Introduction To Electronic Circuits
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Module No 01
Lecture 27: More about Diodes, including Zener Diodes

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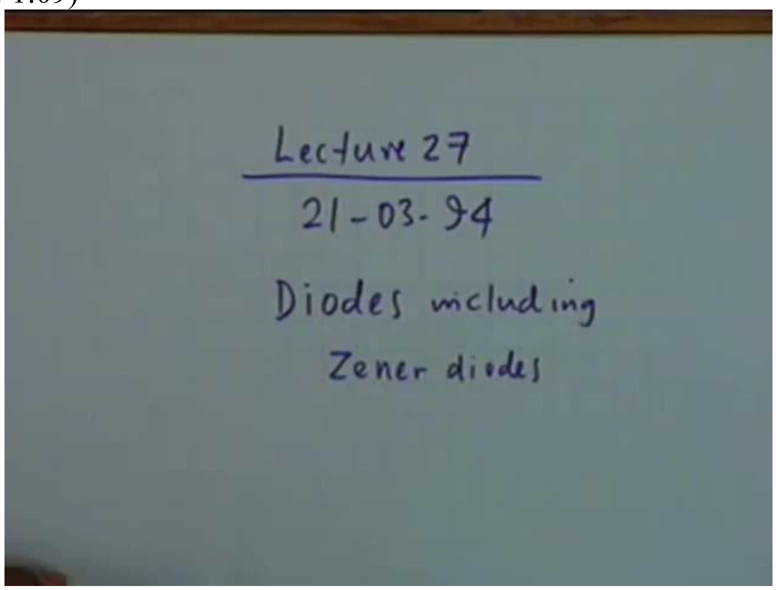

This is the 27th lecture, 21 March 1994 and the topic is, 'More about diodes, includingthe catastrophic diodes namely the Zener diodes'.

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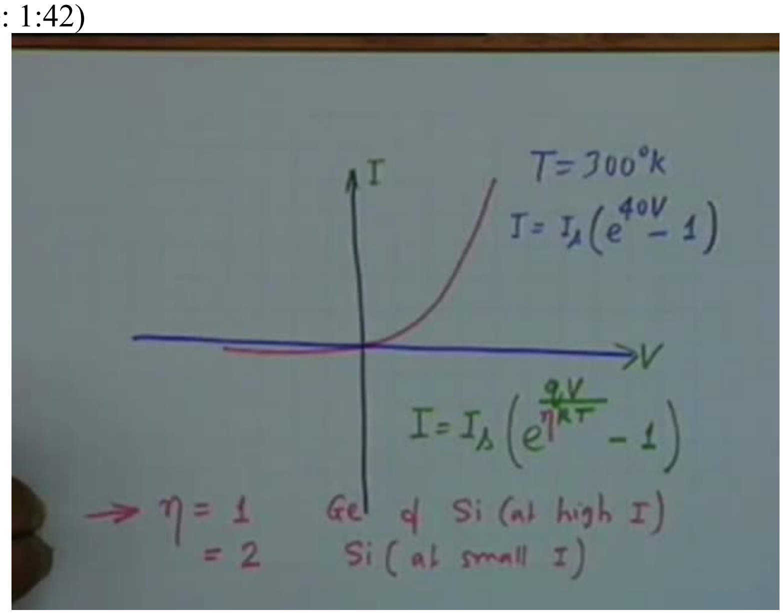

In the last lecture, we had commented that a normal diode which is not allowed to go into the breakdown region, a normal diode which is not allowed to go into the breakdown region, that means if we confine our attention to this region okay, then the equation to the curve, if this is I and this is V, equation to this curve is is represented by Is e to the power qv divided by KT - 1. This is the characteristic that, this is the equation that describes a characteristic like this. Now it is found thatdepending on the material whether that is germanium or silicon and depending on the current level that is conducted, it is safe to put a factor eta here in the dominator were the value of eta is equal to 1 for germanium diodes and for silicon at high currents at high I alright?

At reasonably large currents, silicon and germanium or by this equation eta equal to 1 whereas eta is equal to 2 for silicon at small currents. The transition region, the transition between small current and large current is somewhat fuzzy. So unless otherwise specified, we shall assume that eta equal to 1. If it is specified that eta has to be taken equal to 2, then you take it 2. Otherwise we shall take it to be equal to 1. We also showed that at room temperature, the equation at room temperature where capital T is 300 degree Kelvin at room temperature, the current can be taken as Is e to the power 40 times v - 1 where obviously eta has been taken to be equal to1.

If eta is takenas equal to 2, then instead of 40 we shall have the figure 20. You must also remember that is at temperature where the room temperature is assumed to be how much? 27 degrees C Celsius or 300 degree Kelvin. If the temperature is increased or decreased, correspondingly this figure for T has to be altered. Now as an example of application of this, we shalllet us take a very simple example.

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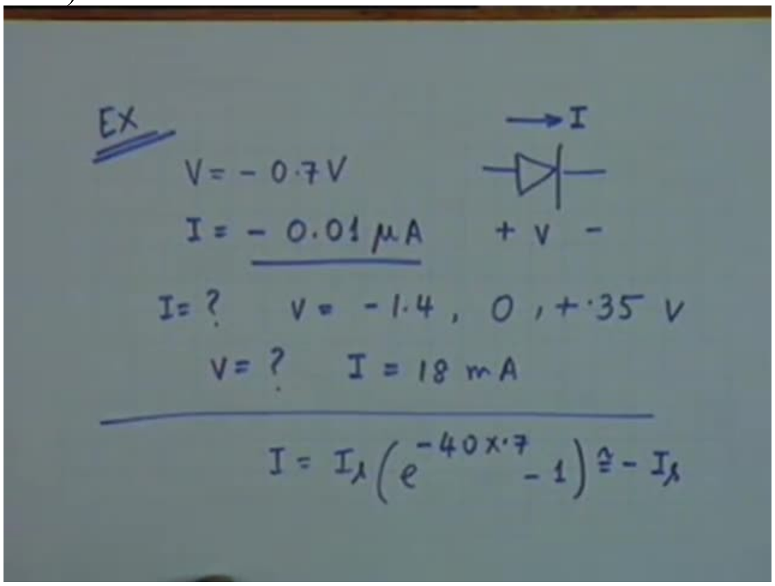

It is given that adiode and the reverse bias, that is V equal to - 0.7volt which means that it is reverse biased. Well, the convention is this, V +-,+ on the p side and - on the n side and the current flows like this, capital I. It is given thatat a reverse bias of - 0.7 the current obviously shall also be reversed. Current is given as - 0.01 microampere. You have to predict the current. What is the current when V is equal to - 1.4, 0,+ 0.35 volt. And in addition, you have to find out voltage okay for current, voltage when the current is 18 milliampere. Okay?

