Micro and Smart Systems
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Lecture – 31
Semiconductor Device Physics

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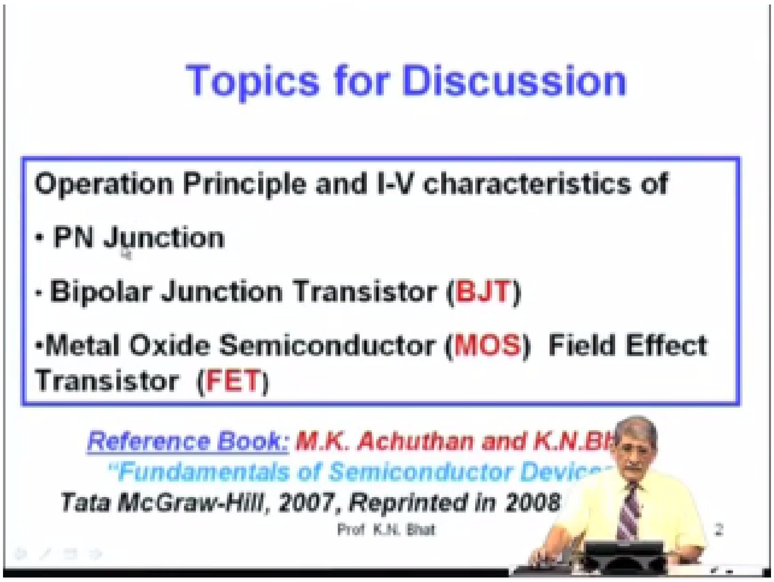

Okay, we start our discussion on semiconductor device physics and today we will discuss the topic that we discuss will be the operation principle and IV characteristic of PN junctions, bipolar junction transistors, BJT, metal oxide semiconductor, MOS, field effect transistor, that is MOS, FET, which you all hear often, you can use if you textbook which is author Professor. M. K. Achuthan and myself K. N. Bhat, fundamentals of semiconductor devices published by Tata McGraw Hill in the year 2007, reprinted in 2008 and 2009.

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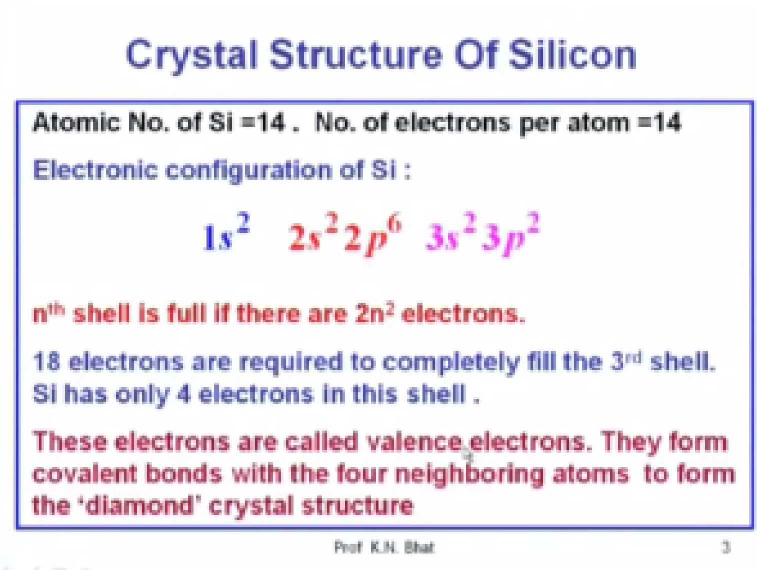

So, it is mainly written for beginners on devices if you are interested you can go through that book. Now, we start our discussion on this PN junction, before we go to that we just very briefly go through what is PN, what is N type material for those of you have forgotten about that, I am sure all of you studied it even in your high school days, so the silicon is the material that is used for making all these integrated circuits today.

It is actually the omnipresent material next to oxygen; it is the most available material on the earth crust in the form of silicates. You go to beach; you can pick up sand you can convert into silicon. Now, the atomic number of silicon is 14, why I am writing that is, briefly see tell you about the structure, so you go that from the atomic structure, the electrons orbit around this nucleus, when the different shells, shell number 1, that is there are 2 electrons, shell number 2, there will be 8 electrons, shell number 3, if it is full there will be 18 electrons.

The formula to remember is N is 1 means, it is the number of electrons is 2N square that is 2, N is 2 means, number of electrons is 2 * 2, 4*2, 8, so that 8 electrons here and this is full but if you see the third shell, there only 4 electrons, whereas you can take a 18 electrons, 3 square * 2, 18, but there are 4 only, these are the outermost shell of the silicon atom, that is why they are called valence electrons.

They can interact with neighbouring atoms to complete the bond. So, these electrons are called valence electrons, the form covalent bond with 4 neighbouring atoms. There are different types of bonds; this is one type of bond where the share electron between the 2 atoms is called covalent bond to form diamond like crystal structure. This is the 2 dimensional picture of the crystal structure.

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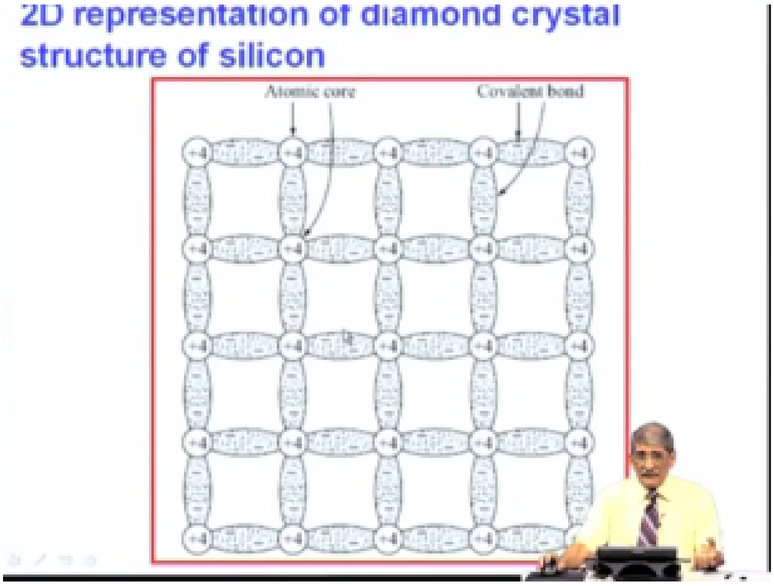

I do not want to draw 3 dimensional complicated, so a very simple picture which is found in the everywhere in text books is this. These are the all these circles are the atoms, you see I have put as 4+, that means the core has got + charge 4 and 4 values electrons are there around that 1, 2, 3, 4, these dash lines, so you can see that; this electron belongs to this atom that nearby and you can see one more dash line is the electron belonging to this atom.

So, actually these 2 electrons move around both the atoms, so have to hold them together, that is called covalent bond. You can see each atom contributes to one bond, so these 2 neighbours; one electron here, one electrons here forming a bond like that. So, there are 4 electrons bond is complete. If any of these electrons are missing, that is the vacancy, okay. Now, at 0 degrees kelvin, the feel have no energy to come out of this bond.

