Mechatronics
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Lecture - 04
Semiconductor Electronics

Welcome you all in this NPTEL online certification course on Mechatronics. Today, we are going to discuss some basic concepts about the Semiconductor Electronics because the various mechatronics component is specifically the controllers are composed of so many semi conductor electronics that is transistor, IC's and so on.

So, emphasis of my today's lecture is to go through some basics of semiconductor electronics so that when we come across these mechatronic devices or mechatronics components, we are able to correlate the things.

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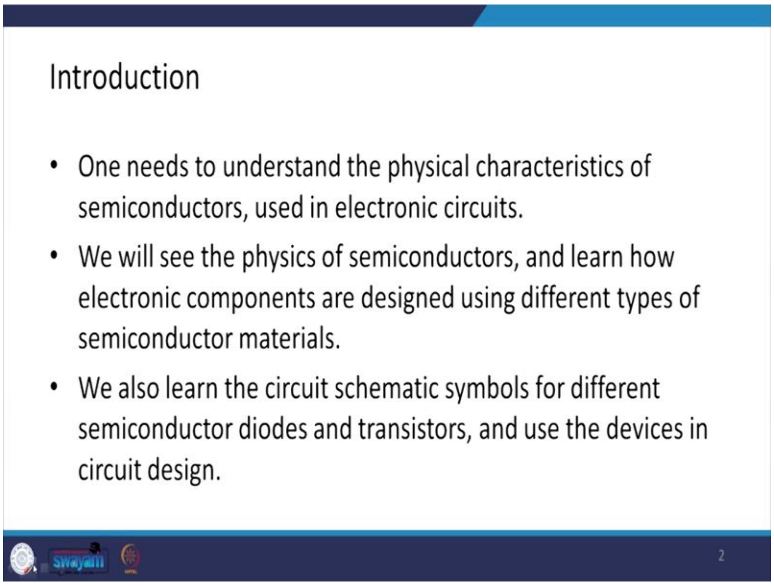

So, as I said one need to understand the physical characteristic of semiconductor which are used in an electronic circuit. We will see the physics of semiconductor and learn how electronics component are designed by using different type of semiconductor materials. We will also learn the circuit schematic symbol for different semiconductor diode and transistor that are used in the circuit design.

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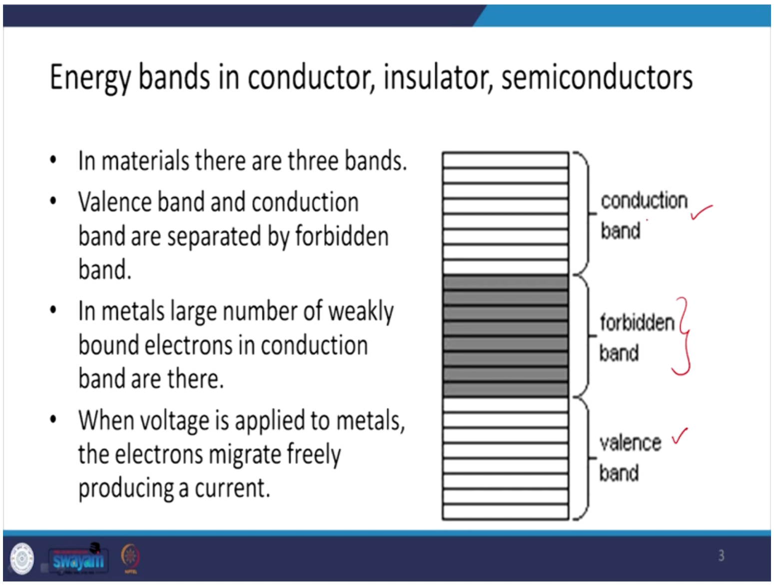

So, first of all, let us begin with the concept of energy bands in conductor, insulator and semiconductors. So, we can see that in any material essentially there are three bands; one is the conduction band and then we have the valence band and these two bands are separated by the forbidden band. It is the conduction band which is responsible for the conduction of the current basically.

And here, if we are talking about say metals, in metals there are very large number of weakly bound electrons in the conduction band and when a voltage is applied to metals, these weakly bound electrons migrate freely and they produce the current. So, we can understand the difference between conductor, insulator and semiconductor with the help of these two bands that is the conduction and valence band and the segregation between these two bands.

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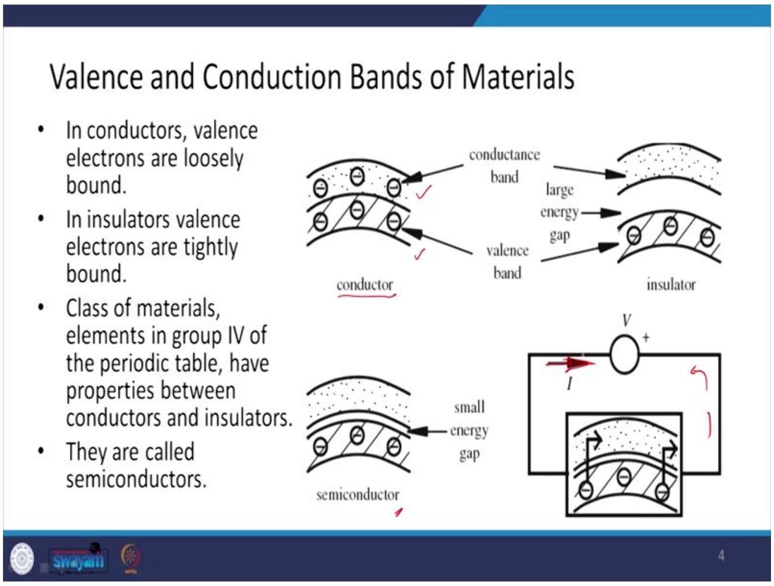

So, let us look at here some of the figures. Say for conductor, we can see that we have a valence band and we have a conduction band. In the conduction band, we have much number of free electrons are there and the segregation between the conduction band and the valence band or that is the energy gap which we call the forbidden energy gap. This forbidden band is very small or insignificant.

If we talk about insulator, then we can see that in insulator, there are very few electrons in the conduction band. There are few almost there are no electrons in conduction band in insulator and there are few electrons in the valence band and there is a very large energy gap between the conduction and valence band that is if an electron has to move from valence band to conduction band very large amount of voltage is required.

So, there is a very large energy gap. So, there are materials which are in between the conductor and insulator and that is what we call it as the semiconductor materials. Now, in case of semiconductor materials, there is a small energy gap between the conduction and the valence band.

And this figure illustrate you when a voltage is applied, these electrons basically move through the positive side of the voltage supply and they move in this direction and so, our conventional current direction is the opposite to that of the electron motion direction and we see the current being moving in this direction.