Basically it is an interplay of the same equation. However there are some simplifying features which I wish you to notice. Firstly, at a voltage of - 0.7, capital I is - 0.01 microfarad. Now if you substitute in this equation,i equal to Is e to the power - 40, you find - because the voltage is negative,- 40 times 0.7 - 1, you see this becomes e to the power - 28 and e to the - 28 can be ignored and therefore this is approximately equal to - Is and which means that this current, 0.1microampere is the value of the reverse circulation current.

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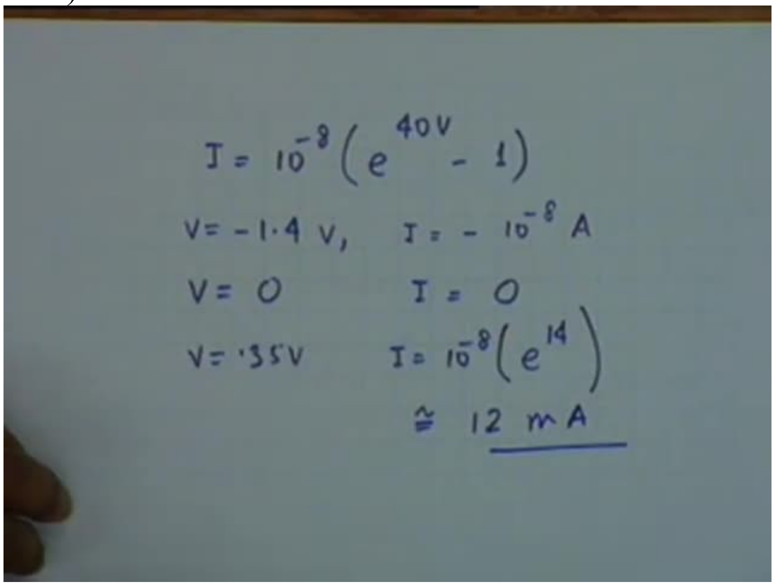

And therefore our equation becomes, our equation becomes capital I equal to 10 to the - 8, 0.01microampere is 10 to the - 8 e to the power 40 v - 1. And we have been asked to find out the current at V equal to - 1.4. But obviously, e to the 40v can be ignored and I would be equal to - 10 to the - 8 amperes. All right? Is that okay? This is double of 0.7. Even at 0.7, we have ignored it. Therefore at 1.4, it would be e to the - 56 all right? So that can be ignored. If v equal to 0, then obviously current shall be equal to 0 and if v equal to 0.35 volt, the current shall be equal to 10 to the - 8. 0.35 times 40 is how much? 1 4, fourteen and therefore e to the power 14 and that 1 can be ignored. All right? And this is my calculation shows it is about 12 milliamperes if I am not mistaking. The last part of the question asks, what is the voltage if capital I is 18 milliampere all right?

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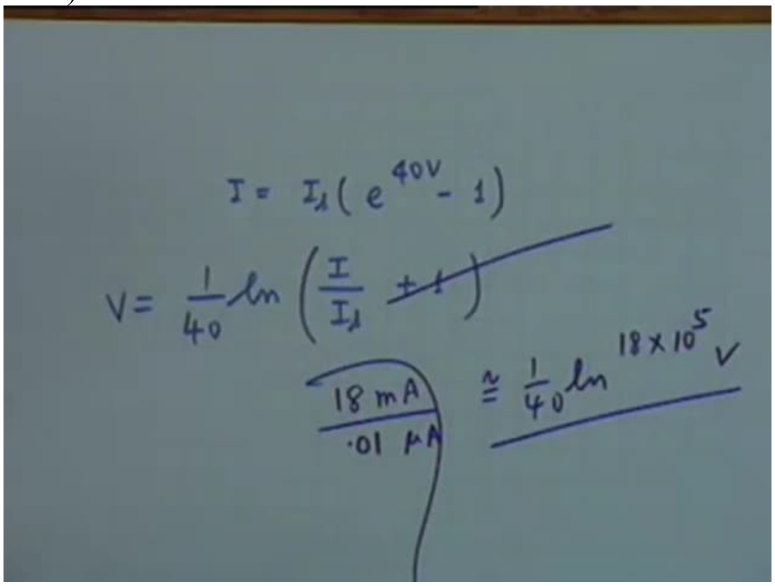

We go back to the equation that is capital I equal to Is e to the power 40v - 1. We have to find out V if I is given and the simplifying feature is, you divide by Is, add unity, take log Ln and divide by 40. This will be V. And in most cases, I by Is would be very large compared to unity. If it is forward biased, then capital I shall be of the order ofmilliamperes. For example here, it is 18 milliampere and Isis 0.01 microampere and therefore this quantity is very large compared to 1 and that can be ignored. And therefore this would be equal to 1 by 40 log of 18 times how much?

Student:(())(8:47)

Professor: 10 raised to the?

Student: 5.

Professor: 5. Okay. So many volts. All right?

