Introduction To Electronic Circuits
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Module No 01
Lecture 26: Semiconductor Physics (Contd.)

In this 26th lecture, we continue our discussion of Semiconductor physics very qualitatively and we propose to end up today in the diode equation.

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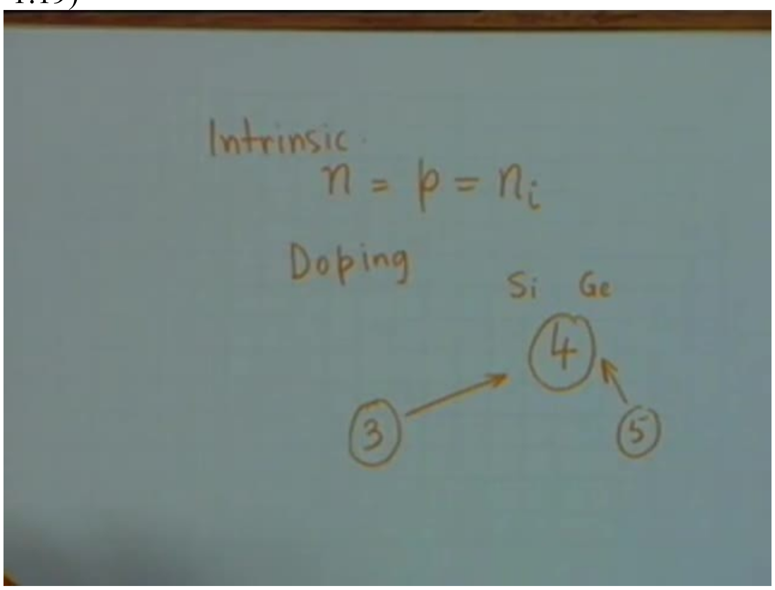

We have seen last time that intrinsically, a semiconductor, the concentration of electrons and holes is the same in an intrinsic semiconductor and this is denoted by the symbol N, the subscript I stands for intrinsic. We have also seen that doping upsets the balance between electrons and holes. For example, doping could be of 2 types. Silicon and germanium, both are at 4th column holders in the periodic table which means that their valency is 4. We can inject either a trivalent impurity like aluminium or boron or inject a pentavalent impurity like arsenic or phosphorus. Any other? Antimony, yes. Any of the adjacent elements.

Depending on what type of element you introduce as impurity, the semiconductor becomes one of the 2 types. For example, if it is a boron or a trivalent impurity, then a trivalent impurity atom occupies the position of a silicon atom and can satisfy only 3 of its bonds. The 4th bond remains unsatisfied which means that this acts as a positive charge and a hole is created there. The the number of holes therefore exceeds the number of electrons and then this is called a p type semiconductor, p type. Similarly and the the bound positive charge is called an acceptor ion. Alright. Is the bound one a positive charge or a negative charge?

This gives, it becomes a negative charge. Is not that right? It gives away, it can accept one of the electrons which means its as a hole. When it accepts, it becomes full but when it does not accept, normally it should have 4 in the silicon crystal structure. So it becomes an acceptor ion, a negative ion, charged negatively. On the other hand, if we introduce an arsenic atom, a pentavalent atom, then 4 of its electrons satisfy the covalent bond and the 5th electron becomes free and it becomes a bound fixed positive charge all right?

And as I have told in the tutorial class, one of the equations that holds good under doping is that the total positive charge should be equal to the total negative charge because as a whole, the semiconductor is neutral.

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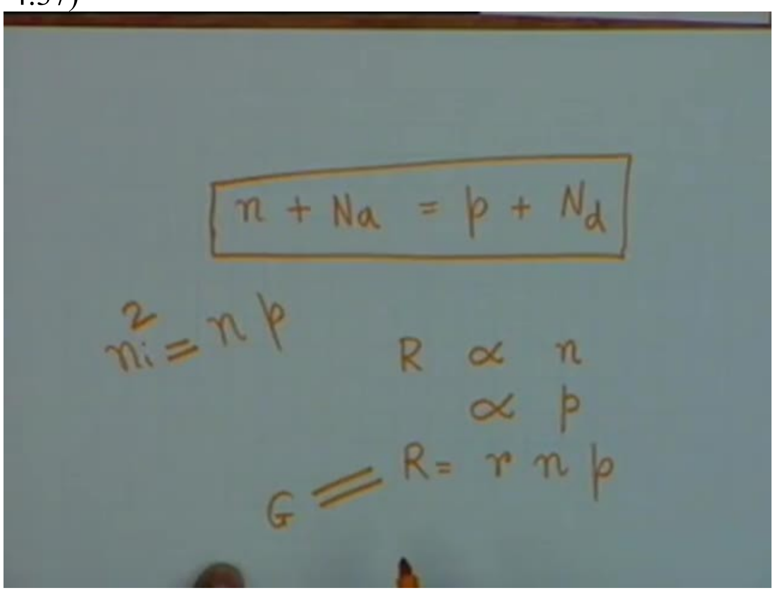

Which means that if I dope a semiconductor with the both types of impurities, that is acceptor as well as donor impurity than the total negative charge n plus should be equal to the total positive charge. Now what is the, which one contributes to fixed positive charge? Donor. Therefore nd. We assume that all donor atoms are ionised. Similarly n plus Na. Small n is the concentration of electrons, small p is the concentration of mobile holes, capital Na is the concentration of acceptor ions and capital Nd is the concentration of donor ions.

This is, this holds in general where we have both types of impurity, that is acceptor as well as donor impurities. In a special case of only one type of impurity, one of the terms on either the left or the right shall cancel. For example, if we introduce a donor type of impurity only, then N sub A shall be equal to 0. If we introduce acceptor type of impurities only, then N sub D shall be equal to 0 but this equation should in general be valid all right? Now when you disturb when you disturb the balance of holes and electrons by doping, there is a certain relationship which holds between the intrinsic consideration ni and the concentrations of n and p as a result of doping and we can we shall show that the product is a constant equal to square of ni.

And this happens, the logic is as follows. That if you leave a semiconductor, let us say an intrinsic semiconductor. If you leave an intrinsic semiconductor at room temperature, undisturbed, if you leave it in peace, then there exists an equilibrium value for p and n at that particular temperature and this equilibrium value is the so called intrinsic concentration. Now as soon as there are mobile holes and mobile electrons, there is a finite probability that the holes and electrons shall recombine with each other alright?

And therefore therefore there exists a generation as well as a recombination. Generation because of thermal energy. Thermal energy is the cause for generation of electrons and holes and recombination occurs because there is a finite probability that an electron shall collide with a hole and therefore they will recombine and disappear. Now normally, the recombination rate is proportional to the concentration of electrons. It is also proportional to the concentration of holes. It stands to reason that if the number of number of electrons increases, the recombination rates will increase.

If the number of holes increases, the recombination shall increase and therefore in general, the recombination rate that the number of electron hole pairs which combine with each other and disappear as neutral charges shall be given by some constant R multiplied by n times p all right? This is the recombination. On the other hand if n and p, if a certain number of electron is and holes recombine with each other and and disappear, obviously there there are vacancies created and therefore the thermal energy now generates electrons and holes to take their place.

And therefore, the rate of generation normally shall be equal to under thermal equilibrium, shall be equal to the rate of recombination that is equal to R times n times p. Is that clear? An equilibrium value at a particular temperature exists only when the rate of generation, thermal generation is equal to the rate of recombination which is equal to r, n and P.

