Electronics for Analog Signal Processing - I
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Lecture # 11
Varactor Diode

Today, it is going to be the last on the series on diodes. Let us therefore sort of discuss what is left on topic connected with diodes and also summarize the whole thing. We will also try to understand some special diodes which has specific application, just like Zener diode for example. Consider the PN junction; this is the semiconductor diode I have told you earlier.

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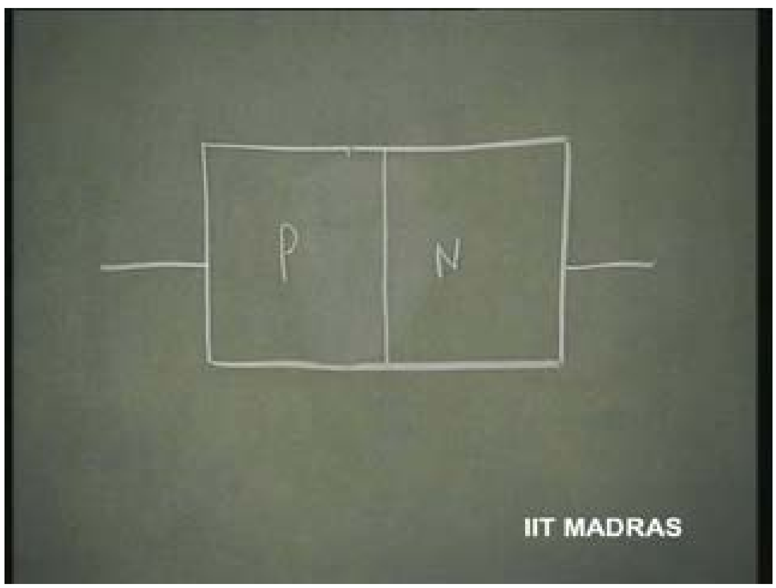

By formulating a PN junction like this, we are able to get the I V characteristics that is pretty close to the ideal diode; I V characteristic being the exponentially related characteristic between current and voltage. Now, apart from that, we would like to see what other terminal characteristics the diode represents. When it is a PN junction like this, at the junction, we have a region depleted of carriers, free carriers. This region is called depletion region.

The P side comprises of free carriers which are called holes; N side comprises of free carriers which are called electrons. Since they are free carriers, the moment they are brought together, a junction is formulated. They have a tendency to merge one another; hole has a tendency to merge with the electron and vanish. Then, this region at the junction becomes free of carriers. Thereby, it develops a potential hill; this is called the junction potential, V junction. And this V junction, according to the semiconductor theory, for silicon, happens to be around point 5 to point 7 volts.

That is why the semiconductor diode was not exactly close to ideal diode. There is a deviation from it. It starts conducting only when a junction potential of about point 5 to point 7 volts is applied, the current is unlimited. Until that time, current is negligible.

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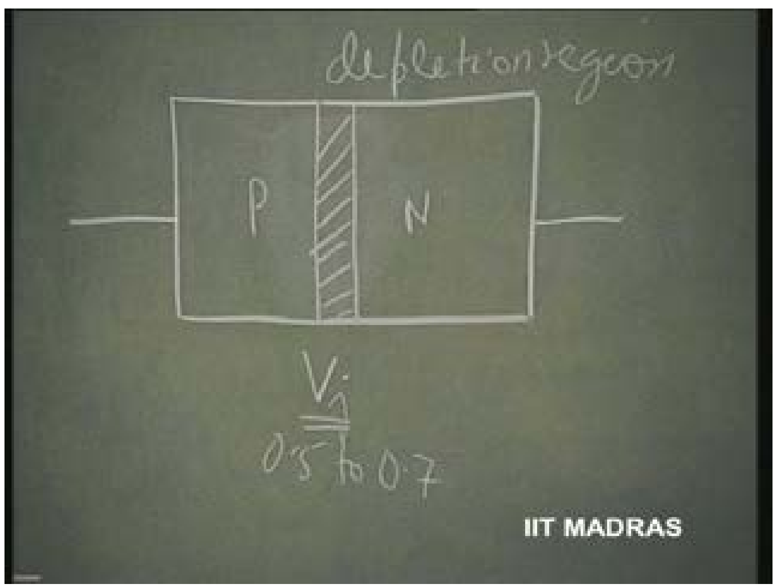

So, this region, where it is depleted of carriers, is called depletion region. So, every PN junction has a depletion region in between; and this depletion region width is dependent upon the voltage. When the junction gets forward biased, the barrier, the potential hill for these carriers decreases; so there is copious amount of free carriers moving from this to, holes from, moving from this to this, and electrons from this to this. And that constitutes a current; large current can flow. Whereas, when it is reverse biased; there is this, potential hill increasing; the reverse bias will help this potential hill to get increased. That means, more area in this gets depleted of carriers and this region widens. So, this depletion layer width is dependent upon the bias. When it is forward biased, the depletion layer width decreases enormously; and junction width decreases enormously; and this, when it is reverse biased, increases.

Now, since it is a depletion region depleted of all carriers, we can consider this region as equivalent to two parallel plates within which we have sandwiched an insulator. No carriers exist; so, it is an insulator. So, it is equivalent to a capacitance. When it is reverse biased particularly, we know that current is not flowing at all. That means, the reverse resistance is very nearly infinity; but it can be now equated to a capacitance; not just an open circuit, but capacitance here. Therefore, we can always say that a junction diode under reverse bias condition apart from being considered ((DC wise - Refer Slide Time: 6:40)) carrying only the reverse current can be also constituted to a capacitance, which is dependent upon this.

So if the depletion layer width is, let us say d, then, the capacitance is epsilon; epsilon corresponds to that of silicon, divided by d into area; the normal way capacitance is defined.

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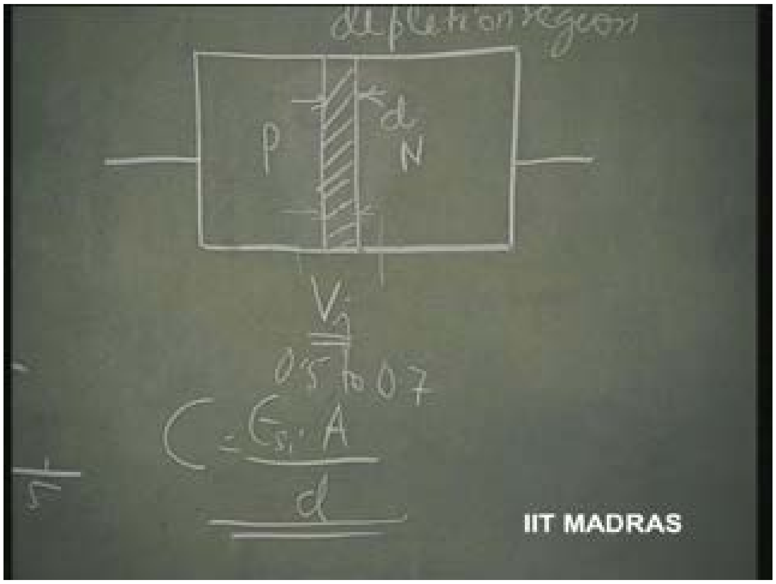

Parallel plate capacitance is nothing but the distance between the parallel plates which is d, coming in the denominator, epsilon, into Area of the capacitance plates. So, this constitutes the effective junction capacitance and this depletion layer width is dependent upon the reverse bias voltage that we apply; and therefore, if we apply a reverse bias voltage which is very large, depletion layer width increases, and therefore, the capacitance decreases.

So, this kind of property of the junction, if it is exploited, then, that particular diode becomes a special diode. We can say it is a diode specially used for its capacitance and the capacitance is now going to be dependent upon the reverse bias voltage. As the reverse bias voltage magnitude, let us say, increases, I am now having the circuit here.

This is our usual diode symbol, diode symbol; and I have just put a resistance here saying that it is a network. This resistance is not going to matter now because, no current is going to flow through this, because, it is reverse biased. So, according to us, the current through this is zero or it is equal to the reverse saturation current; very small.