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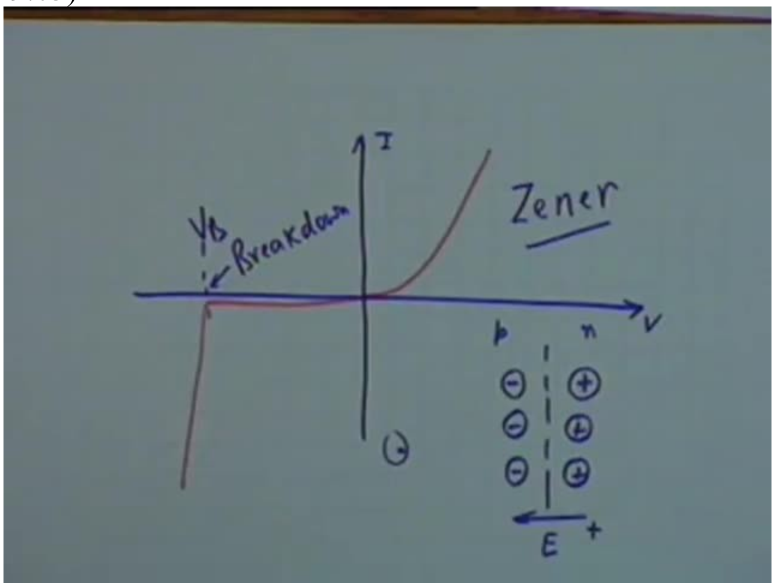

Now let us look at what happens to this characteristic to the diode characteristic when the reverse voltage is increased. This is my current and this is my voltage and the characteristic is like this. It becomes almost constant and then suddenly at some point on thereverse voltage, the current starts increasing drastically as the voltage is increased. A very small increase in reverse voltage causes a very large increase in current. And this is called the onset of breakdown. That is, it is as if the diode cannot resist any further. It breaks down.

Resist, what does it resist? It resists the flow of current. Now why does this happen? Basically there are 2 phenomena that lead to this. One of them is, you know that underreverse bias there is a separation of charges. On the p side we shall have negative charges and on the n side we shall have positive charges. So there is separation of charges and these are uncovered charges, that is the mobile electrons and holes have crossed the junction. The mobile holes from the p type near the junction have crossed to the n region, the mobile electrons near the junction in the n type region have crossed to the left-hand side.

Now under reverse bias, this separation increases all right? The potential barrier increases. As a result, the electric field E which is directed from the positive charge to the negative charge increases. And if the electric field is so large, electric field large means what? Any charge shall acquire an energy of field multiplied by, field multiplied by the charge is the force. What is the energy? Charge multiplied by potential difference okay. Then electric field can be caused only by a difference of potential. So the potential barrier increases and therefore charge multiplied by potential barrier for that energy also increases.

All right? Now if this electric bill is so large that it can attract an electron from a covalent bond, you know there is a silicon atom far removedfrom the junction butif the field is so large that it can attract one of the electronsof this covalent bond, that is if it can cause a rupture of the covalent bond and make electrons free, set electrons free, then as soon as an electron is set free, a hole also is generated. Therefore, what it causes is a electron-hole pair generation all right? And therefore the number of carriers available, that increases all right? And this onset is distinct, it is marked by a certain voltage.

Beyond this, the electric field is sufficient to generate carriers as a result of its ability to draw electrons from acovalent bond. After all, a covalent bond also has a certain amount of binding force. If the attracting force cancels this, then the electron gets free and carriers are generated. And this kind of a breakdown or this kind of an increase in current due to an increase of reverse potentialis the so-called Zener breakdown,Zener and occurs in a junction in which both sides are relative really heavily doped.

In other words,the number of impurity atoms on both sides are relative really large. Heavily doped junction,Zener breakdown occurs and the Zener breakdown voltage V sub B, the voltage, reverse voltage at which the Zener breakdown occurs can be very precisely controlled by controlling doping. That is the large the doping is, the smaller is the Zener voltage. It can be precisely controlled and you can make a Zener diode with almost any breakdown voltage so long as one point must be remembered, so long as you see, as soon as the breakdown occurs, the current increases drastically.

Current multiplied by voltage is the power dissipation. So long as the zener, so long as the diode does not burn out, if the power dissipation, if the power is within the dissipated capability of the diode, then the process is reversible. In other words, as soon as you remove the reverse voltage diode comes back to its original shape and you can again make it breakdown, you can again bring it back to normal operation. These are all reversible operations. And a Zener diode as it is called, a diode relatively heavily doped junction diode which is operated in the breakdown regions, is called a Zener operation or Zener diode.

A Zener diode can also be used as an ordinary diode. All right? In the forward direction, if you if you bias it in the forward direction, it can be used as an ordinary diode. All right? On the other hand suppose the doping is lightbut doping is heavy means that the electric field has a ready access to covalent bonds which it can rupture. Doping is light means it does not have ready access. And therefore, in a junction in which the 2 sides are relative lightly doped,Zener breakdown may not occur but before Zener breakdown can occur, that is before , not before yes okay even before theoretically is the possibility Zener breakdown sets in, the carriers, the minority carriers, for example the what are the minority carriers in the n type region? Holes, thermally generated holes all right?

These travel from the right side to the left side andif the reverse voltage is high, then it might acquire enough energy to set an electron free by colliding with a neutral atom all right? There is a neutral silicon atom here and this hole collides with this.

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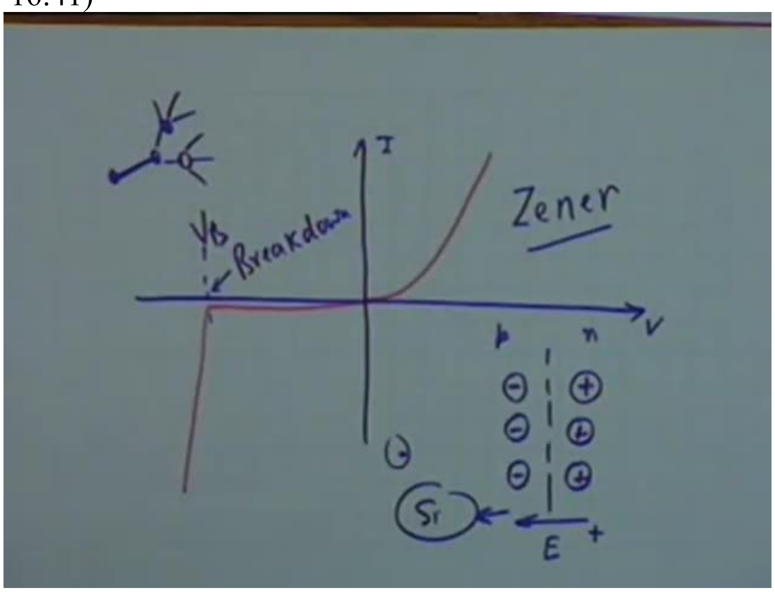

