Basic Electronics
(Module 1 – Semiconductor Diodes)

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Lecture - 1
Semiconductor Materials: Intrinsic and Extrinsic

Today we will discuss about semiconductor materials. Semiconductor materials are the backbone of electronic devices and circuits. What is a semiconductor material? Probably all of you know about conductors and insulators. Conductor is a material which when you apply a voltage source creates a generous flow of charges like for example copper. Copper is a metal and metals are conductors. Insulator is a material that offers a very low level of conductivity when a voltage is applied; for example mica. Semiconductor material is in between this conductor and insulator. It is a material that has conductivity level somewhere between the extremes of an insulator and a conductor.

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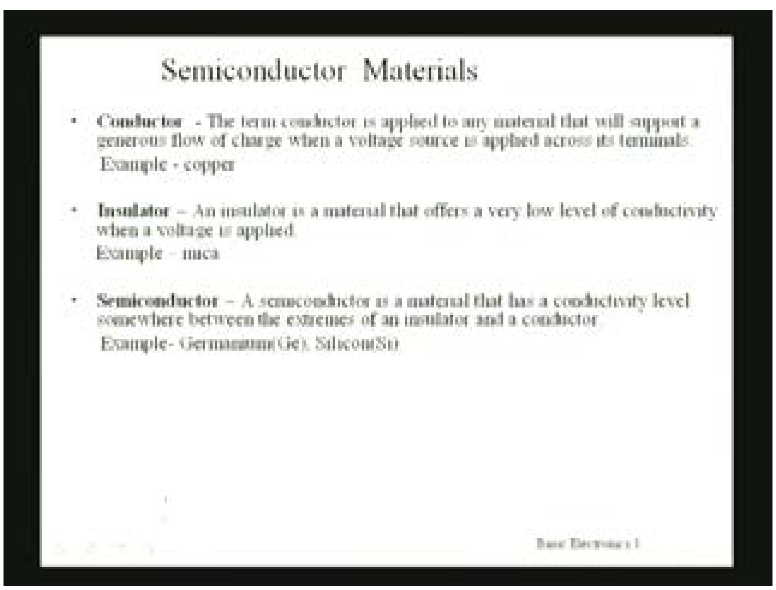

For example germanium and silicon are these two materials which are semiconductors showing similar property. The resistivity of a material is inverse of conductivity. If we compare the resistance levels of conductors, insulators and semiconductors we see that the conductor has resistivity value which is the least among the three. That is, a copper which is a conductor has a maximum conductivity so its resistivity value is around 10^{-6} ohm centimeter whereas an insulator has a resistivity of 10^{12} ohm centimeter. This is much more than conductor but semiconductor like germanium and silicon have resistivity values in between these two. For example if we consider germanium semiconductor it has resistivity value of 50 ohm centimeter and silicon has resistivity value of 50 x 10^{3} ohm centimeter.

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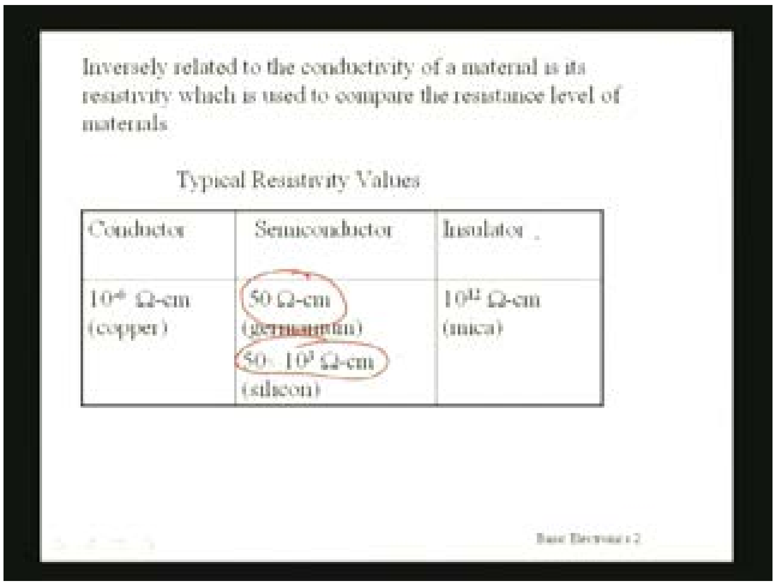

You can see that semiconductor has resistivity in between conductor and insulator. If we consider these three, i.e insulators, conductors and semiconductors and see their energy band diagrams, then we find that the energy gap between the valence band and the conduction band in an insulator is very high.