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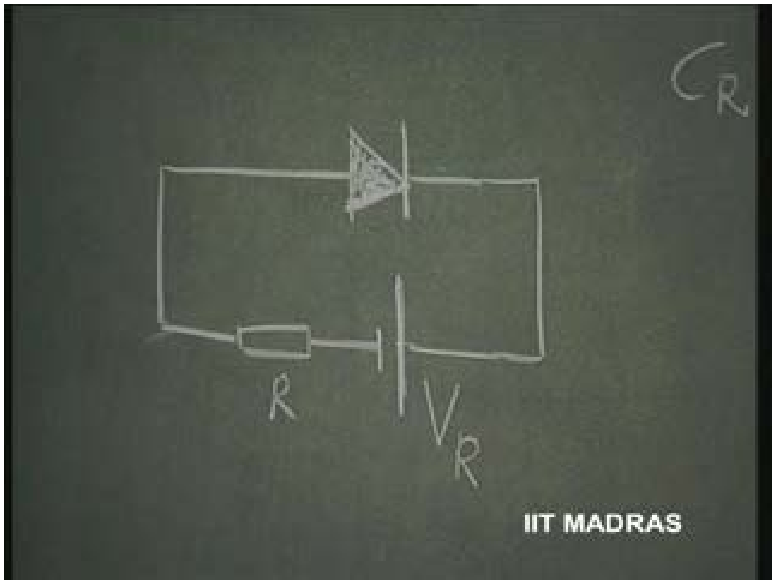

But therefore, the voltage across this is going to very near the voltage that I have applied; so, the magnitude of that voltage is going to determine the value of the capacitance. As the magnitude of the voltage increases, the capacitance decreases. This kind of nature, this capacitance, is of the order of picofarads. So, this diode therefore is called varicap or varactor diode; varicap - variable capacitance; so, either you call it varicap - variable capacitance or varactor diode.

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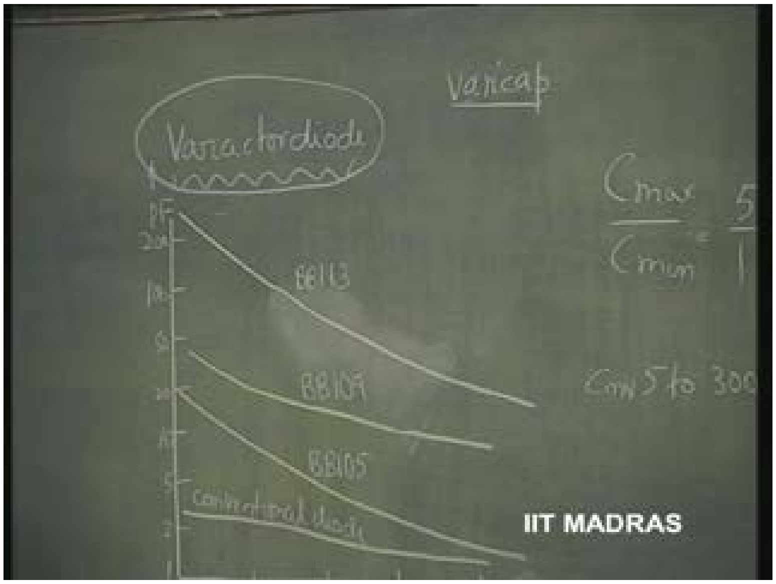

So, I have now given you the typical characteristic of commercially available varactor diodes; three of them, compared with conventional diode, whose variation from maximum to minimum is not going to be significant, because it has not been manufactured for the purpose of using it for its variable capacitance; whereas, these have been specially taken care to see that the capacitance variation is maximum for the voltage that is changing from, may be, zero to 25 volts; typical change in bias voltage of this variable capacitance.

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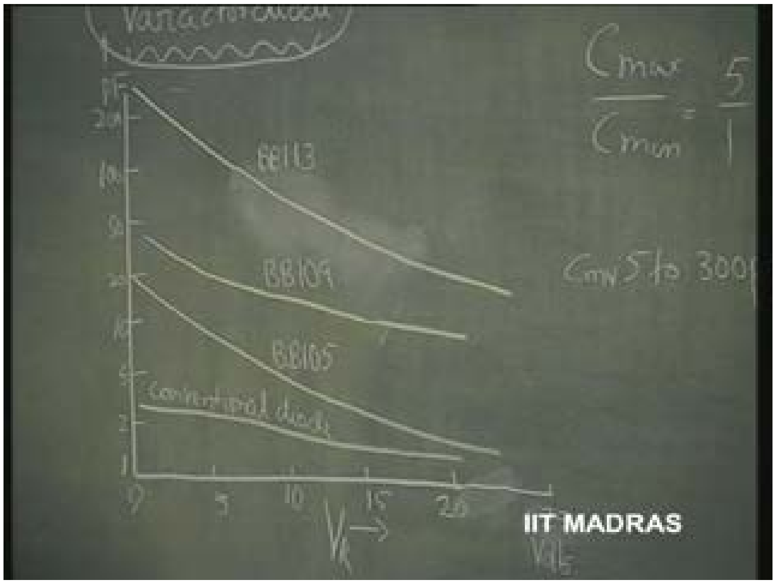

So, maximum to minimum, you should have normally as high ratio as 5; typical.
It is a good varactor diode. And the maximum value of the capacitance itself depends upon the frequency range where you are likely to use it; can be due to construction. It can be made to vary; if the area is increased, it can be higher. So, C max can be anywhere from 5 to 300 picofarads. This is for a high frequency application; this is for a typical low frequency application.

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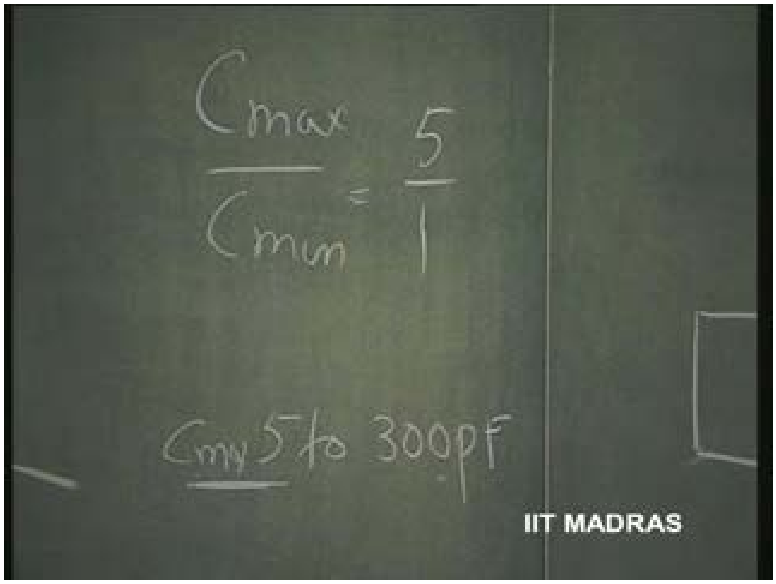

So, this is one of the most important uses of diode in its range; that is, reverse bias, but before breakdown. Now, let us make ourselves clear. The diode has, the ordinary diode has, the forward bias region, the reverse bias region; in the reverse bias region, we have the breakdown. This is the forward bias region; then, this is the reverse bias region. Here, it is having infinite resistance in this region. It is in this region that it is used as varactor. It is in this region it is used as a rectifier diode. It is in this region it is used as a varactor. It is in this region it is used as a Zener diode.

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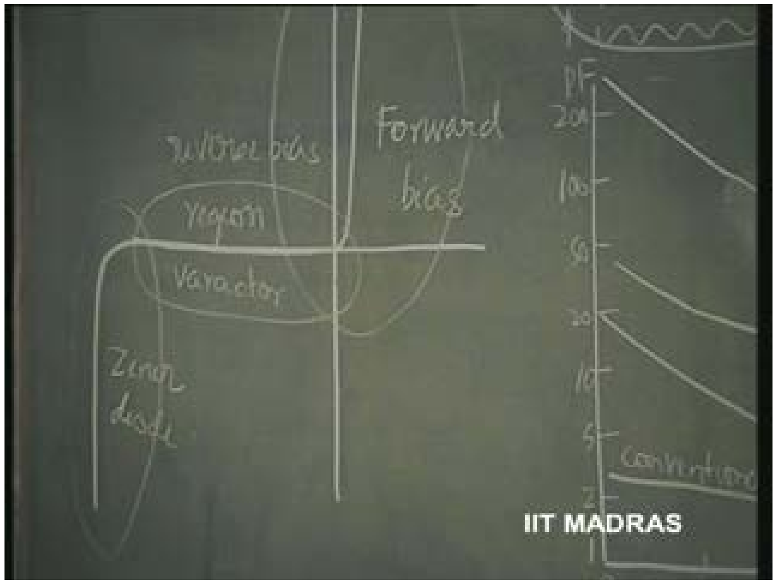

So, in the case of a rectifier diode, you are not much bothered about its use in the reverse bias region where the resistance is infinity. That is going to be a capacitance; but its variation is not going to be much. This is the conventional diode. So, if it is a power diode, the area is going to be larger, and the capacitance is also going to be higher. If it is a small signal diode, the area is going to be smaller; and therefore, the capacitance is going to be lower. This… therefore, you have to remember that power diodes, sometimes, it should not be really used for high speed applications because the capacitance of it is really very high.

