Electronics for Analog Signal Processing

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Lecture - 2
Diodes

In last class we had seen how analog signal involves current and voltages and how certain basic elements are necessary for signal processing and out of these basic elements we were already exposed earlier to some of the passive linear basic elements which are resistors, capacitors, inductors. Then we were exposed to a new element that is the diode, the two terminal element called diode.

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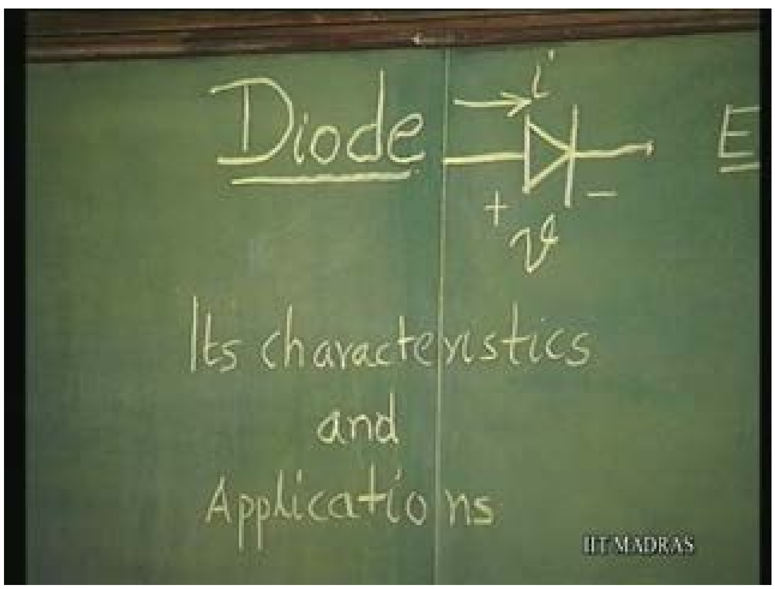

So the symbol for which we had already drawn earlier which is nothing but this and the current is in the forward direction is I, the forward bias voltage here is called v and for this we set i greater than 0, v is equal to 0 for v less than 0, i was equal to 0.

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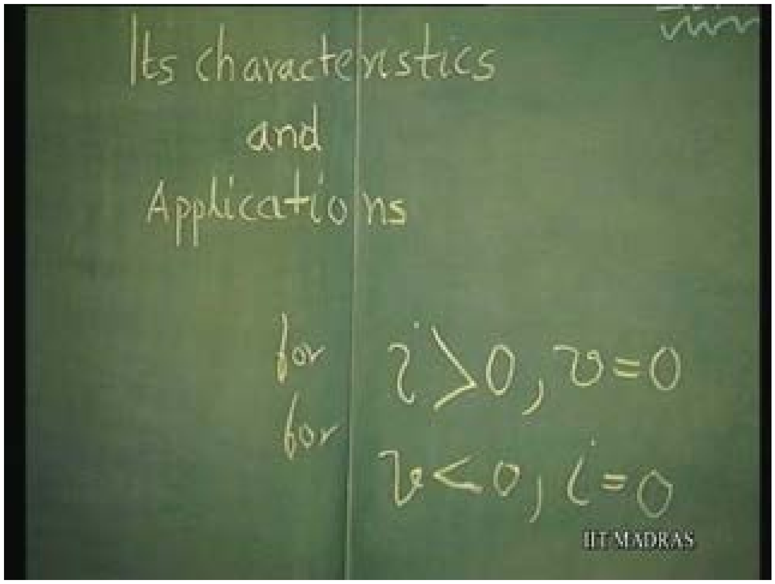

So this is the characteristic of the ideal diode that we have mentioned. Before going to that we also saw what is called the characteristic of the linear resistor. What is a resistor? We know that a resistance R is the ratio of the voltage across it divided by the current. So this is a linear resistance, this is called the ohms law.

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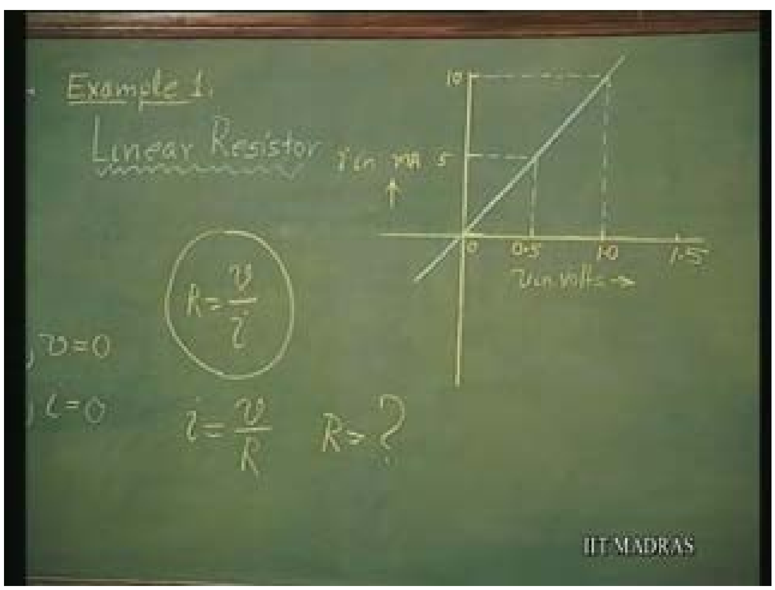

So this is plotted in terms of either i is equal to v by R or v is equal to i into R. This is the plot let us say, i is on the y axis, v is on the x axis, 0, point 5 volts, 1 volt, 1 point 5. Let us see this example; this is a problem that is given to you where you are told this is the linear characteristic of a resistance, find out the value of the resistance. So that is very simple, we know from this for a voltage of 1 volt change it is producing a current of 10 milli amperes; for a 1 volt change it is producing a current of 10 milli amperes change or for point 5 volts change it is producing a current of 5 milli amperes. Therefore the slope of this inverse the slope of this will give you resistance or slope of this will give you 1 over the resistance. So let us find out what it is, here 1 volt divided by 10 volts, this is the change here; this 1 volt divided by this change 10 volts gives you the resistance 1 volt by 10 milli amperes which will be nothing but 1 divided by 10 into 10 to power minus 3 volts divided by amperes which is called ohms that is unit for resistance.