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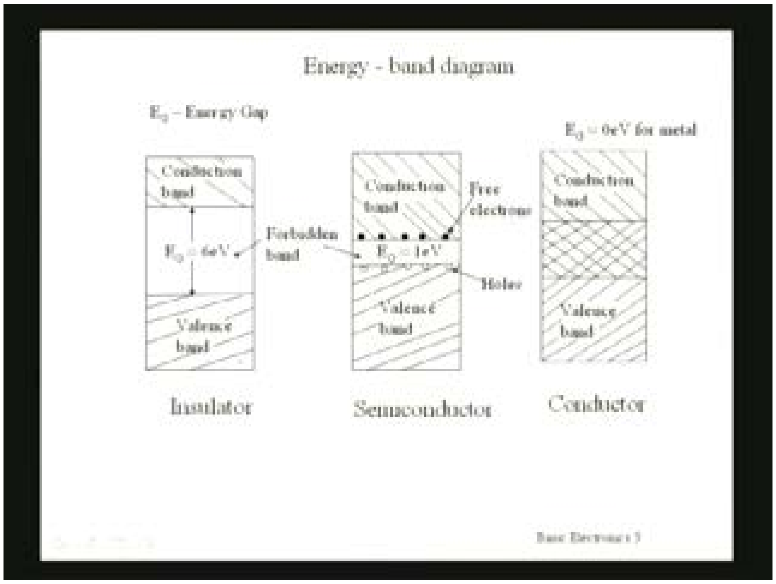

It is around 6 electron volts as is seen here. This energy gap means it is a forbidden band and the electrons will have to acquire this much of energy to become conductive and enter the conduction band. But semiconductor does not have such a high forbidden energy gap which is around 1 electron volt as is seen here. Electrons can acquire that much of energy which is 1 electron volt only to jump from valence band to the conduction band in order to become conductive and metals like copper which are conductors have overlapping conduction band and valence band and they have zero electron volt. That is why they conduct because electrons can very easily shift between valence band and conduction band and take part in conduction. Semiconductor is a material that has conductivity level between the extremes of insulator and conductor and why this is so?

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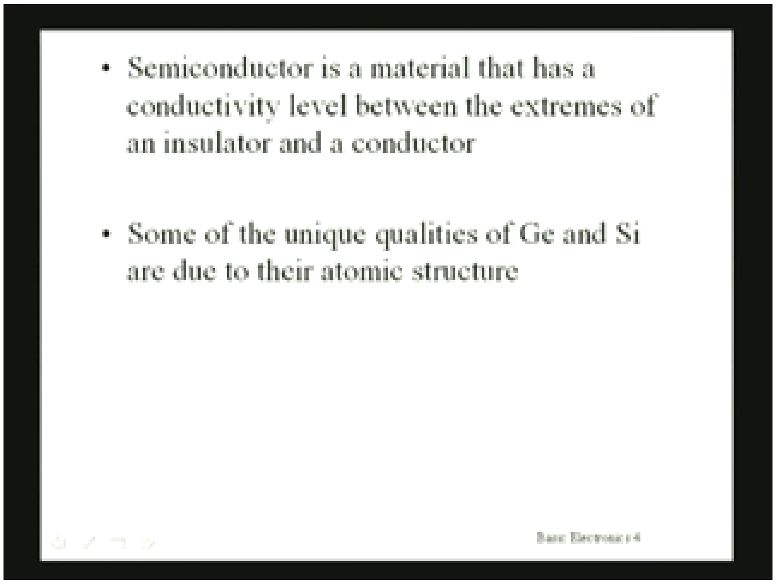

That is because the semiconductor like germanium and silicon have some unique qualities which are due to their position in the periodic table and their atomic structure. These are group IV elements. The atoms of these materials like germanium and silicon have a very different and definite pattern that is periodic in nature. That is it continuously repeats itself and one complete pattern is called a crystal and the periodic arrangement of the atoms is a lattice. Both germanium and silicon have 4 electrons in the outer most orbit which are called valence electrons. In order to complete the structure of inert gas they will always try to complete the 8 electrons in the outer most orbit.

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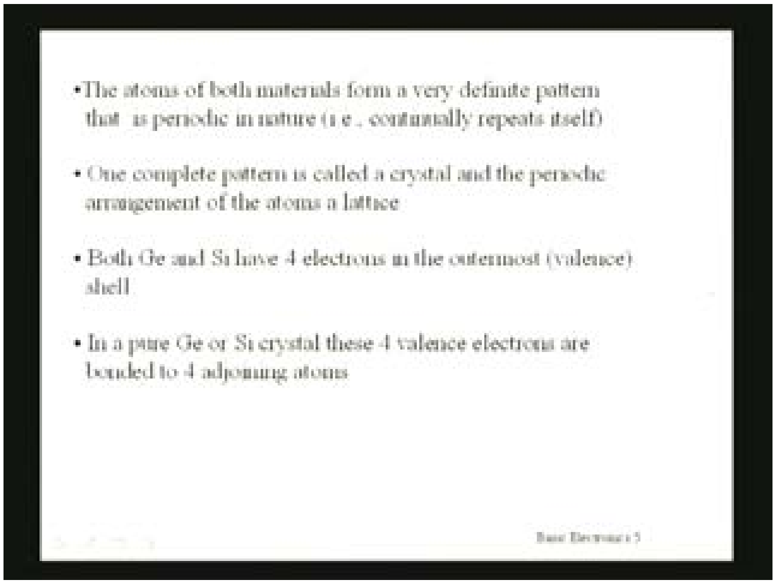

In the pure germanium or silicon crystal these 4 valence electrons will be bonded to 4 neighboring atoms as shown in this diagram. If I consider a germanium atom it has 1, 2, 3, 4 electrons in the outer most orbit which are called valence electrons. Similarly silicon will also have 4 electrons in the outer most orbit because they are group IV materials.