So, that means, high frequency rectification, you should not use conventional power diodes which are used for 50 Hertz. This is the normal confusion that exists. For rectifying a high frequency waveform, you must never use a power diode, because, it is going to still conduct because of the capacitance. Therefore, this kind of thing, we should be very careful about. In this region, where it is neither breaking down nor going to the forward region, when it is biased properly, it can be used as a capacitor.

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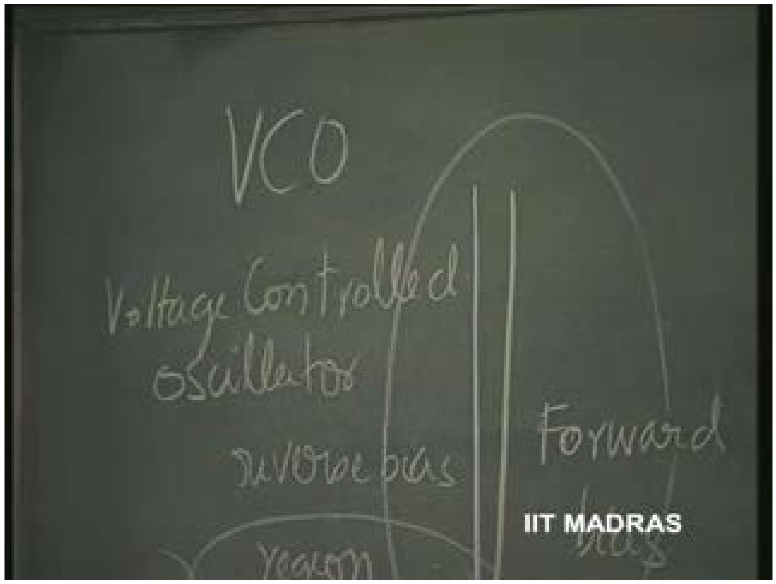

Where do you use this variable capacitor or varactor diode? Whenever we want an oscillator, LC oscillator, we will discuss this later, whose frequency of oscillation has to be varied by varying a voltage; a voltage controlled oscillator can use this variable capacitor. Or, a filter, which has to be tuned voltage, controlled filter voltage, controlled oscillator, all these things use this varactor diode for varying the capacitance of the electrode, thereby vary the frequency of the solution or the frequency of the filter.

So this is the application. We will later see how we can utilize this. Finally, the Zener diode has already been discussed; so you can see that the manufacturer will concentrate on its use as a Zener diode. Then the breakdown voltage is going to be within a certain percentage accuracy. Here, we will maximize the ratio between C max to C min and specify what value of maximum capacitance it has; and then here, he will say at what forward current it has to be operated, what is the average forward current, repetitive forward current; all these things, when it is being used as a rectifier diode. What should be the peak inverse voltage rating of this, if it is to be used as a rectifier diode? These are the different ratings. So, different diodes have different emphasis on the ratings.

So, we will now discuss other variety of diodes which are not extracted from the same characteristic, that may have different sort of material used for the fabrication, different characteristics, as special diodes. So, continuing with our discussion on special diodes, varactor diode - the symbol is that of the ordinary diode with the capacitor put alongside. Sometimes, the capacitor is put at this point also; either the capacitor is put alongside the diode or along with the diode here, in line with this diode. So, that is the symbol for the varactor diode.

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Now, let us consider another important diode, which is called, photo diode. What is it?

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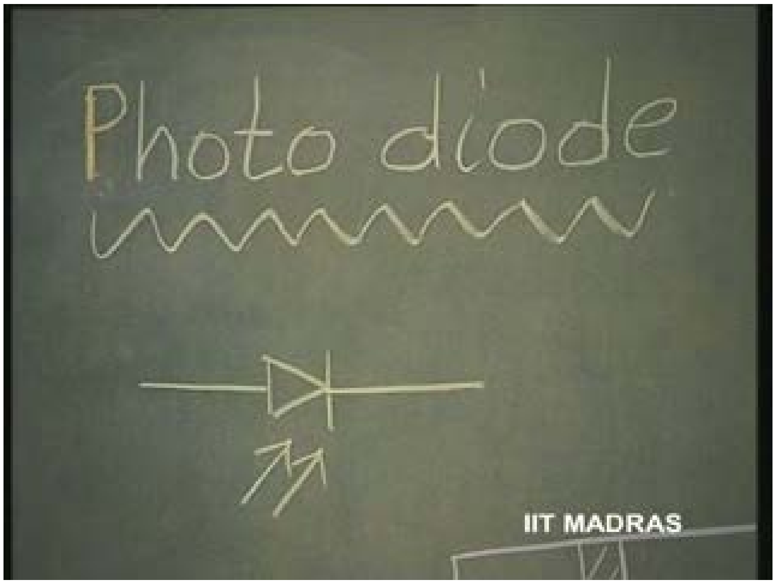

Again, we can go back to our PN junction. The PN junction has certain amount of leakage current in it; that is, the P material has majority carriers which are holes and minority carriers which are electrons. Here, we have majority carriers which are electrons but minority carriers which are holes. Even though for the holes here as well as the electrons here, there has been a barrier, potential hill, corresponding to point 5, 2 point 7, I would say, because of the existence of the depletion layer. This is happening the moment I formulate the junction. For us to have an equilibrium here, there is a potential hill created.

Now, this particular junction is still permitting the minority carriers from here to easily go to this because, this potential hill, which is an obstruction for the majority carriers, is a sort of an aid for them to flow freely. So, there is a hill here which will help these minority carriers moving from here to here, and the minority carriers from moving here.

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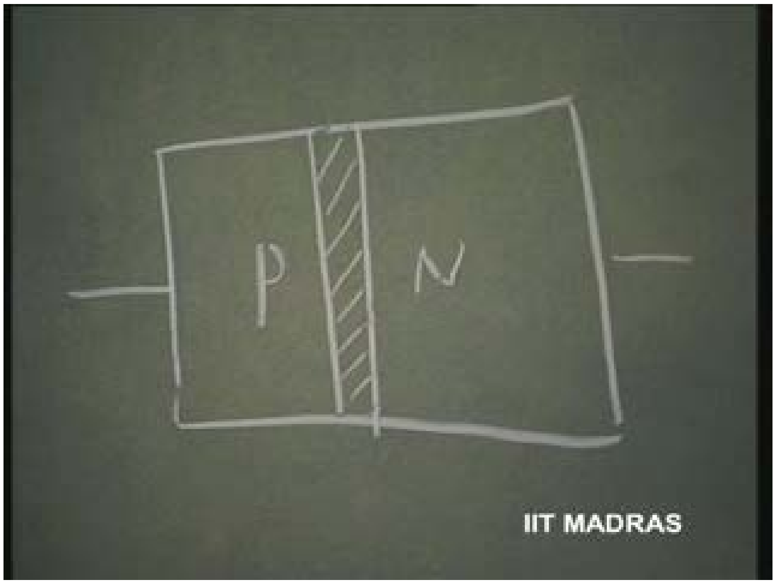

This minority carrier flow obviously will increase if this hill for the majority carrier increases; but there is only a maximum limit, because these are all saturation value corresponding to the saturation current. It will reach ultimately the current when it is reverse biased. That will be flowing only because of this kind of current due to minority carriers. This is called the reverse saturation current or leakage current; and that get saturated at a value I s for the diode. So, for a conventional diode, we know that this current in the reverse bias is zero for zero bias; and gradually increases and reaches a saturation.

If you magnify this several times, this is the way it will get saturated at I s. I s is, I diode is, equal to I s exponent V by eta V t. This is the usual expression that we have been using. This is the reverse saturation current. So, it reaches saturation. This is of the order of, may be, picoamperes or even less for the silicon.

