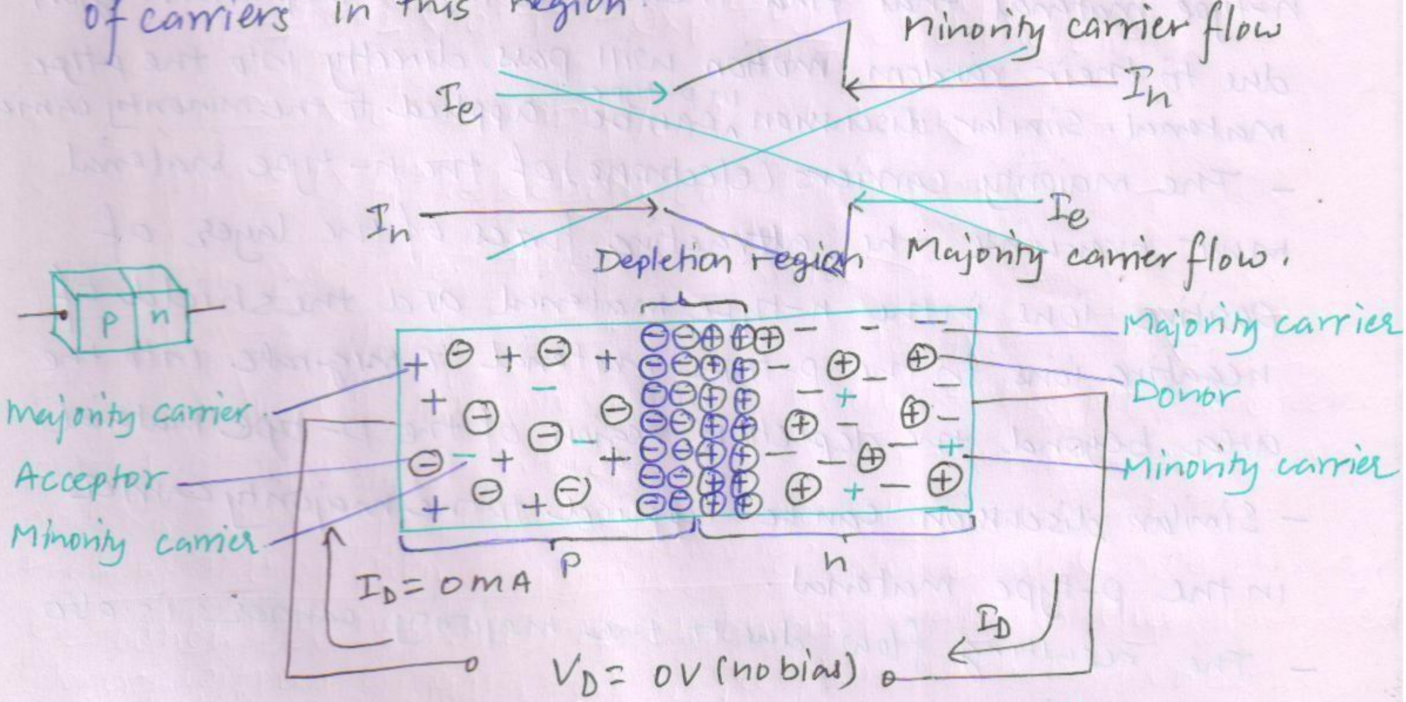
Junction Diode

- The semiconductor diode is formed by simply bringing n- and p-type materials together. (constructed from the same base - Ge or Si), as shown in the figure.
- At the instant the two materials are "joined" the electron and holes in the region of the junction will combine, resulting in a lack of carriers in the region near the junction.
- This region of uncovered positive and negative ions is called the depletion region due to the depletion of carriers in this region.



p-n junction with no external bias.

- Since the diode is a two terminal device, the application of a voltage across its terminals leaves three possibilities.