If there is a collision, there is a sharing of energy and if this hole shares some of its energy to silicon atom then it might give at 1.1 electron volt to an electron and it might set free. All right? So this basically occurs due to collision whereas in the Zener region, there is no collision. It is a,Zener breakdown is a freely fit whereas the one that you are talking of, occurs due to collision of high-energy particles with neutral atoms. All right? Now suppose a high-energy charge carrier collides with a fixed atom and sets one carrier free, this carrier, the carrier that is set free in turn accelerates in the field and can set other electrons free from other atoms. And this sort of builds up this sets let us say 2 electrons, then this goes and this sets more electron all right? Andit is a kind of an avalanche effect, avalanche effect.

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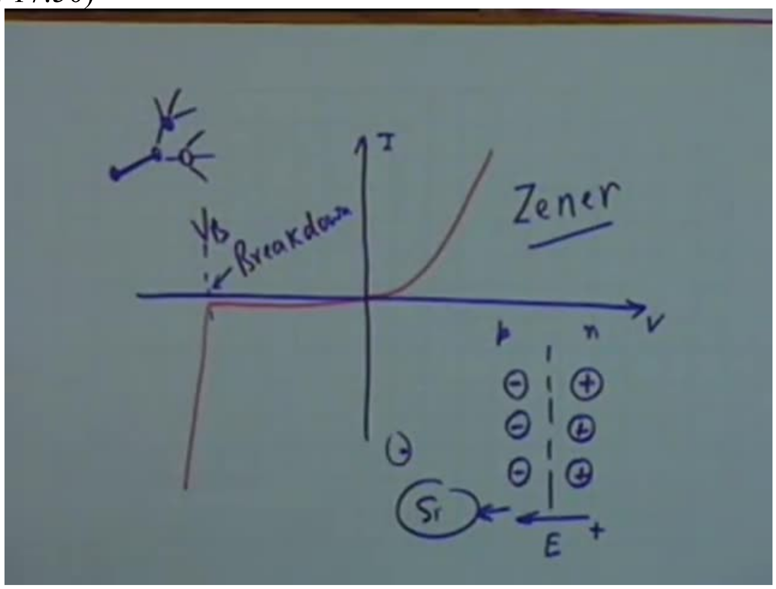

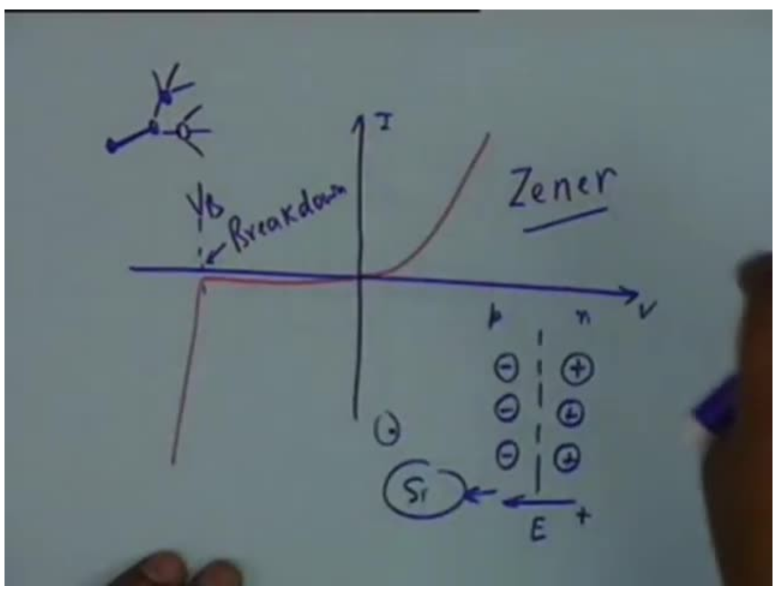

And this kind of a breakdown which are caused due to collision of carriers which fixed atoms is called avalanche breakdown. The only thing that is remembered is that Zener breakdown occurs due to electric field in a material in which there is relatively heavy doping, avalanche breakdown occurs due to actual collision of high-energy particles with fixed atoms and can occur even in lightly doped junctions all right? In practice when a breakdown occurs in a diode, it is usually a combination of both. That is, the electric field and also high-energy particles. They come into effect.

However, as I said, the Zener effect is more popular because it can be precisely controlled, avalanche breakdown is not as precisely controllable as Zener breakdown. And therefore Zener diodes are very popular in situations where you wish to keep voltage across a load constant irrespective of the current drawn by it.

If you look at this, the ideal characteristic would be, if this curve falls sharply, vertically down, then you will see the voltage remains the same but the current can increase depending on, current can increase or decrease depending on what you want, what the load wants. The capability of a Zener to maintain a constant voltage irrespective of the current, constant voltage irrespective of the current,what is it in terms of circuit theoretic terms? It is a voltage source, not current source. It is a voltage source, keeps its voltage constant irrespective of the current. And therefore, the Zener can be used as a voltage source which means that you can stabilise voltage across a load.

And in that situation, a Zener diode is the circuit that uses a Zener diode to make such constant voltage across a load is called, the circuit is called a Zener regulator. We shall look into the Zener regulator in a moment. But let us systematically proceed to find circuit equivalence,, electrical circuit equivalence of the normal diode and the Zener diode. Then we shall see how it is applied.