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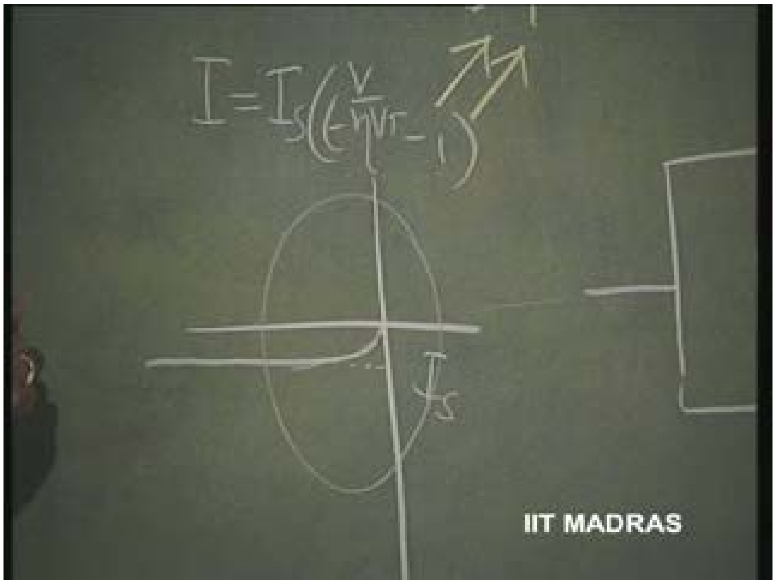

Now, what happens if I make light fall on this junction. So, that means, there should be a facility to expose the junction to light. So, that is the constructional feature of a photo diode where this junction is physically exposed to light; which means, these diodes will have a sort of glass window, which will expose the junction directly to light.

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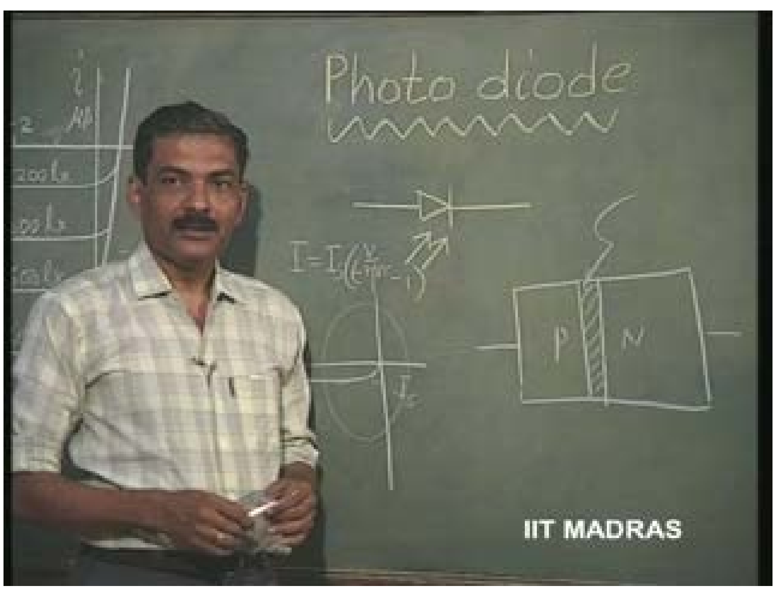

That is the only difference in constructional feature for these photo diodes. Is it clear now? If light falls on this junction, that will create further carriers. This will give enough energy here to break bonds and create free carriers. So, the carriers here will increase. So, this is, this energy is a source for creating more carriers. So, that means, more current, reverse saturation current can be sustained, for the same reverse voltage. That means, the characteristic will now look like something like this.

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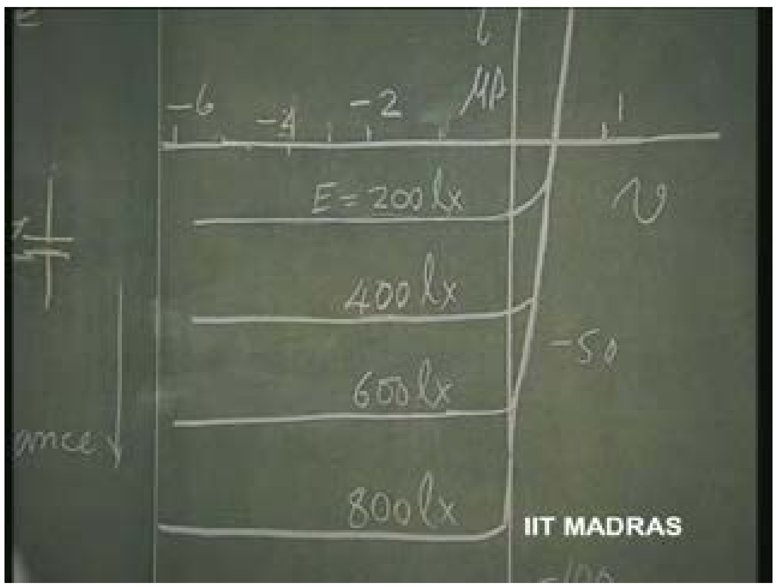

So, basically, remember that you are increasing the reverse saturation current and providing a sustained reverse saturation current of increased magnitude by giving an energy here, light energy. So this is the source from which it gets the energy. So, this particular diode characteristic now will be like this. This is the reverse saturation current, saturated here.

Not only that, because it can be sustained like this, it is going to have an open circuit voltage because, this, the current is zero; this open circuit voltage, if the intensity is large enough, gradually goes towards the point 5 value for silicon.

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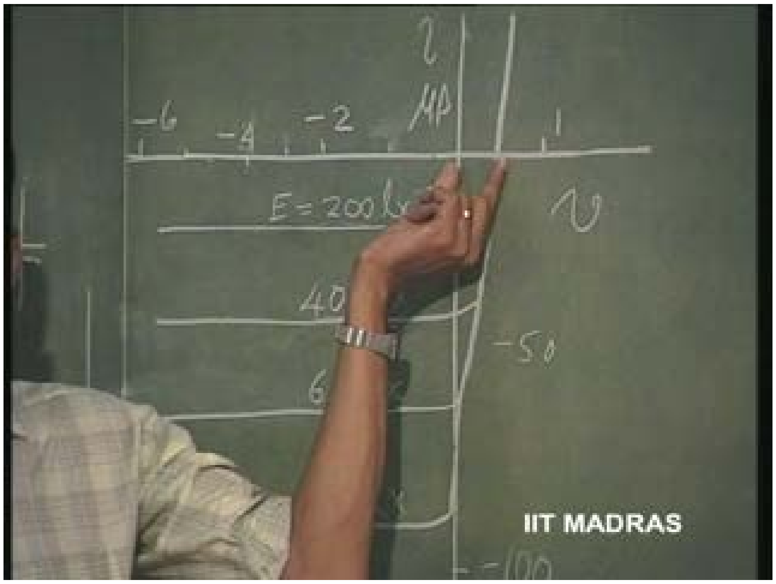

So, this is the open circuit voltage and therefore it can be used as a voltage source, a battery. That function of this diode, photo diode, is known as solar cell. That battery, which you can sustain by giving an external source of energy to the junction constantly, that junction voltage for silicon, is typically around point 5; and you can now find out that of your own.

So, this is an important application of photo diode as a solar cell. Obviously, in order to collect lot of light, we must expose the entire area of this junction to light. So, that is the constructional feature of the solar cell as distinct from a photo diode. That photo diode also requires lot of light; but in the case of solar cell, the efficiency, you want to be optimized. So, you will take care to see that maximum area of this is exposed to solar; so, if we will increase the area, large area, photo diode becomes nothing but a solar cell.

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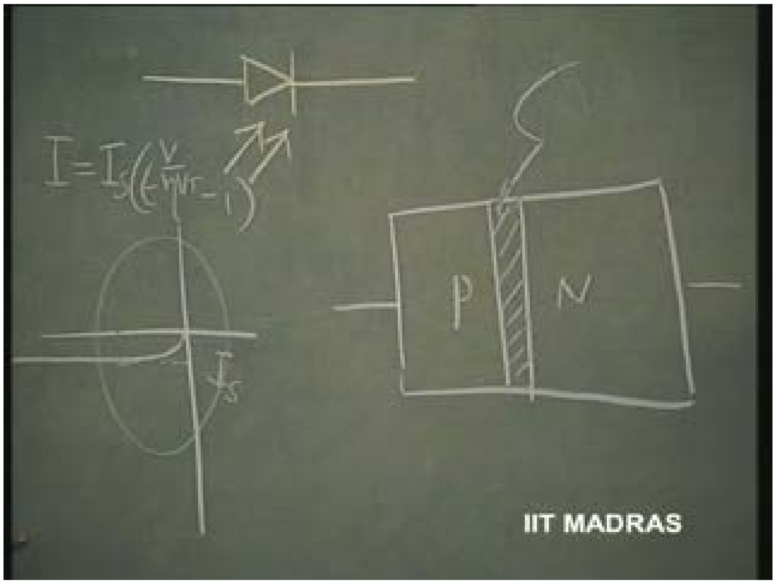

So, these solar cells can be stacked in series, as well as in parallel, to constitute a power pack which can deliver power to your satellite or anything you want, whenever there is light energy falling on it. So, in all your satellites, you will have the mounting of the solar cell panels, always sort of control and pointing towards the light source, the Sun, for example. And then, if the light is not there, it can be sort of charging a battery so as to conserve energy, when the light is not falling on it.