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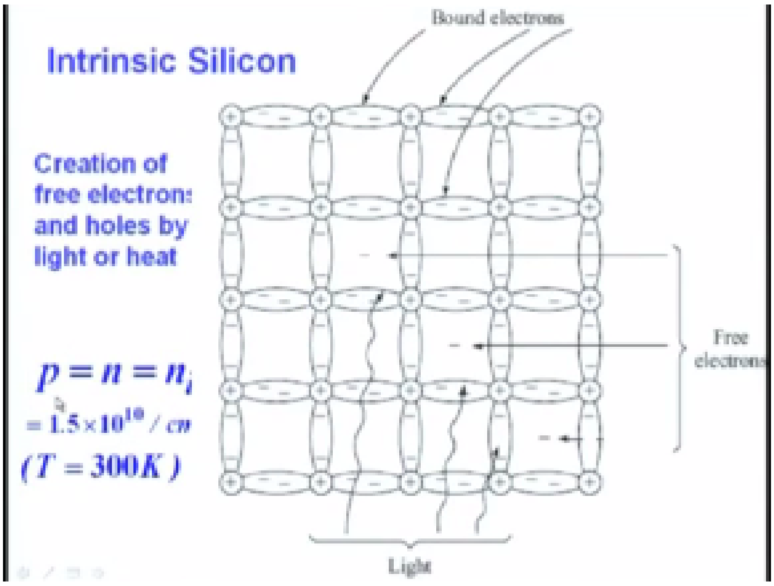

So, the electron tendency will be 0 and silicon will actually gave like an insulator at 0 degrees kelvin, okay. So, but in go to room; the room temperature, so what I showed you is intrinsic silicon, in the sense there are no impurities, purely it is silicon. Now, this intrinsic silicon at room temperature what happens is; some of these bonds, for example you can see there is one electron is missing from this.

There are 2 usually in each bond, one of them is missing here, because that electron has broken come out of the bond and is made free. It has required the energy from the temperature because the crystal is at room temperature. So, at 0 degree kelvin, this electron was sitting all in the bond, go free electron, now this electron will come out that there number of electrons are break bonds, there are pi * 10 to the power of 22 silicon atoms per cm cube.

Many of them will break bonds, many of these electrons; okay from this bond will come out, when they free, so those are n is the number of electron per cm cube, okay, so as you break one bond here, you can see 1 electron is formed leaving behind one vacancy there, so it is as if that region is + charge, put together this neutral but when the electrons comes out of that, it leaves the + charge there.

So, this + charge also can move because electrons from here can jump to that from neighbour, it can jump and move there, so this vacancy which behave like a + charge can move from here to here. In other words, in silicon or in semiconductors, you have got 2 types of charges, in metals you have got only electrons, in semiconductors, you have got electrons and this vacancy which behaves like a positive charges.

So, there are negative charges called electrons, positive charges called holes. Here symbol used is p per holes, p type; p for positive, holes, n for negative that is electrons. Positive charge or negative charge in the intrinsic material whenever 1 electron is created, it leaves behind one hole that means number of electrons is equal to number of holes; p = n. Now, on the p quick question on this, we are going to answer is; due to temperature, there is continuous making of covalent bonds.

That means, continuously electrons and holes pairs are created in pairs or 1 electron there is one hole created, there is for 1 negative charge, 1 + charge is created, both are mobile, okay. But, given a chance that electron will go back to this vacancy and occupy that position. When it goes back to that vacancy, what happens is; the electrons has merge with the hole, negative and + charge both combined together; that is recombined that is called recombination.

If it recombines both electrons and holes disappear. Because the electrons, which are come out from here, that goes back and occupy their position, there is no more electron, no more hole. So, what happens is; as you keep on keeping the temperature on, both the hole electron pairs will be created. Simultaneously, there will be recombination rate also, where they will be killing each other, okay.

So, at steady state, the hole density is equal to electron density, okay that is generation rate; the rate at which carriers are generated matches with the recombination rate. It is like, if you take a, I show this bottle, okay and you can see, if I make number of holes here around this bottle, number of holes and if I keep filling this with water at a certain rate that is a generation rate, it keeps on filling and it will stabilise at a particular value.

If I continue to pour, there are hole through that hole that will be coming out, when the rate at which I am pouring is exactly equal to the rate at which coming out through the holes that level is stabilised, that is a steady state, that is what is happening here, where rate at which hole electron pairs are created is equal to rate at which it is recombining; the rate at which this water is coming out of this glass, okay.

So, under steady state conditions for an intrinsic material, few material, hole concentration, you call it as ni, which is for silicon, it is 1.5 * 10 to the power 10 per centimetre cube, okay.

So, that there is a cube here; centimetre cube at T = 300 centigrade. If it is germanium, that will be much larger, it is about 2.5 * 10 to the power 13 per centimetre cube, if it is gallium, it is more difficult to break the bonds.

Therefore, the density will be about 10 to the power of 6 per centimetre cube. With that intrinsic material, now you can see silicon, there are only 10 to the power 10 electron hole pairs per centimetre cube. The resistivity of this material will be very high; it will be about 300, 000 ohm centimetres. So, you want to have controlled over this resistivity, you should be able to change the resistivity, how do you do that?

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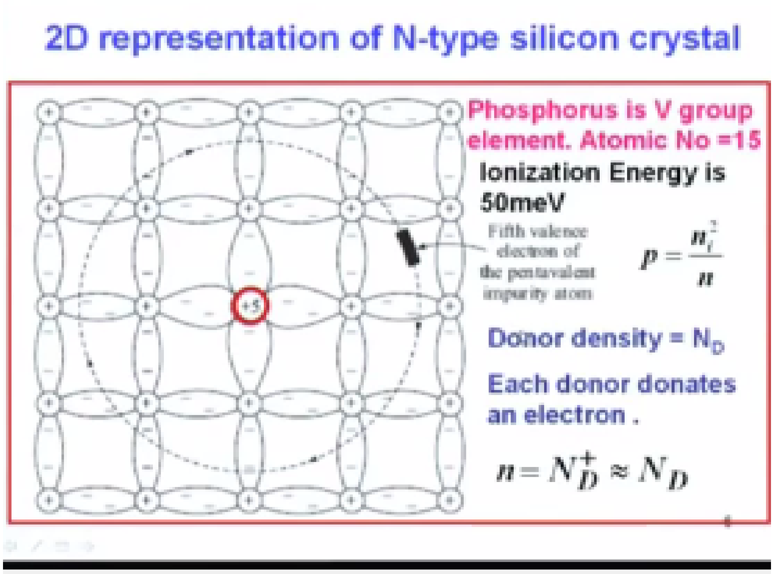

You add impurities to that, like this. For example, to that lattice what we saw, I had phosphorous which is actually fifth group element in the periodic table, it is the fifth group element and its atomic number is 15, you see silicon was atomic number of 14, there were 4 free electron, 4 valence electrons, whereas phosphorous is 15, that is there are 5 valence electrons.

If this atom is sitting there where the silicon atom is about to sitting, it can contribute 5 electrons, but there are only 4 sides; 1, 2, 3, 4 sides to form the bond. The fifth electron, they thought of a chance to found the bond, so it is holding around that, it is larger radius and it is still around that, at this the orbit of that particular fifth electron which will be in that is very loosely bound to this parent atom.