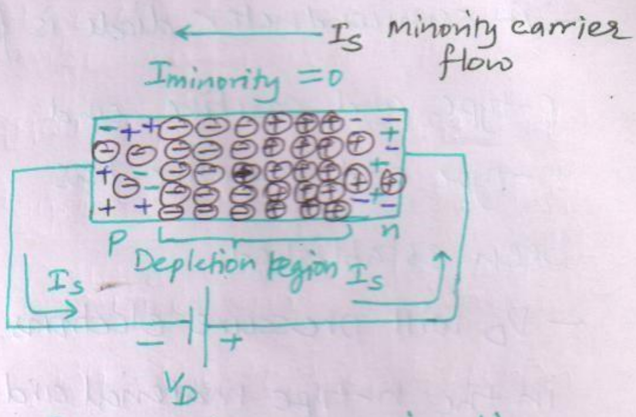
1- no bias ($V_D = 0V$)
2- forward bias ($V_D > 0V$)
3- reverse bias ($V_D < 0V$)

No Bias ($V_D = 0$)

- Under no-bias (no applied voltage) conditions, any minority carriers (holes) in n-type material that find themselves within the depletion region will pass directly into the p-type material.
- The closer the minority carrier is to the junction, the greater the attraction for the layer of negative ions and the less the opposition of the positive ions in the depletion region of the n-type material.
- We shall assume that all the minority carriers of the n-type material that find themselves in the depletion region due to their random motion will pass directly into the p-type material. Similar discussion can be applied to the minority carriers in p-type.
- The majority carriers (electrons) of the n-type material must overcome the attractive forces of the layer of positive ions in the n-type material and the shield of negative ions in the p-type material to migrate into the area beyond the depletion region of the p-type material.
- Similar discussion can be applied to the majority carriers in the p-type material.
- The resulting flow due to the majority carriers is also shown in fig.
- The relative magnitude of the flow vectors are such that the net flow in either direction is zero.
- This cancellation of vectors has been indicated by crossed lines.
- In the absence of an applied bias voltage, the net flow of charge in any one direction for a semiconductor diode is zero.

Reverse Bias Condition ($V_D < 0V$)

- If external voltage V_D applied across the p-n junction such as shown in the figure, (Reverse bias condition) the number of uncovered positive ions in the depletion region of the n-type material will increase due to large number of free electron drawn to the positive potential of the applied voltage. For the similar reason, the number of uncovered negtive ions will increase in the p-type material.

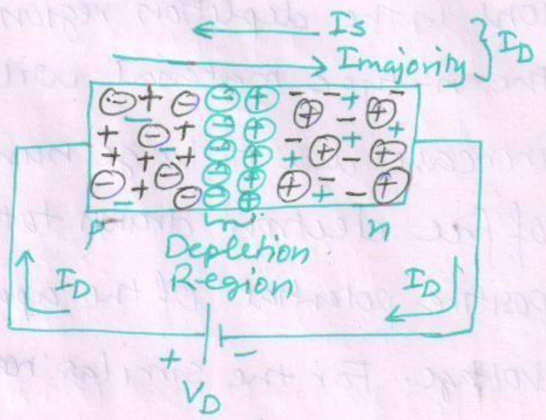


Reverse-biased p-n junction

- The net effect is a widening of the depletion region.
- Effectively reduction in the majority carrier flow to zero as shown in the figure.
- It will not change minority carrier flow vectors of the diode.
- The current that exists under reverse bias conditions is called the reverse saturation current and is represented by I_s.
- Saturation current is in the range of nano amphperes to low microamphers.
- The term saturation comes from the fact that it reaches its maximum level quickly and does not change significantly with increase in reverse biased potential.

Forward Bias Condition ($V_D > 0V$)

- A forward bias or "on" condition is established as shown in the figure
- A semiconductor diode is forward biased when the association p-type and positive and n-type and negative has been established.
- V_D will pressure electrons in the n-type material and holes in p-type material to recombine with the ions near the boundary and reduce the width of the depletion region as shown in figure.



