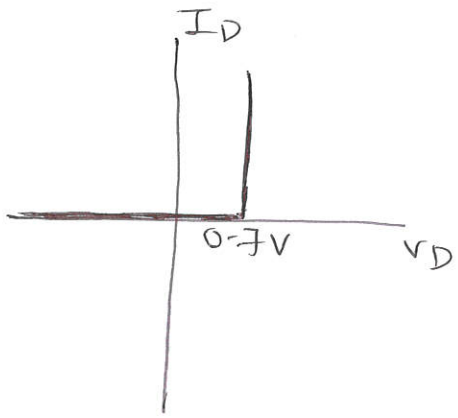
3-3 The Second approximation:

→ The ideal approximation is all right in most troubleshooting situations.

→ But we are not always troubleshooting.

→ sometimes, we want a more accurate value for load current and load voltage.

→ This is where the second approximation comes in.



→ Figure shows the graph of current versus voltage for the second approximation.

→ The graph says that no current exists until 0.7V appears across the diode.

→ At this point, the diode turns on.

→ Thereafter only 0.7V can appear across the diode, no matter what the current.

→ The figure below shows the equivalent circuit for the second approximation of a silicon diode.

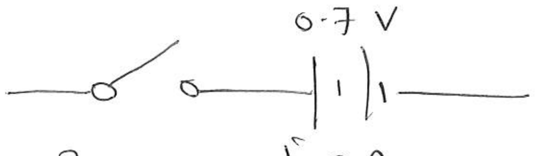
2D approximation

→ we think of a diode as a switch in series with a barrier potential of 0.7 V.

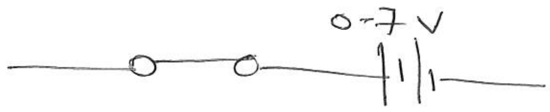
→ If the thevenin voltage facing the diode is greater than 0.7 V, the switch will close.

→ when conducting, the diode voltage is 0.7 V for any forward current.

→ on the other hand, the thevenin voltage is less than 0.7 V, the switch will open.



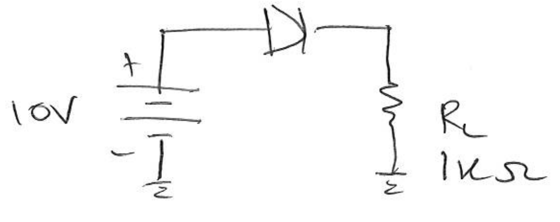
Reverse bias



Forward bias.

<u>Example 3-5</u>:

use the second approximation to calculate the load voltage, load current and diode power



$V_L = 10V - 0.7V = 9.3V$

with ohm's law, the load current is

$$I_L = \frac{9.3V}{1k\Omega} = 9.3 mA$$

The diode power is

$$P_D = (0.7V)(9.3mA) = 6.51 mW$$

Practice Problem 3.5 :

Changing v_g source in 3-5 to 5V. Calculate the new load voltage, current & diode power

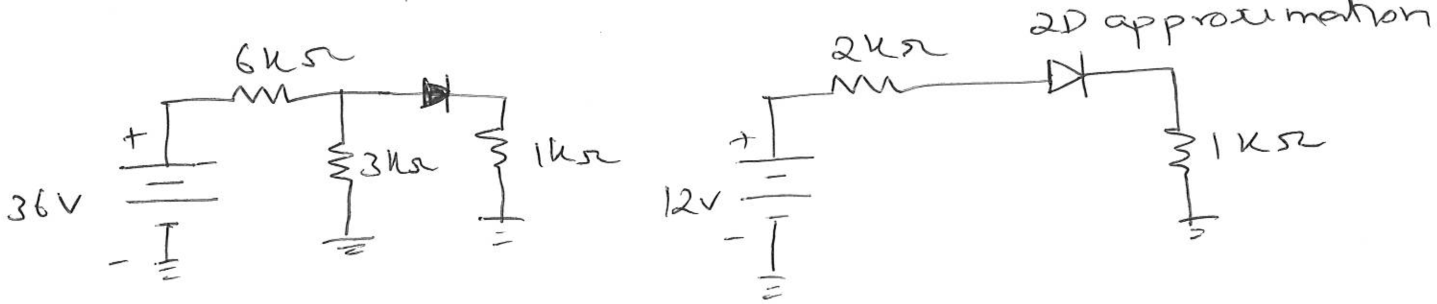
$$V_L = 5V - 0.7V = 4.3V$$

$$I_L = \frac{4.3}{1k\Omega} = 4.3mA$$

The diode power is $P_D = (0.7V)(4.3mA)$
$= 3.01\ mW$

Example 3.6 :

Calculate the load voltage, load current and diode power in figure below using the second approximation.



$$I_L = \frac{12V - 0.7V}{3k\Omega} = 3.77mA$$

The load voltage is

$$V_L = (3.77mA)(1k\Omega) = 3.77V$$

and the diode power is

$$P_D = (0.7V)(3.77mA)$$
$= 2.64\ mW$.