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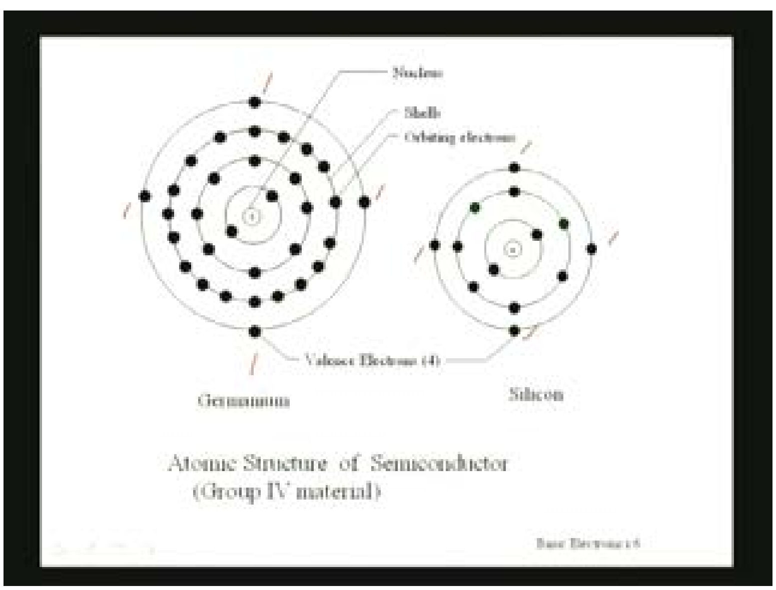

They will try to complete the 8 electron structure. That is why they will share electrons with the neighboring atoms as is seen here. If we consider silicon atom, these 4 electrons in the outermost orbit are sharing electrons among themselves so that the total number becomes 4 and 4, 8. These atoms which are nearby are sharing these covalent bonds.

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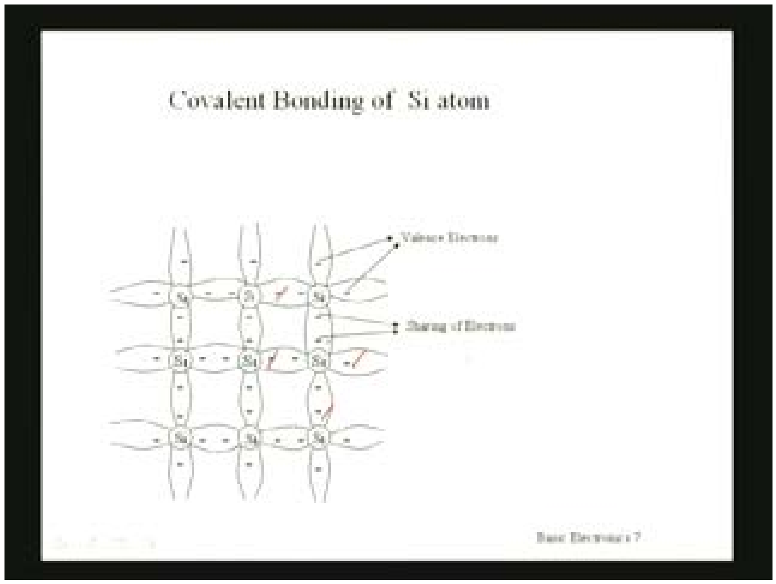

These covalent bonds are formed between neighboring atoms of silicon and thereby they complete the structure of the inert gas having 8 electrons in the outermost orbit so that they become stable. These semiconductors which are in the purest form are known as intrinsic semiconductors. In these intrinsic semiconductors the free electrons are due to only natural causes like thermal energy or light energy which impart extra energy to the electrons to become free and thereby they get additional kinetic energy from these natural causes and they break this covalent bond. These covalent bonds will break in order to become free. 1 electron will become free when it absorbs kinetic energy from either the surrounding or any light is falling on them.

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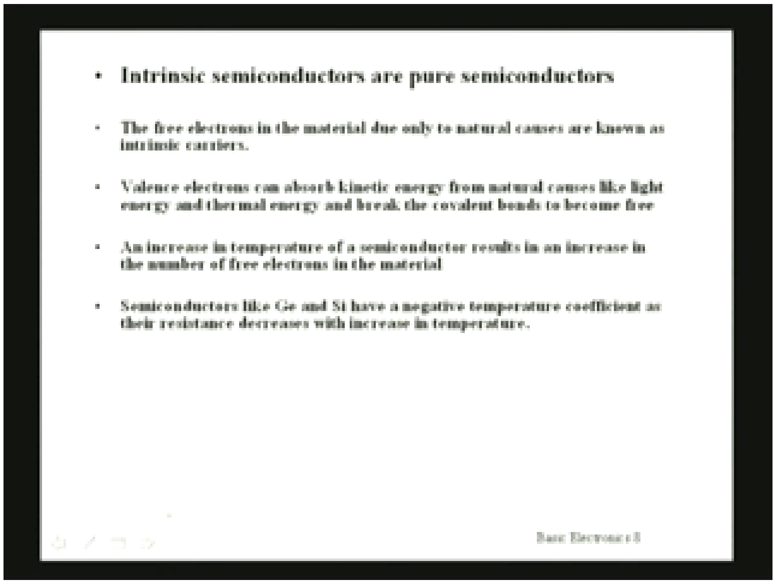

An increase in temperature is naturally the reason for more conductivity in semiconductors. This increase in temperature of a semiconductor results in increase in the number of free electrons in the material so they become more and more conductive. Even though they may be not so conductive at certain temperature but if we increase the temperature they will absorb more kinetic energy and will become more conductive. The semiconductors like germanium and silicon they have negative temperature coefficient as the resistance will decrease with increase in temperature. This is a peculiar phenomena that is seen in semiconductors which is just opposite to your conductors like metal.