Now, this is the way the saturation current varies depending upon the various illuminance level, illuminance is increased; so, in this direction, the current capability here... This is open circuit voltage; this is the short circuit current.

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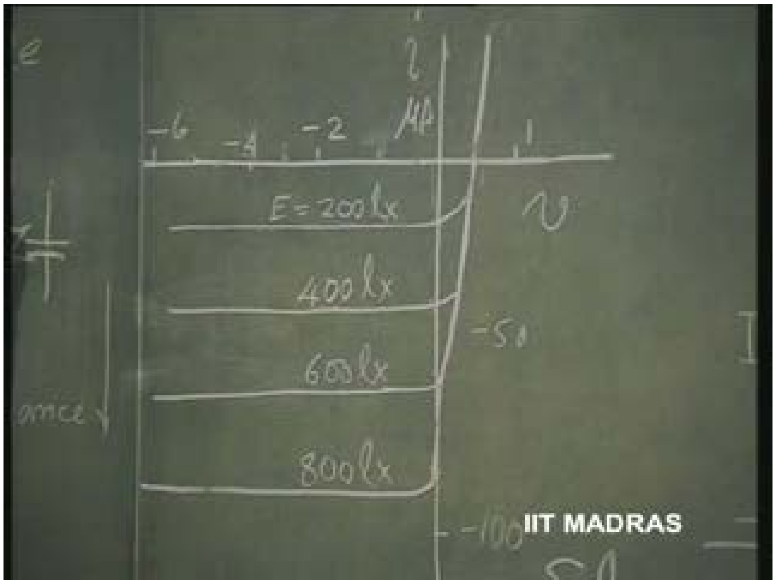

This, this value of current is going to be the short circuit current and this is the open circuit voltage for this photo diode or solar cell. And, the symbol for that is just the ordinary diode with light falling on the junction indicated by arrows; so light is falling on the junction as indicated. That is a photo diode symbol.

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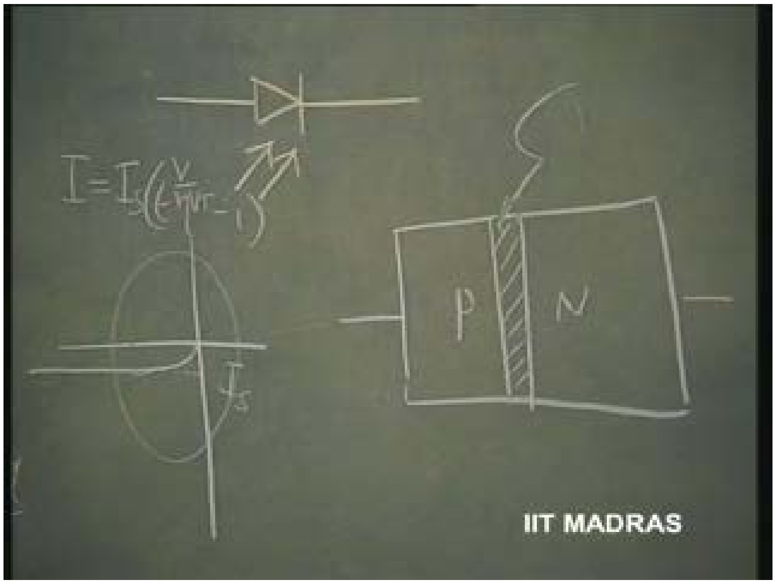

This can also be used to convert light energy into electrical energy. Also, measurement of light; for measurement of light, you can use this as a transducer, apart from using it as a battery. These are the various important applications of photo diode.

Now, let us go to another diode which is almost sort of a counterpart of this photo diode. This is called light emitting diode or LED, popularly known as, light emitting diode. So, the symbol is, when this is forward biased, this junction, see, remember that; there, this is the reverse bias saturation current which is controlled; here, this junction, when it is forward biased, under forward biased condition, this emits light. This is important.

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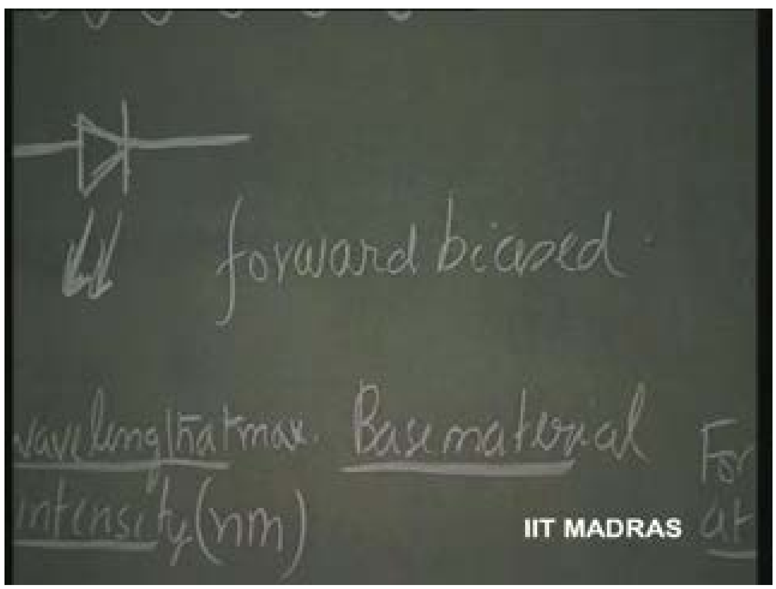

But, such a diode is, not a silicon diode. It is made out of, not group 4 element, which is silicon; 3 5 compound element, which is called, gallium arsenide or gallium arsenide phosphide or gallium nitrite, gallium phosphide. This material, when a P N junction is formed using this compound, 3 5 compound in the periodic table.

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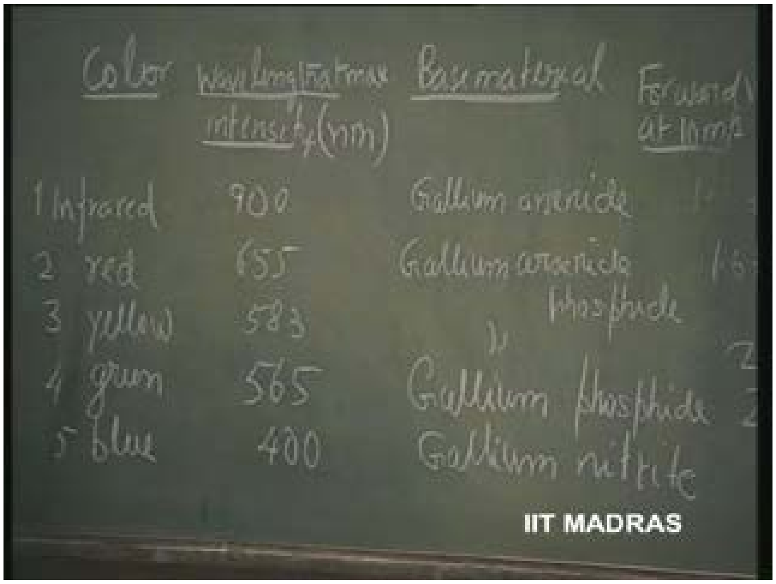

Silicon is group 4. This is 3 5 and when it is combined like this and a junction diode is formed, P N junction diode is formed, then that behaves like an LED. If sufficient forward current is applied, typically 10 milliamperes or so, and the typical voltage, forward bias voltage; now, please compare this with the forward bias voltage of a silicon diode which is of the order of point 5 to point 7, we said, at currents of the order of milliamperes. Gradually, it might become point 8 to 1 as it goes to higher currents. But here, it is greater than 1 for 10 milliamperes itself; 1 point ((five Refer Slide Time – 28:00)) to 1 point 5 volts.