It can knocked out with very small energy like 50 million electron volts, that means even at room temperature, this particular electron will be available as a free electron and what it implies is; when I introduce one phosphorus atom into the lattice, it release one free electron to the lattice. That is it donates one free electron that is why it is called as donor atom and the donor density you call it as ND.

If there are 10 to the power of 15 phosphorous atoms which have donated, it will donate 10 to power of 15 electrons to the crystal. So, what was originally 10 to the power 10 volts and 10 to the power 10 electrons now becomes 10 to the power of 15 electrons but the whole density will died on drastically. There are many of these electrons will participate in killing those holes, recombining with the holes.

The thumb rule is that, the pn product is ni square; ni is 1.5 * 10 to the power of 10, so ni square is 2. 2 * 10 to the power 20, so if I have donors which are 10 to the power of 15, n= 10 to the power of 15, so p will be 2.2 * 10 to the power of 20/ 2.2 to the power of 15 that is hole concentration will be about 10 to the power of 5 only. So, now notice I have introduced 10 to the power of 15 phosphorous atoms which has donated 10 to the power of 15 electrons to the crystal per centimetre cube, which has reduce the whole density to about 10 to the power of 5.

So, you have got now 2 types of carriers, one of them is majority carrier that is electrons 10 to the power of 15 per centimetre cube, the other one is minority carriers, their holes p type, denoted by p. So, this is; the conductivity is controlled by mostly by the electrons n type, so this semiconductor where electrons are the majority carriers, you called n type material. Current flow is mainly controlled by the electrons, negative charges, okay.

So, that is the basic thing to understand what I put here is ND + because one electron; if all the 5 electrons are there around this nucleus that is neutral but if one of the electrons is removed away from that the nucleus is charged with +1 charge not +5, +5 is the nucleus charge when 5 electrons are around at neutral but one electron if you remove it has + charge of one, please remember that.

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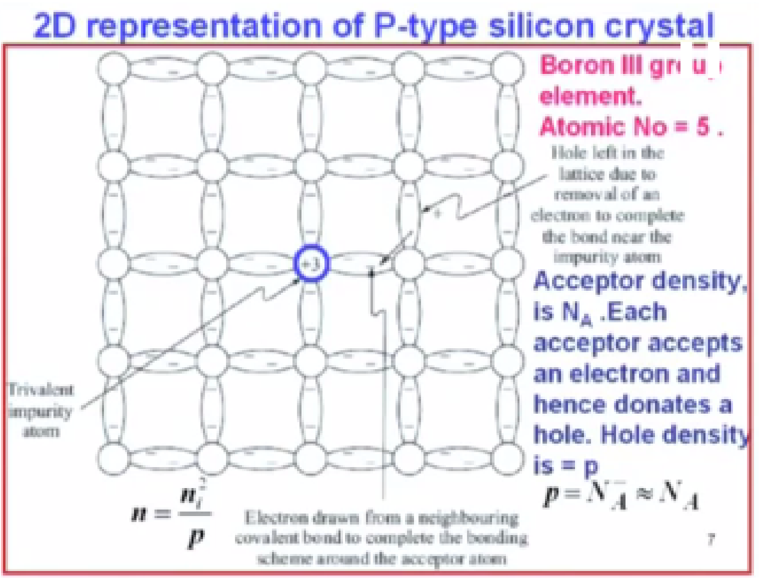

If it has moved away from atom far away whether there is net + charge there around that please remember that when you go to PN junction, so it is n type material. Now, the p type material, see instead of introducing phosphorous which is atomic number is 15, valence electron 5. I introduce boron; boron is a third group element in the periodic table and its atomic number is 5 which would be there will be 5; atomic number is 5.

And since it is in the third group, there will be 3 valence electron see in the previous case, it was fifth group, it has 5 valence electrons, and third group has got 3 valence electrons. Now, if it is sitting in the lattice here, say I put +3 here that is 3 valence electrons are there, so the 3 valence electrons are there, they are the only one which is available for participation, there is no electron just available for forming this bond here, okay.

So, if that is the situation, it is sub neutral but now what happens is there will be a vacancy here okay because only 3 electrons are available with the boron, which is valence belongs third row, so these 3 electrons are occupying the bond but the fourth one, there is no electron, so what is does is; it takes an electrons from the neighbouring bond and it moves into that portion, jumps from there to there, what happen now?

This region one it has accepted electrons it has become negatively charged, when there is no electron accepted into that atom, it is neutral, if it is accepted electrons to negatively charge, what has happened as a result? It has left behind the charge here, that means it has created, here it has satisfied this bond by moving this negative charge from here and making this negatively charge but a + charge is there.

But this is not mobile here once it is bound, so here is the + charge, that is a hole or a vacancy which can move from one bond to another jump because for example, let us say an electrons from here jumps into this vacancy what has happened is, the effect is this vacancy has more there, that is the + charge has move from here to here. The difference between the charge movements is in the previous case, the free electron, okay, if the electron can move through the crystal way freely.

Of course there will be collisions but this movement of this + charge is also movement of electrons, it is movement of electron jumping from here to here and here to here, so this + charge has moved here due to movement of electron but it is not a free movement it is a jump movement, so at break this bond and go to this position, okay. So, the movement of these + charges which are holes are rather restricted not as free as free electrons.

As a result the velocity of these + charges which you call it as holes or less compared to those of electrons, okay. So, usually that is where they preferred to make device of with electrons as transferred to carriers rather than holes because they are rather slow, higher speed devices usually involve electrons, okay but you need also p type materials, so in this case positively charges are the ones which are available for conduction, + charges, that is why we call it as p type silicon.

And you can see, if I introduce 10 to the power of 15 boron atoms, it introduces 10 to the power of 15 vacancies that is 10 to the power of 15 + charges, so 10 to the power of 15 holes per centimetre cube, so hole concentration will be equal to; this is ionised means electrons which has an accepted equal to the boron that you have introduced per centimetre cube, hole concentration.

Now, when the amount of hole concentration has been reduced to 10 to the power of 15, or 10 to the power of 16, the electron concentration comes down decided by this relationship, p n power of to the same, I am not getting down to the theory of that, so the product will be the same, the hole thing is because of recombination. Large numbers of holes are present, so electron concentration comes down.

If this is 10 to the power of 15 per centimetre cube, electron concentration come down to 10 to the power of 5 * 2.5, so the electrons are minority here, holes are majority here, okay. So, that introduction now you got seen n type material, p type material, intrinsic material, nobody uses intrinsic take it as it is, usually they will use either P type or N type and most of the time it is used in combination like this.