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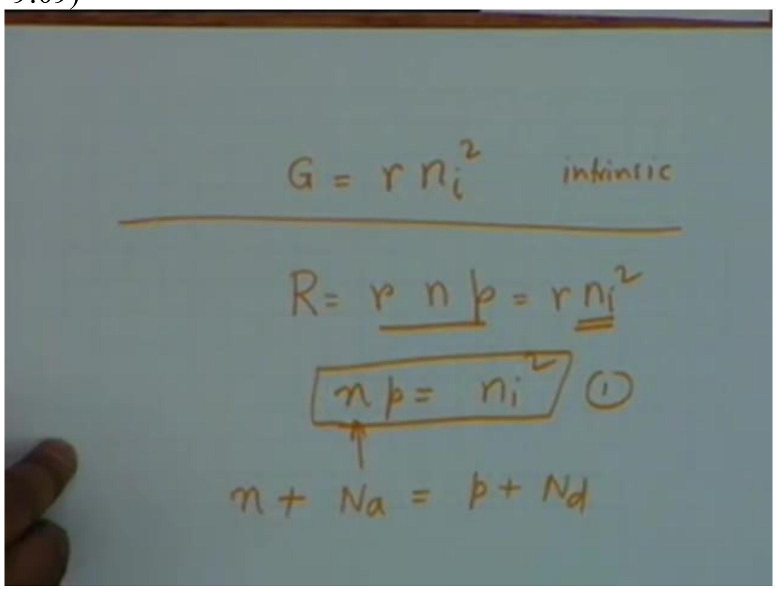

And if it is an intrinsic semiconductor if it is an intrinsic semiconductor, then G the rate of generation is given by r n i square. Intrinsic. And this must be equal to r times n times p alright? This is the story of intrinsic semiconductor. If it is a doped semiconductor, the rate of generation does not substantially change because rate of generation, why does generation occur? Because of thermal energy. The rate of, you see the doping is very very light. There may be 1 hole generated per 10 to the 7 silicon atoms and therefore the rate of generation basically depends on temperature means that at under any condition of doping, the rate of generation remains the same, which means that the rate of recombination which is equal to r times n times p under thermal equilibrium could be equal to r n i squared under any condition of doping.

Whatever be the doping, doping does not disturb the rate of generation. And therefore, it shall not disturb the rate of recombination either because in thermal equilibrium, they should be equal. Which means that if there is an unbalance between n and p, a product n and p must be equal to n i square which means that if you increase n by doping, p necessarily has to decrease by the same ratio. If you increase n 10 times, p must decrease 10 times all right? Similarly if you increase p by acceptor impurity, then n must decrease by the same ratio in order that, this is one of the fundamental relations, number 1 and the other relation is which I have already written, charged neutrality requires that n plus Na is equal to p plus Nd all right?

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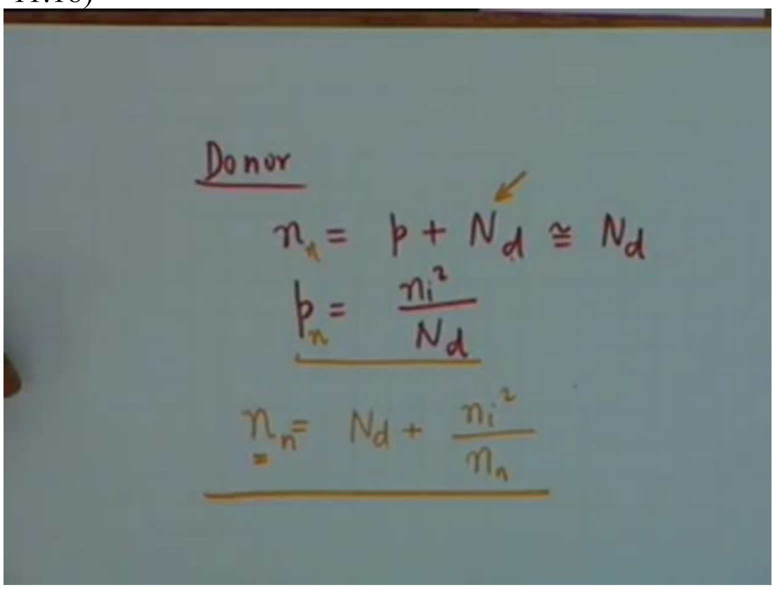

Let us consider 2 special cases. Namely, let us consider a donor type of impurity a donor type of impurity. That will mean that n, donor type impurity means. N sub capital A is equal to 0, that means n should be equal to p plus Nd. Normally, Nd will be much greater than the intrinsic concentration of p type of carrier. In silicon, it is 1.5 times 10 to the 16 and the donor impurity will normally be about 4 orders of magnitude higher. That is of the order of 10 to the 20 and therefore Nd shall be much greater than p and therefore is approximately equal to Nd.

And then, the p impurity, P type of the the concentration of holes shall therefore be equal to n i squared divided by Nd alright? This is what type of semiconductor now with a donor impurity? n 5. So we denote this by a subscript, another subscript nn and this is pn. That means, in an n type semiconductor, nn the concentration of electrons is approximately equal to the concentration of donor atoms. We assume that all donor atoms are ionised. Similarly the concentration of holes in the n type material is given by this.

If this is not true, that is if doping is not as large as to make it as to make Nd much greater than ni, if Nd is comparable with the intrinsic concentration, then you shall have to solve a quadratic equation, that means you shall have to solve n equal to nn equal to Nd plus ni square divided by nn to be able to solve for nn all right. If the assumption made here is not valid, then you shall have to solve this quadratic equation to find the value of nn alright? Normally one does not have to but at elevated temperatures, one might be required to.

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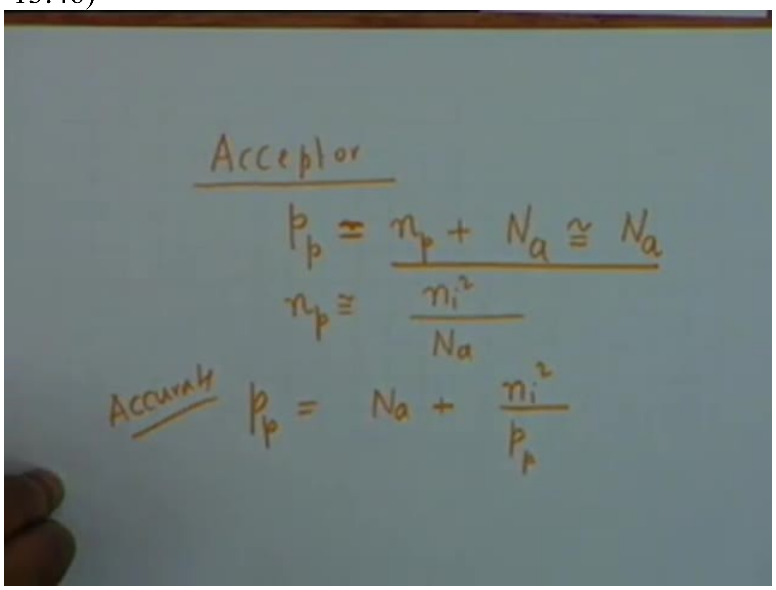

For, similarly for an acceptor type of impurity or a P type semiconductor, P type semiconductor, pp shall be approximately well the exact relation is pp shall be equal to np plus capital Na alright? And normally this is approximately equal to Na so that np that is the hole that is the electron concentration in a P type material shall be given by n i square divided by Na. Here again, if the assumption leading to this is not valid then you shall have solve the quadratic equation.

An accurate equation is that pp is equal to Na plus n i squared divided by pp alright? This gives the concentration of the P and N types of carriers in a doped semiconductor.