We have been talking about the intrinsic semiconductors. Those are the purest form of semiconductors without any impurity in them. But there is another type of semiconductor which is extrinsic semiconductor.

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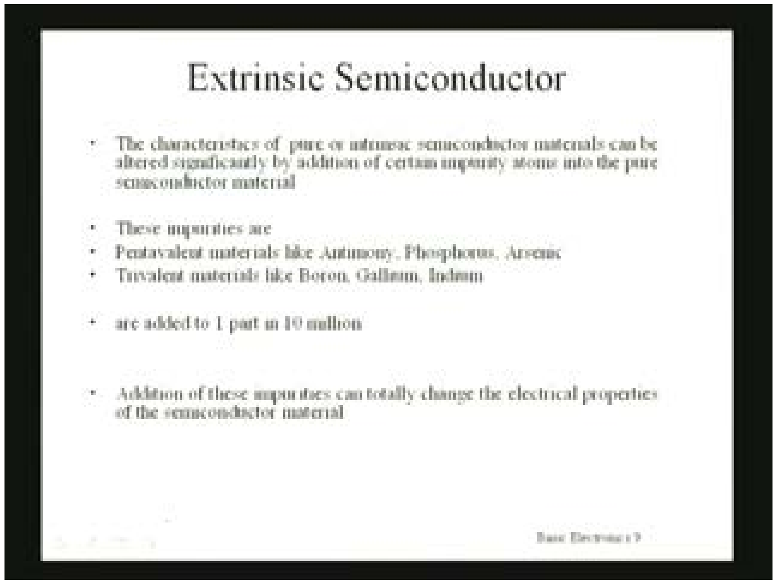

This extrinsic semiconductor has the characteristics such that their property can be significantly altered by addition of certain impurity atoms into the pure semiconductor material. The impurities added to the purest semiconductor to make an intrinsic into extrinsic semiconductor are defined. We can add pentavalent impurity materials like antimony, arsenic and phosphorous which are group V elements and have 5 electrons in the outer most orbit or we can add trivalent materials like boron, gallium and indium which are group III materials and have 3 electrons in their outer most orbit and the standard norm of adding is that they are added 1 part in 10 millions. That is to 10 million atoms of intrinsic semiconductor you add one impurity atom.

We will discuss how the addition of this impurity totally changes the electrical properties of the intrinsic semiconducting material. When certain impurity atoms like antimony or boron are added to a pure semiconductor material we get an extrinsic semiconductor and this process of adding certain impurity atoms like antimony or boron into pure semiconductor like silicon is called the doping process. As a result of this doping we get extrinsic semiconductor either n-type or p-type.

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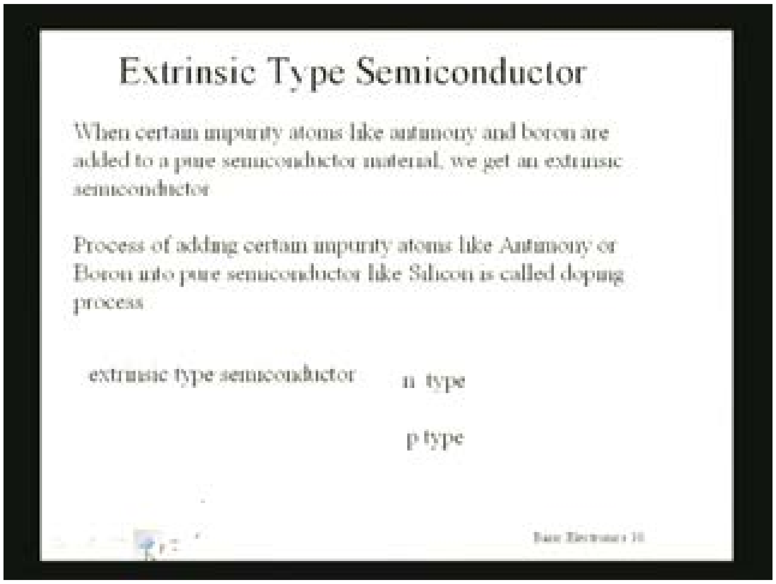

That is you can get n-type extrinsic semiconductor if you add pentavalent impurity material like antimony or phosphorous into a pure semiconductor like germanium or silicon or you can have p-type extrinsic semiconductor when you add trivalent impurity material like boron or indium into a pure germanium or silicon semiconductor.