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These values, typical values, you should know, in order to bias these so that they can emit sufficient intensity of light. So, the light intensity obviously depends upon the current, magnitude of current, flowing through it. So, the color, for example. Infrared - not visible; this is very useful for defense applications. There is light but it is not visible to the human eyes. So, this is commonly used for military applications. Infrared, red, infrared, 6, that is, 900 nanometers.

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That is the wavelength of this particular light and gallium arsenide is the material which gives you this color. And the forward voltage is one point 5 to, 1 point 3 to one point 5 volts.

Second, the red color - 655 nanometers; gallium arsenide phosphide is the material, 1 point 6 to 1 point 8 volts. Yellow color, 583 nanometers; again, gallium arsenide phosphide, 2 to 2 point 2 volts is the forward voltage at 10 milliamperes; green color, 565 nanometers, gallium phosphide; now, 2 point 2 to 2 point 4 volts, forward voltage; blue color, 400 nanometers wavelength, gallium nitrite is the material and 3 to 5 volts is the forward voltage.

So, you should know these typical values for different colors so as to design a circuit to bias this, so as to emit light. Where is the application of this? Obviously, all the display units for showing you the different numbers or letters, etcetera. These are called… There are different types of displays available. This has 1, 2, 3, 4, 5, 6, 7 - this is called 7 segment display. Each segment can be an array of LEDs so as to form this kind of segment. For example, typically, I want 3, number three; so, this will glow, this will glow, this will glow, this will glow, this will glow, this will glow.

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So, by control circuit you can get all numerical, numerals, using this kind of 7 segment display. Another display is called dot matrix so that you can get both numbers as well as letters being displayed.

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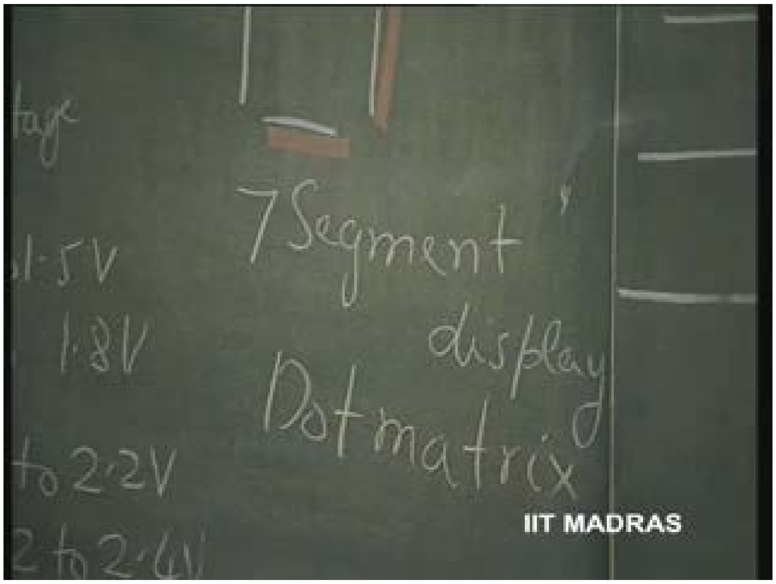

So, this is the important application of LED; but slowly these displays are going to, getting replaced by what are called LCDs. These have nothing to do with diodes; these are called liquid crystal displays. However, when primarily, the reason is, you can see the amount of power dissipated; 10 milliamperes into, let us say, 1 point 5 volts is going to be 15 millivolts just to sustain an LED. So, it consumes too much power. So, even though, before the advent of LCDs, these were being used for this place, with the advent of LCDs, these have gone out of use for most of the cheap displays like wrist watch display, etcetera.

We cannot afford to waste current and power of this order of magnitude. So, however, for, if, for large displays and things like that, you do not mind wasting some amount of power on this display, these displays are still being used. Now, a combination of photo diode along with LED; LED to detect light, LED, LED, that is, LED to emit light corresponding to some current, let us say. This is the current flowing in some circuit, assume. Corresponding to this current, some amount of light is going to emerge. This light, let it fall on another photo diode. So, let us say, this light is made to fall on a photo diode. So, this is an LED; this is a photo diode. So, the combination is an important unit in present day electronics, particularly with this optical fibre coming into picture, etcetera, this becomes an important unit where this light itself, which is generated by a current, can fall on this photo diode and generate a corresponding current. So, this current which is generated here, is dependent upon this current.

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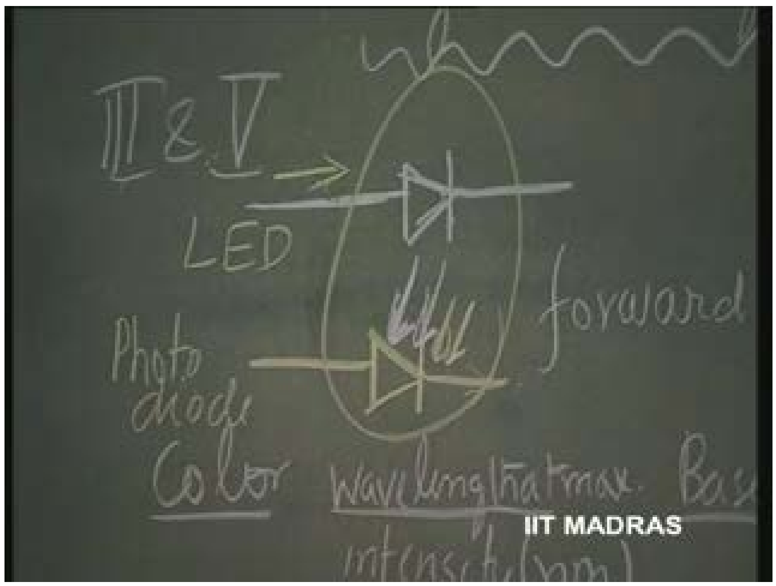

This light, magnitude, intensity, is dependent upon this current. And the current generated here depends upon the illuminance level of this here. So, in turn, you have a generated a current dependent upon this current and these two are perfectly isolated. So, this can be in one circuit and this can be in another circuit. This can be in, let us say, high voltage circuit this can be in the low voltage circuit, which is measurement circuit.

So, this is an isolator. This is an optoisolator or this is also called optocoupler. This can couple as well as isolate. This will couple this signal to this; this will isolate this signal from this; this circuit from this circuit; so these are called optocouplers or isolators.

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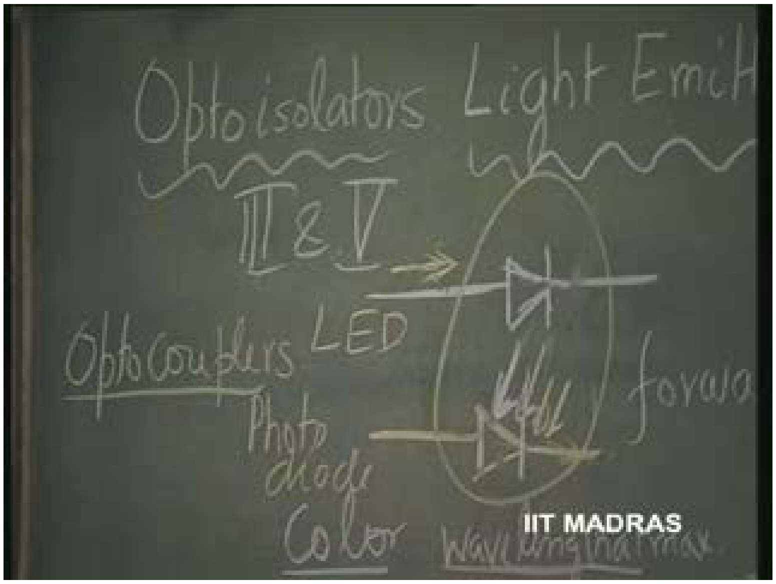

Important key names like these are available for variety of applications, where you would now rather not use transformers and things like that, for isolation purposes. You would like to use some electronic element like this which is quite convenient. Very intelligent designs are available where these can be used for precision measurement of current in high voltage circuits, etcetera. So, this is another application of this combination of photo diode with light emitting diode, which is called optocoupler or optoisolator.

Now you are going to be shown some of the diodes which are used in practice. Consider this. This is a small signal germanium diode; you can see, very small size and its specifications are that it can tolerate a forward current of the order of 50 milliamperes which is quite small you consider; and reverse voltage of about, peak inverse voltage rating of about, 90 volts, and the forward drop is considerable. This is apart from the junction drop; also that is considerable top series resistance drop here, about 1 volt.