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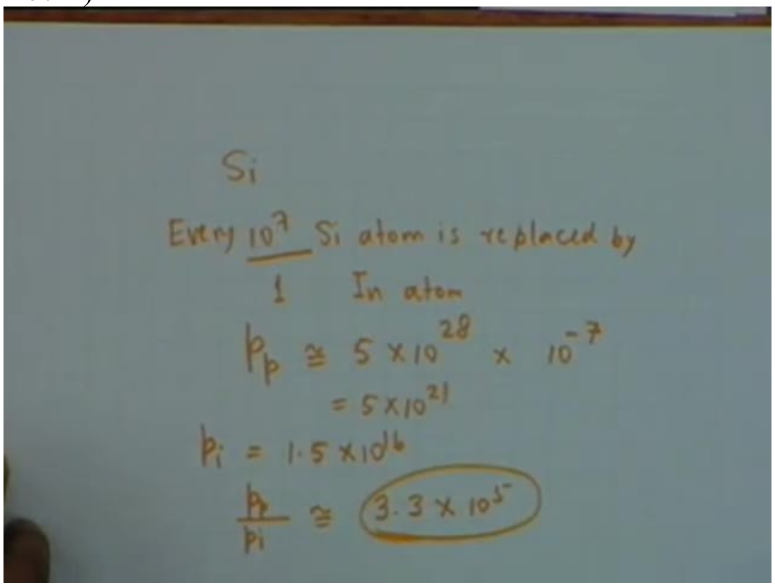

To get an idea of how the unbalance between N and P creates a creates a new electrical property or or modifies the electrical conduction property, we can we can simply take an example of let us say silicon, a bulk silicon in which every 10 to the 7 silicon atom is replaced by let us say 1 indium atom. Indium atom means it is a donor or acceptor?

Student: acceptor.

Student: acceptor.

Professor: Indium atom is acceptor? That is correct.

If it was antimony, that it would have been donor all right. All right. You see the the impurities are very sparse impurity. Every 10 to the 7 silicon atoms cause is replaced by 1 indium atom alright? Now this makes p p as approximately equal to every 10 to the 7, now what is the concentration of silicon? It is 5 times 10 to the 28 multiplied by 10 to the minus 7 which is 5 times 10 to the 21 whereas in the intrinsic silicon, intrinsic silicon that is pi is how much? 1.5 times 10 to the 16. So you see, the ratio pp to pi is approximately equal to 3.3 times 10 to the 5.

The whole concentration has increased by this factor and therefore the lead from concentration must decrease by the same factor.

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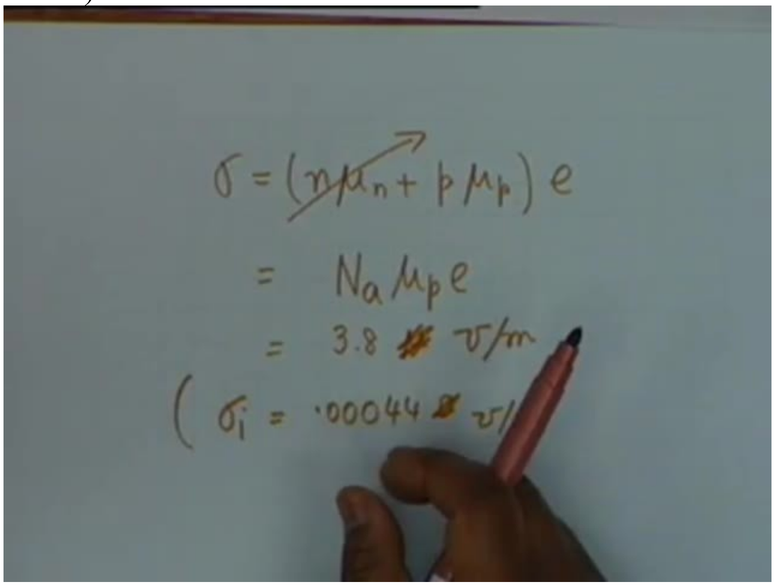

And if you wish to calculate the conductivity, the conductivity that is Sigma of the doped semiconductor normally this is given by n mew n plus p mew p times, here because it is a P type impurity and the concentration of P is much larger than the concentration of n, what is the order of the difference between mew p and mew n? Pardon me? 10 to the?

Student: 10.

Professor: Only 10. What are the values of mew N and mew P?

Student: 0.135.

Professor: So it is about 3 times, it is an order of 3 difference but n and p differ by 3.3 times 10 to the 5. Is that correct? No, this is square of this ratio because p is increased by 3.3 times 10 to the 5, n is decreased by the same ratio. All right? And therefore this term can be ignored compared to this term, compared to the 2nd term and small p is approximately equal to N Na all right mew p e and this calculates out to 3.8 3.8 mho per metre. If you compare this with Sigma I, the intrinsic conductivity is of the order of 0.0004, three 0s 44 I beg your pardon, mho per metre. You can see how many times how many times the conductivity has increased.

Even a small amount of doping which amounts to only 1 atom in 10 to the 7. And this is the main reason why semiconductors are so important. Now in a semiconductor in a semiconductor current flows due to 2 mechanisms. In a conductor, current flows due to one mechanism. In conductor, a metal for example, it is simply electric field. It is due to an electric field that current flows. If you apply no field, no current shall flow because pardon me? Because?

Student: Due to the electrons.

Student: electron.

Professor: Drift velocity would be 0. There is no net motion in any direction. It is random motion and the average velocity in any direction is equal to 0. All right?

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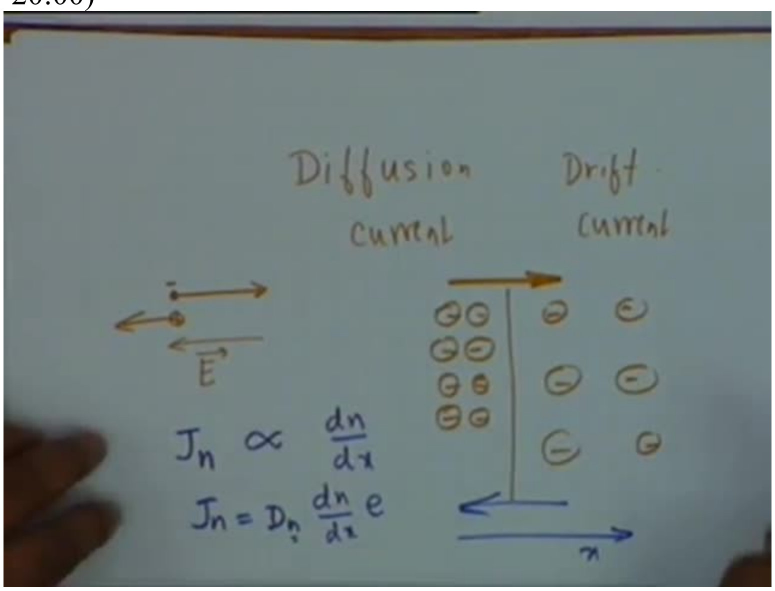

In a semiconductor however, there occurs a 2 distinct mechanisms for current flow. One is diffusion and the other is drift and we shall look at both of them separately. In a semiconductor, current flows due to 2 mechanisms, one is diffusion and the other is drift. Drift is easily understood. If there is an electric field, then the electrons move opposite to the direction of the electric field, electrons and the holes move in the direction of the electric field. And both contribute to current. If this is the direction of the electric field then electrons move electrons move opposite to the direction of the electric field and holes move in the direction of the electric field. Both contribute to electric current in the direction of the electric field. Is that clear? Because electrons are negatively charged alright?

