Basic Electronics
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Lecture - 13
Diode circuits

Welcome back to Basic Electronics. We will now start with a new topic namely Diode Circuits. To begin with we will look at the current versus voltage that is i V relationship for a diode, we will look at a simple model first, we will also look at another model called Shockley model which is based on semiconductor physics. For circuit analysis the simple model would be adequate for our purposes, but the Shockley model would turn out to be very useful, where we look at the Bipolar Junction Transistor. Let us get started.

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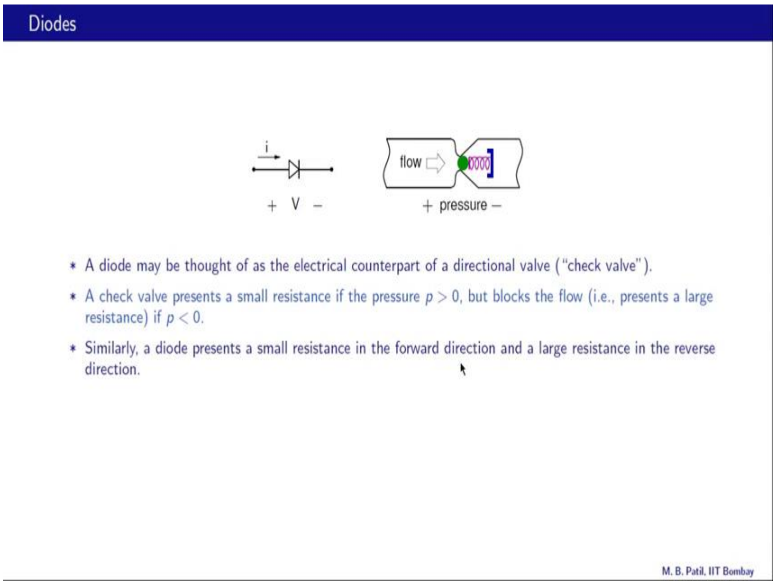

Let us now start our discussion of diodes. A diode is a 2 terminal device as shown here this side is called the p end or the anode, and this side is called the n and or the cathode. The voltage difference across the device is denoted by V, and the current through the device is denoted by i. Now a diode is very different from a register, as we have seen the i V relationship for a resistor is simply a straight line passing through the origin for a diode that is not the case. Let us look at this analogy, which will help us to understand how a diode works. A diode may be thought of as the electrical counterpart of a directional valve or check valve shown in this figure.

So, we what do we have over here? We have a pipe this one now this structure is attached to the inner valve of this pipe and then we have this spin, the spin can get compressed or elongated in that direction and then there is this ball, the ball can move in that direction. When the pressure is positive the water pressure then this ball gets pushed in that direction, and the water from here can flow around like that; and when the pressure is negative, the ball gets pushed in that direction and it gets stuck in this constriction here and no water flow is possible.

In other words a check valve presents a small resistance to water flow, if the pressure p is positive, but blocks the flow that is it presents a large resistance to water flow if the pressure is negative; and similarly a diode presents a small resistance in the forward direction, that is in this direction and a large resistance in the reverse direction that is this direction.

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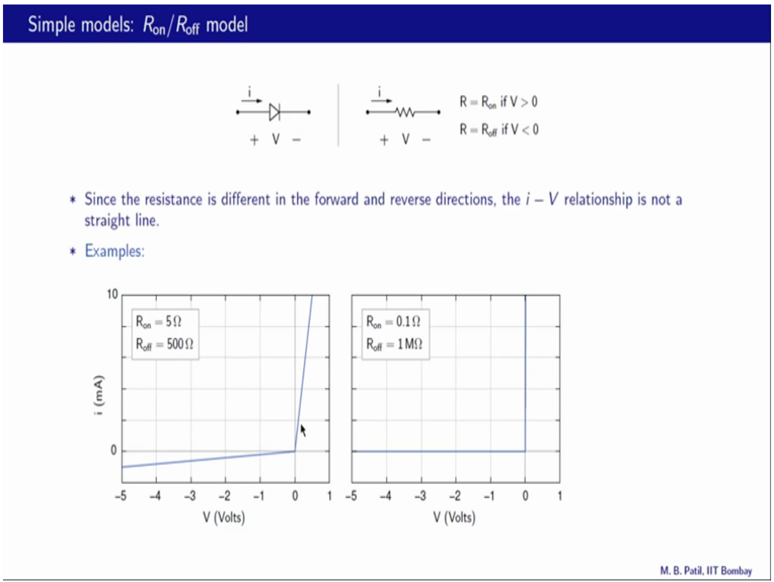