What happens when you add an impurity atom to a pure semiconductor? Let us take for example an n-type semiconductor. How it is formed? N-type semiconductor means we have to add pentavalent impurity material. Let us take the example of adding antimony which is a pentavalent impurity material which is a group V material having 5 electrons in the outer most orbit to a silicon semiconductor. This silicon atom has 4 electrons in the outer most orbit. These are silicon outermost orbit electrons and now as we have added 1 antimony atom which has 5 electrons in the outer most orbit, it will share these electrons with the silicon atoms and these covalent bonds will be completed. 4 and 4, 8 electrons are there so these covalent bonds will be completed. But then 1 electron is in excess. That is it is extra. This fifth electron is donated by this antimony atom. This fifth electron is free. It can take part in conduction easily. That is why it is donating 1 electron. It is excess of 1 electron which is negatively charged.

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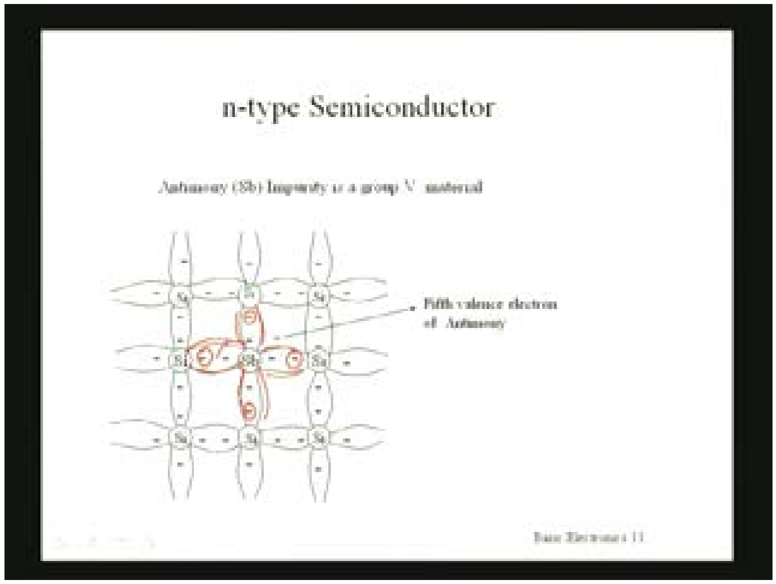

This is called n-type semiconductor. What happens when we add p-type semiconductor? We have seen how n-type semiconductor is formed by adding pentavalent impurity material to intrinsic semiconductor like germanium or silicon. Let us see how p-type semiconductor is formed from pure semiconductor like germanium or silicon by adding trivalent impurity material like boron or indium. Let us add boron impurity which is a group III material having 3 electrons in the outer most orbit to a silicon semiconductor. This boron has 3 electrons in the outer most orbit. It will complete its covalent bond with neighboring silicon atom having shared these 2 electrons as is seen here. These 2 electrons will form a covalent bond. In this process 3 covalent bonds are now completed. What about the other covalent bond? This covalent bond is now devoid or it is short of 1 electron to complete its covalent bond. This shortage of 1 electron means it is having less negative charge. This less negative charge or a positive charge is there in this covalent bond. This is called a hole. Hole means it is basically devoid of 1 electron. So there is a hole formed here in this covalent bond and this hole is a positively charged particle.

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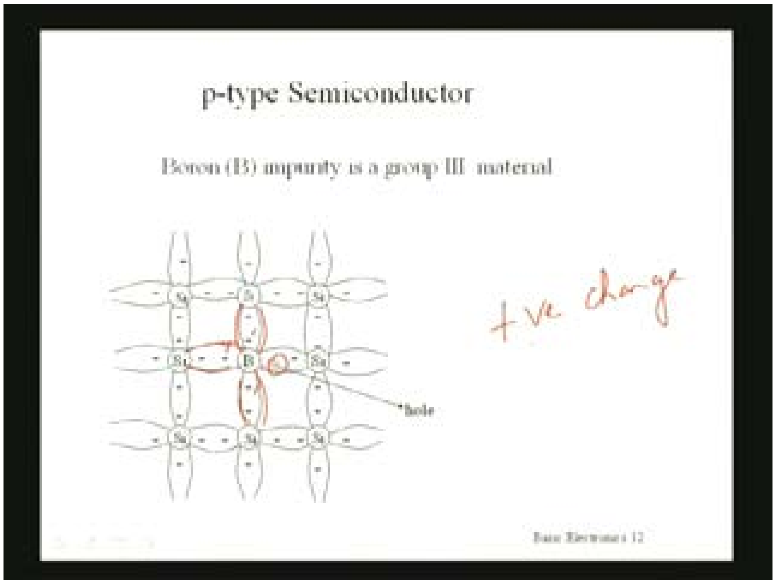

So this p- type semiconductor basically is formed in this way which will have holes as charge carriers.

If we consider again the n-type material we have seen that in n-type material which is an extrinsic semiconductor it has donated 1 electron. As it has donated 1 electron, the atom of this extrinsic semiconductor is now having 1 positive charge which is called an ion. 1 atom of this extrinsic semiconductor when it donates one electron it becomes ion having 1 positive charge which is shown here. The donor ions are having 1 positive charge and there will be electrons which are in abundance in the n-type material. These are called majority carriers. In an n-type material the majority carriers are electrons but there will also be in less number the minority carriers which are holes. These holes will be from this intrinsic material that is coming. If n-type material is considered altogether we will see majority carriers as electrons, minority carriers as holes and immobile ions which are positively charged or donor ions.