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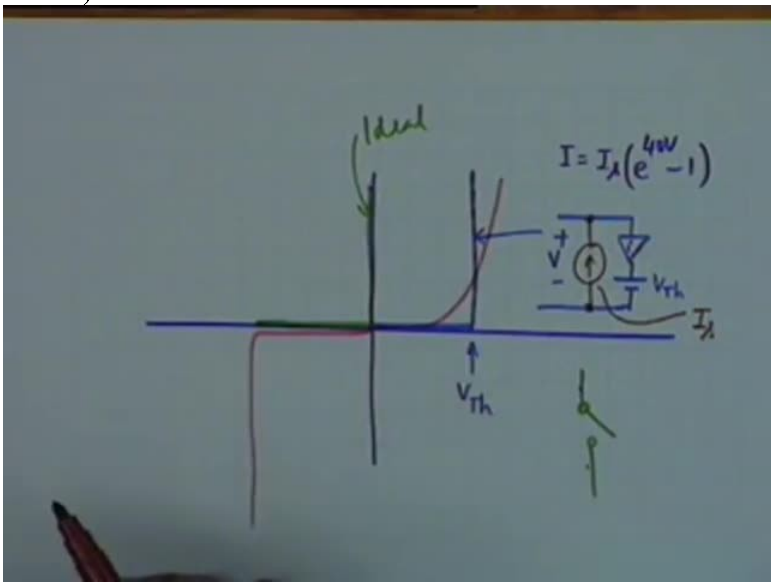

A normal diode, you see we can always work of course in terms of, I beg your pardon. This is not correct. A normal diode has a characteristic like this. It rises sharply like this, then it goes below and falls sharply like this. There is no kink here. It is a it is a continuous curve all right? Now we can of course work in terms of thecurrent voltage relation that is I equal toIs e to the power 40v - 1. But this as you see is a non-linear relationship all right? And analysis every time by invoking this equation becomes a difficult job. So Electronics engineers prefer to have a model and that too a linear circuit model all right?

So what one does is, one of the most ideal things that one does is, one assumes that the diode characteristics one one, this Isis a very small quantity. So for an ideal diode, it should have been 0. For an ideal diode, as soon as the voltage is positive, it should conduct. So this green characteristic is that of an ideal diode. An ideal diode is like an ideal switch. It is either on or off. When a switch is on, when a switch is on, it can conduct any amount of current with a voltage drop of 0. That is what is represented by the green curve all right?

So an ideal diode is like a switch. When it is off, the currentis 0. Any voltage drop can occur but the current is 0. You can connect any voltage source between these 2 but no current. When it is on, the switch is on, any current can be conducted with 0 voltage across it all right? This is the ideal situation. Nowone of the ways that a non-ideal situation can be taken into account is to approximate this by means of a straight line, a vertical line here all right? Soit is 0, the current is

0 up to this and then goes up like this. We have introduced one nonidealness, namely we have said that the current, the diode does not conduct exactly at 0.

It conducts at some voltage here. Mainly we are approximating this red curve by the blue curve and this voltage is called the threshold voltage,Vth and is of the order of 0.7 for silicon and 0.3 for germanium. Now this curve can be approximated by an ideal diode, now we shall use the symbol I inside to denote that it is ideal all right? An ideal diode that is a switch but these diode does not conduct till this potential rises to 0.7 volts. So we shall have, we have a battery which is equal to the threshold voltage. So this is the symbol, this is the model for the nonideal diode,nonidealness being only in terms of the threshold voltage all right?

This diode in the reverse direction, this model, if the voltage here polarity is reversed it does not conduct. All right? This diode conducts only when V exceeds Vth and once V exceeds Vth, the diode acts as a short all right? Now what happens in the reverse direction? This dialogue does not conduct in the reverse direction. Is not that right? If the polarity of V is reverse, there is no current flow. Now to account for the current flow in the reverse direction that is the reverse saturation current, we can if we so desire, modify this to include a current source here whose value is equal to Is all right?

This accounts fora practical diode. Thisis a good model for a practical diode when the diode is still thought of as a switch all right in the forward direction. In the forward direction, it is a switch, in the reverse direction the current is a constant. This current is almost a constant. All right? Now let us complicate it further. Let us make a more practical model.

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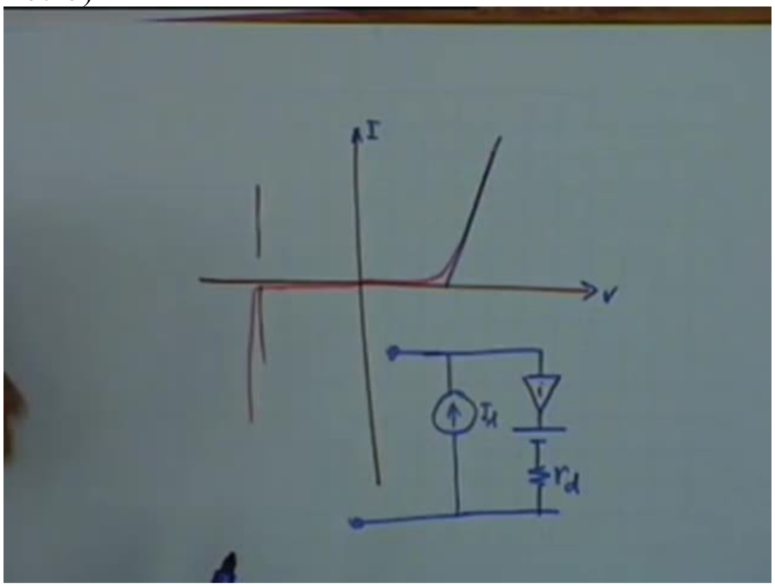

And for a more practical model, let us draw the characteristic, negative and then we are confining our attention before the breakdown, before breakdown occurs all right. And what we do now is that werepresent this part of the curves by means of a straight line. All right? The rising part. It is not completely vertical. The rising part, we make itwe approximate it by means of a tangent, straight-line all right which is inclined at an angle slightly less than 90. If it was 90, then our previous model would have been valid. Now obviouslythe resistance of this, the resistance corresponding to this, this is current, this is voltage, the resistance corresponding to this, what is the resistance?

Delta V delta I. In the previous model when it was vertical, the resistance was 0 and therefore all that we have to do now is to take an ideal diode I, then the threshold voltage Vth, which is 0.7 for silicon and we shall have to use a small resistance, we call this Rd, the d stands for dynamic. That is it is the slope of this line all right? And then if you want the reverse saturation current also to be taken into account, well you connect a current source and this is the linear equivalent circuit of a diode. And most of our practical diode circuits can be analysed in terms of this equivalent circuit. On the other hand if we take well before we take a Zener,let me take 1 or 2 examples.