Let us now look at a simple model for the diode based on our discussion in the previous slide, but before that let us look at the polarity of this voltage and the direction of this current. This is the p end of the diode or the anode and this is the n end of the diode or the cathode; this V is marked with plus on the p side and minus on the n side and this direction of the current is marked from p to l, and here is the diode model it is simply a resistance, but it is not a constant resistance. If V is positive then this resistance is a small resistance denoted by R on over here and if V is negative then this resistance is a large resistance denoted by R off here. So, we say that the diode is on if this voltage is positive, it offers a small resistance to current flow and otherwise that is if this V is negative then we say that the diode is not conducting or it off, and in that case it presents a large resistance to current flow.

Here are some examples, what are we plotting here? We are plotting the diode current I from p to n as a function of the diode voltage with plus on the p side, and minus on the n side. This is p equal to 0, so this region is called forward bias; this region is called reverse bias.

Let us take this example first R on equal to 5 ohms, and R off equal to 500 ohms. The i Versus V relationship for the diode is given by a straight line if we use this simple model, what is the slope of the straight line? If V is positive the resistance is R on so therefore, this slope is 1 over R on. Remember we are plotting I as a function of V, and therefore the slope is one over R when V is negative the slope is given by 1 over R off now here since R on is much smaller than R off this slope is much larger than this slope.

Let us look at the second case now where we have reduced R on to 0.1 ohm and we have increased R off to one meg, and as a result of that the slope in their forward bias region has increased as compared to this one here and the slope in their reverse bias region has decreased as compared to this one here; and if we make R on equal to 0 and R off equal to infinity that is we consider the diode to be ideal, then this line is going to coincide with the y axis, and this line is going to coincide with the x axis. So, that is the ideal diode i V relationship.

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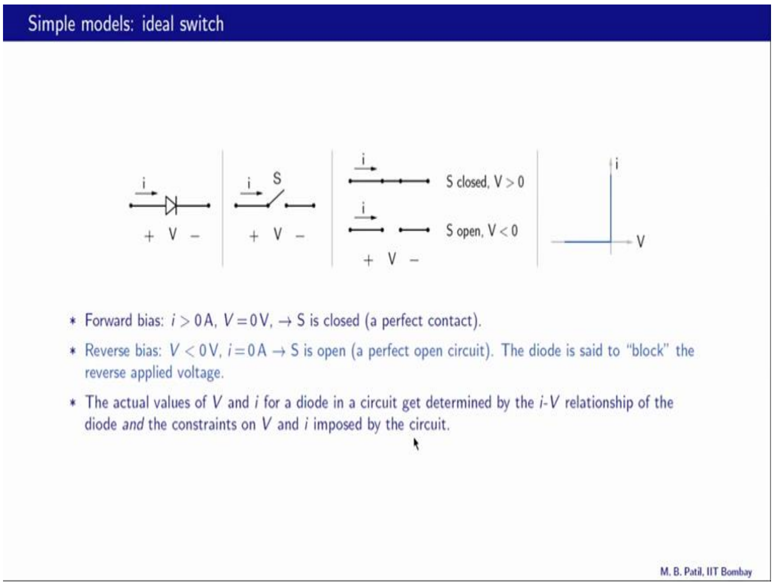

With R on equal to 0 and R off equal to infinity, the diode behaves like an ideal switch shown in this figure. If V is greater than 0 then the switch s is closed like that, it presents 0 resistance to current flow and this vertical line then describes the i V relationship for the diode.

If V its negative, then the switch is open it presents infinite resistance to current flow and the i V relationship for the diode is then given by this horizontal line. In summary under forward bias the diode current is positive as shown over here and the diode voltage is infinitesimally small because R on it is very small or 0, and we say that the diode voltage in that case is nearly 0 volts.