So, as I was telling you about semiconductor, basically these are actually the class of elements in group IV of the periodic table which have properties between conductor and insulator and as I said, their properties is between conductor and insulator, they are called semiconductor. So, ideally you can identify them with a very small energy gap.

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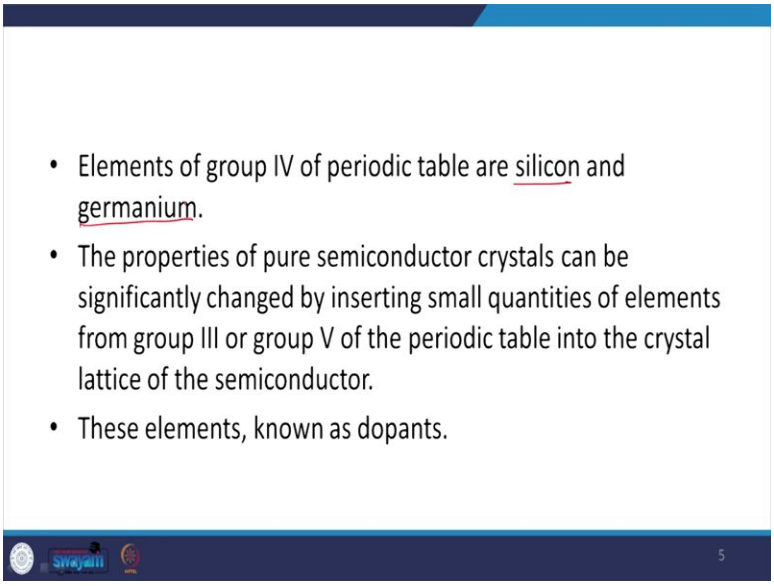

So, what happens if we look at the elements in group IV of the periodic table? Say we have silicon and germanium and the properties of pure semiconductor crystal can be significantly changed by inserting a small quantities of elements from either the higher group or say group V or the lower group say group III of the periodic table into the crystal lattice of the semiconductor. And this process is what we call it as the doping and these elements are basically called the dopants.

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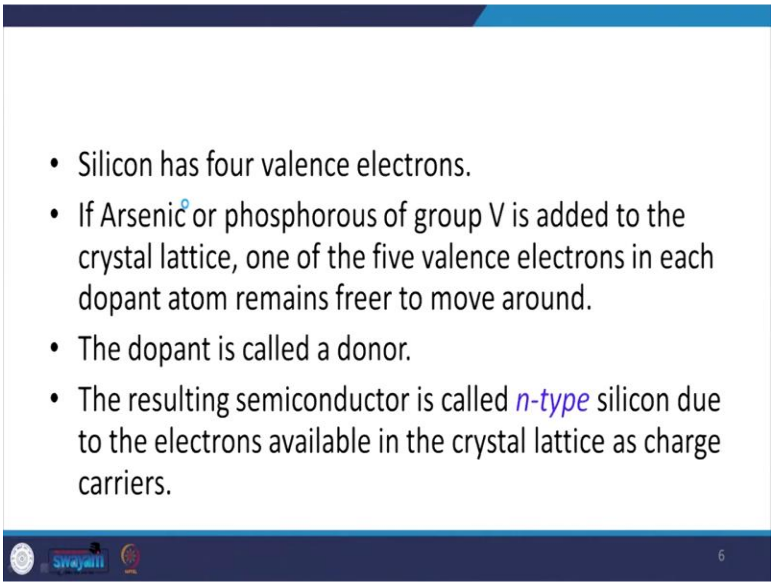

So, as I was telling you the silicon has got four valence electrons. So, if arsenic or phosphorus of say group V is added into the crystal lattice, then what happens? One of the five valence electron, we know eight electrons are required for the to get it as a saturated state.

So, after eight electron, if silicon has got the four valence electrons so, if we are aiding arsenic or phosphorous which has five electrons; so, totally we will be having nine electrons. So, the eight electrons will be making it ideal basically. So, the one additional electron which will be there that will be the free electron and that remains freer to move around and the dopant is called what we know as the donor.

And since, here electrons we have one additional electrons or one free electron rather, the resulting semiconductor is called a n-type silicon due to the availability of the electron in the crystal lattice as a charge carrier.

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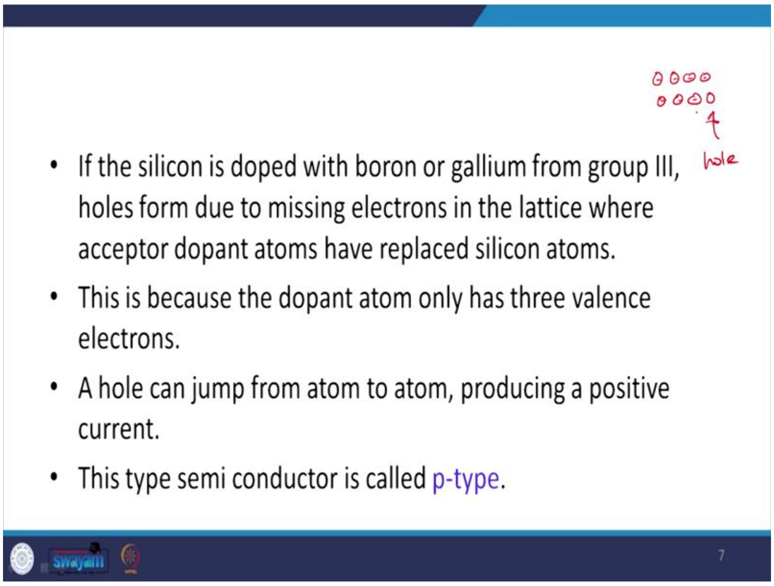

Now, if the silicon is doped with boron or gallium say from the group III, then holes form due to the missing electrons in the lattice where acceptor dopants atoms have replaced the silicon atom. Now, this is because the dopant atom only has got the three valence electrons.

So, basically what you will be having is that you will be having say here 1, 2, 3, 4 say 5, 6, 7, 8 so, you have the total 7 electrons and there is a hole. So, there is a hole which is being created if I am putting an element that is either boron or gallium from group III with the silicon. Now, this hole can jump from atom to atom and this produce a positive current and this type of semiconductor is called a p-type semiconductor.