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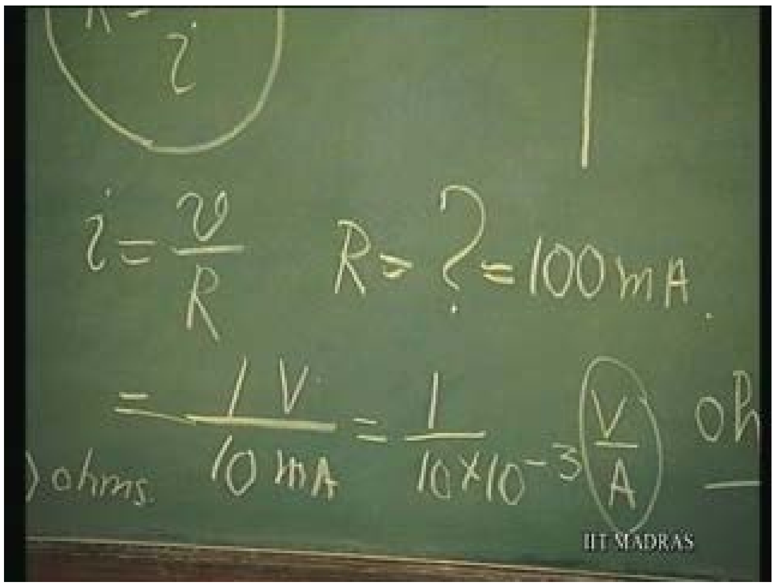

So this is nothing but 100 ohms resistance that is if you have 100 ohms resistance and if you apply 1 volt across it, it will produce a current of 10 milli amperes. So this is nothing but the linear resistor. So we have found out that value of this is equal to 100 ohms from the graph. So let us therefore see how this can be changed over to a non-linear resistance, this is a linear resistance. Let us have a non-linear resistor; it has a characteristic given that it has a characteristic of this type. You are now asked to find out, explain its behavior for different voltages in terms of current.

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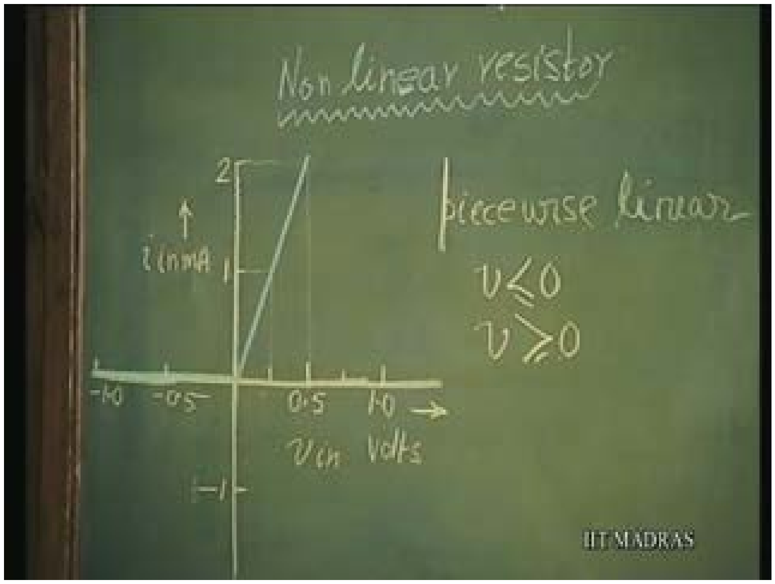

Now that can be explained very simply in the following manner, let us see. There are 2 regions where it is piece wise linear. It is linear here, it is linear here, this is one range that is for v less than 0 it has some property, for v greater than 0 it has some other property. So that is why it is called non linear resistor. Now for v less than 0, i is always going to be equal to 0 or v less than, whatever be the value i is always equal to 0. So what is it? Whatever change in current I take, let us say 0 to minus point 5; change in voltage I take 0 to minus point 5 shunt change; the current is going to be 0.

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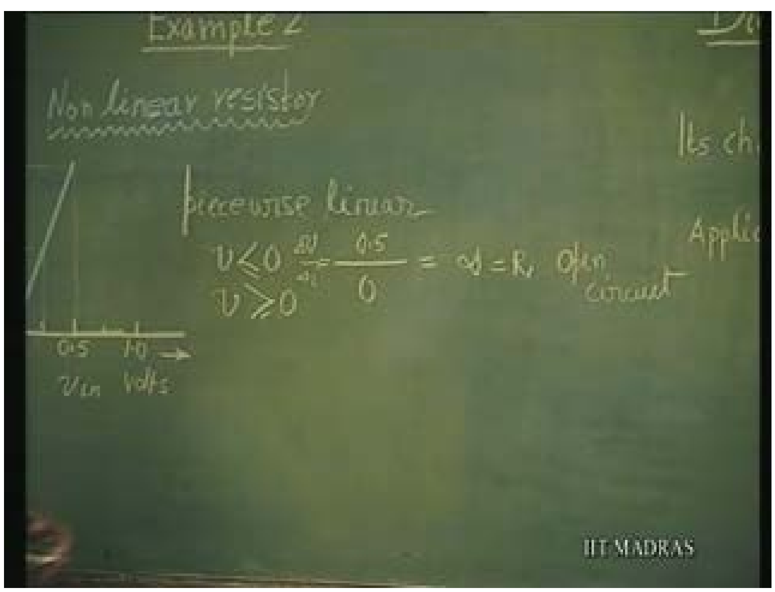

So v by, change in voltage delta v by delta i let us say is going to be something finite may be point 5 divided by, change in current is 0 so the resistance is infinity, so resistance in this region, this is the resistance in that region. The change in voltage divided by the change in current, change in voltage is point 5, change in current is 0; change in voltage is 1, change in current is 0 whatever value you put here right? This current is going to remain 0, so the resistance in the entire region is going to be infinity. So it is equivalent to an open circuit there because it is not permitting any current to flow here. Consider this region, in this region it is linear again but for a change in voltage of point 5, point 5 there is a change in current of 1 milli ampere, So many volts per ampere or so many ohms right.