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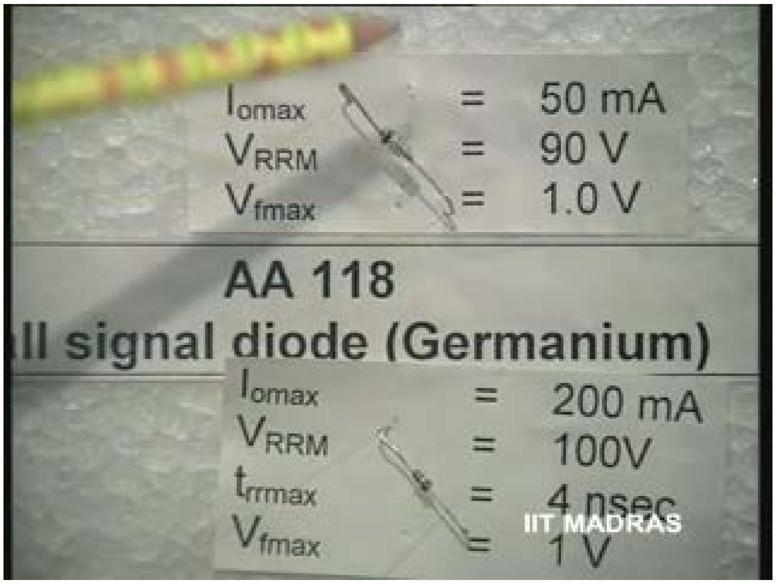

And the next one, the next one is a small signal silicon diode. Again, operating current, maximum forward bias current, maximum, is of the order of 200 milliamperes; peak inverse voltage rating is about 100 volts and is supposed to be a fast diode; and therefore, this recovery time from forward bias mode to the reverse bias, there is a delay time of the order of 4 nanoseconds.

This is important in diodes which are used for switching applications which should be kept very small; and when it is forward biased; the typical voltage at the currents of the order of 200 milliamperes is about 1 volt.

Finally in this, we have a power diode. You can see the size compared to the other ones; the size is bigger, and it can carry a current of the order of 1 ampere and its peak inverse voltage rating is of the order of 1 point 2 Kilo Volts.

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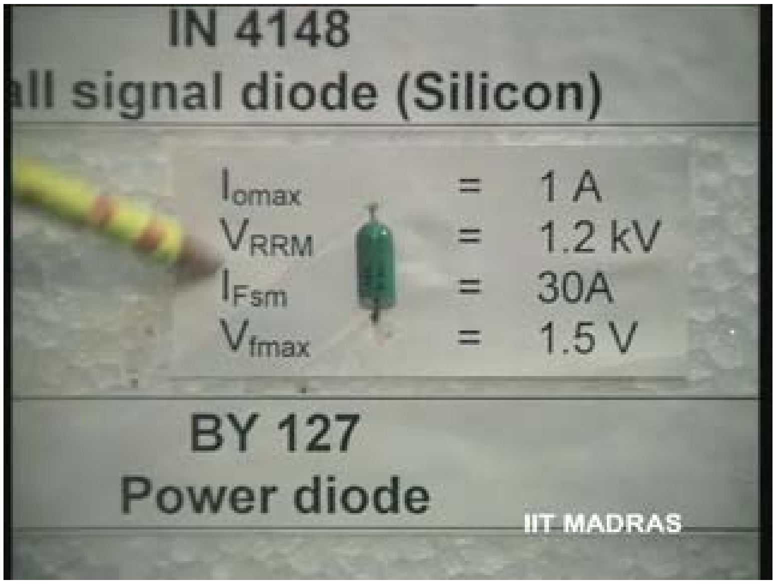

And this is what I have discussed when we designed our rectifier. The forward current, that is of the order of, 30 amperes it can sustain; and V f maximum is of the order of 1 point 5 volts. You can see therefore that the forward voltage is taken as about point 5 to point 7 only when the current is very small, of the order of milliamperes or less. Otherwise, at currents of the order of 30 amperes, apart from the junction drop, the series resistance drop also comes into picture and it is of the order of 1 point 5 volts. This is a power diode, BY 127.

Now, you consider a series of Zener diodes being shown to you. As the size itself indicates, this is a low power Zener diode, 400 milliwatts, 3 point 9 volts; 3 point 9 volts is the breakdown voltage of the Zener.

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Next one is 5 point 6 volts breakdown voltage; but higher wattage, 1 watt Zener; slightly bigger in size. 1 watt Zener; power rating is higher.

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The next one is really a power Zener, 13 volts Zener with 3 watt power; maximum dissipation permissible. So, you can see the size; comparatively bigger in size compared to the other ones.

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The next one is another power, this thing; it is 6 point 8 volts, 10 watts Zener diode.

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So, all these things can be really used as secondary sources of power. Maximum power it can dissipate is 10 watts and the voltage is, for regulated voltage of 6 point 8 volts, you can use for power supply. So, you can really use it for large current output.

Coming to special diodes, we have now here a varactor diode. As you can see, the nominal value of the capacitance, C total, is 20 picofarads. C 1 by C 2, that is maximum to minimum ratio, typically is 5 I said, 4 point 5 in this case. And the maximum voltage that you can apply is 30 volts. So, this is BB 1 naught 9, which we have also plotted in the earlier class, Varactor Diode.

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The next one is a light emitting diode, LED red color. This also we had indicated; the I f max is 30 milliamperes; that is maximum current that you can apply under forward biased mode. And the voltage drop maximum corresponds to about 3 volts at that point. I f typically is 10 milliamperes and P naught max is about 100 milliwatts, maximum power dissipation permissible. Peak wavelength is 635 nanometers for this LED.

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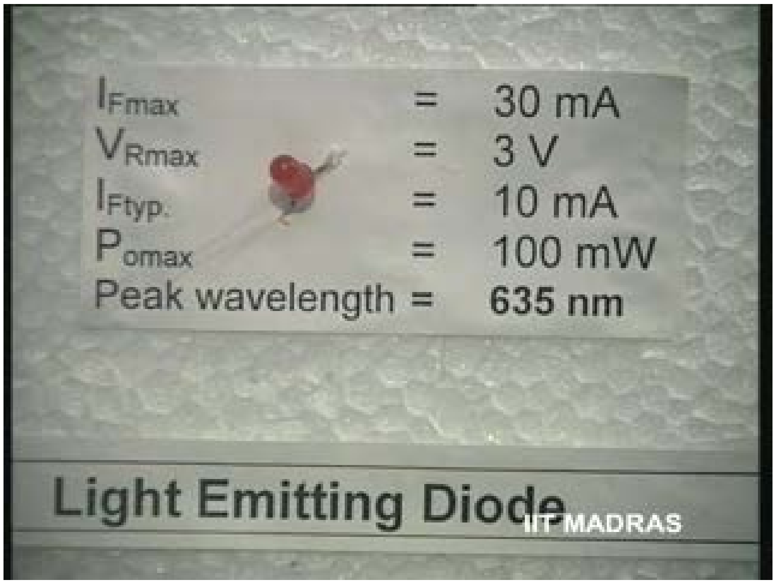

Now, you can see the solar cell that we discussed at the photo diode. We have a series of solar cells connected in series and parallel forming a panel, glass panel here, so as to collect maximum amount of light on to the surface of this. All the junctions are exposed here. And finally, all these are connected in parallel series and parallel and coming out as a two terminal solar cell. We have the two terminals brought out here. We have the two terminals brought out for the composite structure which is formulating the solar cell.

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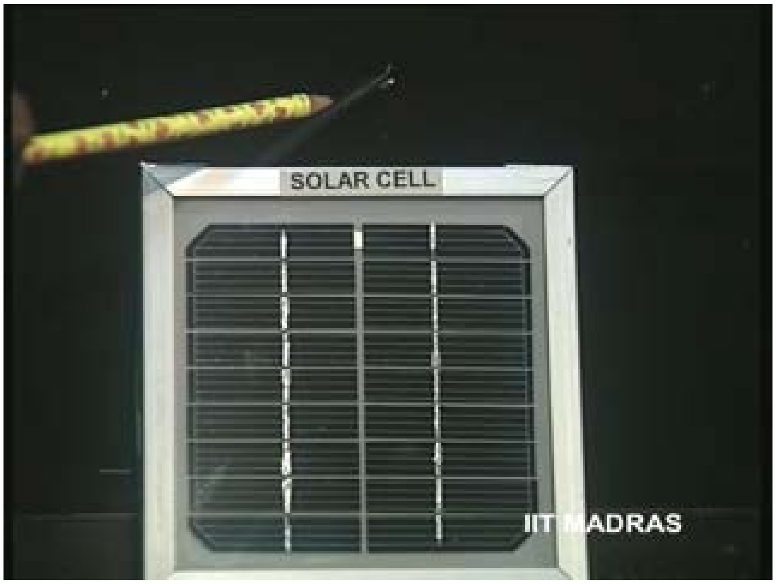

You have some of the diodes like Schottky diode which is not a, semiconductor PN junction, as we had discussed in earlier diodes. It is a metal to semiconductor junction.