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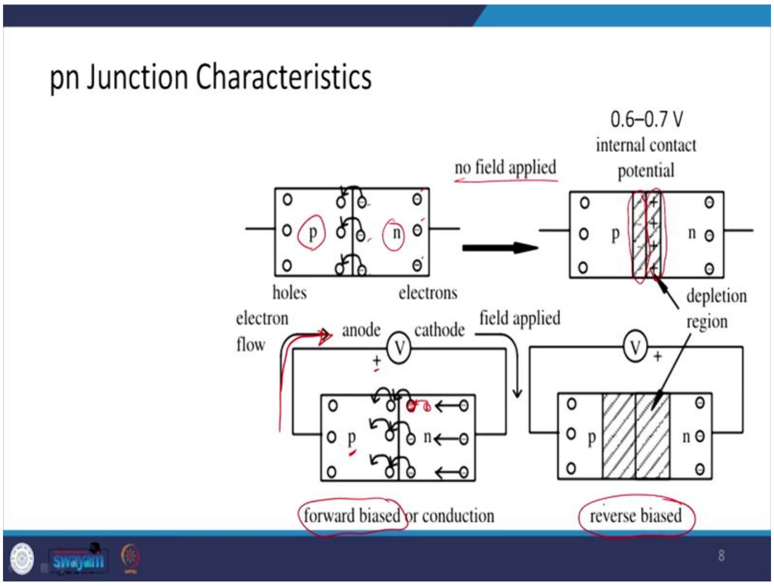

So, let us look at the pn junction characteristic, pn junction means what we are doing essentially is that a p-type semiconductor and a n-type semiconductor we are putting together. So, we have the p-type semiconductor, we have the n-type semiconductor. In n-type semiconductor, we have free electrons which are readily available to move, whereas in p-type semiconductor, we have the holes which are readily available to move.

So, if there is no field applied across the two terminal of say this pn junction, then what happens? Some of the electron jump from n side to the p side as you can see here; similarly, some of the holes jump from p side to n side as you can see over here and there is a internal contact potential which is around 0.6 to 0.7 volt that is formed.

Now, what happens if I apply a voltage across the two terminal of this pn junction? So, suppose I apply a voltage here across the pn junction, that my positive side of the source or anode is connected to the here p-type material and similarly, cathode is connected to the n side here. Then what happens basically, this negative side will be in contact with the n side here, so these charges will be repelled.

Similarly, the holes (the positive side) being in contact with the holes over here there will be motion of the holes in this direction or the motion of the electrons in the opposite direction and we will be having a flow of electrons or what we can say is that the flow of current.

So, here we can see that a electron is moving to this side. So, again here a hole will be created, this hole space will be again taken by an electron from here and so on. So, effectively our electron will be flowing in this direction and of course, your current direction will be the opposite one. So, this case where we can see that there is flow of current across this pn junction is what we call it as the forward biased.

And similarly, if we apply now the voltage across these two terminals in a opposite way that is the positive side is connected to the n-type of material and negative side connected to the p-type of material, then what happens? These charge will be attracted towards the anode. The depletion region here and will be increasing further prohibiting any motion of the electrons across the junction and this is what is called as the reverse bias.

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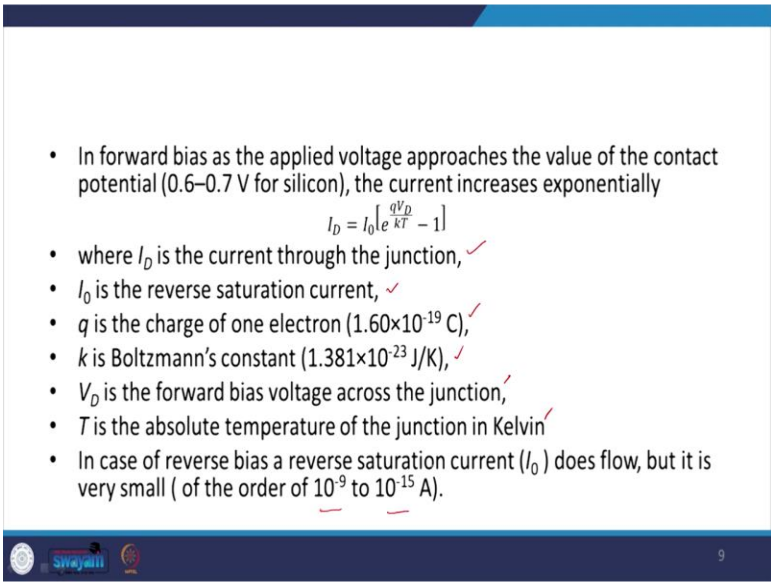

So, in forward bias as the applied voltage approaches the value of the contact potential say 0.6 to 0.7 volt for silicon, the current increases exponentially and this current is given by,

$$I_o[e^{\frac{qV_D}{kT}} -]$$

where I_D is the current through the junction, I_0 is the reverse saturation current, q is the charge of one electron that is $1.60 \times 10^{-19}\ C$ and k is the Boltzmann's constant that is $1.381 \times 10^{-23}\ J/K$ and V_D here is the forward bias voltage across the junction and T is the absolute temperature of the junction in Kelvin.

Now, in case of the reverse bias, the reverse saturation current I_0 does flow, but this current is very small of the order of 10^{-9} to 10^{-15}. So, that is why we assume that the current flow across the junction in case of reverse bias is almost 0.

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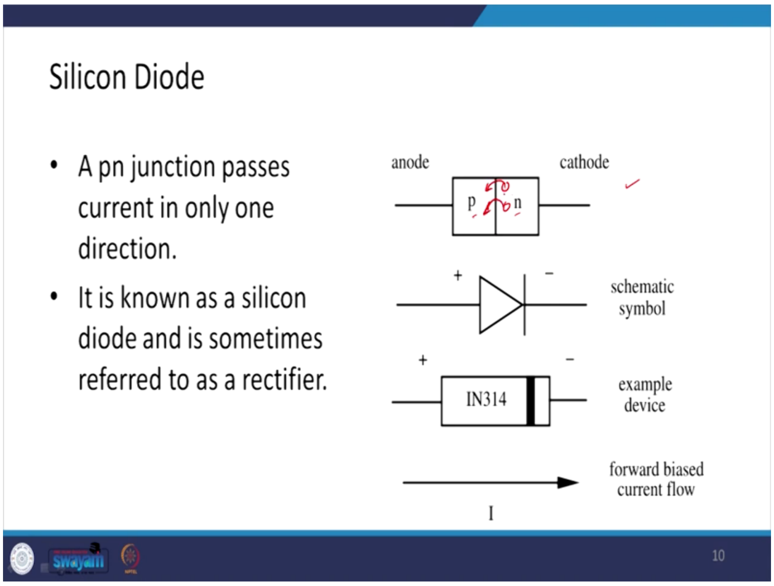

Now, here what we have seen that when the pn junction is forward biased, we get the current through it and when the it is reverse biased, there is no current; so, basically it passes current only in one direction that is the case when it is forward bias. So, silicon diode is that is why sometimes it referred as rectifier because it passes current only in one direction.

So, this is how we represent it. That is you have a pn junction over here and there is a symbolic representation for it here and this positive and negative is shown. And this is the example device say IN314, is a diode and the direction of the current or forward bias current flow direction that is the opposite to the direction of motion of the electron which we consider because we have seen that we assume the electrons flow in this direction.