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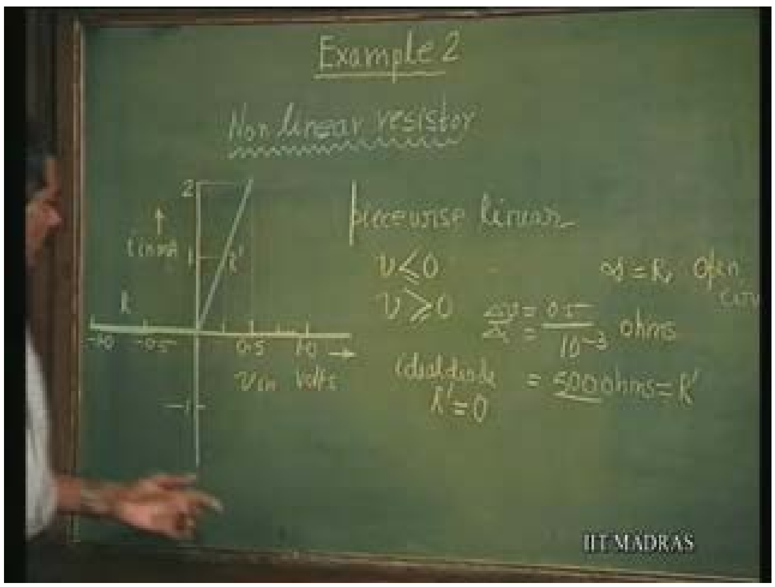

This is nothing but 500 ohms, point 5 divided by 10 to power minus 3 amperes or 1 milli ampere is nothing but 500 ohms that is the resistance of this region. So this is R let us call this, this is R dash. So it is taking on different values, in this region it has a resistance of R which is infinity and in this region it has R dash which is 500 ohms, so this is called a non linear resistor. So a non linear resistor normally can be approximated in terms of piece wise linearity assuming that over a small range it is linear, we can say that it can be approximated as a piece wise linear resistor. Now what is the diode, ideal diode? So this is some arbitrary non linear resistor which we can synthesize may be using ideal diode and resistor that we will see later. But presently what is an ideal diode? Ideal diode is one where R is infinity and R dash is equal to 0 that means ideal diode can be converted into a diode whose R dash is equal to 0.

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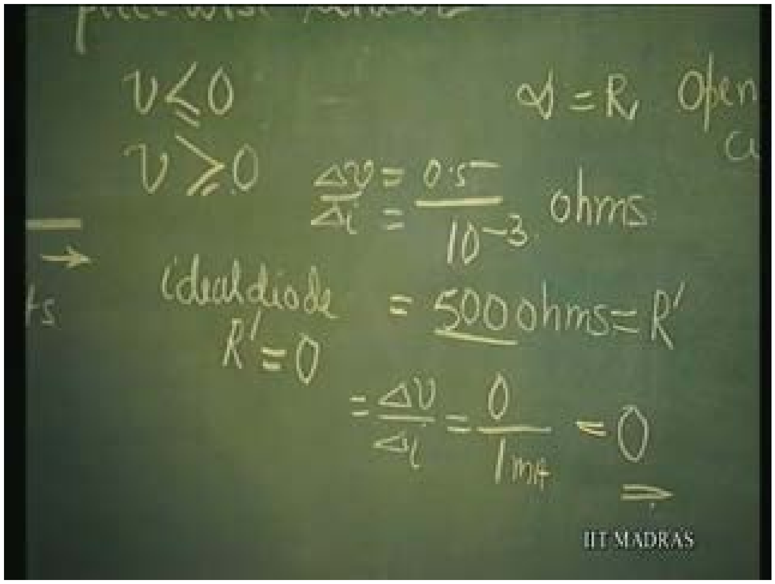

R dash is 0 means what? Whatever be the change in current, change in current may be 1 milli ampere; change in voltage is 0 so you have delta v divided by delta I, this is equal to 0, whatever be the current you can have 1 milli ampere change, does not make any difference. So the resistance is uniquely 0. So that means we can just say that this characteristic will change to something which is going to have its characteristic like this.

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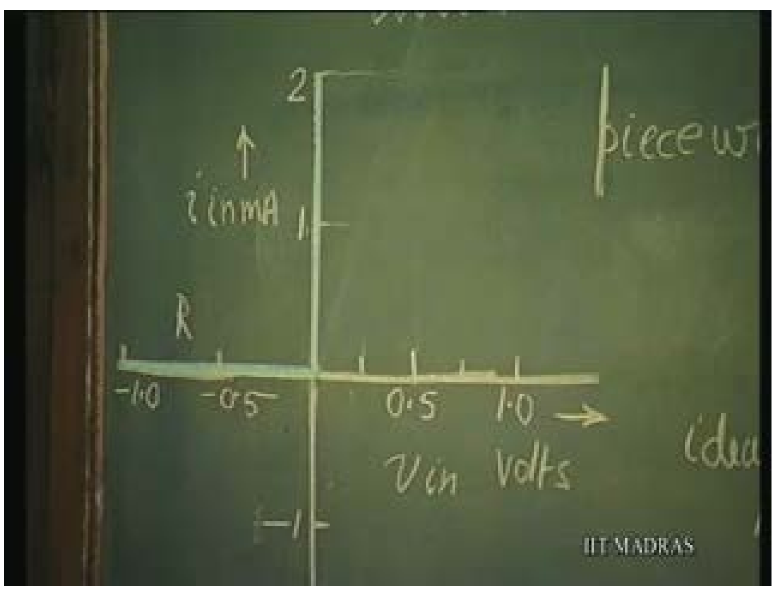

So this is what it is, ideal diode has its R dash equal to 0 and R equal to infinity. What is it? That is whatever be the change in voltage that may be let us say point 5, change in current is 0 that is why; so that is why its resistance is infinity.