Practice problem 3.6

Repeat example 3.6 using 18 V as the voltage source value.

$$I_L = \frac{6V - 0.7V}{3k\Omega} = 1.76\,mA$$

$$V_L = (1.76\,mA)(1k\Omega) = 1.76\,V$$

Diode power is

$$P_D = (0.7)(1.76) = 1.232\,mW$$

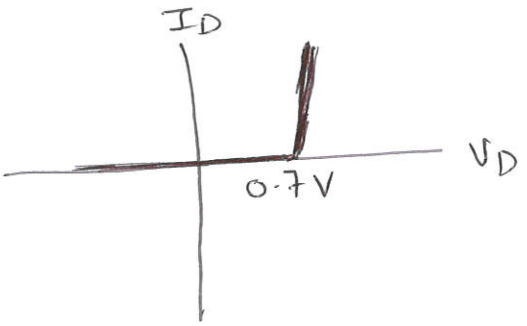
3.4 Third Approximation

→ In the third approximation of a diode, we include bulk resistence R_B.

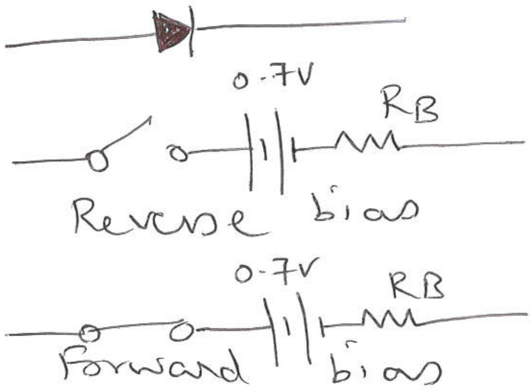
→ Figure below shows the effect that R_B has on the diode curve.

→ After the silicon diode turn on, the voltage increases linearly with an increase in current.

→ The greater the current, the larger the diode voltage because of the voltage drop across the bulk resistence.



3D approximation



→ The equivalent circuit for the third approximation is a switch in series with a barrier potential of 0.7 V and a resistence of R_B.

→ When the diode voltage is larger than 0.7 V, the diode conducts.

→ During conduction, the total voltage across the diode is

$$V_D = 0.7\,V + I_D R_B.$$

→ Often the bulk resistence is less than $1\,\Omega$, and we can safely ignore it in our calculations.

→ A useful guideline for ignoring bulk resistence is this definition.

$$\text{Ignore bulk}: R_B < 0.01\,R_{TH}$$

Example 3.7

The 1N4001 of figure below has a bulk resistence of $0.23\,\Omega$. What is the load voltage, load current, & diode power?

Soln: The bulk resistance is small enough to ignore because it is less than 1/100 of the load resistance.

Hence load voltage = 9.3 V
load current = 9.3 mA
Diode power = 6.51 mW

Example 3.8 :

Repeat the preceding example for a load resistence of $10\,\Omega$

$R_T = 0.23\,\Omega + 10\,\Omega = 10.23\,\Omega$

The total voltage across R_T is

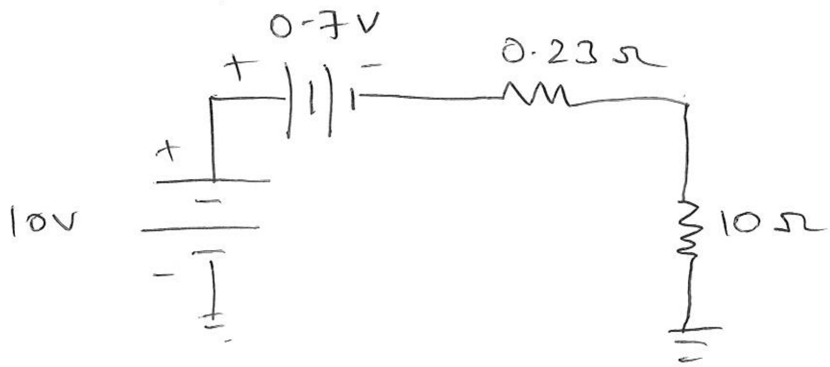
$V_T = 10V - 0.7V = 9.3V$

Therefore the load current is

$$I_L = \frac{9.3V}{10.23\,\Omega} = 0.909A$$

The load voltage is :

$V_L = (0.909A)(10\,\Omega) = 9.09V$



Diode power $= P_D = I_D \cdot V_D$

$V_D = 10V - 9.09V = 0.91V$

$V_D = 0.7V + (0.909A)(0.23\,\Omega)$

$= 0.909V$

$P_P = (0.909V)(0.909A)$

$= 0.826\,W.$

4.10 Clippers and Limiters

→ The diodes used in low frequency power supplies are rectifier diodes.

→ These diodes are optimized for use at 60HZ and ~~p~~ have power ratings greater than 0.5 W.

→ Except for power supplies, rectifier diodes have little use because most circuits inside electronics equipment are running at much higher frequencies.

Small-signal diodes:

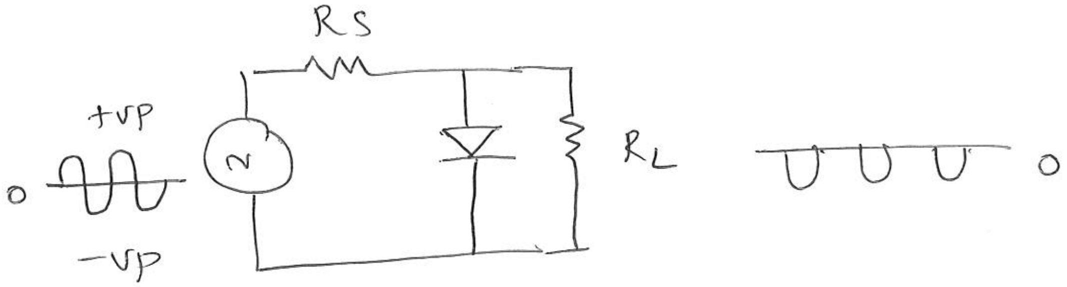
→ These diodes are optimized for use at high frequencies and have power ratings less than 0.5 w.