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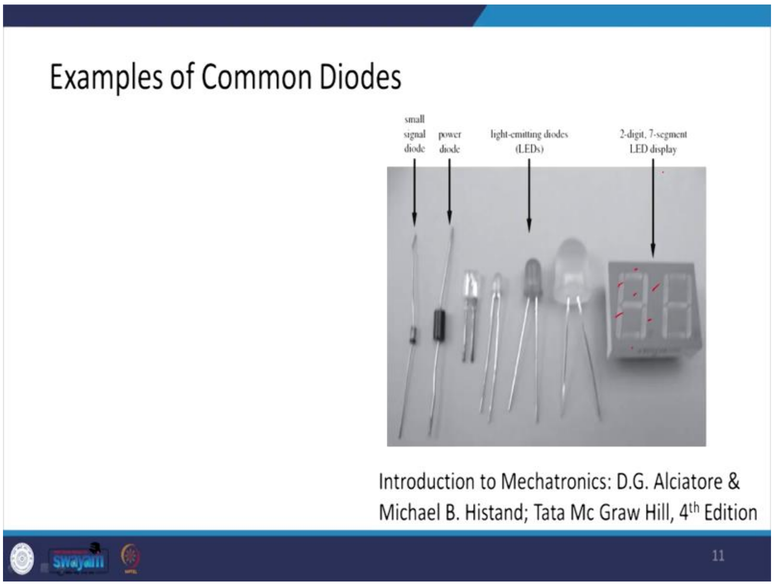

This figure shows basically some of the commercially available common diode. So, you can see small signal diode, power diodes are there, then LEDs or Light Emitting Diodes are there and 2-digits or 7-segment LED displays are there. So, you can see that there are 7-segments here 1, 2, 3, 4, 5, 6 and 7. So, these are what we call 2-digit 7-segment display because we can display the 2-digits with the help of 7-segment.

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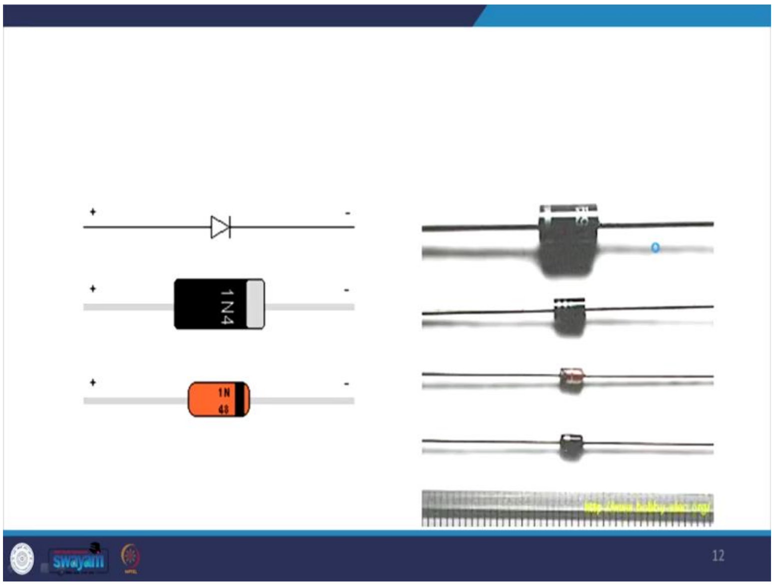

Again, this figure shows you some of the commercially available diodes.

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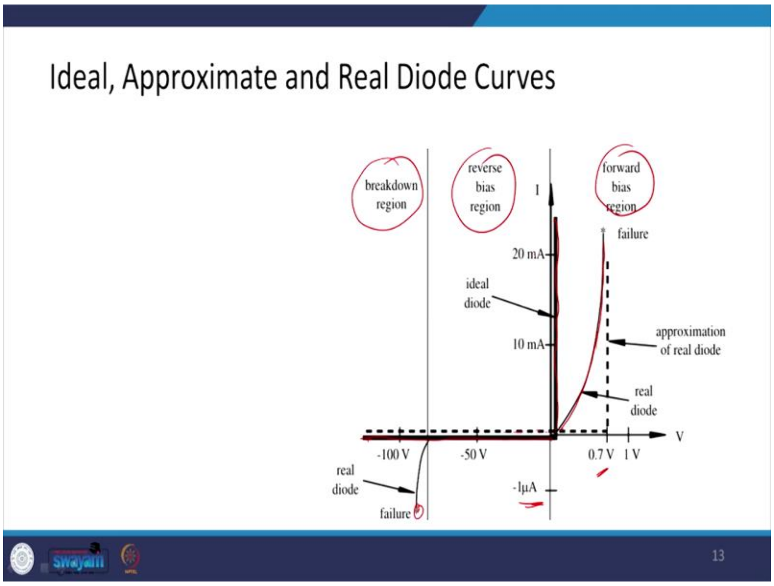

Now, I just discussed in the previous slide that there is a current flow if it is forward bias and there is no current flow if it is reverse bias. So, if we plot the voltage and current characteristic curve for the diode, then you can see that this is how it looks like.

So, ideally what happens that; with a small voltage in the forward bias, you are going to get a very large current as you can see here; whereas, in the reverse bias as you keep on increasing the voltage; but your current is not going to change.

Now, the real diode curve is something like this, there is a exponential growth basically, exponential growth in the current value in the forward bias region and that gets a peak basically for silicon diode around 0.7 volt; and approximation of the real diode can be done with the help of dashed line as it is shown here. So, this is the behavior in the forward bias region.

Now, in reverse bias region what happens, if you keep on increasing the voltage, initially there will not be a current, but in the break down reason you are going to have at a high voltage, you are going to have increase in the current value and ultimately it leads to the failure over here.

And this steep increase is basically increase in current as almost constant voltage is helpful in designing the voltage regulator what we call it as, rather the Zener diode which I will be discussing in the coming slides.

So, we have the forward bias region, this is the behavior, and this is the reverse bias region and this what we call it as the breakdown region because here, the failure takes place. And you can see that here the current magnitude is in the micro range basically micro ampere whereas, when it is forward bias, we have it is in the milli ampere range.