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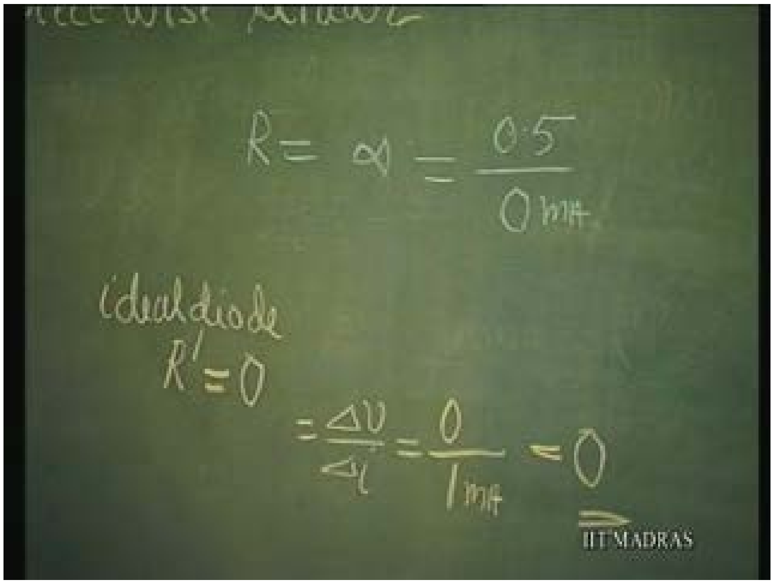

Now you can have seen in our example that we have seen what a linear resistor is, it is having the same slope whatever be range of the voltage or current and as far this is concerned in a certain range of voltage or current, this particular thing is linear for certain range and takes on a certain value in other range it is still linear and it takes on a different value. So once again let us discuss resistance in terms of, a resistance for change in voltage divided by change in current. When I apply a change in voltage, what is the change in current? The ratio of change in voltage by change in current gives me the resistance of this different regions where they are said to be piece wise linear. So these two examples demonstrate the sort of characteristic of the ideal diode which is going to be, now used by us in variety of applications but before we go to the ideal diode let us see whether practically we have a diode which is going to closely approximate in its characteristic to that of the ideal diode. So this is what I mentioned at the end of the last class, when I said a semiconductor diode can closely approximate an ideal diode.

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So what is a semiconductor diode? So we have what is called as a pn junction, a p type semiconductor n type semiconductor joined together to formulate a pn junction here. This has this property that it will allow current to flow in one direction and block current in the, allow current to flow in this direction and block current in the opposite direction, this is the blocked symbol right? So this is what it is going to do. This property is such that it is allowing current in one direction; it will block current in opposite direction.

Now we have also said that in this direction where this end is positive and this end is negative it is said to be forward biased or when i is greater than 0 the diode is forward biased, this is what we have called earlier forward bias where its resistance is 0 and R is equal to infinity, this is a short circuit, this is an open circuit where it is reverse biased. So by applying a current you can forward bias the diode, by applying a reverse bias voltage you can block the current in the diode. So this semiconductor diode the symbol is this, that p side is, p side is going to be made positive and n side is going to be made negative when you forward bias it and when you reverse bias it, this n side is going to be made positive and p is going to be made negative, so this is what is called biasing. Now what is the characteristic of pn semiconductor diode?

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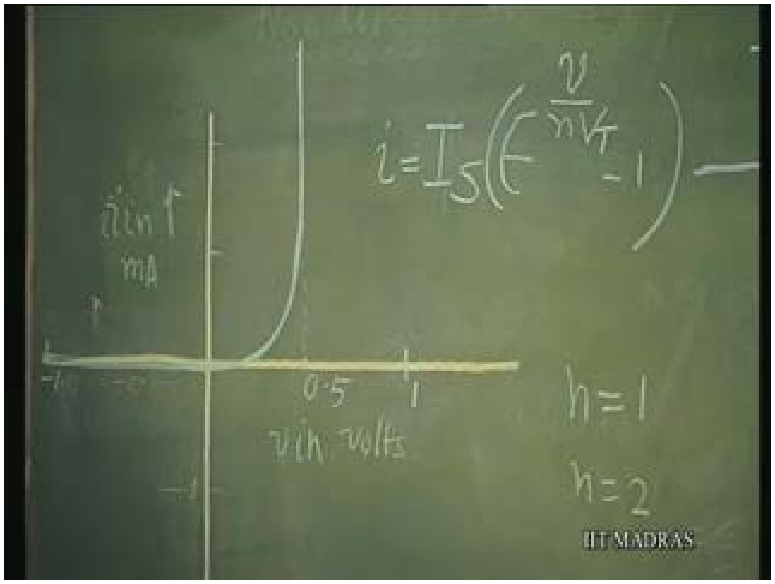

Let us therefore see how closely it is approximating to the ideal diode. The semiconductor diode follows a characteristic some what like this, this characteristic of the semiconductor diode somewhere around let us say point 5, 1 volt. So what is this? This is i equal to I_s (exponent v divided by n v_T minus 1). This is an exponential characteristic, the current i and the voltage v are related in an exponential manner. In the case of a semiconductor diode, let us say silicon diode which is commonly used diode nowadays, if this n in the case of IC, integrated circuit diodes is around 1, in the case discrete diodes it is around 2, so basically n is between 1 and 2 for diodes. In the case of integrated circuit diodes n is closer to 1 and in the case of discrete diodes n is closer to 2. What is this v_T? v_T is called thermal voltage, so this has to be dimensionless quantity so that is v is the variable voltage, v_T is the constant thermal voltage which is approximately equal to 26 milli volts at room temperature, 26 milli volts at room temperature.