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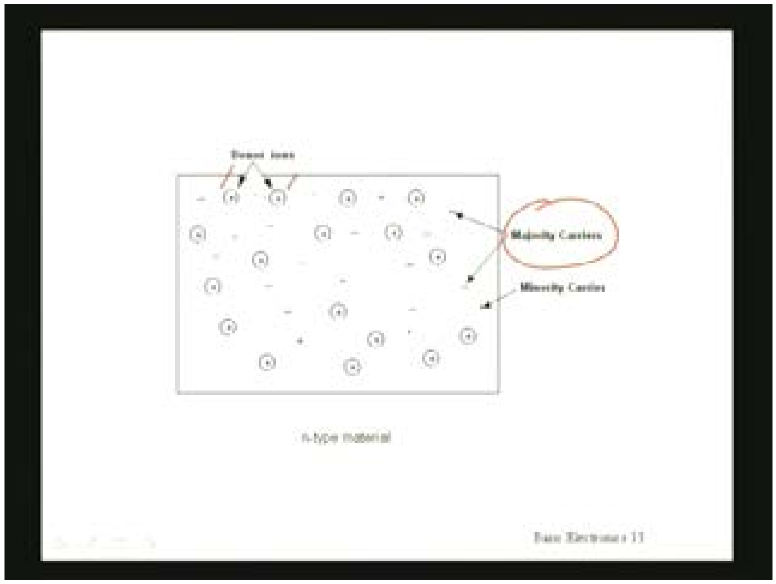

This is the structure of n-type material. Similarly if we consider a p-type material, p-type material has acceptor ions. In the p-type material we have seen that there is a hole and as it is devoid of an electron it will be always trying to get an electron from the neighborhood atoms. The electron from the neighborhood atom will come and fill up this hole and as a result this boron atom will be negatively charged. It is accepting 1 electron so it will be negatively charged.

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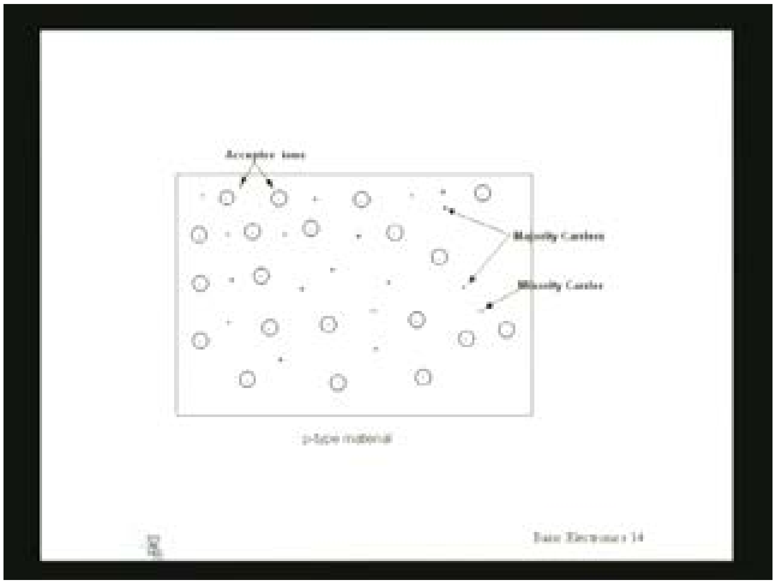

That means in a p-type material the atom of the impurity will be an acceptor ion having a negative charge and there will be holes which are positively charged as majority carriers and also very less in numbers although there will be presence of minority carriers which are electrons which are coming from the intrinsic semiconductor. This is p-type material where all these carriers and ions you see here. We can summarize that in n-type semiconductor the majority carriers are electrons and minority carriers are holes and in p-type semiconductor majority carriers are holes but minority carriers are electrons.

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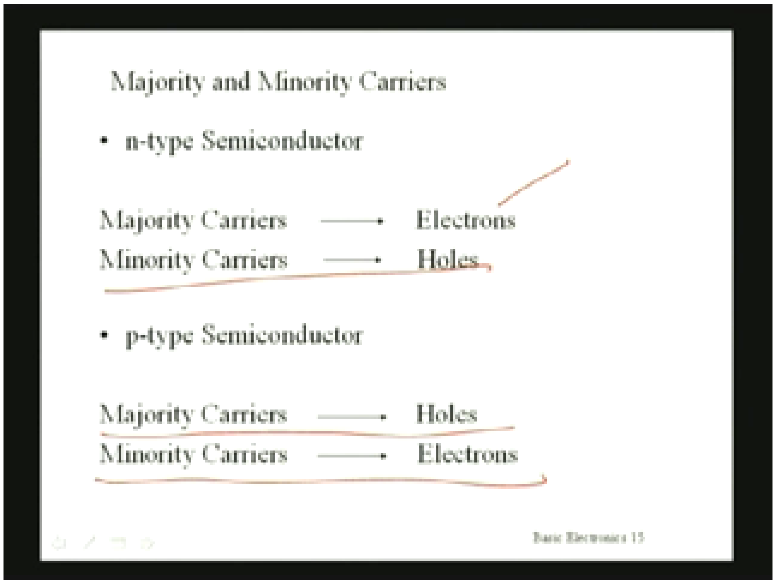