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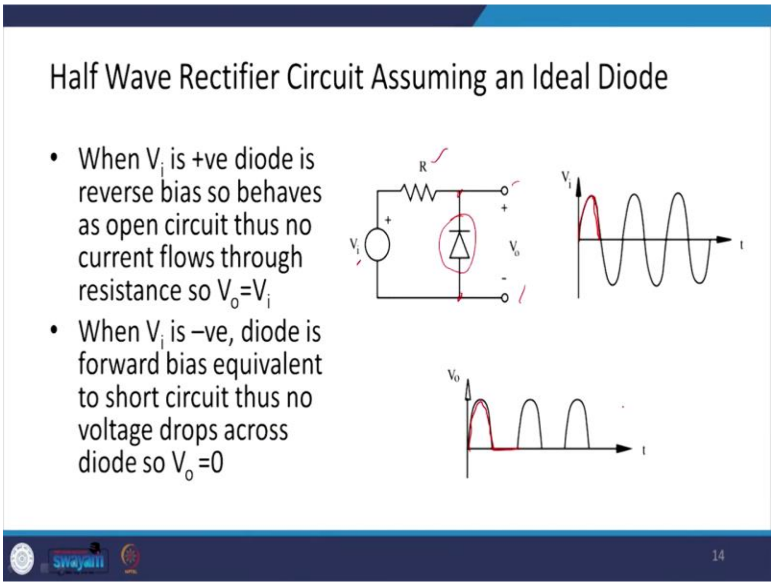

Now, this characteristic of the diode that it allows current only in one direction can be used for the rectification purpose. So, here, suppose I have got a voltage source V_i and this voltage is a varying say and let there is a circuit where we have a resistor and I am a putting diode over here and from this diode, I am typing the output voltage.

So, over here there is a sinusoidal input, so you can see that sinusoidal input that is the voltage goes or input voltage is both in the positive side as well as in the negative side and we want to rectify it also that is we want it only in the positive side.

So, here what happens? You can see that when V_i is positive and this is the negative side of the diode so, what happens? This becomes the reverse bias. Thus, diodes gets a reverse bias; now, in reverse bias, there is no current flow so, when there is no current flow from that diode, then what happens? Whatever V_i is there, the same V_0 is available across the terminal. So, this input is whatever is there, we have the output over here.

And in next half of the cycle, this becomes negative and this of course is negative so, this diode becomes the forward bias and in case of forward bias, there is flow of current so, there is no voltage drop across this one; so, we have the voltage 0 here across the terminal. So, this is how the we get the voltage rectified.

So, I repeat again when V_i is negative, diode is forward bias and we have an equivalent to a short circuit thus no voltage drop across diode so, we get the 0 voltage and this cycle repeated.

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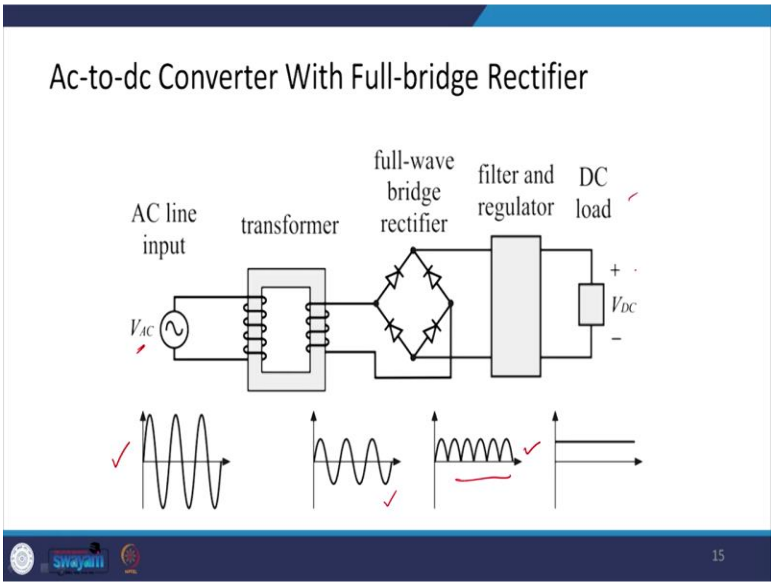

Now, we can use the same diode circuit in a bridge fashion to rectify it, or what we call it rather a full bridge rectifier. So, I have AC line input say V_{AC} is there, this is the nature of the input supply, I have a transformer which say step down transformer here, so the voltage is reduced with the help of transformer.

Now, this secondary winding of the transformer is connected through diode and this diode rectifies it and then, there are filters and regulators and these filter and regulator gives us the constant voltage that is the constant voltage which can be obtained across the DC load.

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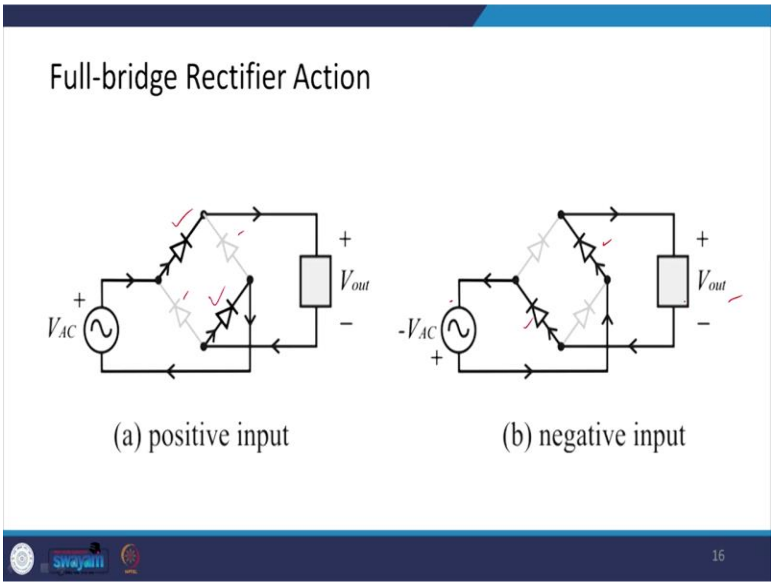

Now, how does this work basically? It is simple. So, if there is a positive input basically, so this is positive side; So, what happens? Positive side being connected to the positive side, so this is being forward bias. So, your current will be passing from here and similarly, this is positive side connected to the positive side so, forward bias.

So, these two electrons basically work in the forward bias whereas, you can see that this positive side being connected to the negative side this makes the diode in the reverse bias. So, this way these two diodes are in the forward bias mode. Similarly, current flows and we can get the voltage across the load here. Similarly, if negative voltage is here, then these two diodes are in the forward bias. So, current flows through them and we get the output voltage here.

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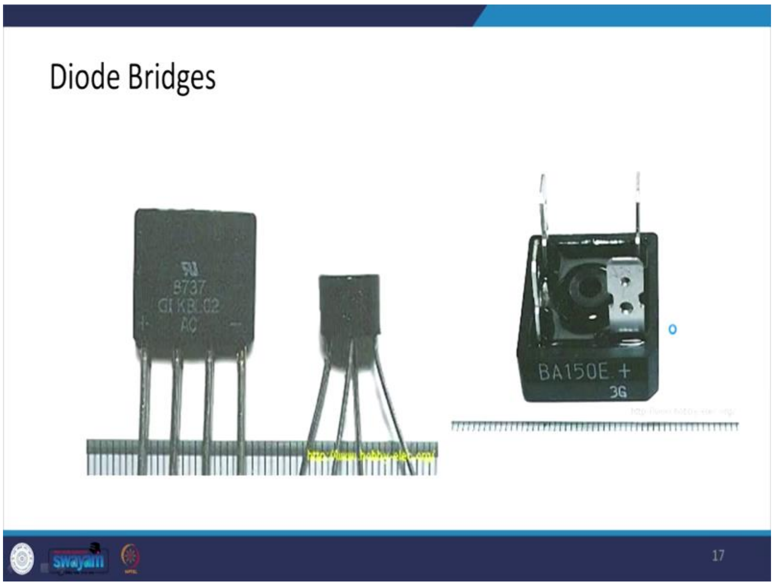

So, here are the diode bridges which are commercially available in the market.