→ It is smaller and lighter construction that allows the diode to work at higher frequencies.

The positive clipper:

→ A clipper is a circuit that removes either positive or negative parts of a waveform.

→ This kind of processing is useful for signal shaping, circuit protection, & communications.



→ The figure shows a positive clipper.

→ The circuit removes all the positive parts of the input signal.

→ This is why the output signal has only negative half cycles.

Here is how the circuit works:

→ During the positive half cycle, the diode turns on and looks like a short across the output terminals.

→ Ideally the output voltage is zero.

→ On the negative half cycle, the diode is open.

→ In this case, a negative half cycle appears across the output.

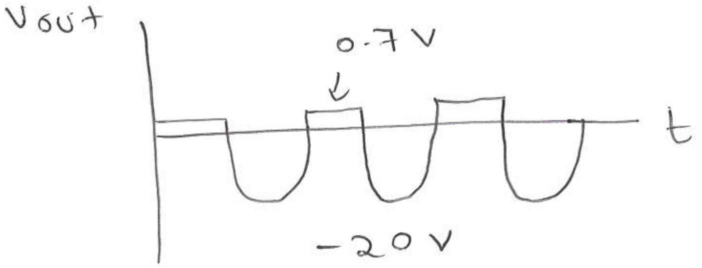
→ By design $R_S < R_L$.

→ This is why the negative output peak is $-V_p$

→ To a second approximation, the diode voltage is 0.7 when conducting.

→ Therefore the clipping level is not zero, but 0.7 V.

→ For instance, if the input signal has a peak value of 20 V, the output of the clipper will look like Fig (b) below



Defining conditions.

→ Small signal diodes have a smaller junction area than rectifier diodes because they are optimized to work at higher frequencies.

→ As a result they have more bulk resistance

Ex :- 1N914 — 10 mA at 1 V

$$R_B = \frac{1V - 0.7V}{10mA} = 30\Omega$$

→ clipper wont work properly unless the series resistance R_s is much greater than bulk resistance and much smaller than load resistance.

Stiff clipper : $100 R_B < R_S < 0.01 R_L$

→ series resistance must be 100 times greater than bulk resistance and 100 times lesser than Load resistance.

Ex :- $R_B = 30\,\Omega$

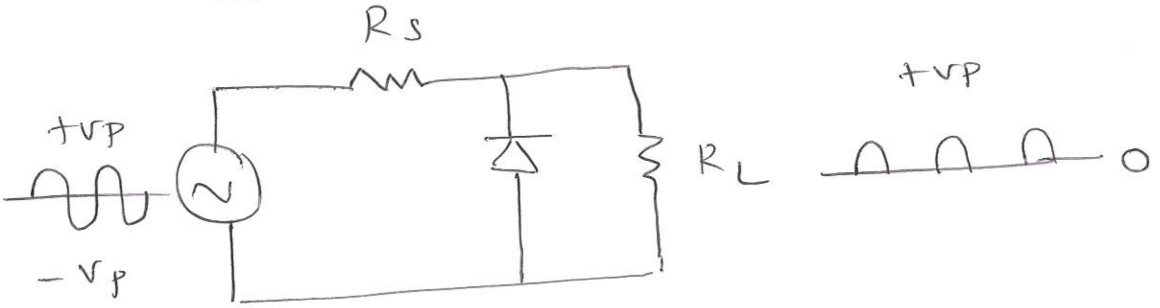
$R_S = 3k\,\Omega$

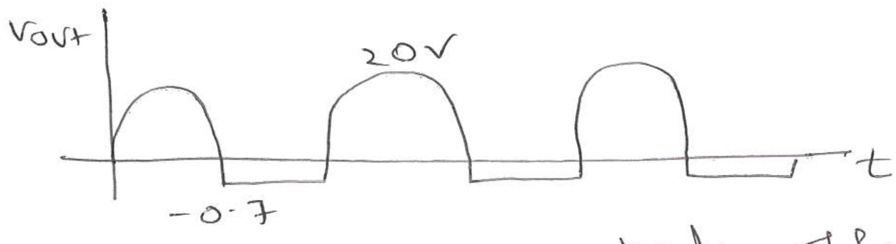
$R_L = 300\,k\,\Omega$

The Negative clipper :

→ If we reverse the polarity of the diode as shown in fig below we get a negative clipper.

→ This removes the negative parts of the signal





→ Because of the diode offset voltage the clipping level is at $-0.7\,V$.