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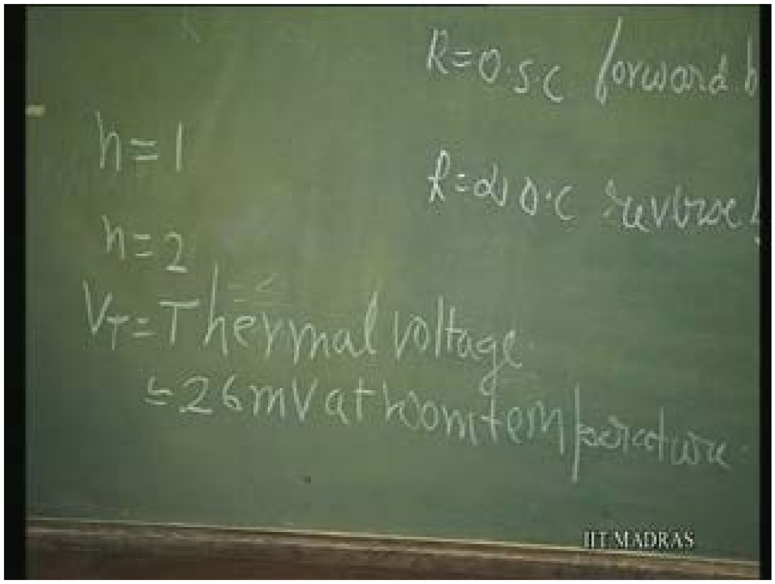

So v_T is also a constant which is called k Boltman's constant, T absolute temperature divided by q which is electronic charge.

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And if you evaluate it at room temperature, this value comes out to be 26 milli volts at room temperature. So we know all about this part of the expression, what is I_s? You can see that when v is large negative value this quantity goes towards 0 and current i becomes minus I_s which means if I apply a large reverse bias voltage to the diode, what is reverse bias? This side, n side is made positive and p side is made negative, in such a situation I am applying reverse bias voltage, if it is large then this quantity becomes very small, goes towards 0 and the current becomes i equal to approximately equal to minus I_s in this region, becomes constant, this is therefore called reverse saturation current.

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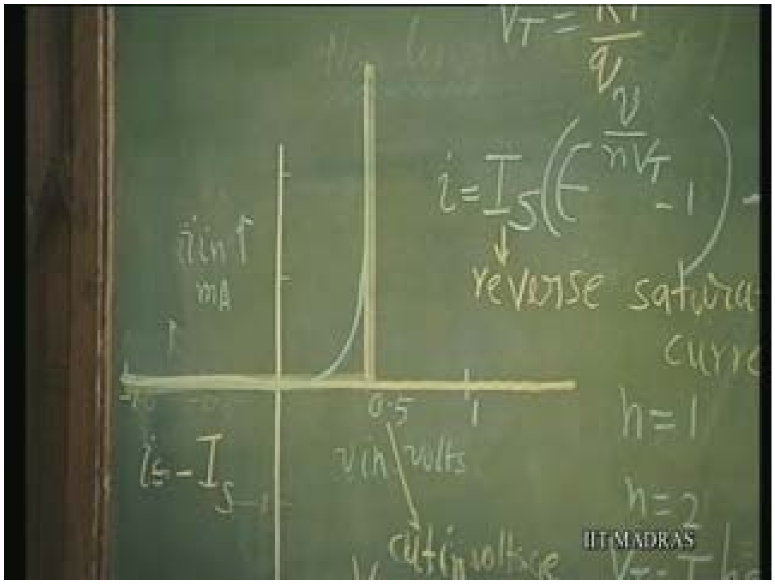

It is the property of the material, this is going to be of the order of nano amperes for normal diodes and therefore this is called reverse saturation current that is the current at which the current through the diode will saturate to a small value if it is reverse biased that means it is not blocking current totally, it is permitting a small value of current to still flow. So this current at which it is saturating is called the reverse saturation current, so the property of the diode is uniquely characterized by the reverse saturation current you can see. So the fabrication of the diode we will see to it that it takes on a certain value. So i is equal to I_s (exponent v by n v_T minus 1). In the forward bias region, what is forward bias region? Let us see, this is positive and this negative; the p side is made positive and n side is made negative then the current flow is possible in this direction and it can sustain any amount of current, ideally speaking it can sustain it. So an ideal semiconductor diode is going to follow this relationship and a practical semiconductor diode also follows this very closely over several decades of variation in current, all the way from microamperes up to hundreds of milli amperes this relationship is faithfully power produced.

This is a unique device, electronic device where the mathematical relationship is followed almost exactly over such wide variation in current. So now in the forward direction how is it closely representing our diode, we can say that along as v is much greater than some value that value is called the cut in voltage for the, what is cut in voltage? I just try to draw this almost like a straight line and it intersects at a certain point where the voltage is about point 5 to point 6 and that is called the cut in voltage of the diode. So this cut in voltage is called v_{gamma} so this is typically for silicon around point 5 to point 7. So after that voltage the current is increasing enormously for a small change in voltage which means the resistance if you want to approximate this diode, you can approximate the semiconductor diode as similar to this kind of characteristic that is it has almost a vertical line here and almost a horizontal line here. A semiconductor diode therefore is not exactly same as an ideal diode but is supposed to behave like an ideal diode beyond the cut in voltage. So beyond the cut in voltage or at the cut in voltage the current is going to increase enormously or above the cut in voltage we have the current being permissible made permissible to flow, below the cut in voltage we can assume that there is no current flow. So it is as though the ideal diode characteristic is shifted in its axis up to point 5 volts or also we have some battery coming in series with the ideal diode. Let us therefore see what its characteristic is going to look like, so if it is forward biased it is not going to conduct immediately, it is as though that we have a battery in series with it which is the cut in voltage v_{gamma} and thereafter we have the ideal diode.