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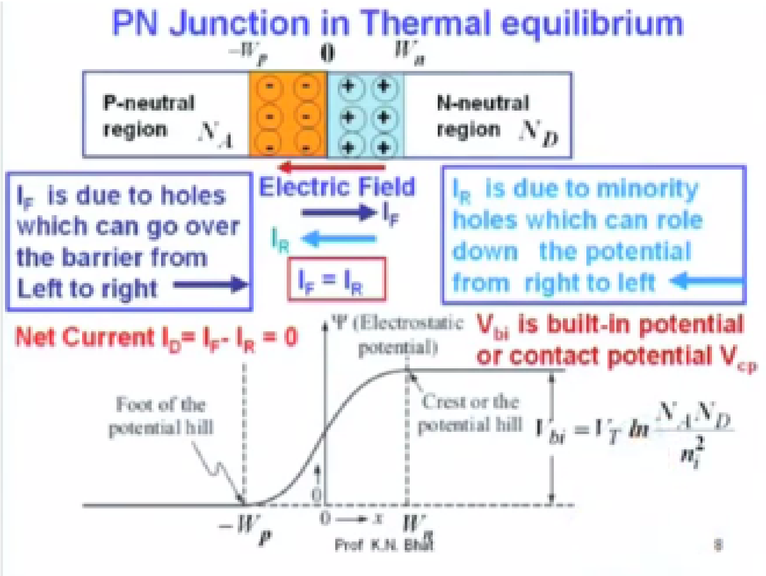

You take P type material and N type material, if you take the entire region of the material, for example if you take this entire region, or the P type material is neutral it has here and there + charges that correspond to + charges , there is a negative charger, totally it is neutral. Now, if I take this region as the boundary between the P type and N type material, this is PN junction, 0 where I put? Okay in the PN junction.

At the instant of forming the junction, you recall the entire region is in N type, the entire region has about 10 to the power of 15 electrons per centimetre cube, okay. Now, if any of the electrons move away from that; from this region, that leaves behind + charge, 1 charge because for one donor electron, if the electron is present near the donor, it is charge neutral. But if it moves away, it leaves behind 1+ charge; please remember that.

So, now at the instant, when this layer junction is found by bonding or whatever mechanism, large density of electrons are present to the right side of the 0, 10 to the power of 15 electrons per centimetre cube, to the left side of the 0, it is large density of holes are present, but the electron concentration is very low, 10 to the power of 5 per centimetre cube, okay. So, just across this boundary, there is a concentration gradient of electrons from this side to this side.

Similarly, if I come from left to right large number of holes are + charges are present, mobile plus charge are present and there is a concentration gradient of holes. Now, let us talk of one of them. So, on the right hand side, there are large number of electrons, hole thing was charge neutral but because of concentration gradient, the electrons will move by mechanism known as diffusion, okay.

The driving force is the concentration gradient, to understand what is meant by diffusion, we take a very good physical example. If I take the again this bottle, okay I open the bottle and introduce by means of a filler just put some ink at the bottom of this, this is water capillary at the bottom I put 1 or 2 drops of ink, so that I can see the colour. I take out without disturbing the water, the ink will remain at the bottle.

But if I leave it there for some time, the ink comes up and occupies the top portion, how has it come up? It will go down, you will say that may it is gravity but in this case the ink has come up here what was the driving force? Driving force was ink is present at the bottom moving here, the driving force or the concentration gradient receive the law of nature, if the concentration gradient if the things can move, it will move, okay.

If they are free to move, if it has enough energy to move. Now, the atoms will not move, if there is large number of donor atoms are there on through their side, right side, they will not move because they require lot of energy to move, we can move them, if you give lot of energy by heat in the crystal to the top 30 degree centigrade, then they can move but the electrons which are present here can move because of concentration gradient even at room temperature because they can; they are free to move.

So, what happens is; the moment junction is formed because of the concentration gradient from the right side to the left side, the electrons will move, the moment electrons move from the right side to left side, what is left on the right side, originally it was sub neutral. Now, if electrons are moved out, it leaves behind + charges which are the core of the nucleus, you may recall the phosphorous atom is neutral, if the electrons is surround that.

If one electron moves out, it leaves behind 1 + charge which is core, that + charge is fixed charge it would not move towards this atom, that is very heavy, electrons move on that side.

So, right side; there is + charge it leaves behind the core which will not move; next left side is negative charge because of movement of the electrons. Similarly, because of hole concentration the mobiles holes will move on; the vacancy is move to the right.

That again, charges a right side to + leaving negative charges.to core, net effect is; there is the immobile + charges here on the right hand side because of movement of electrons from right to left, there will be immobile negative charges on the left because of the + mobiles holes can move to the right. So, the doping concentrations are equal, the width of this region and the width of this region will be same. This is called the depletion layer.

Because it depleted off mobile carriers, it is called depleted layer or post charge layer, okay. What is the consequence of this? The consequence of this is + charges are present here, the negative charges are present here, field lines will originate on this + charge and terminate on the negative charges, there will be electric field from this side to this side. All the charges originating on the right side will go through the centre portion.

So, there will be peak electric field here and there will be zero electric field at this boundary. For electric field direction is from right to left, okay, from the right to left that is the electric field direction. Now, the magnitude of this depends upon the amount of charge that is present here which depends upon the doping concentrations, okay. So, what is the consequence of this? If this electric field were not present what would have happened?

The transfer of electrons from right to left would have gone infinitely but because of the transfer of charge, there is an electric field and because of electric field there is a potential difference between this point and this point; + charge on the right side, negative on the left hand side. So, if I go from this left hand side from here to here, that is from –Wp to + Wn; n is the n region, W is the width of that region.

If I go from here to here, there will be potential rise; electrostatic potential go up because + charges on the right hand side, okay. How much is the potential depends upon how much is the electric field? If it is uniform you will say electric field into distance gives you the voltage but it is not uniform, it is varying field but there will be built in potential. So this is called the built in potential, okay. What is the consequence of this built in potential?

Vbi or contact potential Vcp both thermals are used interchangeably. What is the consequence of this? The consequence of this is that electrons tend to move from right side to left to because of concentration gradient. Now, notice the electric field has built up here from right side to left side because of transfer of electrons leaving behind + charges on the right side, okay and making this side negatively charged.

Now, this negative charge are built up so much, that this electric field in this directions prevents any further movements of the electrons from right side to left side. So, the voltage that has developed here or the electric field that has developed here reaches such a value that field and that potential is sufficiently large to prevent any further transfer of electrons from right hand side to left hand side.

See there are 2 force of community picture; one is the concentration gradient which pushes the electrons from right to left. Other one is the electric field from right to left which will actually keep the electron push to the right, okay. So, if you say the electric field pushes the electron from negative side to the positive side, okay, electric field pushes the electrons from the negative side to the positive side.

Whereas the concentration gradient pushes the electrons from right to left, okay. So, the electric field now is sufficiently large, so that the movement from right to left is exactly balance from movement from left to right. Same thing is holding for good for the holes, there is stack of hole, IF, there will be a forward current from left to right, continuous hole through left to right that I marked as IF.

But because of this field in this direction, okay there will be reverse flow of holes in the direction. These ones are look into that, ultimately there is no flow what you say is; forward flow or reverse flow are balance equally each other. So, what you say is because of this concentration gradient IF, I marked with this arrow here, IF, there will be flow of holes from left to right, okay concentration gradient.

But on the right hand side, there are minority holes you remember, there are 10 to the power of 15 electrons, there are 10 to the power 5 holes per centimetre cube, they are present here minority and from here to here, there is an electric field in this direction. So, those minority holes will move from right hand side to left hand side, that is the exact electric field is sufficiently large.