This switch s is closed that is it makes a perfect contact; under reverse bias the diode voltage is negative as shown here and the current is 0 that means, the switch s is open that is it is a perfect open circuit and the diode is then said to block the reverse applied voltage; and let us note that the actual values of V and i for a diode in a circuit will get determined by not only the i V relationship of the diode given here, but also the constraints which are imposed by the circuit on V and i and when we look at diode circuits this point will become more clear.

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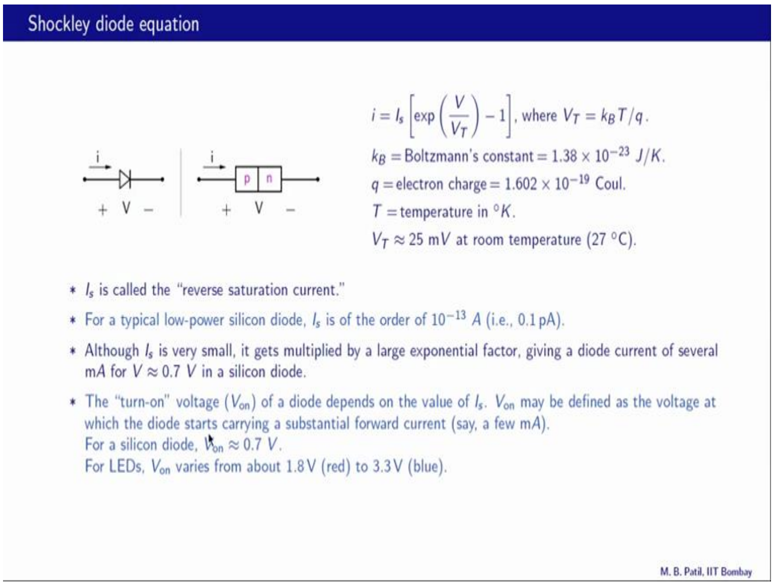

What we have looked at so far is the ideal diode model, and now let us look at a more physics based diode model namely the Shockley diode model. Shockley of course, was one of the inventors of the Bipolar Junction Transistor, as we have seen in the history of electronics lecture, what is a diode? Diode is nothing, but a junction between a p type semiconductor region and an n type semiconductor region as shown here and the diode equation given by Shockley is i equal to I s times e raised to V by V T minus 1, where V T is called the thermal voltage and it is given by k B times T divided by q, k B is the Boltzmann's constant 1.38 10 raised to minus 23 joules per kelvin, q is the electronic charge 1.602 10 raised to minus 19 coulombs and the important thing to remember is that this V T the thermal voltage is about 25 millivolts at room temperature, that is 27 degrees centigrade or 300 degrees kelvin.

This I s here which has dimensions of current is called the reverse saturation current and for a typical low power silicon diode, I s is of the order of 10 raised to minus 13 amperes or 0.1 pico ampere. So, it is rather small now although I s is very small it gets multiplied by a very large exponential factor this factor here, giving a diode current of several milliamps for a forward voltage of about 0.7 volts in a silicon diode. So, if we start with p equal to 0 and start increasing the forward bias, at about 0.7 volts, the current starts becoming significantly large before that it is very small and it is negligible and that brings us to the definition of the turn on voltage. The turn on voltage V on of a diode depends on the value of I s and we all may be defined as the voltage at which the diode starts carrying a substantial forward current say a few milliamps.

Now, for a silicon diode V on turns out to be about 0.7 volts whereas, for other diodes such as light emitting diodes V on is different and for LEDs in particular, V on varies in a reasonably wide range for a red LED it is about 1.8 volts, for a blue LED it is 3.3 volts; in our course we are going to look at electronic circuits which will use silicon diodes. So, for us this number is important.