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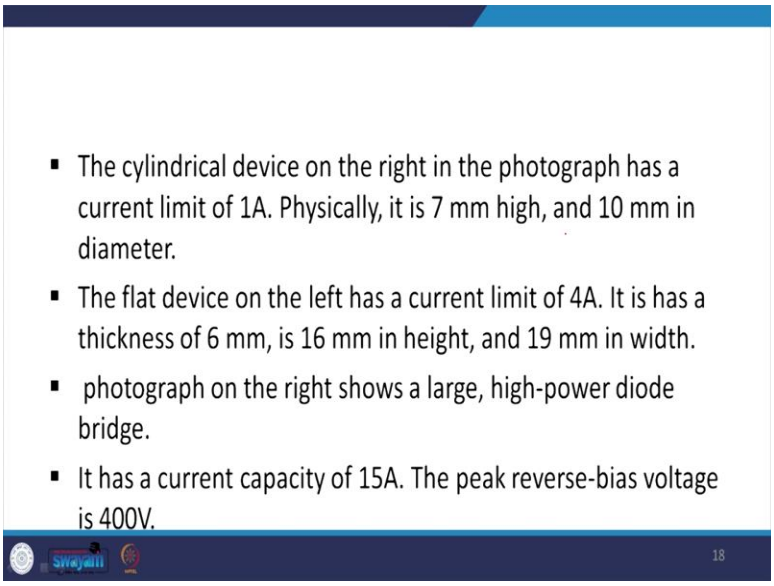

The cylindrical device on the right in the photograph as a current limit of 1 ampere. Physical, it is 7 millimeter high and 10 millimeter in diameter. The flat device on the left has a current limit of 4 ampere. It is it has a thickness of 6 millimeter and 16 millimeter height and 19 mm width and on the right there is a large high-power diode bridge which has current capacity of 15 ampere and peak reverse-bias voltage of 400 volts. So, these are the commercially available.

Now, let us exploit the characteristic of the diode in the reverse bias. In case of reverse bias, if we keep on increasing the voltage, so when the voltage is very high, there is some current which we are getting and this characteristic is used as the voltage regulator.

So, most diode breakdown voltage is around 15 volt and these have steep breakdown curve as I said with well-defined breakdown voltage, and thus they maintain nearly constant voltage over a wide range of current. They are good voltage regulator and this property used in the zener diode circuit, the zener should be reversed bias with value kept in excess of its breakdown or zener voltage.

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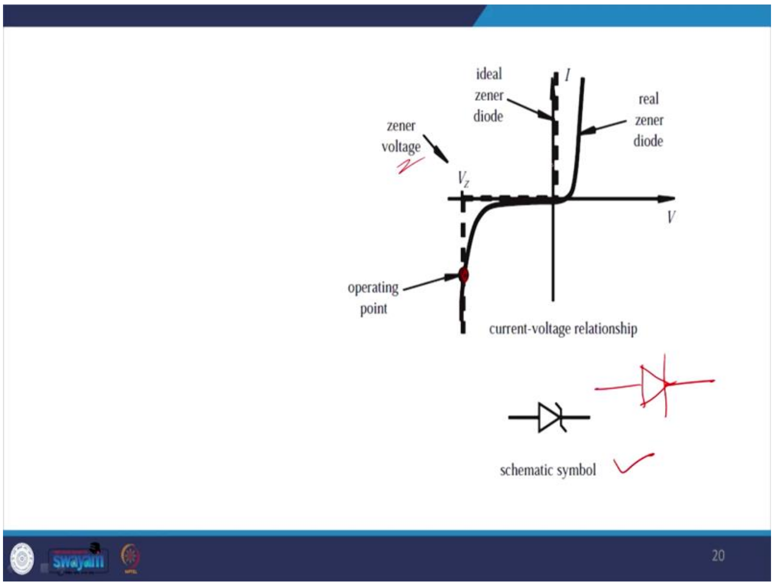

So, here we can see the schematic symbol of the zener diode, here you can see the difference whereas, for the normal diode, the symbol is this one. But in case of zener one, we have a different symbol and this is the V-I characteristic of it and here we are interested the zener being reverse bias. Here you can see that the voltage where we get current is called a zener voltage and this is the operating point around which we want to operate this.

Here, dash line shows ideal zener diode characteristic in the forward and reverse bias.

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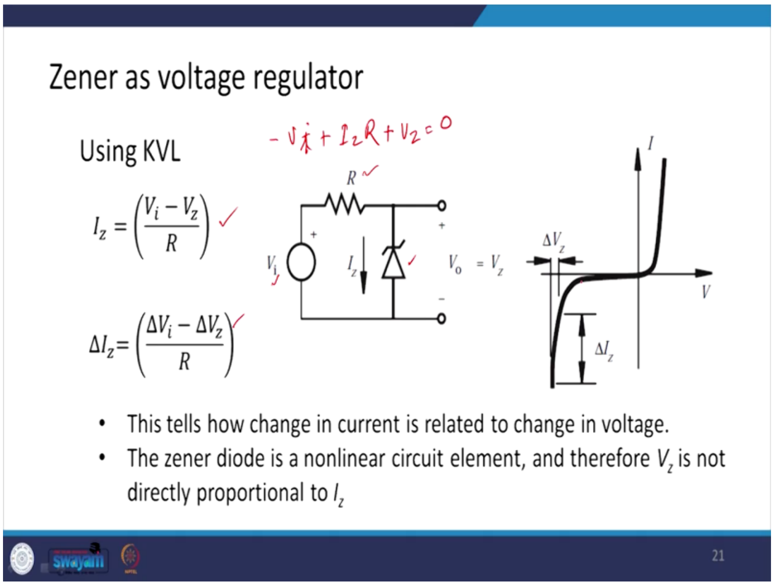

So, if we see zener as a voltage regulator, then the circuit with a voltage V_i, there is a resistor R and here is a zener diode and I am interested in using this zener diode as a voltage regulator, basically that is the one which gives me a constant voltage.

So, if I analyze this circuit say, if I apply the Kirchhoff's voltage law, then

$$-V_i + I_z R + V_z = 0$$

So, I get

$$I_z = \left(\frac{V_i - V_z}{R}\right)$$

So, change in the this zener current basically will be,

$$\Delta I_z = \left(\frac{\Delta V_i - \Delta V_z}{R}\right)$$

So, here, we can see that there is a non-linear relationship basically.