So, that the transfer of minority hole from right hand side to left hand side can balance exactly if the transfer of holes from left hand side to right hand side which is due to concentration gradient, so the current is 0, so if you look a t the barrier here, okay the holes moving from right hand side to left hand side, enjoy moving down the potential hill. If you keep your hole here at the tip of this hill, it will just roll down the potential hill okay.

Say for example if have a slope like this, if I bring a particle here, it will rolled down that, whether this is increased or reduced, so long that there is a slope there, it will move down, so that is what is happening. The hole present on the right hand side or their minority areas which are due to thermal generation, so long there is temperature, number will be decided at room temperature is 10 to the power of 5 per centimetre cube.

If I increase the temperature, the hole concentration increased, number rolling down will increase. So, this is actually terms of electrons due to the electric field or rolling down the potential hill, independent of the slope. Now, from the left hand side to the right hand side, if the hole has to come from this side, this side, it has the enough energy to go up the barrier, okay, that will always be present due to their ambient temperature, the electrons.

The holes will be distributed after certain height, some of them will have enough energy to cross the barrier, suppose I increase this barrier, the holes has to go up the larger barrier, so if I increase the barrier, the hole crossing from left hand side to right hand side will be reduced, the less number of them will be able to cross. If I reduce the barrier, barrier height is reduced, more will be able to cross the barrier.

So, the moral of the story is what flows from right hand side to left side depends only on temperature, irrespective of the height it will be constant but what flows from the left hand side to right hand side will depend upon the barrier. If I reduce the barrier, more will flows to the right, if I increase the barrier, it will completely cut down what can go from left to right. So, that is the thing that we are going to see now.

So, we will concentrate only on one charge because same thing happen to the electrons also, so here the IF is due to those which are able to cross from the left hand side to the right hand side, IR is those which are crossing from right hand side to left hand side rolling down the barrier, okay. Now, IF = IR 0 current, no voltage applied. Let us go back and now see what happens if I apply; if I increase this barrier? How do I increase this barrier?

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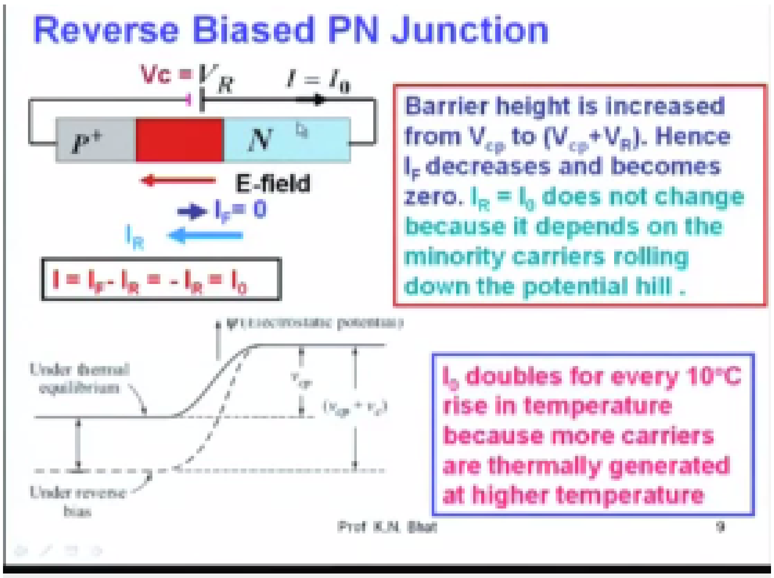

Make this side; right side more positive compared to the negative side, how do I do that? I apply voltage across the junction with this N side more positive compared to the P side, so that is like this. So, I made P side +, I applied a still voltage VC which you can call it as VR, you call it as a reverse bias. You call it reverse bias because you have increased what if originally the height was VCP or VBI, now you applied both this side.

Both positive by applying external voltage VR or VC, so that this barrier height is no longer VCP it is increased from VCP to VCP + VR, okay. So, what is the result of that? Remember the hole which are present minority carrier on N side there fixed for a temperature, so and number available here on the right hand side is fixed. Now, also this plane, the inclination a slope of this only has increased, the height has increased.

But whatever is, there down these planes, you can roll down the potential hill very comfortably whether it is VCP or VC + VR. So, number rolling down there from here, there is IR, see if you remember when we went behind earlier the IR marked this size this also, this same size here, here IR is remaining the same thing because the number crossing from right hand side to left hand side remaining the same thing for a given temperature.

But if I increase the temperature, that will go up. Remember that and these IR is usually called as I0 which you can call it as reverse saturation current because when you in this bias condition this IR remains the same thing , what about IF? Previously, IF was equal to IR, now because you increase this barrier, okay the holes which are present are here at this level originally, some of them had energy more than this height.

So, they were able to giving this IF comparable to IR. But, now since the barrier height is increased, okay the how much energy level these electrons have depends upon the temperature that is fixed, so they can come only after some level they cannot cross this barrier. So, that IF comes reduces and become 0, so now you can see when you have this bias + on the right hand side okay, that this is going to reversed bias.

Because we are cutting down this IF and allowing only the IR to be present which is a constant for a given temperature, so IF ; I = IF – IR in that direction, in this direction IF is 0, IR I put negative and I marking the current in that direction. If you; then to P that is positive, P to N if you consider negative. So, to avoid confusion, we will say that I0 will be N to P, please remember now.

By any chance if you are able bring the + charges near this potential barrier, if I increase that concentration either by increasing the temperature or by a mechanism which we break this covalent bonds that is by standing light, then this I0 will go up, in fact the solar cell, you do that, you shine light, so that you generate carriers, current can be collected, okay. So, this is the reverse current will be constant I0 is at a temperature, okay.

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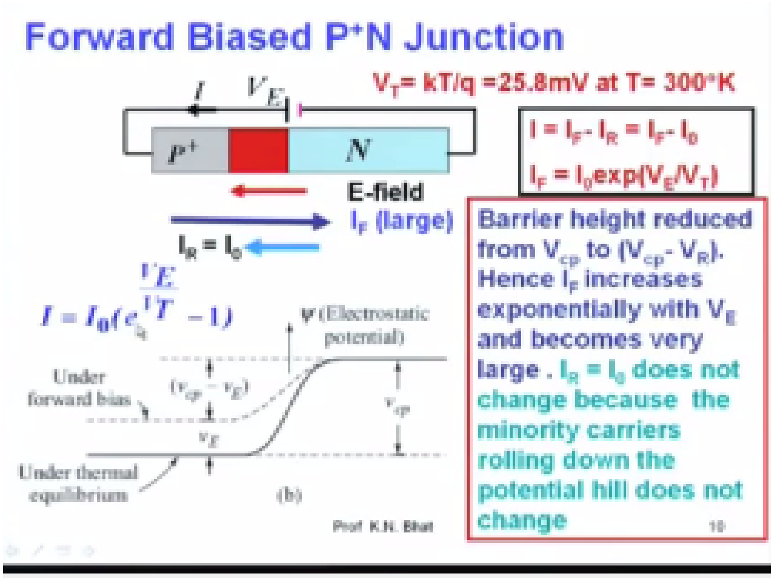

Now, let me see if I being instead of making this N side more positive and make P side more positive in the sense, originally it was VCP with + here, - here, I apply opposite velocity that is P side positive , N side negative like this; +=on the P side, so originally it was VCP like this with + here, - here, I apply + here, - which add some to that, so the voltage VE is applied, therefore the barrier height is reduced from VCP by VE.