$I_D = I_{majority} - I_s$

Forward biased p-n junction

- The resulting minority carrier flow of electrons from p-type material to n-type material and holes from n-type material to p-type material has not changed in magnitude.
- Reduction in the width of the depletion region has resulted in a heavy majority flow across the junction
- As applied bias increases in magnitude the depletion region will continue to decrease in width untill a flood of electrons can pass through the junction, resulting in an exponential rise in current.
- It can be demostrated through the use of solid state physics that general characteristics of a semiconductor diode can be defined by the following eq. for forward - and reverse regions'

$$I_D = I_S (e^{KV_D/T_K} - 1)$$

I_S - reverse saturation current
$k = 11600/\eta$ $\eta = 1$ for Ge, $\eta = 2$ for Si

$T_K = T_C + 273^0$

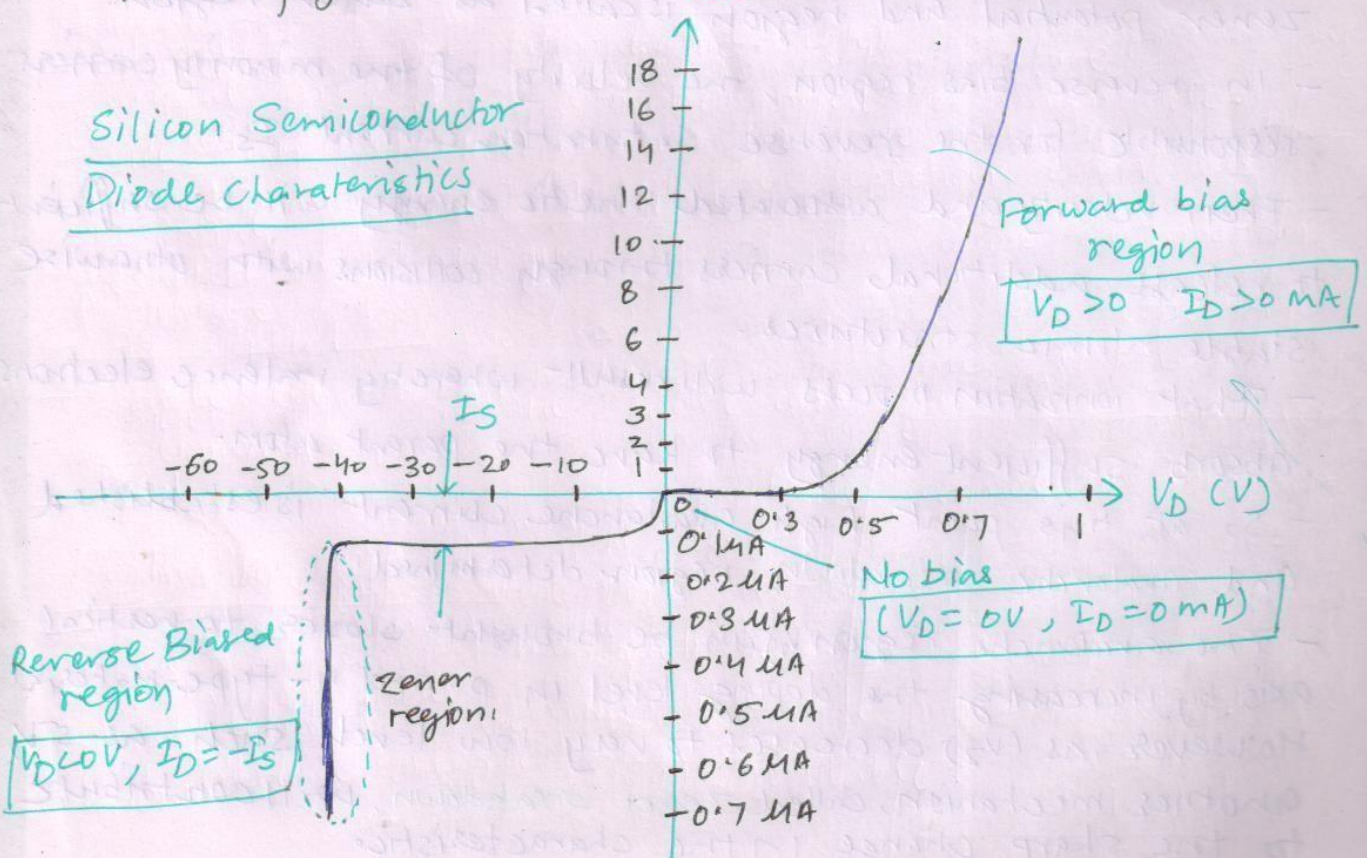
Semiconductor Diode V-I characteristics

- p-n junction diode formed from junction of n-type and p-type. When it is forward biased, it will pass current. When it is reverse biased, current flow is blocked.
- A plot of following equation will describe the V-I relationship for each region.

$$I_D = I_S\left(e^{kV_D/T_K} - 1\right)$$

- For forward biased region, positive values of V_D the first term of the equation above will grow very quickly and overpower the effect of the second term. The result is that for positive values of V_D, I_D will be positive and grow as the function of $y = e^x$ apporing in the figure.

Silicon Semiconductor Diode Charateristics



- At $V_D = 0V$ $I_D = I_S(e^0 - 1) = I_S(1-1) = 0$ mA
as appearing in the figure
- For negative values of V_D the first term will quickly drop off below I_S, resulting $I_D = -I_S$ which is simply the horizontal line as shown in the figure.
- The break in the characteristics at $V_D = 0V$ is simply due to the dramatic change in scale from mA to µA.