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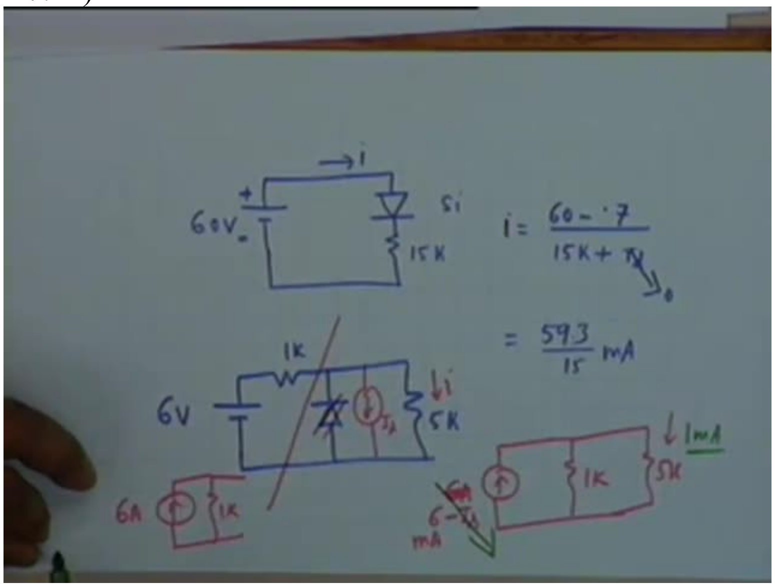

Suppose you have a 60 volts source, a silicon diode. A silicon diode means the threshold is 0.7. And then you have a 15 K resistance all right? We want to find out the current in the circuit. Obviously, the current in the circuit shall be, if you replace this by its equivalent circuit model, it is a forward biased diode, forward biased 60 volts +- and therefore Is shall have very little effect. All right? So you can ignore Is. If you also ignore Rd, the dynamic resistance of the diode, well if you want, you can include it. Obviously, the current in the circuit shall be 60 - V threshold that is 0.7divided by 15 K + Rd.

Usually Rd is of the order of a few tens of ohms and therefore this can be ignored and the current become is 59.3 divided by15 milliamperes all right? And this, yes?

Student: If we are not ignoring Is, then (())(28:46)?

Professor: If you are not ignoring Is all right, then you apply superposition. That is, 1st you find out due to 60 volt, then you find out due to Is. Is is now current source. So you have a circuit in which both current and voltage sources are there and have to fall bit exactly. For an example, if I have the, if I have a reverse connection, let us say I have a 6 volts, then a 1 K, then a diode connected in the other direction, this would serve as a good example. If I if Iif I have a diode like this, then obviously,this diode is reverse biased and in reverse bias, you can ignore the ideal diode,the threshold voltage and the dynamic resistance. So all that you have to do is to replace this by means of Is.

Now will it go down or up?

Student: Up

Professor: It will go down. It is the reverse saturation current.

And therefore what you have now is a 6 volt, 1K, one 5K and Is and you have to find out the current through the load, this I obviously you can replace this by a Norton source. Then you have 6 ampere. Actually it will be 6 - Is all right? 6 ampere current source and then another current source Is in parallel with 1K and 5K. So this current can now be obtained by current division all right? 6 -or 6 +? 6 -because the equivalent source of this is 6 ampere, 1K, that is it. This current goes down. So 6 - Is.

Student: (30:50)

Professor: 6 milliamperes, yes that is correct. 6 milliamperes- Is. Is is of the order of micro and therefore the current shall be controlled by basically by 6 milliampere and you can show that this would be, how much would this be? 1 milliampere okay.

So if we are given a diode model or if we are given a diode characteristic, we can find out a model and analyse circuits in terms of the model rather than using capital I equal to Is e to the power 2v because taking logarithm, anti-logarithm and in a non-linear circuit, you never know, you never are very sure of what you are doing.

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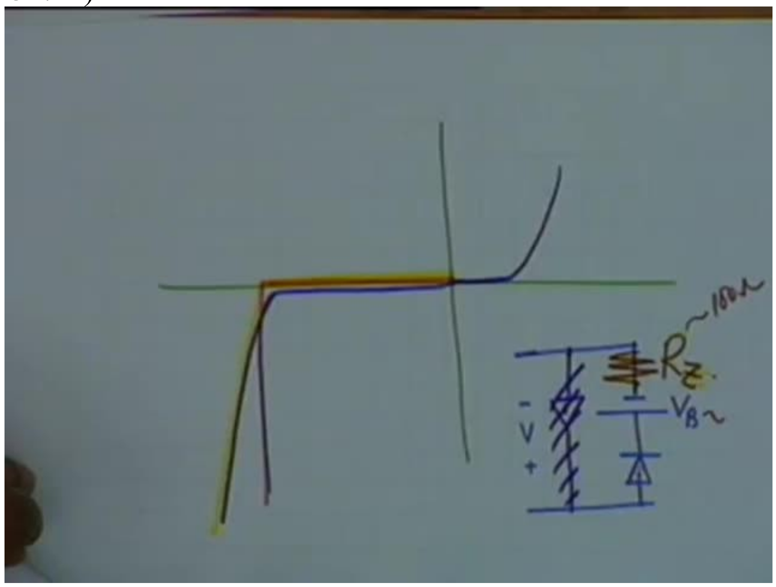

Now let us look at the Zener diode. A Zener diode as I said, can be worked as a normal diode in the forward biasing condition. That is in the forward biased condition, well you can represent it by a switch if you so desire. Switch with a threshold if you so desire. Switch with a threshold and a dynamic resistance. Switch with a threshold, a dynamic resistance and a reverse saturation current, all these apply under normal conditions. It is, a Zener diode is not operated under normal condition. That is not its purpose.

A Zener diode is operated in the reverse biasing condition. And one of the model that one uses is this. That is, one approximates this by means of 0 current,Isis put equal to 0 and thena vertical line like this. I must tell you that the actual characteristic is like this, not the, not a vertical line. This is the actual characteristic. It has a slope, it has a finite slope. All right? Now how do you represent the Zener diode? All right? How,what circuit model do you use for the Zener diode? Well, if I use the red approximation, red characteristics, then obviously all that I have to do is that there would be a threshold voltage all right?