So, barrier height is VCP –VE, what is the implication over that? What is happen to the IR? IR as I told you will depend upon only number which is present here, whether this is plane, this is reduced, that is reduced like that; if it is like this or like this, now you have reduced it. What are the particles I have put here, it will go down whether it is like this or like that, so that IR is not changing that is kelvin even in this bias.

But the carrier which are here originally they have to climb up this barrier from left 2 side + charges but now you reduced the barrier by applying this bias, you call it as forward bias, because it enables more of these charges because they took off from this side to this side, because the barrier height is reduced from this height to this height by the mode e, so more charges are able to cross.

And the charges which can cross exponentially depend upon the applied voltage or the barrier. So, what you can say is without deriving that the current flow which originally was both IF forward and reverse for I0; the reverse is I0 now, this current but IF has gone up by a factor e to the power of VE/VT. Originally, you can see here thermal equilibrium condition no applied voltage, IF and IR both were equal to I0.

Now, when in reverse IF tend out to 0 and current flow in that direction IR is I0 but when the forward bias I0 will be the same thing but IF has gone up by a factor e to the power of VE/VT that is I0 e to the power of VE/VT. So, in this direction, you have I0 e to the power of VE/VT and in other direction that I0 is always present. So, that current flow from P to N is I0 e to the power of VE/VT from here to here and right to left is I0 that is the current flow here, okay.

So, this all what I have written here barrier height is reduced from VCP to VCP –VR in fact VCP – VE in this case and IF increase with response with VE and become very large and IR does not change and IF increase by that time, what are they if it in here, okay. Now, that completes my discussion on forward bias reverse bias. Let us now take a look at a characteristic quickly, okay.

So, please remember forward bias that is the characteristic which goes up exponentially, reverse is a constant current from right to left buy in both cases the net current flow is from the positive side of the barrier, negative side of the barrier, easy to remember. The reverse bias from positive side it is comes like that , in the device it sent to P, forward direction, net current is from positive side to negative side because the driving force in the battery if it has got be from positive to negative, okay.

Other thing that you must remember is, when I go to transistor action. If I increase the holes minority carriers here that current will increase okay and reverse bias, when the reverse bias current flow is will increase if increase hole concentration. Here when a forward bias, what happens to the hole concentration is injected from? Is raised here because you are injecting holes from left hand side to right hand side.

Large concentrations are there, they are ultimately recombined, okay. Now, remember this, so minority carriers are injected from this majority holes from here to here when the forward bias and if I have a P side of this side that can collect those hole, say for example, here if I had injecting; if I inject holes here if I rise the hole concentration here that can flow from here to here that will see later, okay.

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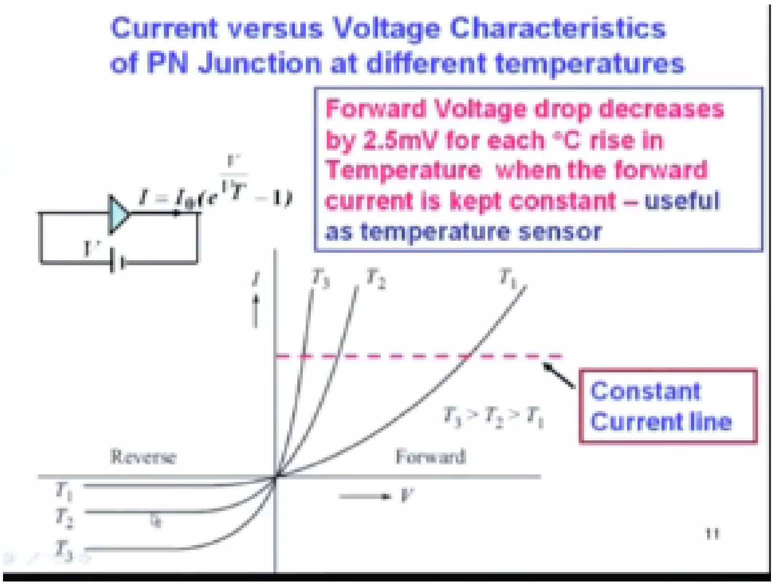

So, now the IV characteristics, forward bias I = I0, e to the power VE/VT -1 that is the characteristics at room temperature t1 exponentially increasing and forward bias, reverse bias; reverse is polarity, V is negative, so e to the power – VE/VT; VT is about 25 electron volts, VT is actually KT/q, K is Boltzmann constant, T is temperature, q is electronic charge.

So, that VT called thermal voltage is about 25. 8 millivolts okay. So, if this is e to the power -100/25 that is e to the power of -4 that is very small compared to 1. So, if you apply 100 millivolts in that direction, this term is negligible and the current is in the opposite direction that is the reverse bias. So, and that saturates I0, so you can see that forward bias current increases exponentially reverse bias current saturate at T1.

If I raise the temperature I0 goes up because the hole concentration goes up, minority is here, if I increase the temperature, the carrier concentration here goes up, so more current flow from more + charge flow from N to P current, more current; more use current, so you can see the T1 to T2 current goes up that is I0oes up, if I0 goes up entire thing goes up in the forward direction.

So, both go up in this direction for a given forward voltage, the current keeps on increasing the forward direction, for a given reverse direction, the current also increases as go on increasing the temperature, okay. So, this is the IV characteristics. Now, this rise in temperature, for example if I take reverse current for every 10 degree centigrade I am sorry just here you can see the reverse current doubles for every 10 degree centigrade rise in temperature okay.

Here okay. It double for every 10 degree centigrade rise in temperature whereas for a given constant current, if you go along this line, the forward voltage drops from T1 to T2, you can see that voltage drops falls, T2 to T3 the forward voltage drops on same current and this rate at which falls is about 25 millivolts the drop will be 25 millivolts for each degree centigrade rise in temperature okay, so that is the very useful parameter.

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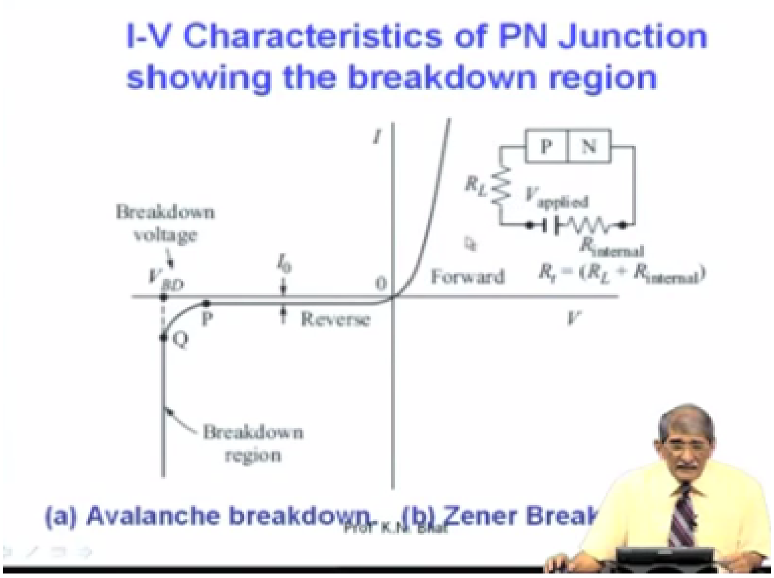

In the sense, you can use it, I would access or temperature sensing when forward bias was kept constant, you can measure the voltage doubler thing, as a function of temperature, so you can calibrate it by noting that the forward voltage drops by 25 millivolts for each rise, degree centigrade rise in temperature. So, this is actually the full characteristics, forward characteristics, reverse characteristics, this is I0, e to the power VE/VT.