Zener Region

- As shown in the figure in tens of volts in negative region, there is a point where the application of too negative a voltage will result in a sharp change in the characteristics.
- The current increase at a very rapid rate in a direction opposite to that of the positive voltage region.
- This dramatic change in characteristics is called the zener potential and region is called as zener region.
- In reverse bias region, the velocity of the minority carriers responsible for the reverse saturation current I_S.
- Their velocity and associated kinetic energy will be sufficient to release additional carriers through collisions with otherwise stable atomic structures.
- That ionization process will result whereby valence electrons absorb sufficient energy to leave the parent atom.
- So at this point high avalanche current is established and avalanche breakdown region determined.
- The avalanche region (V_Z) can be brought closer to vertical axis by increasing the doping level in p- and n-type material. However, as (V_Z) decreases to very low levels, such as −5V, another mechanism, called zener breakdown, will contribute to the sharp change in the characteristic.

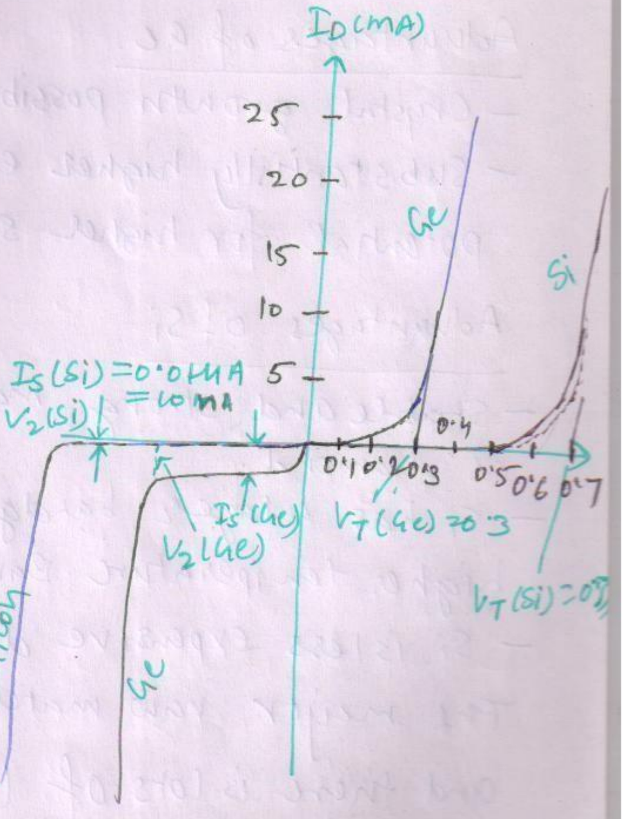
- zener breakdown occurs because there is a strong electric field in the region of the junction that can disrupt the bonding forces within the atom and "generate" carriers.
- Although the zener breakdown mechanism is a significant contributor only at lower level of V_Z, this sharp change in the characteristic at any level is called the zener region and diodes employing this unique portion of the characteristic of a p-n junction are called zener diodes.
- The maximum reverse bias potential that can be applied before entering the zener region is called the peak inverse voltage (PIV) or peak reverse voltage. (PRV)