And then this is good enough. We have an ideal diodeinconjunction with a threshold voltage which obviously is the breakdown voltage, the voltage at which break down occurs all right? And you see that if you apply a reverse bias here, then the diode shall conduct. If you apply a bias like this, if you apply a voltage like this, the diode conducts only when V exceeds Vb all right? And after that, if it is the red curve, then we have approximated by an ideal diode all right.

Now in thisif you want to include its behaviour as a normal diode, obviously you should put a ideal diode here or an ideal diode in conjunction with threshold voltage Rd, reverse saturation and all that all right?

Now since we are not using a Zener diode in the normal operation, we can forget about this. Is that clear? We are only considering the equivalent circuit when it is biased, when it is used in the Zener region or the Zener mode of operation. Now once again, this sloping character of the actual Zener diode can be approximated by including a resistance and therefore what we do is I should use some other colour, let us use yellow. What we do is, we approximate up to this all right, the yellow line and then we approximate by a straight line whose angle with this axis is slightly less than 90 and you can define a dynamic resistance for this characteristic.

And all that you have to do is to include a resistance here. Include a resistance here, you call this Rz, the dynamic resistance of the Zener diode all right? Can you see this? Can you see the yellow colour? No. All right, this is Rz and this is a fairly good representation of a Zener diode.Vb as I said, can be controlled. You can get Zener diodes right from let us say 6 or 7 volts to 100 volts by controlling the doping. The resistance, this resistance is of the order of 100 ohms all right? And to to illustrate the applicationof the Zener diode, themost important application namely as Zener voltage regulator, we take an example.

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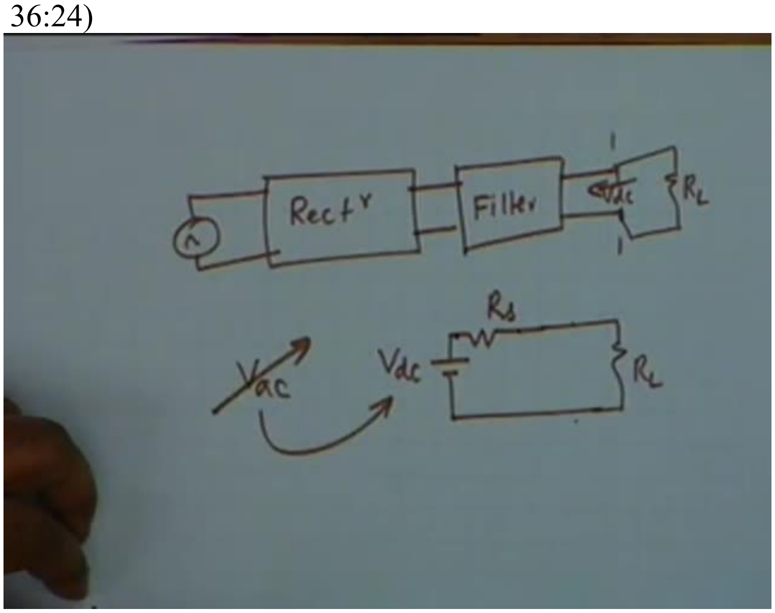

Well, the motivation is this that if you want a DC power supply, what you do is, you take an AC, you transform it, step up or step down, subject it to rectification, halfway, full wave, bridge or the other type, then you use to kill the ripples, you use filter. You smoothe out. And the output should be pure DC all right? This is Vdc and then you apply it to the load, let us say RL. Now obviously this Vdc is not an ideal voltage source. Why? Becauselooking back, the thevenin equivalent resistance is not 0.

The filter has series inductors which have resistance, the rectifier has diodes which have resistance, dynamic resistance, the transformer has resistance and therefore this Vdc that you see can be used as a voltage source and a resistance Rs, a source resistance Rs and then an RL. Now if Vac changes, if the line voltage fluctuates which is a very very common and unpopular phenomenon in Delhi and the rest of India. The line fluctuates from anywhere between 190 to 400 volts. Then obviously,Vdc shall also change.Vac shall cause a change in Vdc.

That is one thing. 2nd thing is, if the load fluctuates, you want the fan to be at half speed or full speed, you want to control the lights all right then RL fluctuates. If RL actuates, the current drawn by the load fluctuates and therefore the voltage drop in Rs also fluctuates which means that the load voltage fluctuates all right. To counter both of these, we use a Zener all right and the circuit is like this, very simple circuit.

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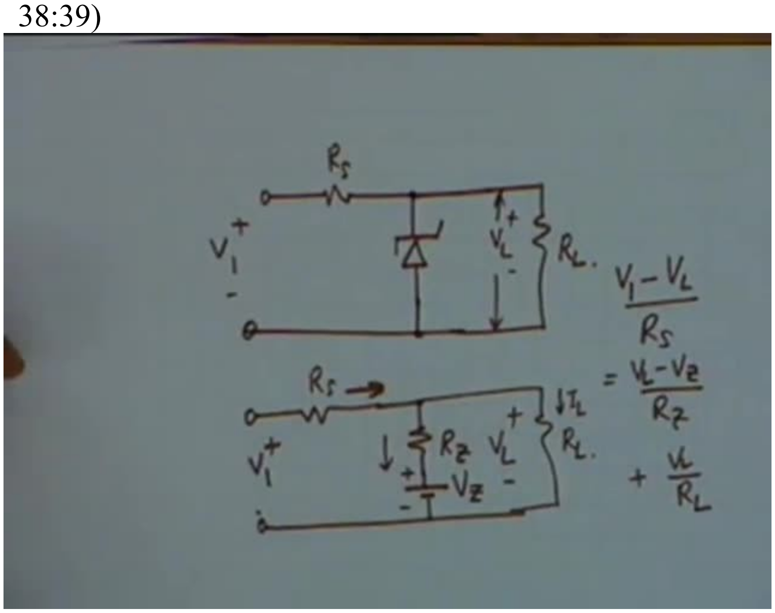

What we do is, theVdc source, we call this V1 +-,this may be present, the source resistance or a resistance connected intentionally. One has to connect a resistance here and then you have the Zener. The Zener is represented like this. It is represented by means of a wavy line here instead of straight line. If it is a straight line, then it is a normal diode. If it is a wavy line like this but then it is a Zener diode and you see, the Zener is connected in the reverse biased mode and then you have the load RL. All right? This is the circuit and it is this voltage which is required to be maintained constant.