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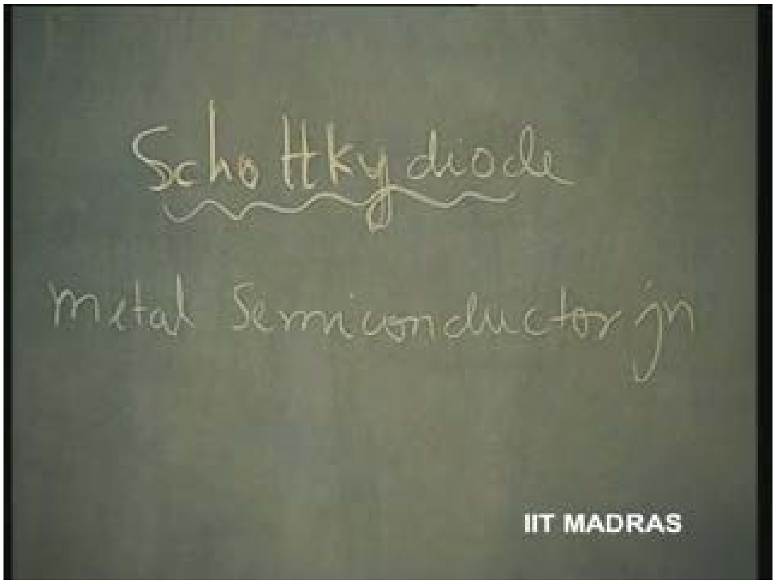

What is the advantage of this? Unlike the silicon diode or germanium diode for that matter, this PN junction diode has a forward voltage which is point 1 to point 2 volts. It is much less than the forward cut-in voltage of silicon which is point 5 to point 6 volts. So, that means, it starts conducting much earlier. So, it is closer to the ideal diode in its forward characteristics than these other semiconductor diodes; and also, it is having a sort of delay time which is of the order of nanoseconds. So, it is a high speed diode.

So, these diodes specifically are used for high speed switching applications and also in preventing, later on we will see, a transistor ((f…. Refer Slide Time: 44:35)) going to deep saturation. In fact, therefore, you have all high speed circuits with Schottky diode connected between collector and the base of the transistor to prevent it from going to, deep into saturation, and becoming slow. So, for high speed applications, the Schottky diode is used. It is a metal to semiconductor junction.

Apart from this, we have a tunnel diode which is typical to terminal diode with negative resistance which is also usable for very high frequency applications. But unfortunately, it, because of the difficulty in fabrication of that, this application has become obsolete now and very few people are using such tunnel diodes.

We have some typical application in power where diode is used as a protective element. I would like to elaborate little bit here. We have an inductor L, let us say, in which a current I is flowing, because the switch is closed; current is flowing in an inductor. Let us now open the switch. Such a situation exists in switching on a relay coil and switching it off. So, this is the relay coil, assume; the relay is operated by injecting a current into it. So, relay has the inductor; the current is flowing in the inductor.

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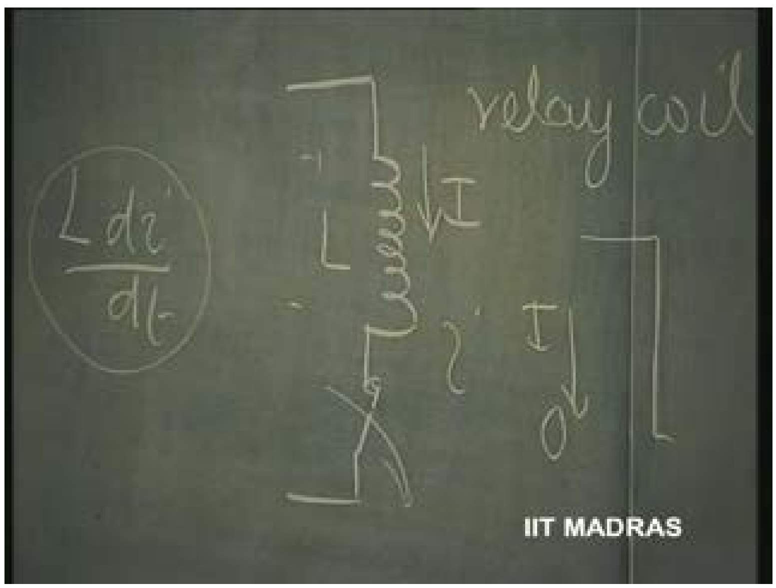

Now, I am disabling the relay by trying to open the switch. The voltage across an inductor is L d i by d t. The current therefore suddenly here becomes from i to zero; sudden drop in current. That means d i by d t is infinity. That means, voltage across the inductor becomes infinity. What does it mean? That, when I am trying to open this switch, this current tries to continue to flow, because, current in an inductor cannot be changed suddenly.

This is mainly because, d i by d t rating, you are trying to force it to zero. If you make it zero actually, that means, d i by d t is enormous; it is changing suddenly from finite value to zero. So, the voltage across the inductor, induced voltage across the inductor, is suddenly going to a very high value. Then, the voltage across this switch okay goes to that higher value, open circuit that just breaks down. That is arcing here. There is arcing here. Why the arcing is there? The current continues to flow. Arcing indicates the current is trying to flow, so as to prevent this from happening.

So, this kind of situation damages the switch. The arcing will damage the switch. How to prevent such a thing? In such a situation, it is advisable to put a protective diode across the inductor so that this current, when this switch is open, this current, continues to flow in this circuit.

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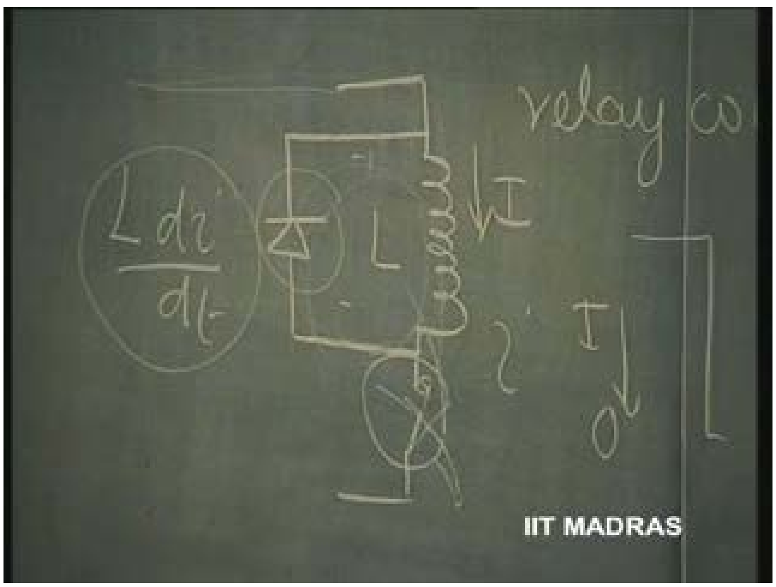

So earlier, this circuit has a current injected through this. The current through the diode is zero because, the diode is reverse biased. So the current cannot flow through the diode in this direction. But the moment the switch is opened, the inductive current now can flow through the diode like this. It will flow through the diode until such time; the entire energy gets dissipated in this circuit itself.

So, this kind of structure will prevent the switch from getting spoiled; so this is a protective diode, which is invariably introduced in almost all power circuits where there is an inductor and through which there is a current, a steady current flowing. So, this kind of application in a relay coil to prevent the switch from getting damaged is quite common in power electronics.

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With this, we conclude the series of diodes, its characteristics and applications. I have covered almost all applications of the diode, starting from its application as a switch, control switch, to its application as a transducer, semiconductor diode as a transducer; we have covered considerable amount, number of applications.

I hope that this will be the foundation for the next chapter on basic electronics. That will be the three terminal elements; this is a two terminal element, three terminal elements, starting with transistors.