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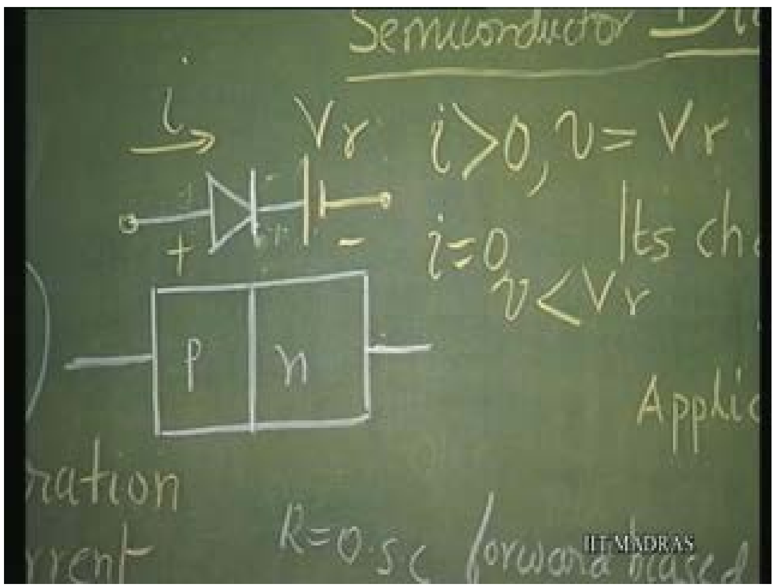

So semiconductor diode to a first degree of approximation can be approximated as an ideal diode in series with the cut in voltage of v_{gamma}. So until v gamma is reached here, it is not going to conduct thereafter it is going to be replaced by a short circuit. So let us therefore see that the equivalent circuit of semiconductor diode can be put down as, for i greater than 0 the v is going to be equal to v_{gamma}. Whereas in the case of an ideal this v was equal to 0, so for i greater than 0 the v for the semiconductor diode which is equivalent to this is nothing but v_{gamma} given indicated by a battery and i is going to be equal to 0 for v less than v_{gamma}, now this is the approximate equivalent circuit of the semiconductor diode. Let me now show you the complete characteristic of the semiconductor diode, we just saw the forward bias region where it is going to be almost coinciding to the ideal diode characteristic but for a shift in this axis around this point up to a region called cut in voltage which is v_{gamma} equal to point 5 to point 6, so it is almost vertical that.

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So in the reverse bias region it is almost 0 current because it is current of the order of nano amperes reverse saturation current and therefore it is almost 0 current for all practical purposes but as you reverse bias it more and more, region is reached, this region is called breakdown region. The diode breaks down that is it permits now any amount of flow of current, so this region is called the break down region. This break down can form, can be formed by either what is called zener break down mechanism or avalanche break down but whatever be the mechanism of breakdown, it is popularly called zener diode if we are concentrating on its application in this region. If diodes are fabricated so that they breakdown at specific values of voltages such diodes are called zener diodes, where we are interested in working in this region of breakdown.

This is a reversible phenomena that the current when it is reduced it will again come back to its off state, where the current is going to be maintained at very nearly at 0 value. So this region is called the breakdown region and therefore basically speaking we can work the diode in this region where it is forward biased to carry any amount of current after the cut in voltage of point 5 or in this region where again the current is possible in the reverse direction, reverse direction is in this direction. The current flow is permitted in the direction after the breakdown occurs and the current is unlimited ideally but practically there will be always the maximum current up to which you can operate the diodes in this as well as in this. There will be a maximum current for operation of the diode in the forward bias region and a maximum limiting current in the reverse bias region. So diode fabricated by the manufacturers they will specify up to what value of current you can use in the forward bias region, up to what value of current you can use it in the reverse bias region. It is going to dissipate power here, very much power here because it is going to sustain a voltage which is pretty high and it can also sustain a current which is pretty high, so the power dissipation is nothing but this voltage in to the current at which it is operating. So this maximum limit of current is specified in terms of what is called P_{dmax}

that is, it is nothing but the break down voltage which is represented as zener break down V_z, so this is called V_z that into I diode maximum. So that is maximum power the zener diode is capable of dissipating without permanently getting damaged.

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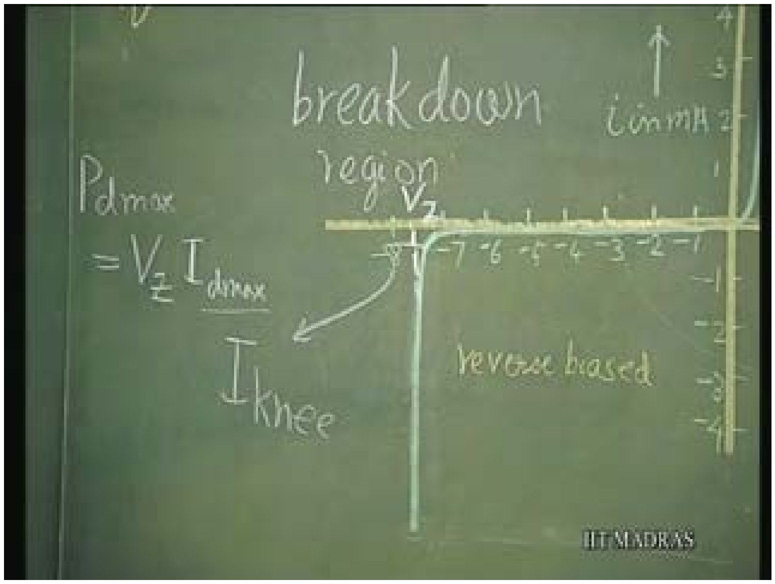

So you should always operate the zener diode below this value of current I_{dmax}. Then there is also a current beyond which this voltage is going to be pretty constant and that is called I_{knee} current. This is in the form of a knee right? So this is called the knee current. Therefore the current through the zener diode should be greater than that in order to sustain a constant voltage which is V_z. So this is the specification for a zener diode that is there will be a P_{dmax} for the diode and there will be an I_{knee} current beyond which only it can be operated as a zener diode for variety of applications, we will see it later.

Similarly here, there will be a maximum current I forward max up to which you can permit the forward current to flow. Again if you exceed this current limit the diode is going to be permanently damaged. So these are the basic limitations of the practical diode when you are using it in your circuit application. What are the applications for which the diode can be used we will see. Now obviously if the diode is manufactured to operate only in this region that diode is called a rectifier diode. What are the specifications of rectifier diode?