Now you see, theequivalent circuit of this Rs, then the Zener, you shall represent by because it is operated in the reverse direction, all that you need to include is an R sub z andthe breakdown voltage. In which polarity?+up or - up?

Student: up.

Professor: No.

This is Vz let us say, the Zener voltage, the breakdown voltage instead of Vb, we say it is Vz and then you have the load RL or the diode, the diode obviously conducts. Is not it right? Otherwise current cannot flow. That is an ideal diode. So it represents a 0 resistance, short-circuit. So you have not introduced a diode. If you so desire, youinclude a diode. All right? Now this is VL. Now we can analyse this circuit by KCl, that is what we have is V1 - VL divided by Rs, this is the current coming in shall be equal to VL -Vz divided by Rz, is the current through the Zener resistance,Zener diode + the current going through the load, IL which is equal to VL divided by RL all right?

Very simple analysis but very significant improvement in the characteristics. Can I remove this? Have you written down the equation? If I simplify the equation, now I can find out VL in terms of V1 and Vz.

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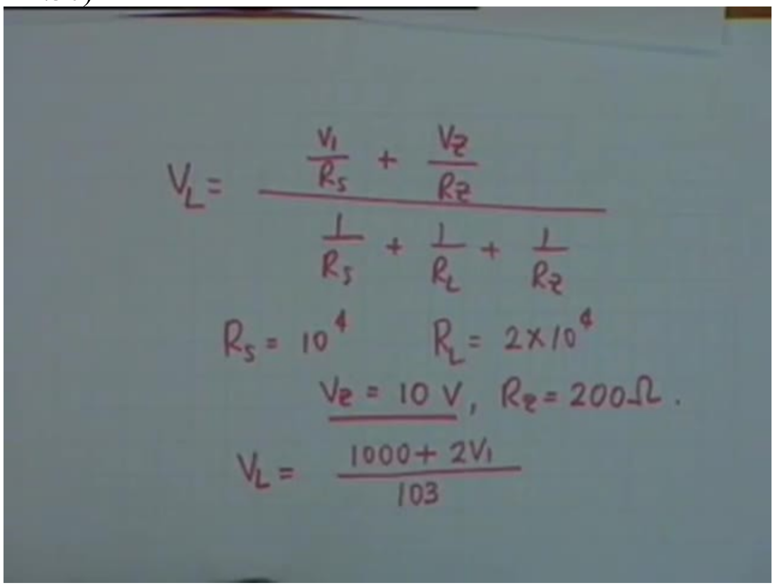

And the relation, I will skip the algebra, the relation I have worked out to be V1 divided by Rs+Vz divided by Rz divided by 1 over Rs+ 1 over RL + 1 over Rz, simple algebra you can show. To get an idea, let us take some typical value. Let us say Rs is 10 K, 10 to the 4. Let us say RL is 20 K, that is 2 times 10 to the 4 and let us say Vz, the load voltage I want to maintain constant at let us say 10 volts.Vz is 10 volts and typical Rz, the dynamic resistance of the Zener diode is 200 ohms. Then you can show that VL, if you substitute these values, you can show that VL is 1000, again I skip the arithmetic, 1000 + twice V1 divided by 103. All right? Now Vz is 10 volts. Now V1, unless 2V1 is comparable to 1000, obviously VL shall remain a constant at 1000 divided by103 which is slightly less than 10 volts. All right?

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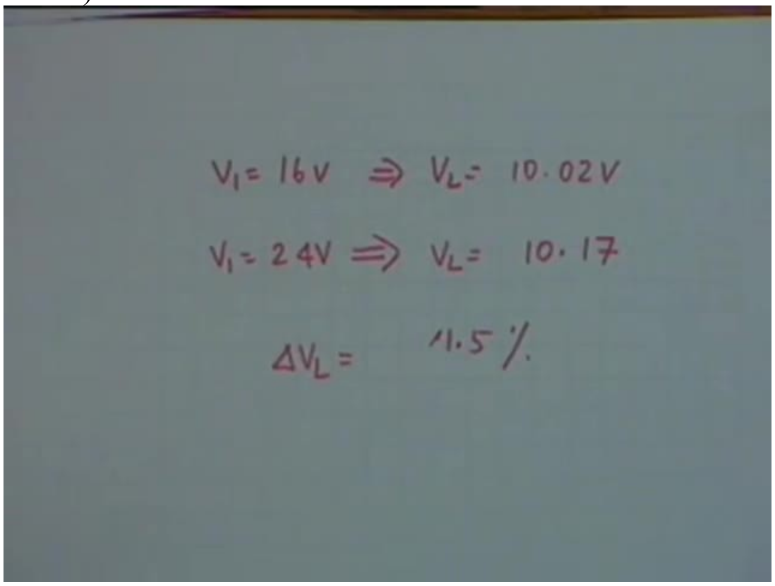

For example, suppose V1 is 16 volts. This gives you VL equal to, I have calculated this to 10.02 volt. If V1 now increases, the DC voltage increases by 50 percent which means that V1 equal to 24 volt, from 16 to 24 is 50 percent increase, then VL changes only to 10.17. You seehow constant it remains for a while and fluctuation here from 16 to 24, the load voltage changes only from 10.02 to 10.17. And Delta VL if you calculate this, 0.15, oh it issimply how much? 1.5 percent. That is it.

50 percent fluctuation in the DC is reduced to only 1.5 percent fluctuation in the voltage across the load and this is the most common method of voltage regulation. The simplest and the most common method used in instrumentation, used in all kinds of applications. Unfortunately, very high-voltage Zeners are not available. Very high voltage Zeners not available and therefore this kind of regulation is limited to low voltage only. Next time, tomorrow we will start transistors.