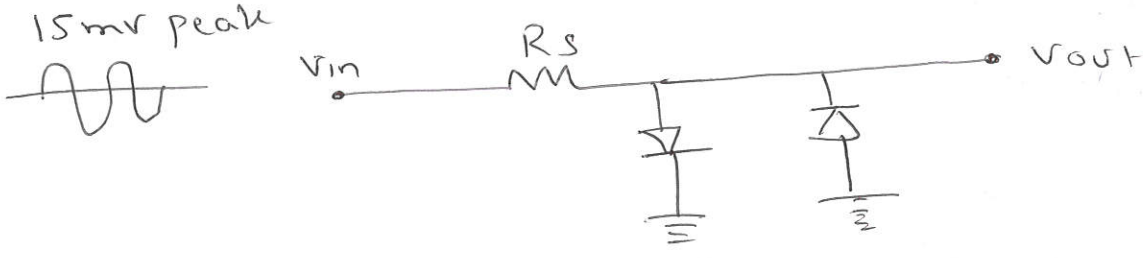
The limiter or diode clamp:

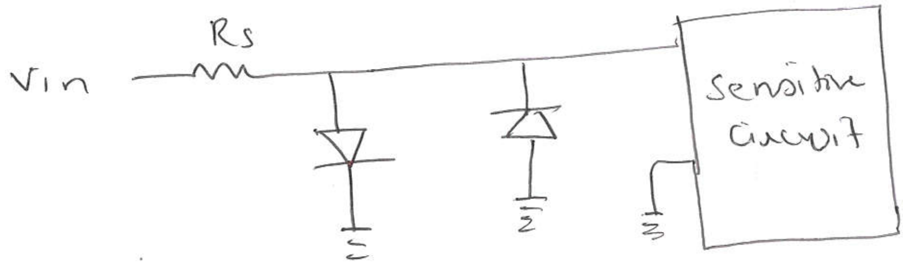
→ The clipper is useful for waveshaping, but the same circuit can be used in totally different way.

→ The normal input to this circuit is a signal with a peak of only 15 mV.

→ Therefore, the normal output is the same signal because neither diode is turned during the cycle.

→ whenever you have a sensitive circuit, one that cannot have too much input, you can use a positive negative limiter to protect its input as shown in b.





→ If the input signal tries to rise above 0.7 V the output is limited to 0.7.

→ on the other hand, if the input signal tries to drop below −0.7 V, the output is limited to −0.7.

→ A limiter on the input side of an op-amp will prevent excessive input voltage from being accidentally applied.

→ Ex: moving coil meter.

→ By including a limiter, we can protect the meter movement against excessive input voltage or current.

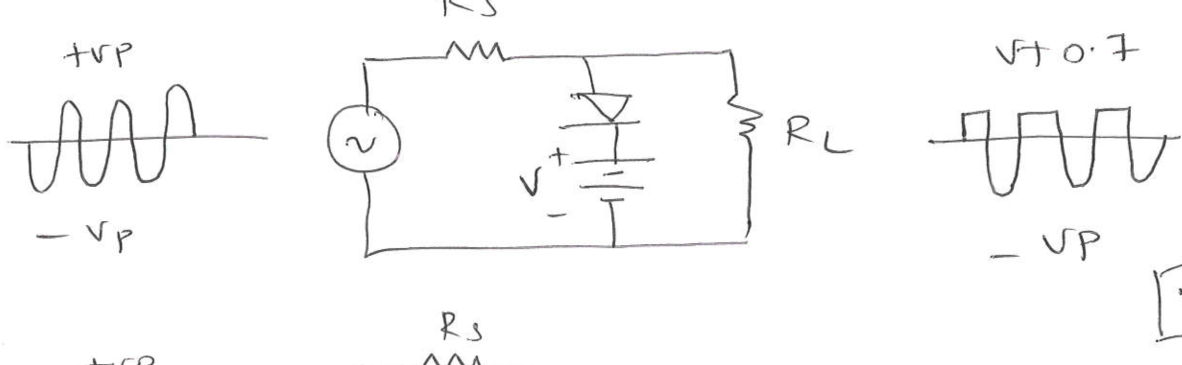
→ The limiter is also called a diode clamp,

→ The term suggests clamping or limiting the voltage to a specified range.

Biased clippers:

→ The reference level of an ~~ideal~~ Positive clipper is ideally zero or 0.7V to a second approx.

→ In electronics, bias means applying an external voltage to change the reference level of a circuit.



$\boxed{V < VP}$

→ Figure is an example of using bias to change the reference level of a positive clipper.

→ By adding a dc voltage source in series with the diode, we can change the clipping level.

→ The new V must be less than V_p for normal operation.

→ With an ideal diode, conduction starts as soon as the input voltage is greater than V.

→ second approximation –

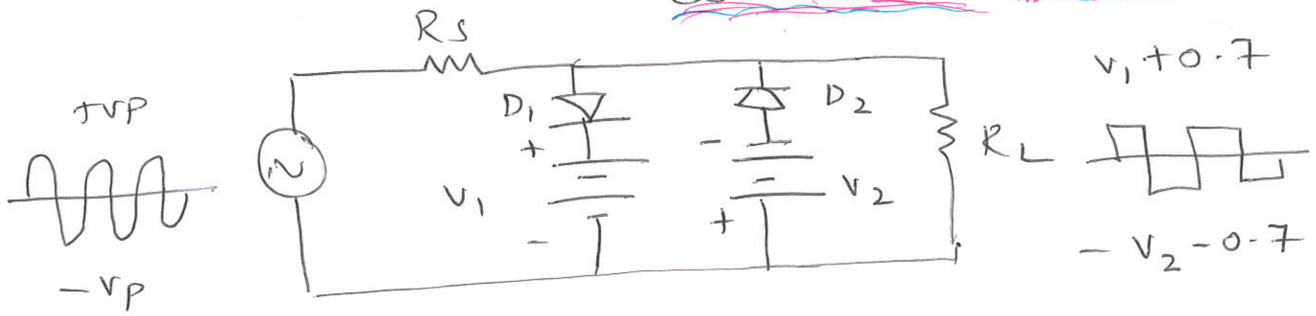
$$V_p \ v_q > V + 0.7V$$

→ Figure below shows how to bias a negative clipper.