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It is in the forward direction permitted to carry a maximum current, in the forward direction there is a maximum current up to which you can operate. Then the break down voltage here we do not put it as V_z. For a rectifier diode break down voltage should be greater than a certain value, greater than a certain value so that when it is reversed biased it does not break down. So it should be as high as possible so that in the region where you are operating it, it does not break down. So these are the two important specifications for a rectifier diode. What are the applications of the rectifier diode? We will see later. Then zener diode as I told you it is not going to be operated here but it is going to be operated in this region of breakdown. So this breakdown voltage is very important, so this should be of a specific value with a certain tolerance here V_z, so it is going to have a certain V_z and P_{dmax} that I mentioned about, these are the specifications for the zener diode.

The breakdown here has to be greater than a certain value up to which you are going to use this forward bias and reverse bias voltages, whereas in the zener case it is the breakdown voltage which is important, it is specifically accurately mentioned in the specification. So let us see what are the equivalent circuits for these and where are the applications of these. Now obviously I told you this diode is the basic fundamental two terminal element which is non-linear, which is used in a variety of signal processing applications, what are they? First let us name these applications of rectifier diode for purpose of clipping; this is an important application of a diode. Clipping that means you want to chop off the waveform.

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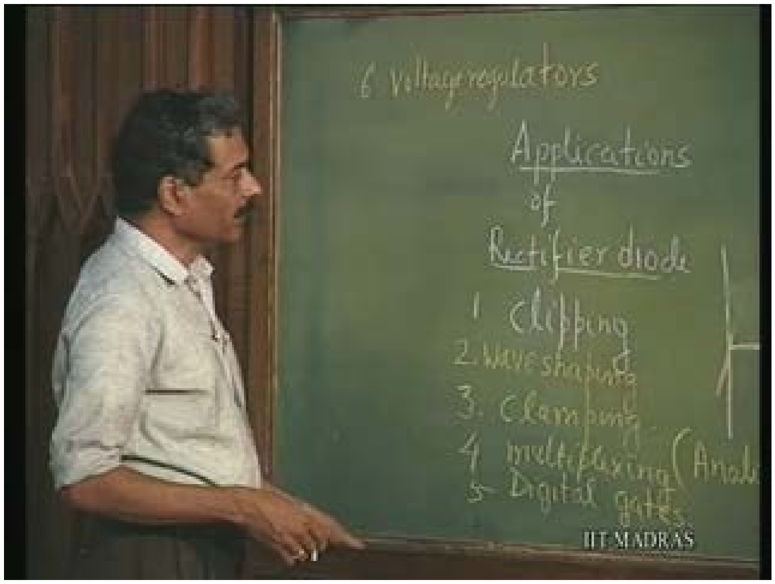

Let us say a given waveform is like this, say this is a sine wave. I want to chop off certain portion of the waveform, clip so clipping is one of the important functions of the diode, chop off this or chop off the entire waveform like this. Simply cut that portion remove it, so this is what is called, a special case of this is called rectification that is why it is called rectifier diode, half wave rectification, from a full wave I can chop off one half and get half wave rectification. So rectifier is a special application of clipping. You can do this clipping in any manner you want, clip off the top one, clip off the bottom one or clip off only portion of the top or portion of the bottom, so that is a variety of clipping operation can be done, so this is mainly called wave shaping.

In fact, you can therefore using this clipping technique you can do wave shaping that means sine wave can be converted into almost a square wave or a trapezoidal wave approximately so this is called wave shaping. Then this is a non-linear operation another non-linear operation is clamping that is the letting the waveform, whatever it is sine wave or triangular wave get clamped at the top or clamped at the bottom so that it can be clamped to any level of voltage or current so this is what is meant by clamping. We will again see this detailed discussion about this later, what is meant by clamping? So clamping is another operation as far as this is concerned. Then this is also used in what is called multiplexing. I would like to permit certain signal to come at certain time; some other signal should not come during that time. Now this is called multiplexing, I want to multiplex different signals so that the load is connected to different signals at times controlled by me, so this is called multiplexing or this is analog multiplexer. Then of course it is also used for digital application in what is called digital gates, logic gates; important application of diode in digital gates. Then it is also used for, in the form of zener diode it is used for voltage regulators. So these are the variety of applications in electronics for which this diode is going to be used. In order to understand this applications let us consider the diode in its simplest form. This is always best that the diode is equivalent to a short circuit when i is greater than 0 and is an open circuit when v is less than 0 must be remembered at all times. If that is remembered then we can do understand this application of diode very easily without any problem what so ever. Now first consider I would, how this diode can be used to obtain a non-linear resistor. So I would like to have a characteristic that we had taken today in the second example of ours. So we took this example and we saw that the characteristic of non-linear resistor was something like this.

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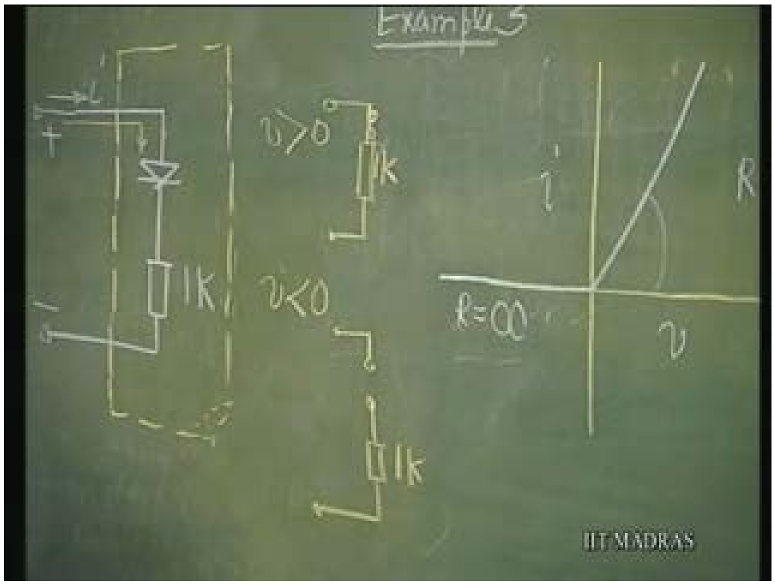

I would like to have a non-linear resistor of this type using an ideal diode, how do I obtain this? I know that if this is v and this is i, the inverse of the slope of this is going to be giving me 1 over R dash here, so R dash is finite not 0 so let us say it is equal to 1k. This is the example 3, so I want an R dash which is 1 kilo ohm and R which is equal to 0 or infinity here. Earlier R dash was 0 and R was infinity, now R dash is 1 kilo ohm and R is equal to infinity. Let us see how we can simulate this so that I get a non-linear resistor of this type. So I know that if I put a diode, ideal diode, it will not permit current when v is less than 0, so that is going to be done by this, when v is less than 0 it will not permit current, any current through it but I want when the current is permitted to flow, let it flow through a resistance of, linear resistance of 1 kilo ohms. So I am putting a linear resistance in series with a diode.