Silicon versus Germanium

- The disadvantage of Silicon as compared to Germanium, is the higher forward bias voltage to reach the region of upward swing.

$V_T = 0.7\,(Si)$ $V_T = 0.3\,(Ge)$

- The potential at which rise occurs is commonly referred to as the offset, threshold or firing potential.



- Temperature effect

> The reverse saturation current I_S will just double in magnitude for every 10°C increase in temperature.

- The reverse saturation current in silicon flows in order of nano ampheres compared to germanium in which reverse current is in order of micro ampheres, because of this the accuracy of non-conduction of the Ge diode in reverse bias falls down whereas Si diode retains it property to greater extent i.e. it allows negligible amount of current to flow.
- Further the Si diode has large reverse breakdown voltage about 70-100V compared to Ge which has the reverse breakdown voltage around 50V.
- Typical values of I_s for silicon diodes are much lower than that of Ge.
- Silicon has better temperature sensitivity than Ge.
- Ge is used for manufacturing photodiodes over Si.

Advantages of Ge.

- Crystal growth possible at lower temperature.
- Substantially higher electron and hole mobility indicating potential for higher speed device.

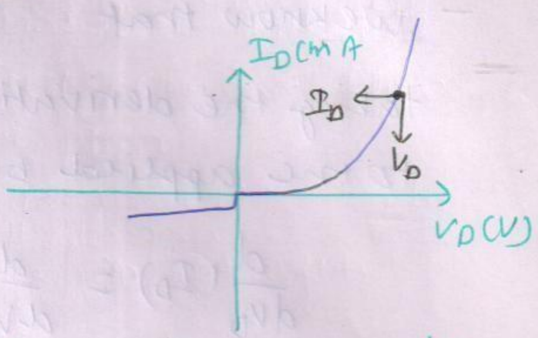
Advantages of Si

- Stable and strong material with same crystal structure as diamond.
- Si has a larger bandgap and thus becomes intrinsic at higher temperature. Bandgap energy for Si $E = 1.1\,eV$ for $Ge = 0.67\,eV$.
- Si is less expensive due to greater abundance of element. The major raw material for Si wafer fabrication is sand and there is lots of (SiO_2) available.

Diode Resistance Levels

- Diode is a nonlinear device. It has three different resistance levels described as follows.

1- DC or Static Resistance

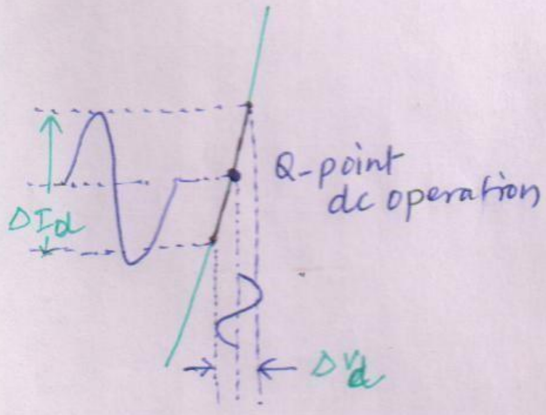


Determining the dc resistance of a Diode at a particular operating point.