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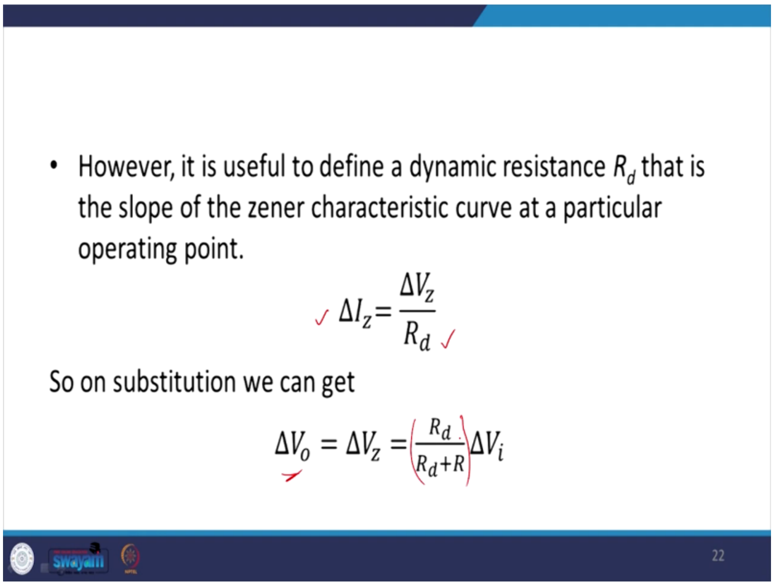

So, to take care of that what we do is, we define a dynamic resistance R_d and we define it like this,

$$\Delta I_z = \frac{\Delta V_z}{R_d}$$

And if I substitute back this equation in the previous one, the output will be,

$$\Delta V_0 = \Delta V_z = \left(\frac{R_d}{R+R_d}\right) \Delta V_i$$

So we get the constant voltage source.

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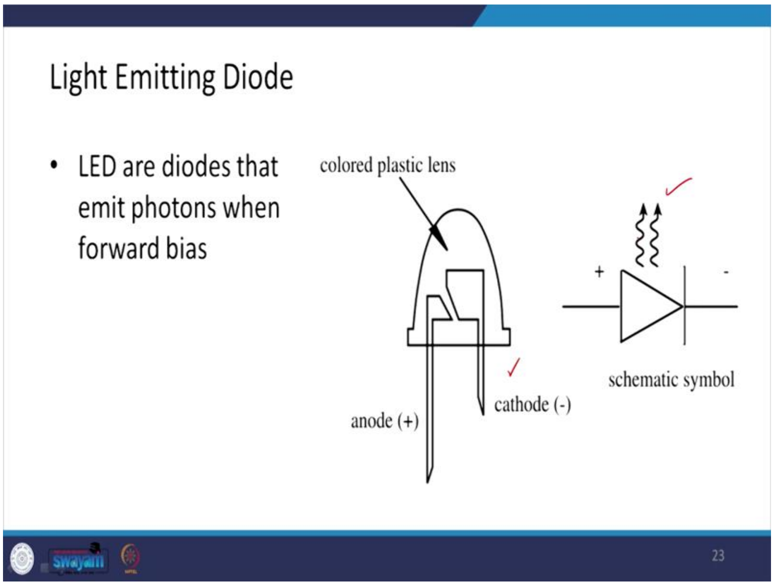

Then, there are a light emitting diodes basically these are the diode that emits photons when forward bias. So, this is the schematic representation for LED. So, photons being emitted when this is forward bias.

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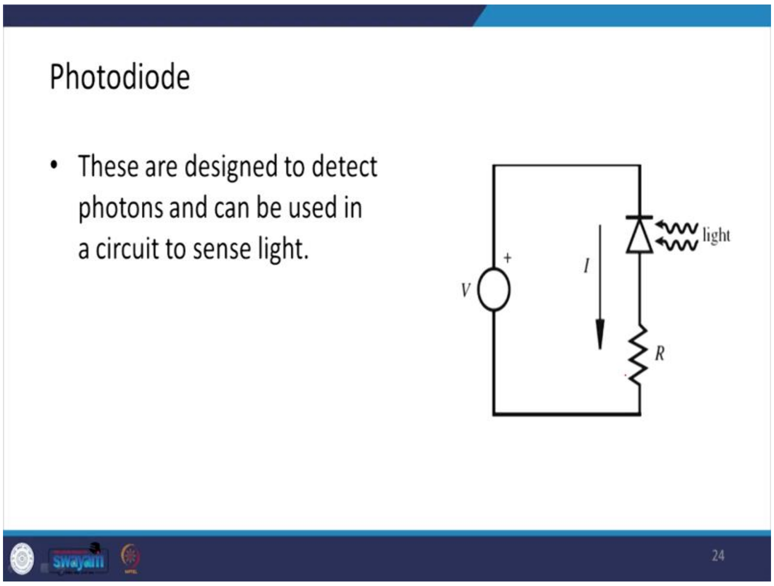

And similarly, there are photodiodes which works in the reverse wave, basically that is if light falls on them a current is produced. So, these are designed to detect the photons and can be used in a circuit to sense the light. So, photodiodes can basically work as a light sensor.

Next, coming next few minutes, I will spend in discussing about a very important component semiconductor device called transistor which has revolutionized the electronics industry basically.

So, there are two types of transistor (a) bipolar junction transistor and, (b) field effect transistors. So, in short, they are called BJT's and FET's.

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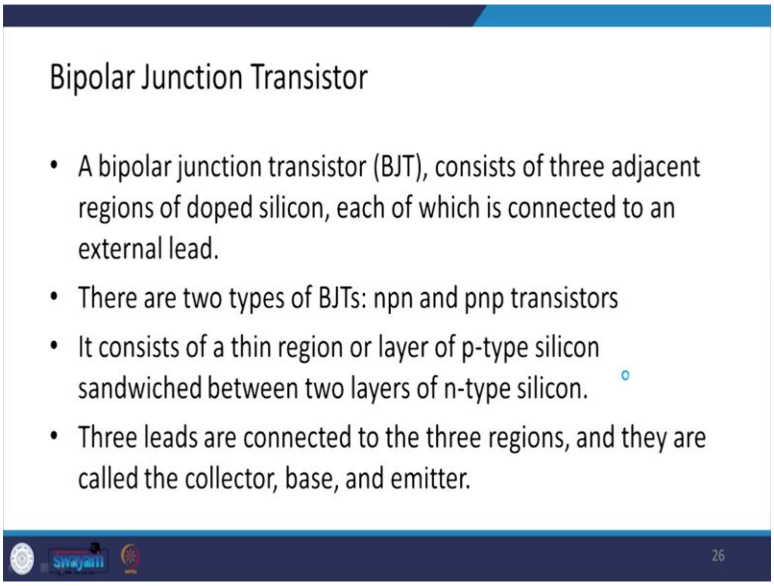

So, the bipolar junction transistor basically consists of three adjacent diode, earlier we had that two adjacent region; one was p-type material and another was n-type material and here, we have the three adjacent regions of dope silicon each of which is connected to an external load.