So now, I am now going to ask you plot v versus i for this special circuit that we have made along with diode and resistor. This is our circuit, two terminal circuit; composite circuit which uses a diode and a resistor. Let us see what this characteristic of this composite circuits looks like. When v is greater than 0 that is, it is going to permit this current in this to flow in this direction, when this is positive and this is negative it is forward biased so a current is going to flow in this direction. And this is going to be a short circuit so at that point of time when v is greater than 0 this is equivalent to 1k because the diode is going to be replaced by a short circuit here, so equivalent circuit when v is greater than 0 is 1k, so we get this resistance of 1k that is because I have put 1k there. When v is less than 0 that is when this is negative and that is positive then we have this diode getting reversed biased, there is no possibility of current in this direction and therefore this particular thing is going to act as an open circuit because of the diode. So equivalent is, let us say this is the place where the diode was existing; this is an open circuit and the resistance is still there and since the open circuit is coming in series with the resistance it is equivalent to an open circuit. So this is the region where the resistance is infinity because the diode is contributing to infinite resistance. So I am able to simulate a characteristic of the non-linear resistor by using this. So if I want now to change this characteristic so that in the forward direction the resistance is 1k but in the reverse direction I want another resistance. So in the reverse direction let us say I want it to appear not as infinity but I want it to appear as 2k, so 2k simply means it will have a higher slope than this so let us say this is the problem that is given to you. In the forward direction it is going to be 1 k, in the reverse direction it is going to be 2k not any longer this R is equal to infinity, so R is equal to 2k.

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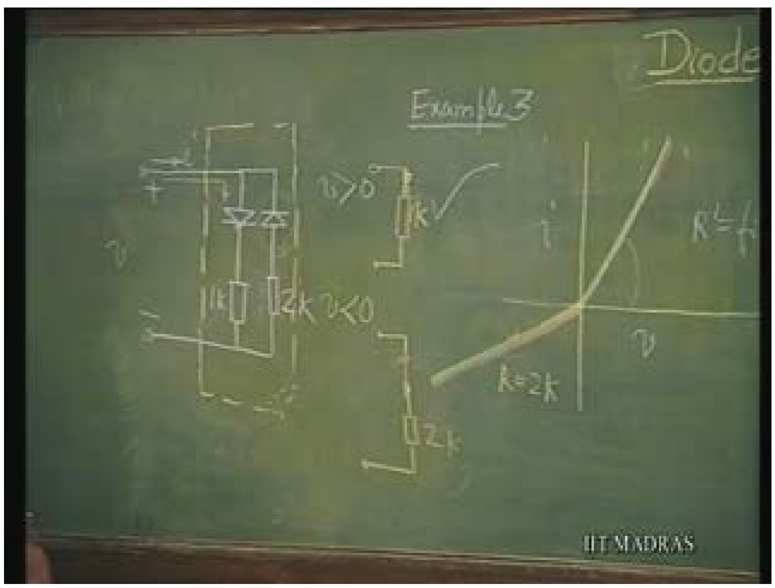

So how do I get it? Now in the forward direction this is going to govern the resistance 1k, in the reverse direction I have to bring in a 2k, I have to make another diode conduct that means when this voltage is positive and this voltage is negative I should now put another resistance but the diode should be in the opposite direction so that the diode is going to conduct and put a resistance here so that, that resistance is equal to 2k. So now what happens? As far as v equal to positive here and negative here is concerned this diode is going to be an open circuit because when v is positive and this is, this terminal is negative this is positive, this particular diode is reverse biased so this is an open circuit so the equivalent circuit is this. This is a short circuit, whereas in this case when v is less than 0 let us say this is positive and this is negative, this diode is going to permit current in this direction and therefore this 2k is going to come into picture and therefore the equivalent is going to be, this is going to be 2k and this is going to be a short because this diode is coming into picture.

So I have now been able to obtain a non-linear characteristic totally using ideal diodes and resistors which is going to be what I want, 1k in this direction and 2k in this direction. So in the next class we will see how this concept of synthesis, now this is synthesis, I just can get the slope I want by putting the resistance I want and making the diode conduct whenever I want so that I can make this piece wise linear characteristics, whatever characteristic I want. So I can synthesize a non-linear characteristic I want purely by using diode and resistors. We will see how this is going to be useful for me to obtain any non-linear characteristic whatever be it; I will simply approximate it to some piece wise linear characteristic and use diodes and resistors and obtain such complex non-linear characteristic. This kind of synthesis of diode circuit with resistors is called diode function generator, a very important application in synthesis of non-linear functions.

This kind of thing is invariably used in all non-linear function generations in analog signal processing. So the basis of this is very simple you bring in a diode with a series resistance at the required region you want therefore the slope keeps on changing depending upon the resistance you bring in. So in the next class we will see more about this diode function generation, a special application of diode function generation obviously is a rectifier diode. Where we have similar non-linear characteristics obtained for processing a specific signal which is called sinusoid. In the next class we will see how this function generation can be adopted for a specific application where the signal is sinusoid and we would like to convert that sinusoid into unidirectional voltage so that we can convert the ac into dc so that this is a ac to dc converter which is having a large number of application in obtaining from power supply from regular ac sources. So this application of the diode as a rectifier is going to be the topic of discussion for the next class.