- Defined as a point on the characteristics
- The resistance of the diode at the operating point can be found simply by finding the corresponding levels of V_D and I_D as shown in fig.

$$R_D = \frac{V_D}{I_D}$$

2- AC or dynamic Resistance



Defining the dynamic or ac resistance

- Defined by a tangent line at the Q-point.
- In general therefore, the lower the Q-point of operation the higher ac resistance.
- An effort should be made to keep the change in voltage and current as small as possible and equidistant to either side of the Q-point.

In equation form,

$$r_d = \frac{\Delta V_d}{\Delta I_d}$$

where Δ signifies a finite change in the quantity.

Determining the ac resistance at a Q-point.

- The derivative of a function at a point is equal to the slope of the tangent line drawn at that point.
- we know that $I_D = I_S (e^{kV_D/T_K} - 1)$.

taking the derivative of above equation with respect to the applied bias will result in

$$\frac{d}{dV_D}(I_D) = \frac{d}{dV_D}\left[I_S (e^{kV_D/T_K} - 1)\right]$$

$$\frac{dI_D}{dV_D} = \frac{k}{T_K}(I_D + I_S)$$

$$\frac{dI_D}{dV_D} \cong \frac{k}{T_K} I_D \qquad (\text{because } I_D \gg I_S)$$

substituting $\eta = 1$ for Ge and Si

$$k = \frac{11600}{\eta} = 11600 \qquad T_K = T_C + 273^0 = 25^0 + 273^0 = 298^0$$

$$\frac{k}{T_K} = \frac{11600}{298} \cong 38.93$$

$$\frac{dI_D}{dV_D} = 38.93 I_D$$

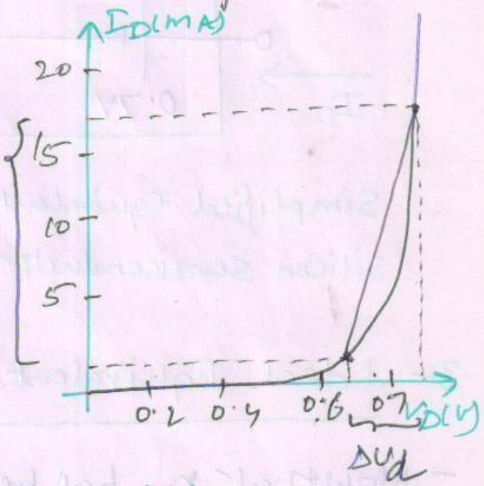
$$\frac{dV_D}{dI_D} \cong \frac{0.026}{I_D}$$

$$\boxed{r_d = \frac{26mV}{I_D}} \text{ Ge, Si}$$

Average AC Resistance

- If the input signal is sufficiently large to produce a broad swing such as indicated in figure, the resistance associated with the device for this region is called the average ac resistance.
- Defined by a straight line between limits of operation.
- In equation form

$$r_{av} = \left.\frac{\Delta V_d}{\Delta I_d}\right|_{pt.\ to\ pt.}$$



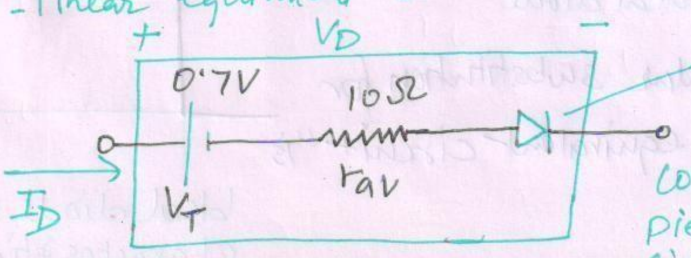
Determining the average ac resistance between indicated limits.

Diode Equivalent Circuits

- An equivalent circuit is a combination of element properly chosen to best represent the actual terminal characteristics of a device, system, or such in a particular operating region.

Piecewise-Linear Equivalent Circuit

- One technique for obtaining an equivalent circuit for a diode is to approximate the characteristics of the device by straight line segment as shown in figure.
- The resulting equivalent circuit is naturally called the piecewise-linear equivalent circuit.