These are the charge carriers available in n-type and p-type semiconductors. How does the current flow in a semiconductor? Current flow is due to the movement of electrons and conventional current is always against the direction of movement of electrons. Suppose if electron moves in this way then conventional current direction will be in opposite way. This is electron movement direction and this is conventional current direction. But we have seen that another type of charge carrier is also there in semiconductors which are holes and which are positively charged. So the current flow will be now due to these two types of carriers; one is electron and other is hole and both are opposite in charge. That is electron is negatively charged and hole is positively charged.

We are having a semiconductor. We have the silicon atom and this is an impurity atom which is boron. It is creating a hole as is seen here. In order to fill up this hole electron from a neighboring atom will come. This movement of electron will be in this direction. When this electron comes and fills up this hole then this place will be now devoid of electron. It will be now a hole. Now hole movement will be from this position to this position. It is just opposite to the electron movement. Electron movement is in the direction of this solid arrow and hole movement is in the direction of this dotted arrow. If we consider the conventional current direction which is opposite to the direction of movement of electrons, then the current direction will be in the same direction, because of both these components. If I consider conventional current direction it will be like this because this electron movement is in this direction and hole movement is in opposite direction. But the final direction of current flow is opposite to the electron movement.

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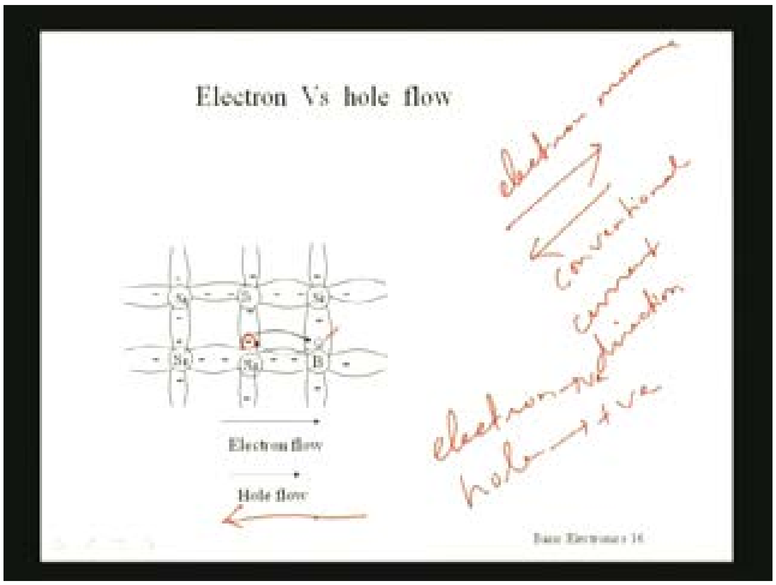

So it will be in opposition to this movement of electron but that is the same direction of the hole movement. We will discuss a very fundamental and very important law which gives the relationship between electron and hole concentration and that is known as mass action law. What is that law? It states that under thermal equilibrium the product of the free negative and positive concentrations is a constant independent of the amount of donor and acceptor impurity doping. That is mathematically if you write np is equal to n_i square where n is the concentration of free electrons in thermal equilibrium, p is the concentration of holes in thermal equilibrium and n_i is the intrinsic carrier concentration.

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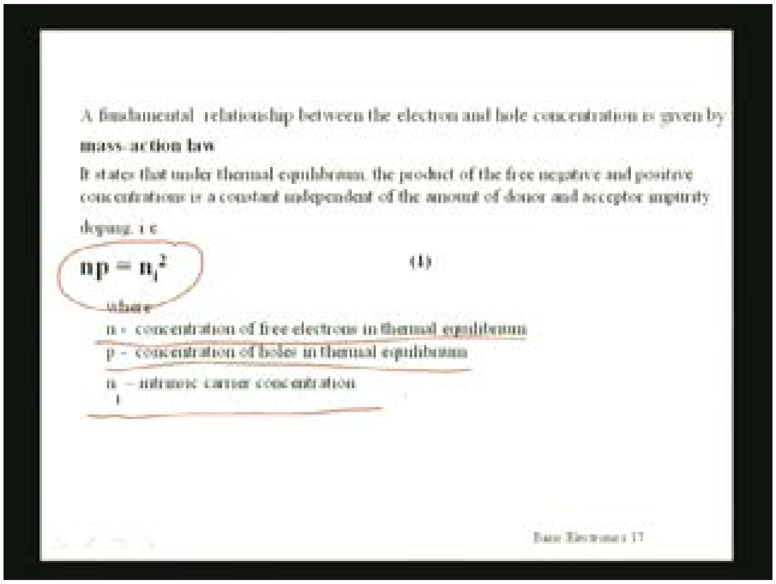