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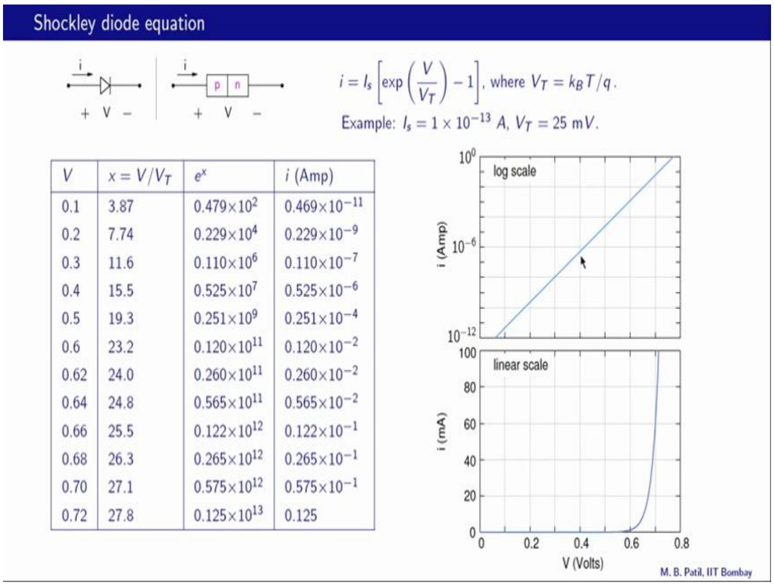

Let us look at the implications of the Shockley diode equation now, and to be specific let us take I s equal to 0.1 pico amperes, that is 10 raised to minus 13 ampere and T as room temperature; that means, p t would be 25 or 26 millivolts to be more exact.

So what we will do now is we will consider forward bias; that means, we will only consider positive V values and we will take p equal to 0.1, 0.2 etcetera and then see how this current is varying with V. Here is a table the first column here is the V value the second column is V by V T that is the argument of this exponential function, this is e raised to x where x is V by V T and finally, this column represents the current.

Let us look at one of these entries say V equal to point one volts. So, we put V equal to 0.1 volts here or V equal to 100 millivolts. V T is 26 millivolts. So, 100 by 26 gives 3.87. So, that is the argument for this exponential function, e raised to 3.87 is 0.479 10 raised to 2, and we note that this number which is about 48 is already much larger than this one over here and as V increases; that means, as the forward bias increases this exponential function is going to get much larger and therefore, we very often ignore this one over here.

Now, this e raised to x gets multiplied by I s that is 0.1 pico ampere, and that gives us the diode current. So, that turns out to be about 0.5 10 raised to minus 11 ampere, this current is too small to be of any practical relevance and therefore, we say that the diode is not conducting when the forward bias is 0.1 volts. What happens when we increase V to 0.2 the current becomes 0.2 10 raise to minus 9, with 0.3 volts its 0.1 10 raise to minus 7 and so on. So, up to about 0.5 the current is very small at 0.5 volts it is something like 25 micro amperes, and we can consider that to be 0; with V equal to 0.6 volts the current is 1.2 milliamps and we see that now the current is becoming significantly large and as we increase V further from 0.6 to 0.62 to 2.64 and so on. We see a rapid increase in the current at 0.62 it is 2.6 milliamps, 0.64 it is 5.6 milliamps 0.66 12 milliamps and when we come to 0.7 the current is 57 milliamps.

Let us now look at the plot of i Versus V in this top plot we have I on the log scale and in the bottom plot we have I on the linear scale. Here we have I equal to 10 raised to minus 12 amperes, this is 10 raised to minus 10 amperes, 10 raised to minus 8 amperes, 10 raised to minus 6, 10 raised to minus 4 and so on and if this one is ignored we can see that if we take log of I then we are going to get a linear variation with respect to V and that is what was observed over here.

Let us now come to the linear plot up to about 0.6 the current is almost 0 of course, it is not quite 0 it is finite, but it is very small and on this scale it appears that it is 0. At about point six volts the current becomes significantly large, it enters the milliampere range and by the time we reach 0.7 it has already crossed 50 milliamps. So, beyond this point the current rises very rapidly and therefore, we say that the turn on voltage for this diode is something like 0.7 volts this of course, is an approximation, but it is good enough for many applications. Before leaving the slide let us see what the current is as predicted by the Shockley equation when V is negative.

As an example let us take V equal to minus 1 volt; minus 1 volt is minus 1000 millivolts. So, minus 1000 millivolts divided by about 25 millivolts is minus 40. So, we are talking about e raised to minus 40 over here and that is very close to 0. So, therefore, i is I s times 0 minus 1 or minus I s and I s is a very small current 0.1 pico amperes in this example and therefore, for all practical purposes we can say that a diode current is 0 when the diode is reverse biased that is when V is negative.