So this is drift but diffusion occurs in a due to a different reason. In a diffusion process, there is no force required. There is no force required. Diffusion simply occurs from a region of higher concentration to a region of lower concentration and the usual example that is given is that if a bottle of perfume is opened at that corner, in a short while, it spreads throughout the room because of diffusion. That at the other corner, there is no perfume molecule and there are plenty here. So they simply, the molecules simply go from higher density region to lower density region.

If you think of let us say electrons which are densely packed on the left-hand side of this line and there are sparsely populated electrons here on the right-hand side, then electrons move from higher concentration region to lower concentration region. And ultimately, if you leave them like that they they behave exactly like gas molecules. If you leave them at peace, after some time the concentration shall become equal to 0 but this movement from higher concentration region to a lower concentration region, gives rise to a current because any motion of charge is a current. The current in this case shall be in which direction? Electrons move this direction, so the current must be in the opposite direction.

This current, the current density if we take a unit area perpendicular to the direction of motion, unit area perpendicular to the direction of motion, then the number of charges, then the total amount of charge crossing this unit area in unit time is equal to the current density. And because they occur due to N type of carriers or electrons, we take the subscript n, Jn the current density is proportional to the concentration gradient that is dn dx. If the concentration here is 10 times larger than the current density shall also be 10 times larger because the the flow is directly proportional to the concentration gradient. If we if there is no concentration gradients, there is no flow of all right?

The diffusion flow is directly proportional to the concentration gradient dn dx. if this is the direction of X, then what is dn dx in this situation? Obviously positive or negative? As X increases, n decreases and therefore dn dx is negative. The current flow is in the opposite direction. The current then is given by, the current must contain charges and therefore it is proportional to dn dx, it is proportional to the charge on the electron and there shall be a proportionality constant, we call this diffusion constant and the subscript n stands for electrons or N type carriers.

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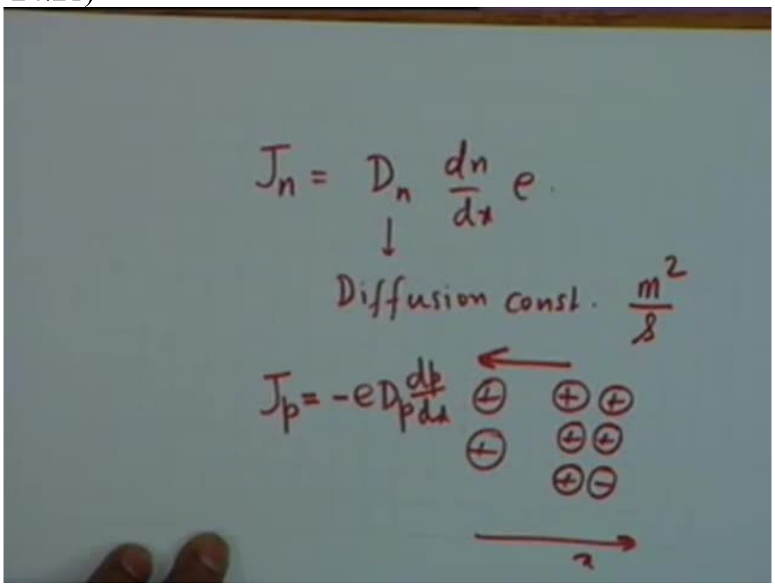

Dn due to electrons Jn is equal to Dn dn dx multiplied by e and this is called the diffusion constant for electrons. What would be its unit? It should be, if you take the units of Jn dn dx, what is the unit of dn dx?

Student: Sir, per metre ohm.

Professor: per metre?

Student: ohm.

Professor: No, what is the what is the unit of n?

Student: per metre cubed.

Professor: Per metre cubed. So per metre cubed per metre is metre to the power minus 4. One must be careful. The the unit of diffusion constant so calculated is metre square per second. One should remember this. Similarly, if you take holes if you take holes, let us say there are holes then sir here, then here, well then holes move in this direction and the current also is in the same direction. Therefore Jp is equal to, what is dn dx if this is the direction of X? dp dx. dp dx is positive and the current therefore becomes equal to minus e Dp dp dx all right?

Why is it negative? Is that the question? dp dx is positive. So the holes move in the opposite direction, in the negative X expression. If dp dx dispositive, holes move in this direction, x is in this direction and therefore the current is negative. You must take care of this sign. And in a general semiconductor, the motion occurs due to both electrons and holes. The diffusion occurs of both, electrons and holes and the 2 currents actually add other. Because of the sign of charges all right because of this because of the sign be different, the 2 currents actually add to each other.

This phenomenon of diffusion and drift assume particular importance when we juxtapose an N type material with a P type material. Juxtapose does not mean physical nearness to each other. It has to be metallurgical. In other words, if an N type region is diffused into a P type region, diffused into a P type region, metallurgically or a P type region is diffused into an N type region, then a junction is created between N type and P type materials and the phenomenon of diffusion and drift assume particular importance. 1st I would like to show you how this diffusion can occur.

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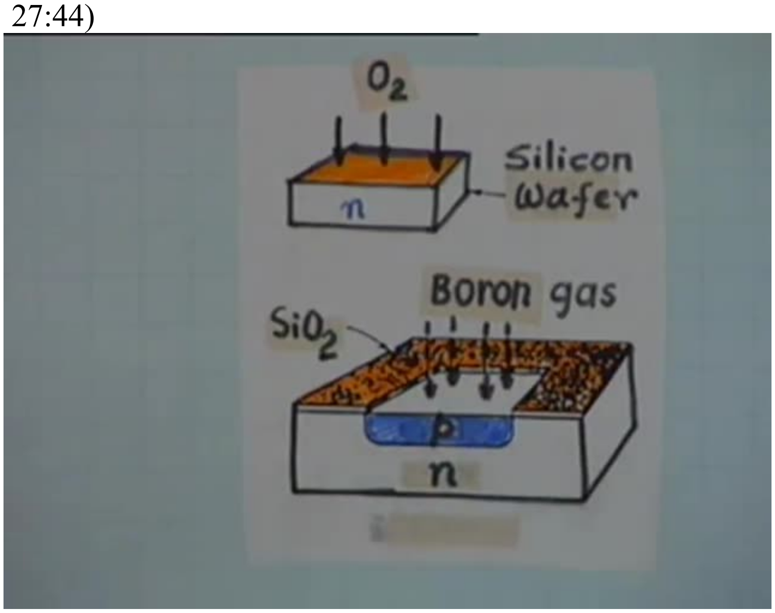

There are various ways of making a diode. Actually what we are showing is how to make a pn junction or a diode. Now there are many ways of doing this and one of the ways, one of the popular ways that I have illustrated here is you take an n type material. How do you make an an n type material? Take an extrinsic silicon, bulk silicon, put it in a furnace and pass let us say phosphorous gas through it at a particular temperature for maybe 5 hours or 6 hours. Then what happens is the impurity atoms diffuse into silicon and make this an n type material. So take a silicon wafer, a small chip of silicon which is n type and then and then expose it to oxygen at elevated temperature.

Then the surface gets oxidised into silicon dioxide and silicon dioxide as you know is an insulator, silicon dioxide is an insulator. What I have shown here is the same chip in an enlarged form where this coloured thing, this fractal type of diagram silicon dioxide deposition. Then what I do is, on a piece of mask, there are special types of masks that you, that can be prepared, you make a window on a mask all right and you cover the silicon dioxide with this mask. Then pass some etching agent like chlorine, chlorine in a gaseos form would do, that eats away a part of silicon dioxide. That is whatever whatever the mask opens, chlorine goes into it and it is it.