→ Notice that diode and battery have been reversed.

→ Because of this reference level changes to $-V - 0.7V$.

Combination clipper:



→ we can combine the two biased clippers as shown in fig (previous page).

→ Diode D_1 clips off positive parts above the positive bias level. and diode D_2 clips off parts below the negative bias level.

→ when the input voltage is very large compared to the bias levels, the output signal is a square wave, as shown in figure.

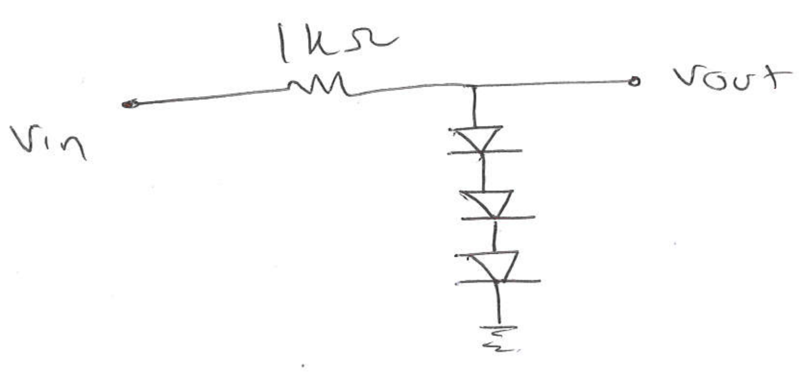
Variations:

→ using batteries to set the clipping level is impractical.

→ one approach is to add more silicon diodes because each produces a bias of 0.7 V.

→ For instance figure below shows three diodes in a positive clipper.

→ since each diode has an offset of around 0.7 V, the three diodes produce a clipping level of approximately +2.1 V.

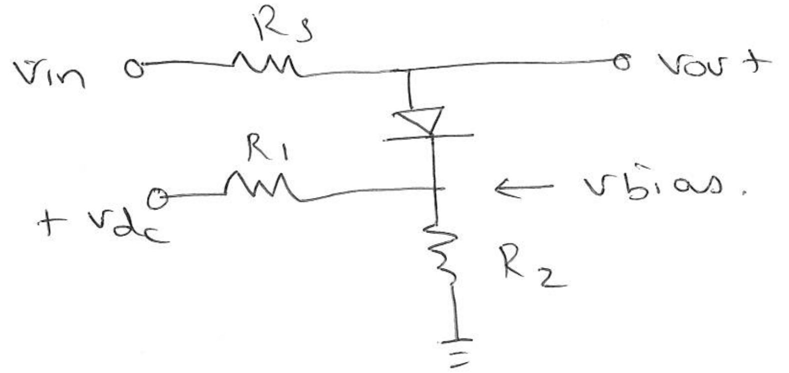


→ Fig below shows another way to bias a clipper without batteries.

→ This time, we are using a voltage divider (R_1 and R_2) to set the bias level.

→ The bias level is given by

$$V_{bias} = \frac{R_2}{R_1 + R_2} V_{dc}.$$

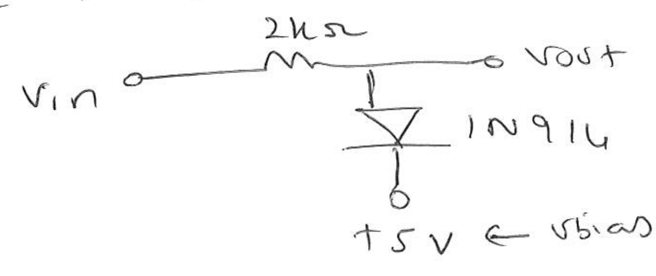


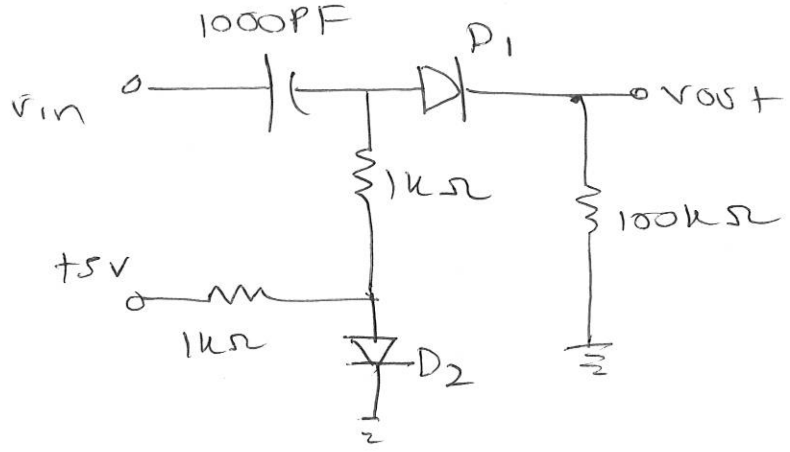
→ Figure below, shows a biased diode clamp.

→ It can be used to protect sensitive circuits from excessive input voltages.

→ The bias level is shown as +5V.