If you go to very high voltages, in the reverse direction, see here the voltage prevents the current flow because the carriers present are very small minority carriers, but if I go to very large voltages okay the current will suite up because there will large number of hole electron pairs created because of a mechanism called Avalanche break down or Zener break down. Zener break down you can understand very easily.

You have the crystal subjected to the electric field stress and you are pulling that electrons and + charges electrons away from the lattice atom, so it creates large number of electrons because they break down, take away this lattice atom leaving behind the plus mobile charges, both these electrons and holes are mobile they give rise to current flow, so if you put in nutshell, very large voltages will allow.

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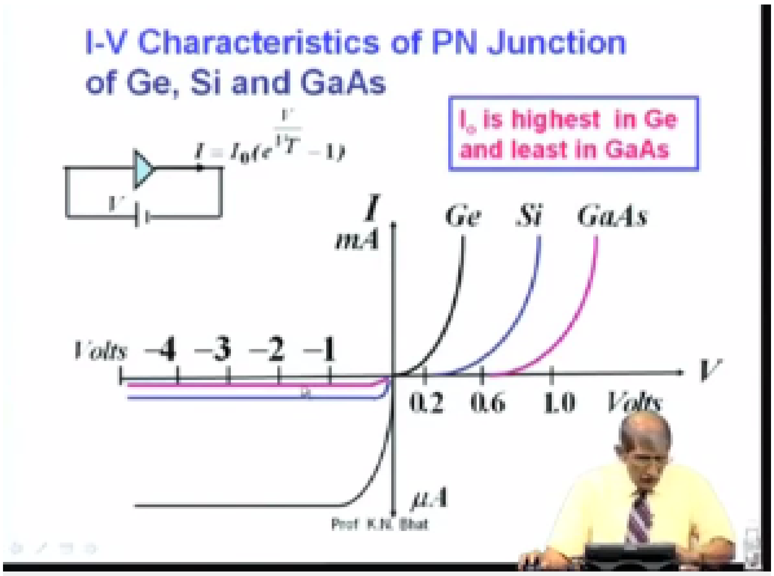

Generates a large number of electrons hole pairs which give rise to large current flow, which will be actually in the same direction as the reverse current flow always supply has to come from the battery, okay. Now, you can actually see the characteristics for different materials, for example, if I take germanium the characteristic is like this, like this is a forward, this is reverse telling you that I0 is very large for germanium.

Because it is very easy to break the bonds in germanium, I0 is very large. Intrinsic array concentration is 10 to the power 13 of that order. Whereas, silicon it is more difficult to break the covalent bond by at a given temperature, so I0 is smaller than that, when I0 is small, you can see, I also will be small for a given voltage forward current is also small, for a given voltage this current is small, that means you double up more voltage to have this current flow here.

Gallium arsenide it is red colour here and I0 is even smaller, so you can see the cutting voltage, if you want cutting voltage, people talk of cutting voltage, where at least one tenth of the designed current like the current normally allowed flows though that, silicon is about 0.2 to 0.5 volts cutting voltage sufficient amount of current will flow in the forward direction, in silicon when it is about 0. 65 volts, germanium by 0.2 volts is sufficient, if you apply forward bias voltage, current will low.

Gallium arsenide, if you apply only 1volt, where current flow sufficiently okay, so you can see the, if you have the hole radio, which was germanium transistor based you cannot replace with silicon transistor because all voltages are different here and if the silicon device is there you cannot replace gallium arsenide, so germanium devices have been going out of market but germanium is coming back with new avatar.

Because of its higher electron velocity compared to silicon, it is taking a first look in the Nano electronics area that we also doing some work on germanium based field effect transistors, okay. So, that is coming up, we will looking at gallium arsenide because of the better electron mobility compared to silicon; germanium also because of better electron mobility but why did they leave germanium? They left germanium.

Because of large reverse saturation current and if you; you cannot operate those devices junction types of devices at temperature in excess of about 80 degree centigrade, the reverse current will become very large, the reverse current I0 become very large both will become a; shows like no IV contact, it will not behave like a diode that is why they left it. But there are other ways of sorting out this problem now.

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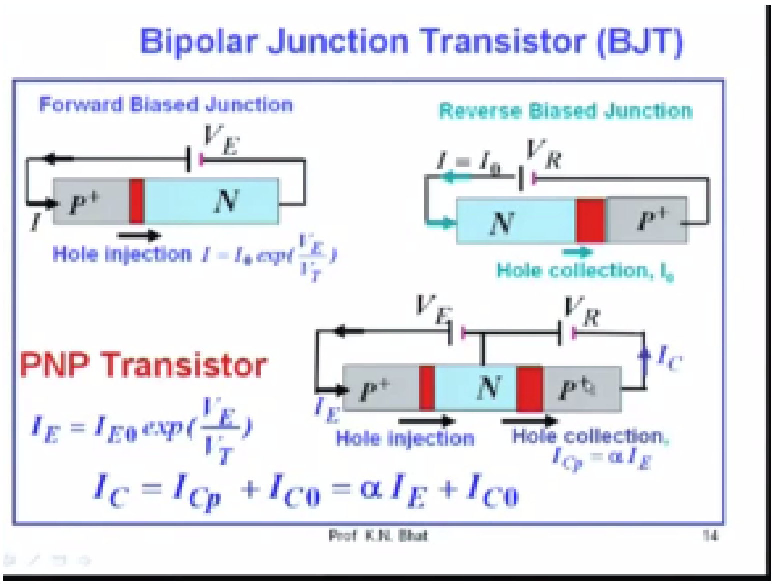

So, silicon you can go to about 150 degree centigrade without worrying about its operation, it will still work as a diode, you go to gallium arsenide, even go to 200, 250 centigrade, it will work as junction, okay, so what we will do now, we will quickly take a look at the bipolar junction transistor, I do not think I can go beyond bipolar junction transistor today and we finish up this junction transistor.

Mostly, I will take up in next lecture if I am not able to do today. I have just drawn this diagram to go from the PN junction to PNP junction. A PN junction has got only one junction okay we can see this is a forward bias junction which injects from holes from P type region to N type region, net current flow from P to N because a large amount of hole flow from P to N very little hole flow from N to P.

Because they are minority there, the N type holes are minority, so very few I0 * e to the power VE/ VT, if the hole current and if you take the current total current there will be –i0 is there because of holes of right to left. Okay but the point that I am trying to make out is they have lot of holes injected here let ultimately will recombine with electrons here creating a electron injection from here to here okay.