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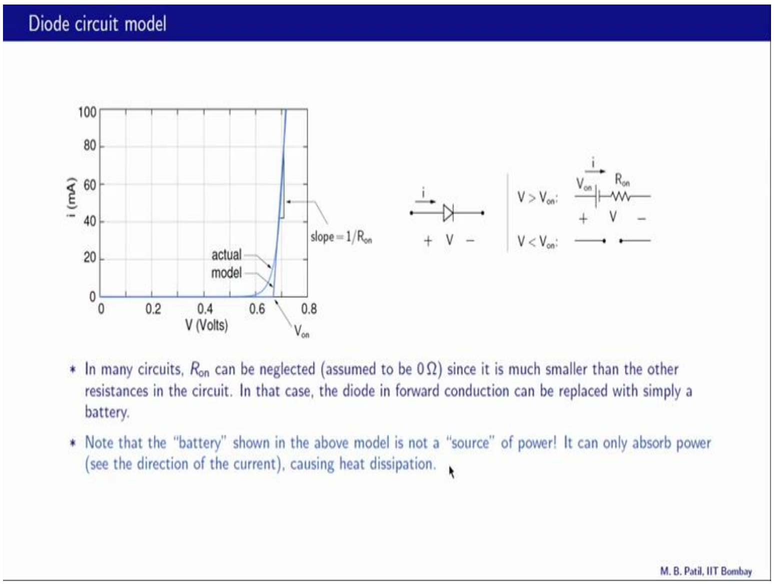

Let us now look at an improved diode model here is our actual i Versus V curve, and we can represent that curve with this simplified model. The current is 0 up to this point which we call V on, and after that it rises with the applied voltage and that behavior is represented by a straight line with a slope equal to1 over R on. This R on is called the on resistance of the diode and now what we will do is to combine these 2 pieces; this piece here and this piece into a single equivalent circuit model, and that is given by this combination over here. So, this model applies if the applied voltage is greater than V on.

It has a battery so there is a voltage drop of V on here and then we have in series a resistance which is equal to R on. In many circuits this R on can be neglected because it is very small much smaller than the other resistances in the circuit. So, in that case what we can do is simply replace this R on with a short circuit, and then the diode in forward conduction can be replaced with simply a battery this part here.

Now, one important comment about this battery note that the battery is shown in the above, model is not a source of power and why do we say that let us calculate the power absorbed by this device as a whole it is V on times I, plus the power absorbed by R on.

Now V on times I can only be positive because we know that the diode can only conduct in that direction and therefore, this diode as a device can only absorb power not deliver power; and where does the power absorbed by the diode go, it goes as heat dissipation and if it is very large then of course, we need to provide a heat sink, otherwise the diode will heat up too much and burnout.

Now one question that comes to mind is whether we should really worry about this V on or just assume that it is 0 volts like we did in the last slide. Now that depends on the context in electronic circuits our supply voltages are of the order of 5 volts or 10 volts and then this 0.7 volts may not be quite negligible compared to the supply voltage and therefore, we need to consider it. On the other hand if we are talking about the power electronic circuit with voltages of 100 of volts then these 0.7 volts may be too small and if we replace that with 0 it really will not cause any loss of accuracy.

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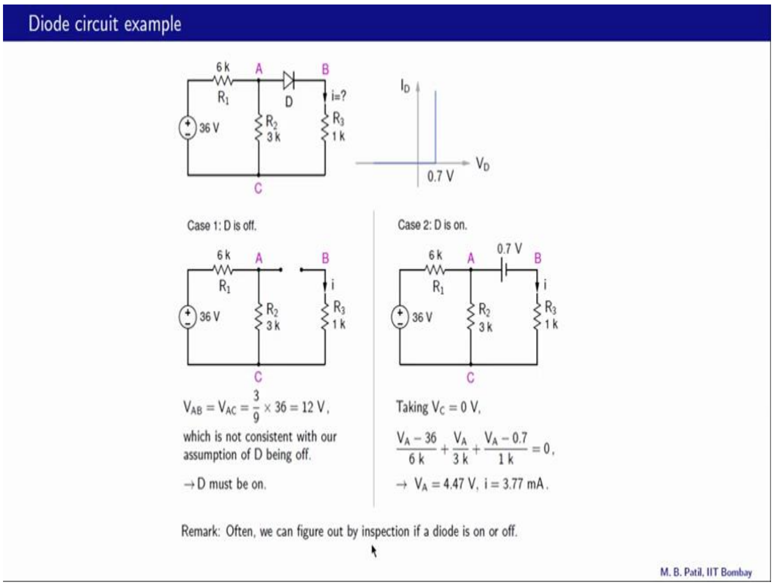