→ With a circuit like this, a destructively large voltage of +100V never reaches the load because the diode limits the output voltage to a maximum value of +5.7 V





→ sometimes a variation like in the figure above is used to remove the offset of the limiting diode D_1.

→ Diode D_2 is biased slightly into forward conduction, so that it has approximately 0.7 V across it.

→ This 0.7 V is applied to 1kΩ in series with D_1 and 100kΩ.

→ This means that diode D_1 is on the verge of conduction.

→ Therefore, when a signal comes in, diode D_1 conducts near 0 V.

4.11 CLAMPERS

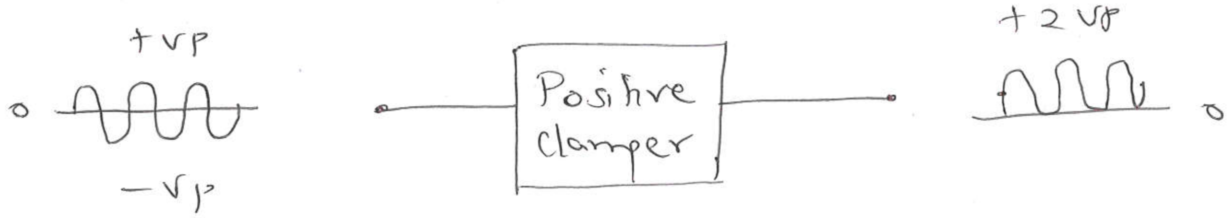
→ Clampers add a dc voltage to the signal.

Positive clamper :

→ Figure below shows the basic idea for a positive clamper.

→ When a positive clamper has a sine-wave input, it adds a positive dc voltage to the sine wave.

→ Each point on the sine wave is shifted upward.



→ Figure below shows an equivalent way of visualizing the effect of a positive clamper.

→ An ac source drives the input side of the clamper

→ The thevenin voltage of the clamper o/p is the superposition of a dc source and an ac source.

→ The ac signal has a dc voltage of Vp added to it

→ The figure (a) below is a positive clamper.

→ Ideally, the capacitor is initially uncharged.

→ on the first negative half cycle of input voltage, the diode turns on. (fig b)

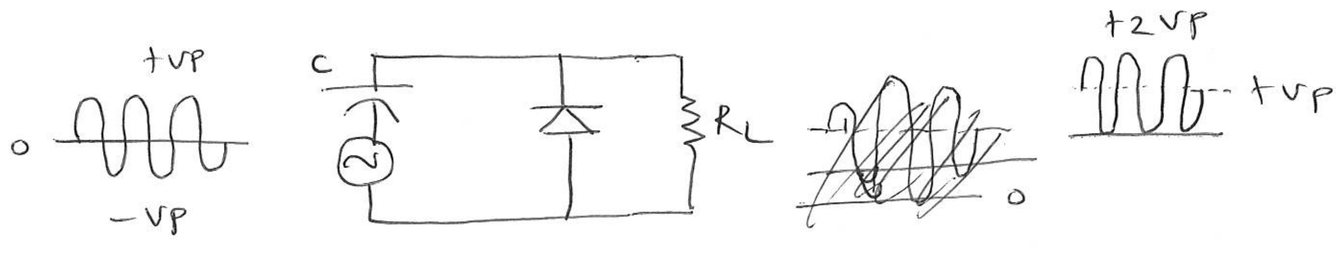
→ At the negative peak of the ac source, the capacitor has fully charged and its voltage is V_p.

→ slightly beyond the negative peak, the diode shuts off (fig – c).

→ The R_LC time constant is deliberately made much larger than the period T of the signal.

stiff clamper : $R_LC > 100T$

→ For this reason, the capacitor remains almost fully charged during the off time of the diode.



(a)

→ The idea is similar to the way a half wave rectifier with a capacitor - input filter works

→ The first quarter cycle charges the capacitor fully.

→ Then the capacitor retains almost all of its charge during subsequent cycles.

→ The small charge that is lost between cycles is replaced by diode conduction.

→ In fig (c) the charged capacitor looks like a battery with a voltage of V_p.

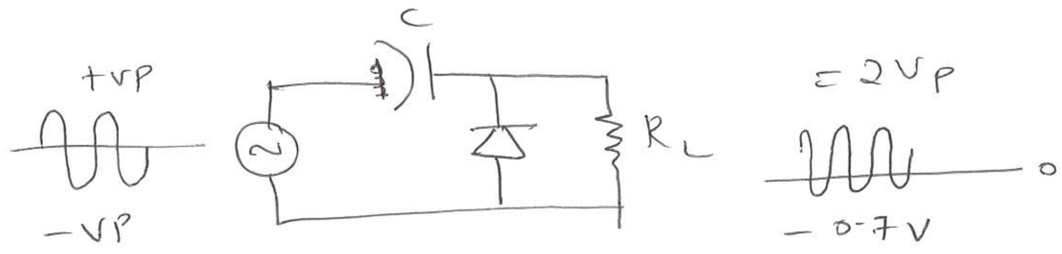
→ This is the dc voltage that is being added to the signal.

→ After the first quarter cycle, the output voltage is a positively clamped sine wave with a reference level of zero; that is it sits on a level of 0 V.

→ Figure below shows the circuit as it is usually drawn.

→ since the diode drops 0.7 V when conducting the capacitor voltage does not ~~require~~ quite reach V_p.