This is called selective etching. It is as if you take a piece of blade, you take a blade, if it was a large dimension, then you take a piece of blade and scratch off some silicon dioxide. So that is silicon is now exposed. Is this clear? The rest of it is silicon dioxide but a part of silicon is exposed by means of etching. Not by a blade but by passing an etching agent all right? Then you diffuse boron gas. Then you push put this wafer in an atmosphere, in an environment of boron gas at a specified temperature. Then what boron does is it diffuses into the n type material.

Now the the depth to which it will diffuse, if it diffuses into an n type material and boron concentration is much higher than the doping concentration of the N type material, then it will convert that n type material into a p type all right? Now the depth to which the p type material is diffused depends on how long you keep it and what is the concentration of the boron gas. These things can be very precisely checked, precisely controlled and therefore, what you have made now is a pn junction. A a p type material metallurgically closed metallurgically diffused into an n type material and therefore a junction is created and this is what is a diode.

All that you have to do now to to make an electrical device is to deposit a metal here. On this exposed surface, you deposit a metal and take a contact. The contact is usually of gold, gold contact all right? That is what gives the price to the device. This gold contact is more precious than the cost of all this silicon and all that. And then you have to deposit a, you have to make a metal contact on the n type material also all right? Therefore a diode is created. A diode which has a p type material on one side and an n type material on the other side. Now we assume that this material, please try to follow this carefully, we assume that do not worry about what is written on the slide.

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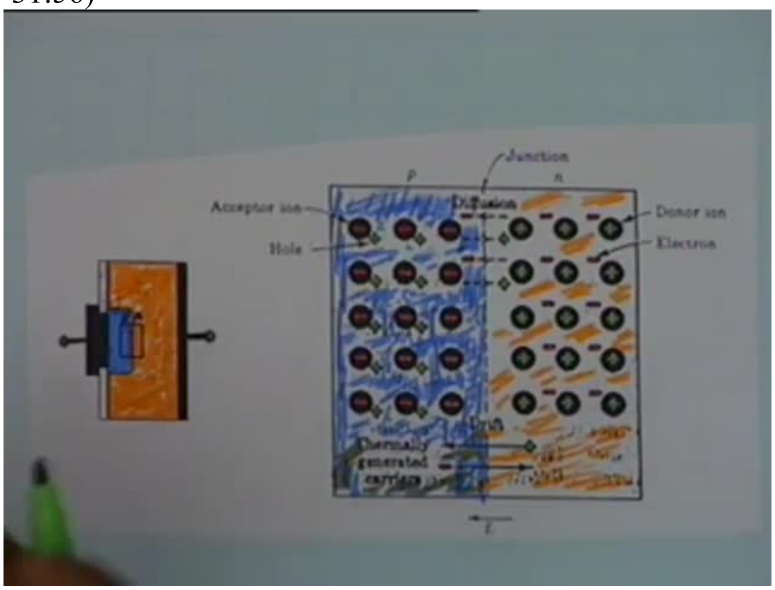

Just look at the picture. This shows the same PN junction in a schematic form. We show everything. We take a cross-section, be sure everything as rectangular. Hardly ever the junction is rectangular all right? This this coloured region is the n type, this is the n type and the blue marked region is the p type, p type has been diffused into n all right and then this is the metal contact, this black slab type of thing is the metal deposition. It makes one contact, the black slab here is another metal deposition, it is another contact. So this becomes a diode.

We assume that the metallurgical junction is an abrupt junction, that is the region separating p and n, we assume that it is a sharp plane. Actually it is not so. It is of nonzero thickness. But it, most of the theory is built around this that we have a an abrupt junction. This dotted line here separating blue and orange is the junction. Now on the left is the p type material, on the right is the n type material. And you can see that on the left, the fixed ions, these are acceptor ions and they are negatively charged. These are bound charges and there are mobile holes.

Actually holes do not move. What moves is an electron but an electron movement is equivalent to motion of a hole. Similarly on the right-hand side, this, these are the donor ions which are bound, fixed positive charges. These are the electrons, the small red bus, they are electrons and they are mobile electrons. They are free to move. Now when there is a junction when there is a junction, the electron concentration on the right-hand side is much higher than the electron concentration on the left-hand side all right?

Similarly the whole concentration in the p region is much higher than the hole concentration in the n region. Now each of these regions has electrons as well as holes all right? The holes here for example here they are mostly contributed by by doping all right? But there are holes also contributed by thermal energy. The electrons are mostly contributed by thermal energy because this region is only acceptor type of impurity, p type and therefore whatever electrons are here, they are mostly thermally generated.

But look at the situation what happens? There is a profusion of electrons here in this region, there is a profusion of holes here in this region and they are brought close together. And therefore, by diffusion, the right-hand side is full of electrons, left-hand side is sparse in electrons. Therefore electrons diffuse from the n type to the p type region. Similarly, holes from the left-hand side diffuse into the right-hand side. And as soon as they cross the barrier, holes for example, they cross the barrier, they meet mobile holes, they meet electrons and therefore they recombine. All right? We have shown some of them here. There is an electron which has come from this side.

There is a hole which has gone from this side and I have shown this part as empty. Why empty? I have shown them, they hem they have already recombined. And therefore, if the device is left to itself, then a region near the junction, near the metallurgical junction shall be devoid of charge carriers. Is not it right?

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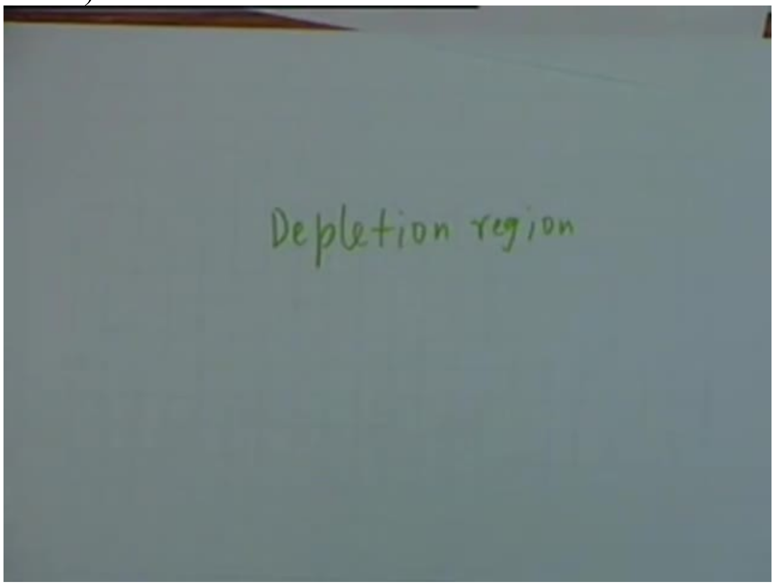

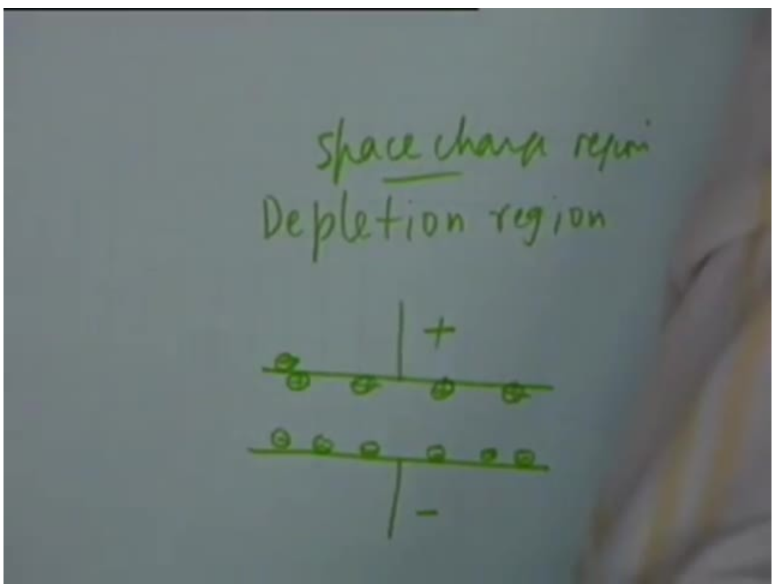

And this region is called the depletion region. D E P L E T I O N, depletion region. Depletion region is a region which is devoid or depleted of charge carriers. All right? If 50 percent of this class now leaves, then we will say that class is depleted by depleted of its strength by 50 percent all right? So there is created a depletion region. Now if a depletion region is created, there are no mobile charge carriers, then the situation is that there are fixed positive charges on the right-hand side and there are fixed negative charges on the left-hand side which is precisely what happens in a parallel plate capacitor.