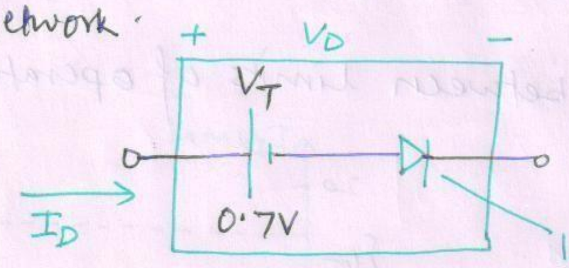


Ideal diode.

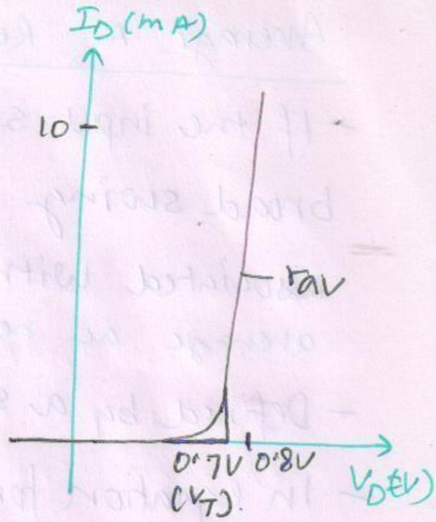
Components of the piecewise-linear equivalent circuit.

2- Simplified Equivalent Circuit

- For most applications, the resistance r_{av} is sufficiently small to be ignored in comparison to the other element of the network.



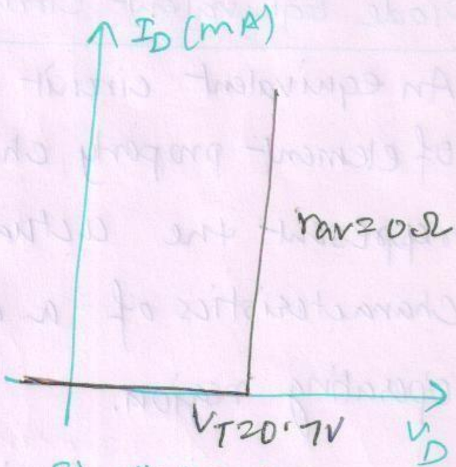
Simplified equivalent circuit for the silicon semiconductor diode.



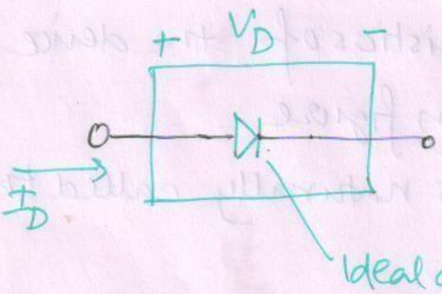
Defining the piecewise linear equivalent circuit using straight-line segments to approximate the characteristic curve.

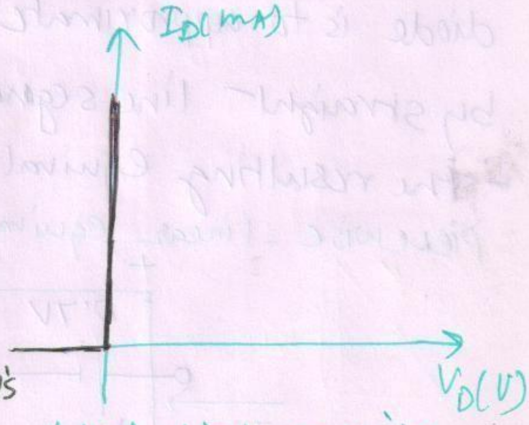
3- Ideal Equivalent Circuit

- Now that r_{av} has been removed from the equivalent circuit let us take it a step further and established that a 0.7V level can often be ignored in comparison to the applied voltage level.



Simplied equivalent circuit for the silicon semiconductor Diode.





Ideal diode and its Characteristics.

- In industry a popular substitution for the phrase "diode equivalent circuit" is diode model.