Holes in the recombined with electrons, electrons are separate from here to here in to these are majority there, so there is a net current flow always like that. Electrons were in that direction, see hole is + charge the current flow is the direction is the same as the direction in this, when which + charge was, electrons is negative charge current flow direction is opposite to the direction in which the electrons moves.

So, the electron moves in this direction, the current flows is in that direction, so here the current flow in this direction left to right but electrons are injected from here to here to neutralise these holes okay that is how the charge transfer is from here to holes recombine here then convert the electron in the way of that electrons matter, thermal holes okay here with the semiconductor we taught of electrons.

Now, take a look at this reverse bias diode, I have just out in opposite way + - current flow is I0 N to P and this flow is because of minority carriers generated here due to thermal generated holes there flow from left to right that give rise to current in this direction. Now, I was telling again to you that if I have a large number of holes here that will give rise to more current. Now, what I will do is; I will merge this N type region with N type region.

So, that I have P, N and P and reduced the length of this to very small width I put P and P. I reduced this to very small width like 1 micro or 2 microns, I micron is 10 to the power of -4 centimetre very small, so that the holes injected from here to here they do not have sufficient path length to recombine, so that whatever is injected here can reach this edge, now this is the reverse bias junction.

Now, remember if there is a hole which is a minority in this region, if it reaches here okay this is negative this is positive , plus to minus, the hole down in potential hill. So, here the hole down from N to P, you supply the holes to this from this junction, this junction injects the holes and those holes because the path length is very small all of them are made available here they can roll down the potential hill.

So, what you have done is, a forward bias junction is injecting the holes and reverse bias junction which is very kept very close to that to collect those holes, so whatever current is here is IE, is IE0 e to the power VE/VT is the forward current okay and that most of it reaches here, so I call it as IE since it is not exactly the same, some of them may recombined multiplied by factor alpha, alpha times whatever IE is there reaches here.

But we can think if I do not have this V applied, there is a current due to the I0 which I call it as IC0. So, the total current through this junction is alpha time IE reach in the collector plus the reverse saturation current of this, okay and alpha if very very close to one, so that it can almost right that if IC is IE is one million ampere alpha e is 0.999 million ampere and IC0 in micro amperes.

So, this is mostly at the 1 million ampere here, 1 million ampere here, you transferred it from a forward bias junction to a reverse bias junction. Forward bias junction is a very low resistance junction the reverse bias junction is a very high resistance junction, so it transfers the current from a lower resistance loop to a high resistance loop, that is why it is called transfer resistor, transistor transfer is the, transfer is the, transfer is the transistor okay.

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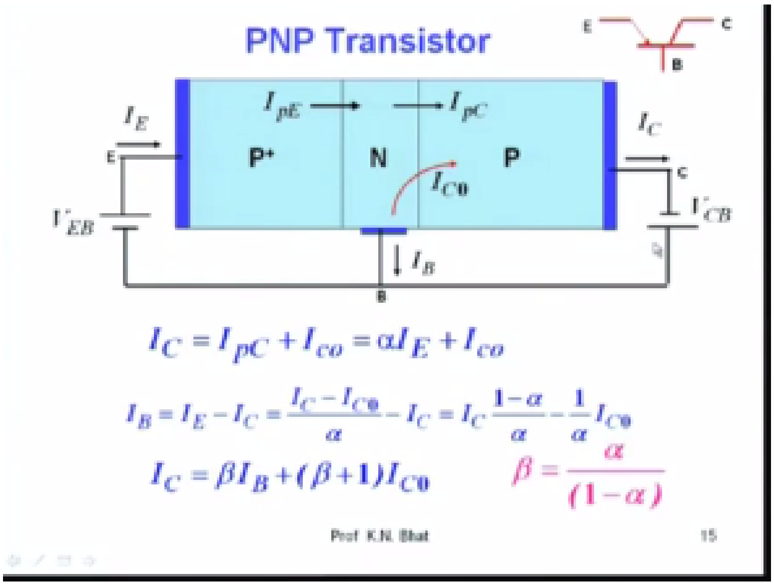

You read out those words, that is why it is called junction transistor, okay. So, now I think I will not have much time may be couple of minute I will have I just go through this; there are 2 types of transistor; PNP transistor and PN, what I have discussed just now is PNP, IE injects the holes and IPC hole current connected there, E is alpha times IE, IE alpha times IE and IC0 is in the direction, so IC that alpha times that I can write.

Now you can see current entering and whatever little recombines comes out of that very little okay, so IC IB is IE – IC and I can write substituting all these; substitute for IE as IC – IC 0/ alpha okay I can write IE is that minus IC, this simplifying I get IB = IC time this quantity, 1-alpha/ alpha, you can see 1- alpha/ alpha, you call beta, it will ultimately be disturbed in IC/IB, that is the current gain of the transistor, common emitter gain of the transistor.

I think beta is alpha so, you see that if alpha is 0.99, 1-alpha is 0.9, beta is 100, okay so that is what you get beta is if it is 0.99, it is 100, so you can see that IC will be 100 times IB, if micron amperes of base current flowing, I can get milli amperes of current flowing, so we inject the signal at the base terminal, I get large amount of current at the collector.

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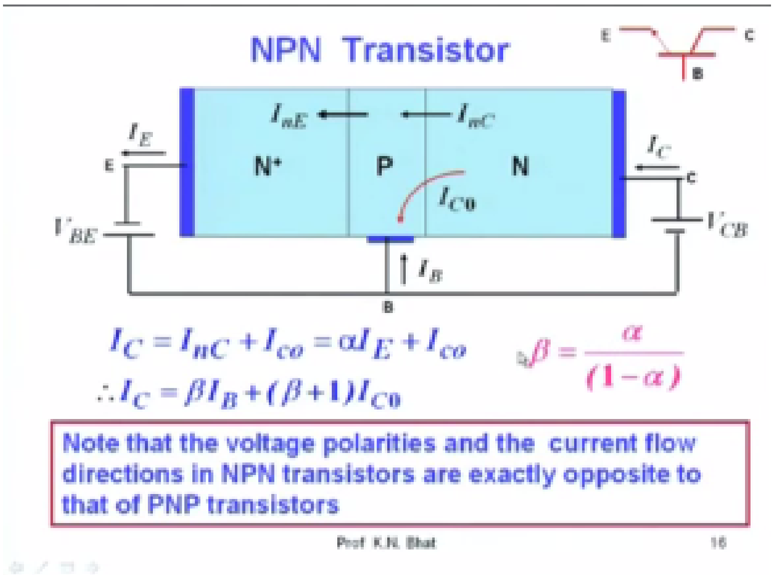

So, I can use it as an amplifier, okay. So, I can have NPN transistor or PNP transistor also okay, so these are the PNP transistor that this exactly same thing what happens is the forward bias junction injects current in the direction, emitter current flow is, you can see exactly opposite to the PNP transistor, collector current also is exactly opposite to the direction.

Base current also exactly opposite, everything is opposite, polarities here, emitter is + base is negative, here emitter is -, base is positive exactly opposite; equations are same, collector current is alpha times IE + IC0 or electric current is beta times IB + beta + one time IC0, this is the principle of transistor action, with this I think we will stop, we will discuss the characteristics tomorrow.