If you if you make this potential positive with respect to this, then there are, this positive charge attracts electrons from the surface of this, the negative potential attracts positive charges here and therefore, there are charges, equal and opposite charges separated by distance. And therefore, the depletion region then acts like a capacitor. Is that clear? The depletion region acts like a capacitor. There are negative charges on the left-hand side, positive charges on the right-hand side and whenever this situation occurs, there is a separation of charge. This region is also called space charge region.

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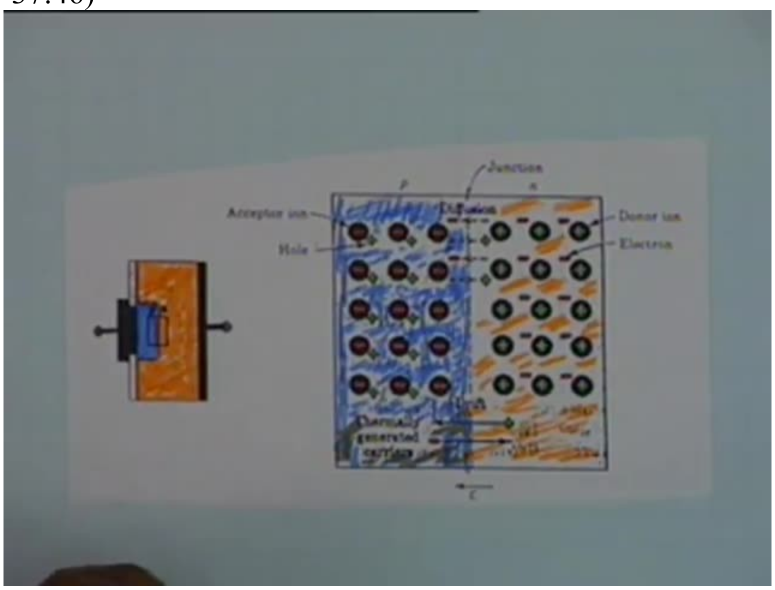

Let me explain why it is called space charge region . You see, in this space, in the depletion region, if you measure charge, then you shall be able, you you you take out you take any portion, any finite area then you shall measure a positive charge on this side. On the other hand, if you measure a small area here, the total charge, it will be negative. But if you go faraway from the junction, for example here, if you measure over a nonzero area, it would be 0 charge because there are fixed charges as well as mobile carriers. There are electrons as well as holes and the total silicon bulk is electrically neutral and therefore this region is also called space charge region. That means in the space that is available, you shall be able to measure charge only in this region. All right? Charges are separated by a distance and this is always accompanied by an electric field. What is the direction? From positive to negative or ne…

Student: Positive to negative.

Professor: Positive to negative. Okay.

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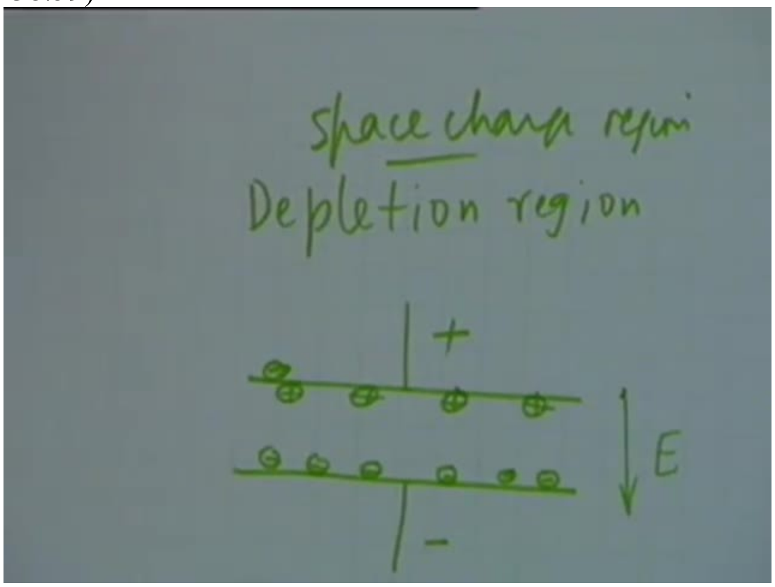

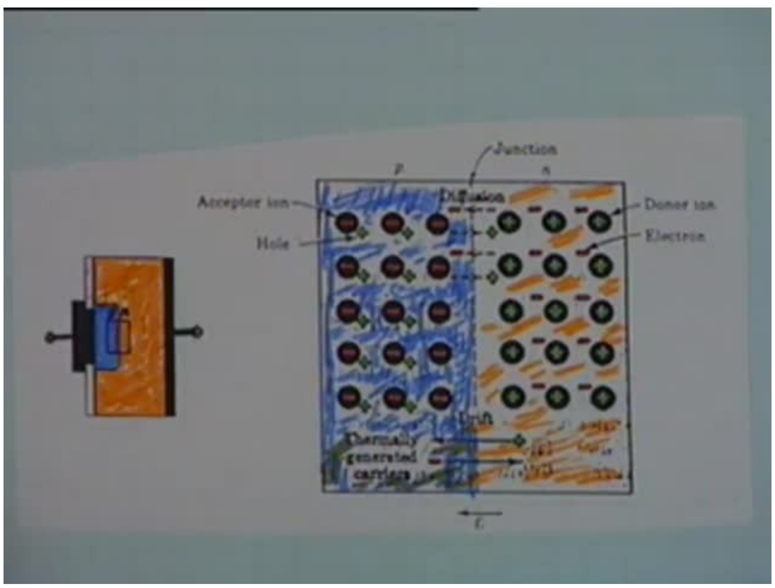

So in the junction, in the junction you see, I bring back the slide. The electric field is in this direction, from right to left because the positive charge is on the right-hand side. Now as soon as an electric field is created, drift can occur now. All right? Who will move under the drift? Obviously drift shall call cause holes to move from right to left and electrons to move from left to right. Now holes in the right region, that is n type region, can occur only due to due to thermal generation.

So it is this thermally generated holes, this green plus signs, they move under the action of drift or electric field from right to left and these electrons which are also thermally generated, they move from left to right all right? So this is why I said in a in a semiconductor junction, diffusion and drift occupy very important places. If there is to be a current flow through this diode, the current flow4 shall have 2 components. One is the diffusion component, and the other is the drift component. One must remember that the diffusion component is mainly due to doping, due to the impurity and drift occurs mainly due to the thermally generated carriers.

At this point of time, it is also appropriate to introduce the term majority and minority. In the political context, the meanings of these terms are absolutely clear. It is the same meaning which is carried over here that is in the n type region, electrons are majority carriers, electrons contributed to by doping and the holes are minority carriers, whereas in the p type region, the holes are majority carriers and the electrons are minority carriers. So in terms of the of the terminology, majority and minority, we can say the current conduction in a diode or in a junction occurs due to both majority carriers as well as minority carriers.