There are two types of BJT's that is either npn or pnp's. It is based on how we are breezing three regions basically. So, it consists of a thin region or layer of p-type silicon sandwich between the two layer of n-type silicon and three leads are connected to the three regions and they are called collector, base and emitter.

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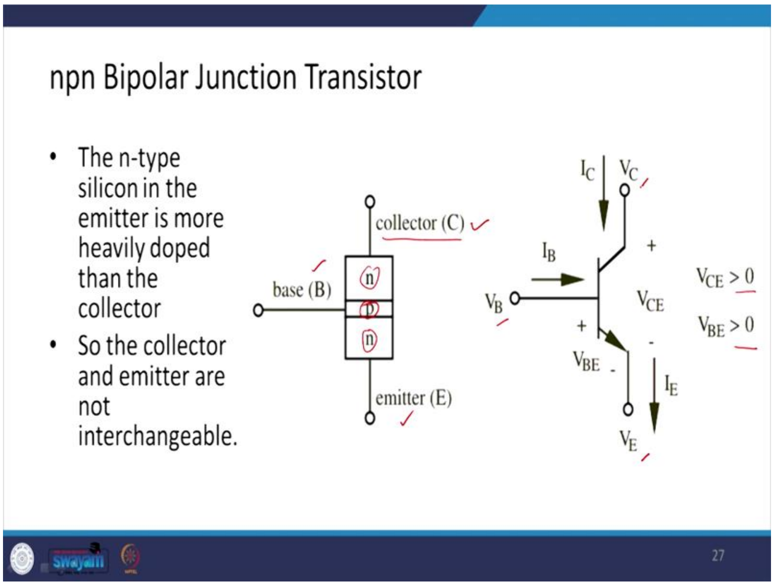

So, this figure you can see that it is a npn transistor basically. So, It is the p-type silicon, we have n-type silicon and n type silicon there. So, the one n terminal is connected here which is called collector, one center one is called base and here this is called emitter.

So, the n-type silicon in the emitter is more heavily doped than the collector. Here as you can see in this figure, basically is we cannot interchange that we cannot make emitter as the collector and the collector as the emitter, because their are doping is different. So, these emitter and collector are not interchangeable.

Here, is the representation for this npn transistor. So, we can see that the base voltage V_B, emitter voltage V_E and collector voltage V_C are shown here. So, it is shown the direction of current through base, through collector and through emitter. It is a summation of base and collector current is there and we can see that the $V_{CE} > 0$ and $V_{BE} > 0$.

So, V_{CE} is basically voltage between the collector and emitter and V_{BE} is the voltage between the base and emitter.

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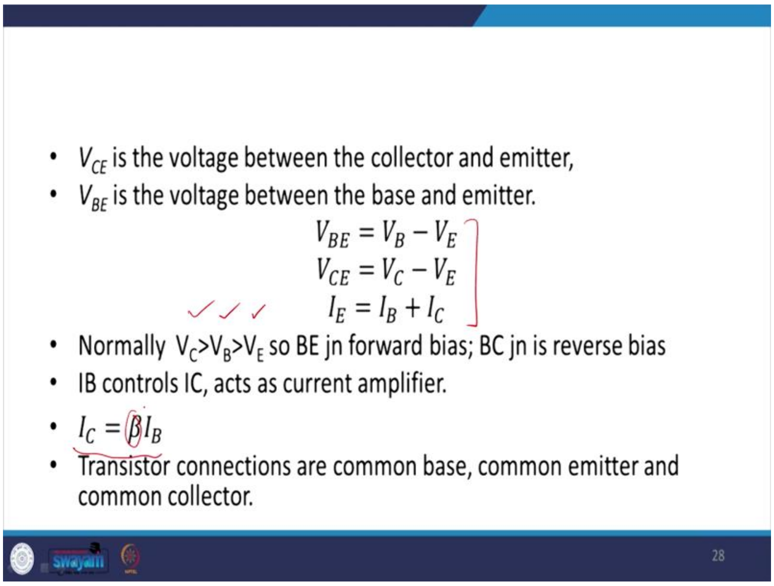

So, these are the basically how they are defined,

$$V_{BE} = V_B - V_E,$$

$$V_{CE} = V_C - V_E,$$

$$I_E = I_B + I_C$$

Normally, $V_C > V_{CB} > V_E$, we can see that BE junction is forward bias and BC junction is reverse bias.

And IB controls that is the base current controls the collector current and it acts as a current amplifier. So, this amplification is,

$$I_C = \beta I_B$$

So, the transistor connection are of various types say common base, common emitter and common collector connections.

So, in my coming lectures, we will be you seeing how these transistors can be used for the different purpose and most importantly is the transistor as a switch. So, that we will be seeing in our next lecture.

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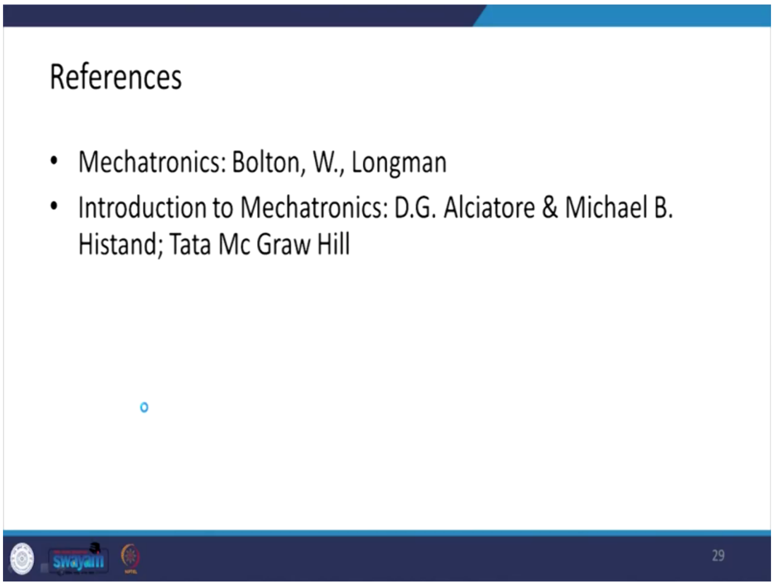

So, these are the references. Most of the material for this lecture has been taken from very good book, Introduction to Mechatronics by Alciatore and Histand. So, if you are interested in further reading, please do refer it.

Thank you.