→ For this reason, the clamping is not perfect, and the negative peaks have a reference level of −0.7 V fig (d)

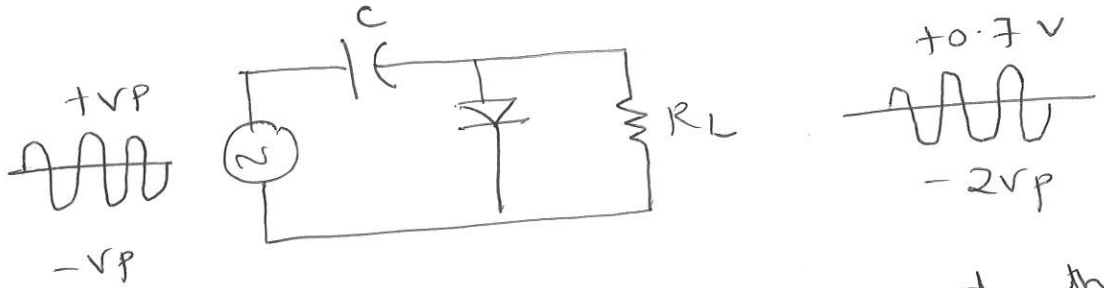


negative clamper :

→ we get a negative clamper if we reverse the diode above.

→ As given below, the capacitor voltage reverses and the circuit becomes a negative clamper.

→ The clamping level is less than perfect because the positive peaks have a reference level of 0.7 V instead of 0V.



→ The diode points downward, the same direction as the shift of the sine wave.

→ Both negative & positive clampers are widely used.

→ for instance television receivers use a clamper to change the reference level of video signals & also in radar and communication circuits.

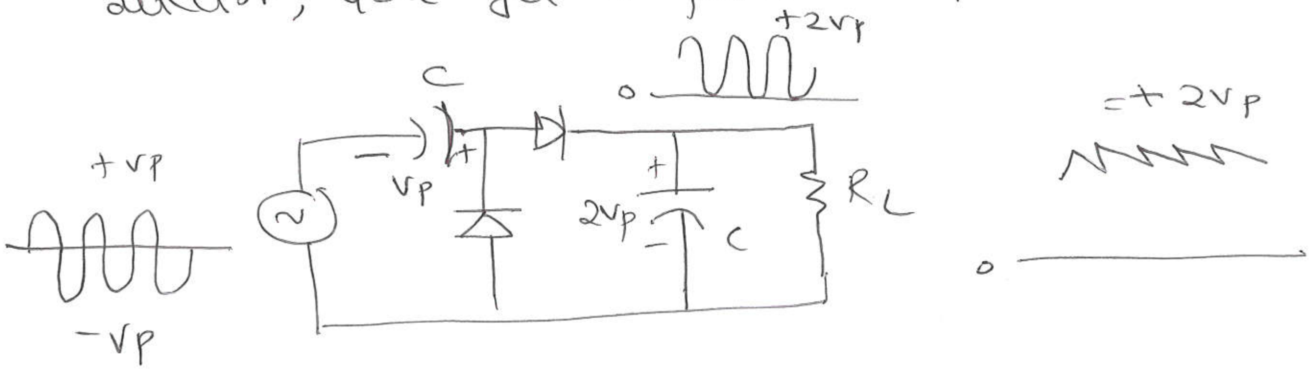
Peak to peak detector

→ A half wave rectifier with a capacitor input filter produces a dc output voltage approximately equal to the peak of the input signal.

→ When the same circuit uses a small signal diode, it is called a peak detector.

→ The output of a peak detector is useful in measurements, signal processing & communications.

→ If you cascade a clamper and a peak detector, you get a peak-to peak detector.



→ The output of a clamper is used as the input to a peak detector.

→ Since the sine wave is positively clamped, the input to the peak detector has a peak value of 2 Vp.

→ This is why the output of the peak detector is a dc voltage equal to 2 Vp.

→ One application is measuring nonsinusoidal signals.

4-12 voltage multipliers

→ A peak-to peak detector uses small signal diodes and operates at high frequencies.

→ By using rectifier diodes and operating at 60 HZ, we can produce a new kind of power supply called a voltage doubler.

voltage doubler :

→ Fig (a) is a voltage doubler.

→ The configuration is the same as a peak-to peak detector, except that we use rectifier diodes and operate at 60 HZ

→ The clamper section adds a dc component to the secondary voltage.

→ The peak detector then produces a dc output voltage that is 2 times the secondary voltage.

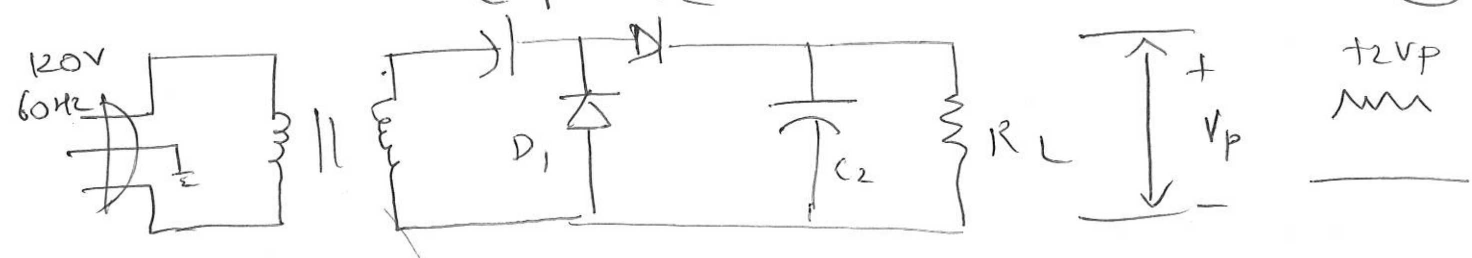
→ Ex : line voltage is 120V rms or 170 V peak

→ If you are trying to produce 3400 Vdc, you will need to use a 1:20 step up transformer.