Majority carriers move by the process of diffusion and minority carriers move by the process of drift all right? So that is as far as the motion of carriers are concerned. Yes. Now look at this carefully.

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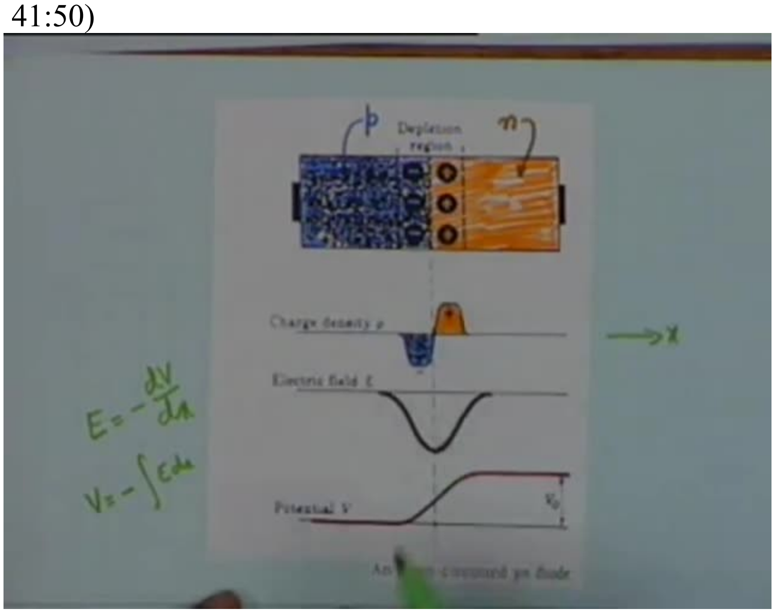

This slide shows, I shall read out what is written here. So do not worry about what is written here. This slide shows the same diode the same diode, you see this is the p type region, this is the n type region and for simplicity, I have shown the n type region except the junction or the depletion region, this is the depletion region, from here to here is the depletion region. There are bound negative charges here, minus minus minus. There are bound positive charges here, plus plus plus. So there is a charge separation causing a depletion.

I have shown this as devoid of charge. I told with that except for the depletion region, the rest of the region is neutral. So I have not shown any holes and electrons. Now if I measure the charge density along the length of this, if this is the x direction let us say, if I measure the charge density rho along this, then obviously, it is neutral here. So there is no charge. It is neutral here, there is no charge. Suddenly, there is an abrupt formation of charge at the depletion region. To the left is negative and to the right is positive all right?

This is how the charge density varies along with distance. The charge density otherwise is 0 except for the space charge region. The density, there is negative charge on the left and positive charged on the right. All right? If there is a difference of charge density, there must be an electric field, charges separated by a distance. The field is 0 in the neutral region, field is 0 in the neutral region and must be maximum in between. And therefore, the field varies like this. Why is the field negative?

Student: The direction is negative.

Professor: The direction is negative. Okay.

The field is negative. Now you know the difference, the the relation between electric field and potential difference. Electric field is the negative gradient of potential and therefore potential is the negative integral of field. So if you integrate this, the potential difference, the potential therefore varies like this. It remains constant in the neutral region at a value V0, it remains constant in this neutral region at a value 0. And therefore and therefore positive charges from the left side if they have to move to the right-hand side, positive charges on the left-hand side, what are they? Holes.

Holes in the p region if they have to move to the n region, they shall have to climb this potential wall and therefore they are discouraged. They cannot move. Similarly, if there is an electron here, they shall have to slide down a potential hill which the electrons find very uncomfortable and therefore they do not move all right? And therefore, if this diode is left open circuited, nothing is connected, this will be the situation and if you take a a sufficiently sensitive electro-meter to measure the potential difference, you shall be able to measure this. This V0 is called the contact potential. That is when 2 regions, p and n are brought into contact with each other, there is a potential difference and the potential difference is of the order of 0.1 volt. It is a very small voltage. Question. Can it be used for driving a current through an external resistor? If I connect this to an external resistor, shall it? No.

Because when you connect an external resistor, there are contact potentials here also and that contact potential, it can be shown accurately, rigourously that it cancels this and therefore this cannot be used as a battery. It is not a battery. It is simply an accumulation of charge but the important point is, what happens when I connect a battery from the p type material to the n type material? Let us say I connect the positive positive terminal of the battery to p, to this contact and the negative terminal to the other contact.

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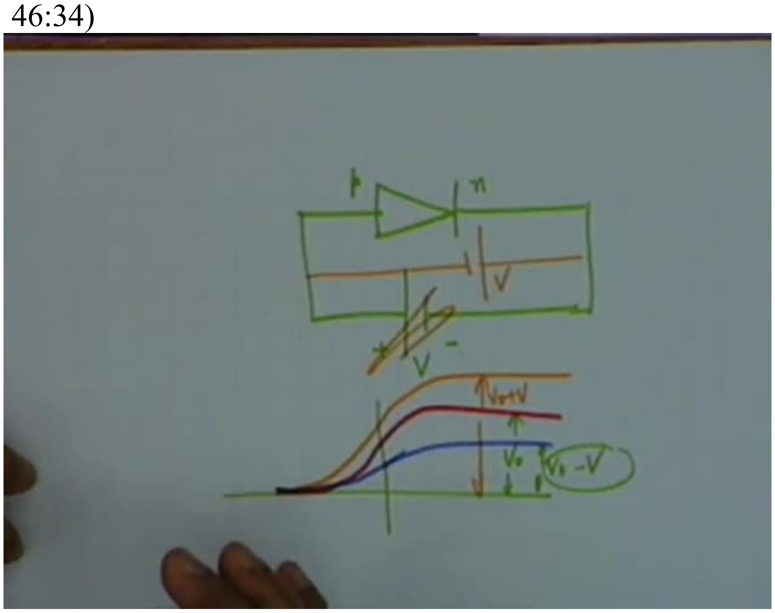

Schematically we represents a diode like this where this is the, the left-hand side is the p type material and this is the n type contact all right? Now if I connect a battery like this what happens? Well if I connect a battery like this, the battery creates an electric field in which direction? To the right or to the left? To the right. And the space charge created an electric field in the reverse direction and therefore this potential difference now shall be reduced and therefore if this voltage, leave it that is okay, if this voltage is V, then the potential profile shall be like this.

This was without the without the X is that a problem? This was under open circuit and this would be V0 minus V. Is it moving?

Student: Yes sir.

Professor: why? Not due to me.

Okay. So the the potential barrier as it is called or the potential hill is reduced if the diode is biased in the appropriate direction and this direction is said to be the forward direction or the forward bias. Now what happens if the potential hill or potential barrier is reduced? Naturally more diffusion now shall occur. That is, current shall flow in the circuit. Who provides the current? Well, holes, holes move from p type to n type, electrons move from n type to p type and it is the battery who sustains the current. Current means flow of charge.

As soon as charge moves, the battery supplies charges and therefore, current flows in the forward direction. On the other hand, if this is, if this battery terminal is reversed, if I connect a battery like this, capital V then obviously the potential hill is heightened or its height increases. And so we shall have a situation like this where this will be V0 plus V. And now, there is further discouragement of majority carriers to flow. However, can you stop minority carriers? No. Minority carriers are encouraged to flow because of the height of potential barrier. All right?