Let us now look at a few diode circuits starting with this simple circuit here; in this circuit we want to find this current high and we are given to all these component values the resistor values and the voltage source value; and we are also given that the i Versus V relationship for the diode is as shown in the figure here. This is I d; that means, the current flowing in that direction, this is V d the diode voltage with plus here and minus here and when the diode conducts in the forward direction its voltage drop is 0.7 volts, and there is no on resistance; that means, the on resistance is 0. So, therefore, this slope here is infinite.

So, when the diode conducts it is represented by the battery that we saw in the last slide, and if the diode voltage is less than 0.7 volts, then the diode does not conduct and I d is 0. Before we proceed with our solution procedure let us try to understand what we mean by finding a solution for this problem, what we want to find is I d and V d which will satisfy this i Versus V relationship for the diode; that means, the I d V d point let me find must lie somewhere on this i V curve, and apart from that it must also satisfy the circuit equations for the circuit; that means, the KCL equations, KVL equations and the branch equations for all of these components.

Where do we begin; we first need to know whether we are on this part of the i V curve for the diode or on this part of the i V curve; that means, we want to know whether the diode is conducting or not conducting. So, what we will do is, we will start with the assumption that the diode is off that is it is not conducting and then let us see what happens. When the diode is not conducting the diode current is 0 and therefore, the diode is replaced with an open circuit.

Now, in this case let us first find the diode voltage, what is the diode voltage? It is V A minus V B. Now since this current is 0, because we have an open circuit here there is no voltage drop across R 3 and therefore V B is the same as V C and V A B therefore, is equal to V A C and V A C is given by voltage division that is R 2, divided by R 1 plus R 2 times 36 volts. So, that is our diode voltage and that turns out to be 12 volts, each V D equal to 12 volts possible let us check. If the diode is not conducting we know that the diode voltage must be less than 0.7 volts, and here we have 12 volts. So, therefore, this number is not consistent with our assumption that the diode is off; what it means is the diode cannot be off in the circuit and if it is not off it must be on that is conducting; and if the diode is conducting then it has V D equal to 0.7 volts and it can be replaced with the battery like we saw in the last slide.

So, this is what the circuit will look like instead of the diode we have this battery now with 0.7 volts, and now let us see how we can obtain the solution, perhaps the easiest way to find the solution is to write KCL at this node A and let us do that by taking this node C as the reference node. So, with respect to these 0 volts here we have 36 volts here and let us call this node voltage as V A. If this is V A then V B is V A minus 0.7 volts because we have this voltage drop of 0.7 volts here and now in terms of V A let us write the KCL equation at node A.

So, that is what the equation looks like what is this first term here V A minus 36 this is V A that is 36. So, V A minus 36 divided by 6 k is this current; what about the second term V A by 3 k. V A minus 0 divided by 3 k that is the second current; and V A minus 0.7by 1 k V A minus 0.7 is this node voltage here and so that divided by 1 k is this current i. So, if we add up these 3 currents we must get 0. The only unknown in this equation is V A, so we can solve for V A and get V A equal to 4.47 volts, once we have V A this i is given by V A minus 0.7 divided by 1 k and that turns out to be 3.77 milliamps.

So, that is our solution. Now, let us note that in this case we went through this elaborate procedure of determining whether this diode is on or off, but very often we can figure that out by inspection and we do not really need to go through all of these steps that we went through this time.

To summarize we have looked at the basic functionality of a diode it is i V relationship, and how we can use a simple diode model to analyze diode circuits; in the next few lectures we will consider a few other diode circuits. See you next time.