→ Here is where the problem comes in

→ very high secondary voltage can be obtained only with bulky transformers.

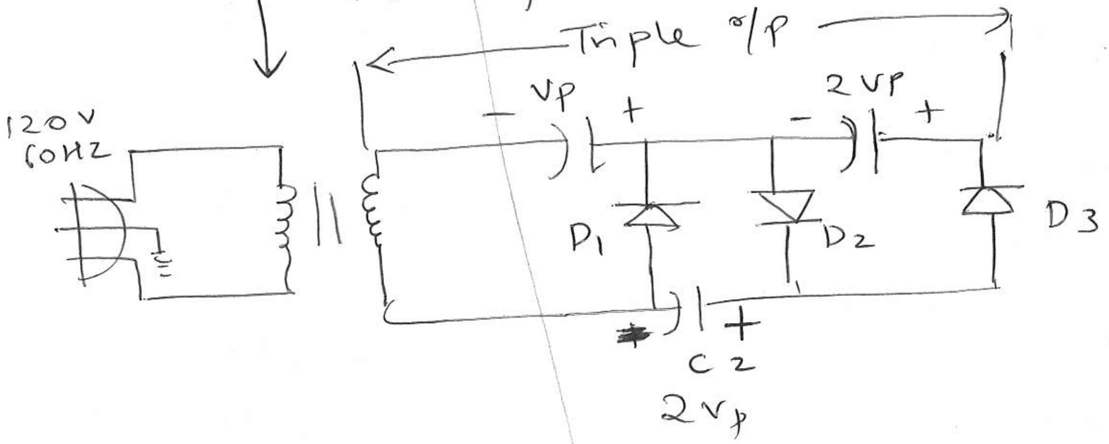
→ It would be simpler to use a voltage doubler and a smaller transformer.



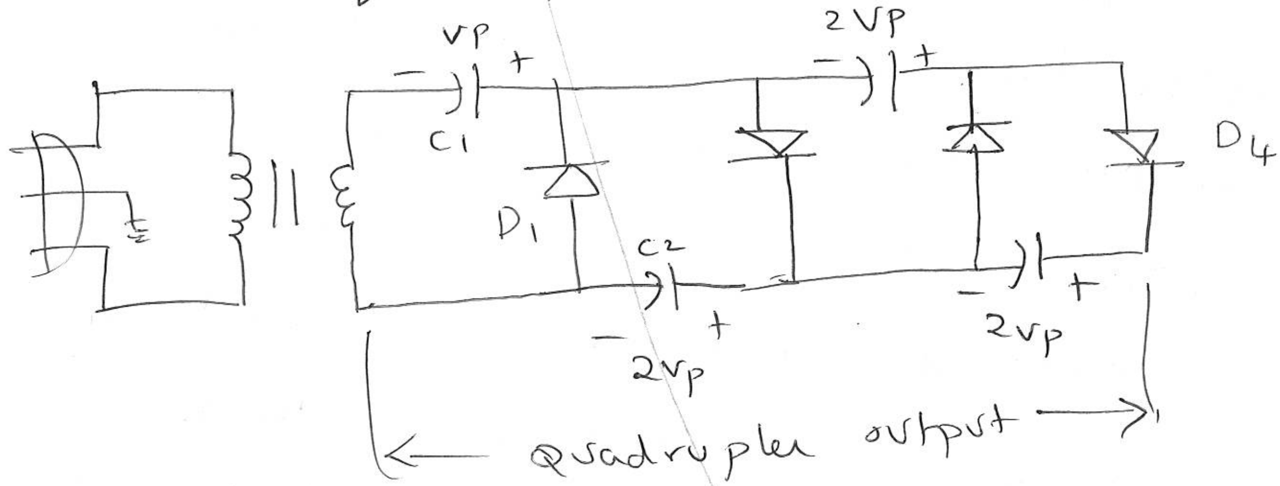
voltage multipliers with floating loads.

(a) Doubler.

(b) Tripler



(c) quadrupler



<u>voltage Tripler</u> :

→ By connecting another section, we get the voltage tripler of fig 4-3 (b).

→ The first two sections act like a doubler.

→ At the peak of the negative half cycle D3 is forward biased.

→ This charges C_3 to $2V_p$ with the polarity shown in fig (b).

→ The tripler output appears across C_1 & C_3.

→ The load resistence can be connected across the triple output.

→ As long as the time constant is long, the output equals approximately $3V_p$.

<u>voltage Quadrupler</u>:

→ Fig (c) is a voltage quadrupler with four sections in cascade.

→ The first three sections are a tripler.

→ The first three sections and the fourth makes the overall circuit a quadrupler.

→ The first capacitor charges to V_p.

→ All others charge to $2V_p$.

→ The quadrupler output is across the series of connection of C_2 and C_4.

→ we can connect a load resistence across the quadrupler output to get an output of $4V_p$.

<u>Variations</u>: of <u>Zener diode</u>

(Refer Text)