So the minority carriers, that means there will be a small current due to the drift component only. There will be no diffusion all right? So if the diode is reverse biased, it is drift which takes over. And drift occurs by whom? Who carries the charges under drift? The minority carriers. Who generates the minority carriers? The thermal energy. And therefore the generation of minority carriers, the rate of generation is approximately constant. That means that the current shall remain approximately constant and therefore if you vary V the current does not change appreciably because very few minority carriers are available and therefore if you increase V it does not really matter.

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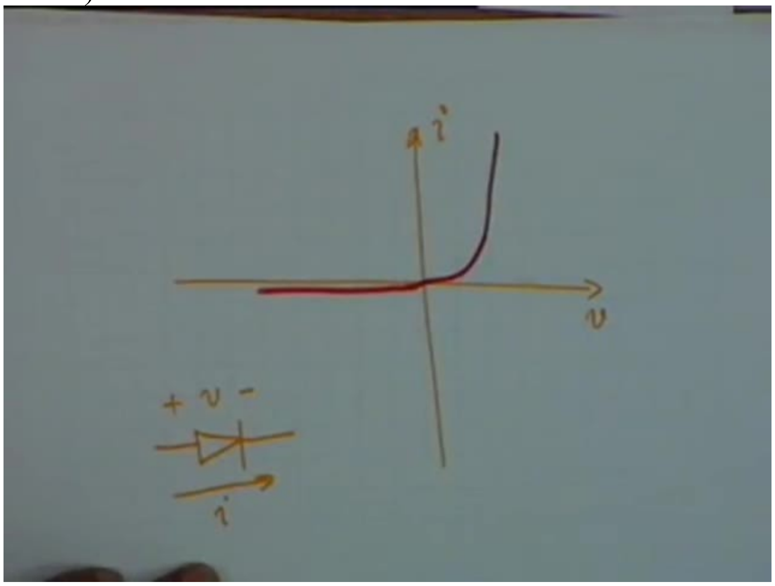

And this leads us to the conclusion that if I plot the current in the diode against the voltage, the diode is represented like this. When we forward bias the diode, the current the current sharply rises like this. As the forward bias is increased, the potential barrier is decreased further and further and so the current rises. In the reverse direction however, that is when the diode is reverse biased, there is a small component of current flows which remains almost constant because the current flow is due to drift of minority carriers but then there is a limit to everything.

Enough is enough. It cannot stand for long time because as you as you increase the reverse bias, you also increase the velocity of the minority carriers and the minority carriers say we can go up to this much. Then they acquire so much energy that they collide with fixed atoms and breakdown and then what happens is an avalanche. The current suddenly increases. All right? For normal diode operation, we confine our attention before this breakdown occurs. We do not want the diode to break down. All right?

And this current, this current is almost constant. It is called the reverse saturation current reverse saturation current.

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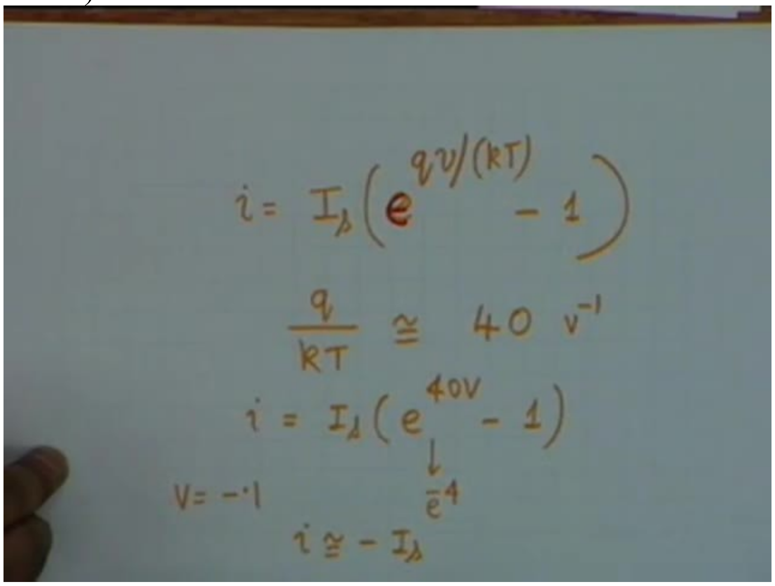

In general, the diode the diode is this characteristic is a very highly non-linear characteristic, can be fairly accurately represented by the equation i equal to Is exponential how do I represent electronic charge? We will represent the exponential by epsilon all right? Electronic charge. Oh, there is another way, e to the power qv by KT all right. We shall use q for electronic charge. Minus 1.

Student: Sir you could have written (())(53:02)

Professor: Yes, I could have written exponential ex, correct.

Okay, normally at room temperature, I am not deriving the situation. This equation can be derived from distribution law. But normally at room temperature, q by KT is approximately, what is room temperature? 300 K, 300 Kelvin. K is the Boltzmann constant, q is the electronic charge. If you substitute this, this approximately will be 40. What will be the unit? Unit of q by KT?

Student: 1 by volt.

Professor: 1 by volt. So volt to the minus 1 because the clue is that when multiplied by volt, it must be dimensionless all right? And therefore, i is equal to Is e to the power 40v minus 1. And you can see that even if V equal to let us say minus 0.1, reverse bias of minus 0.1 volt, then this becomes e to the power minus 4 and e to the minus 4 is approximately 0 as compared to minus 1 and therefore i would be approximately equal to minus Is. And you see how i becomes independent of the reverse voltage. Reverse voltage, you increase it to 0.2, it does not make a substantial difference. From 1, you subtract 10 to the minus 6 or 10 to the minus 8, it hardly matters. So the reverse current is approximately a constant.

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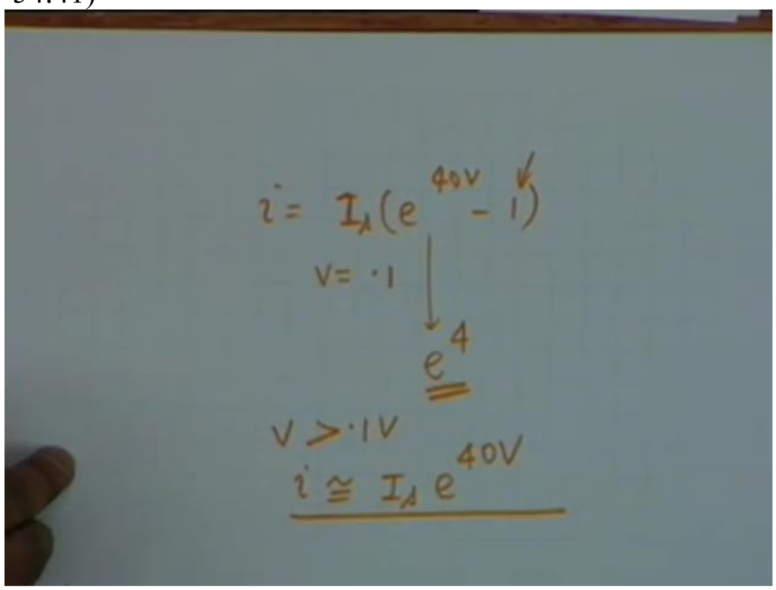

On the other hand on the other hand if I take this immigration, i equal to Is e to the power 40v minus 1 and I say v equal to 0.1 then you say, this quantity becomes e to the power 4. The value of e is between 2 and 3. What is 2 to the 4?

Student: 16.

Professor: 16. And 3 to the 4?

Student: 81.

Professor: 81. So e to the 4 is between 16 and 81 and 1 can be what? 2 to the 4 is 16. Between 16 and 81 and 1 can be ignored. And therefore for capital V greater than 0.1 volt, the current can be approximated by Is e to the power 40v. The current therefore rises exponentially all right? This fairly well describes the diode characteristics. And next time, we will see some applications of this.