This is a very fundamental law in electronics which is mass action law. Now let us consider about the charge densities in a semiconductor. We will consider charge density later. Before that you must also know what is the law of electrical neutrality that is satisfied in the semiconductor? Let us consider a semiconductor material and consider a situation where it is doped by both n-type and p-type materials and let N_D be the concentration of donor atoms. These donor atoms are all ionized and already we have seen that these will be positively charged donor atoms. We have N_D positive charges per cubic meter which are contributed by these donor ions and let p be the hole concentration in the semiconductor so that the total positive charge density in the semiconductor is N_D plus p. That is total positive charge density in the semiconductor which is contributed by donor atoms as well as holes. Similarly if we consider that N_A is the concentration of acceptor ions then these contribute N_A negative charges per cubic meter and let small n be the electron concentration in the semiconductor. So the total negative charge density in the semiconductor will be now N_A plus n and since the semiconductor is electrically neutral we have this law to be satisfied that N_D plus p is equal to N_A plus n. Let us number this equation as 2.

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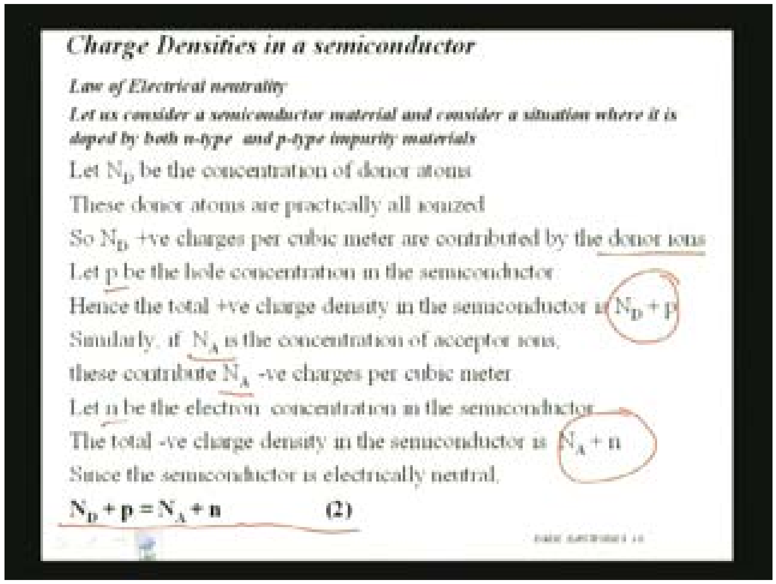

That means this electrical neutrality must be satisfied in a semiconductor given by this equation. Consider solely n-type material. We can either dope by n-type or by p-type impurity. So in an n-type material doping N_A will be zero and then the equation 2 will be now N_D plus p is equal to n since N_A is equal to zero or N_D is equal to n minus p. As it is an n-type material the concentration of electrons is much much more than concentration of the holes. So n minus p we can roughly say that equal to n. Then from this equation we will get that the electron concentration is almost equal to the concentration of the donor atoms N_D and if we use a subscript small n, the electron concentration in an n-type material n_n is equal to capital N subscript capital D. From this equation we can get now hole concentration for this n-type material which is given by p_n is equal to n_i square by N_D. Here we are using equation number 1, mass action law.

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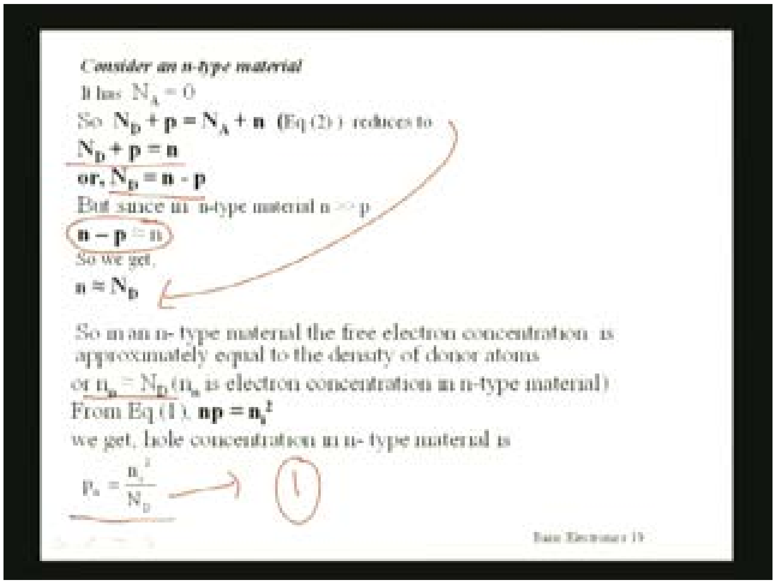

Similarly if we consider a p-type material, the donor concentration is zero since it is a p-type material. So the equation 2 will be now reduced to p is equal to N_A plus small n or N_A is equal to p minus n and since it is a p-type material the hole concentration is much, much more than the electron concentration, p minus n can be approximately written to be equal to p. Finally in the equation 2 we get p almost equal to N_A. So in a p-type material hole concentration is approximately equal to the density of acceptor atoms. If I use a subscript small p, p subscript p is almost equal to N_A and similarly from equation 1, mass action law if we use, we can find out the concentration of electron in a p-type material which is equal to n_i square by N_A.

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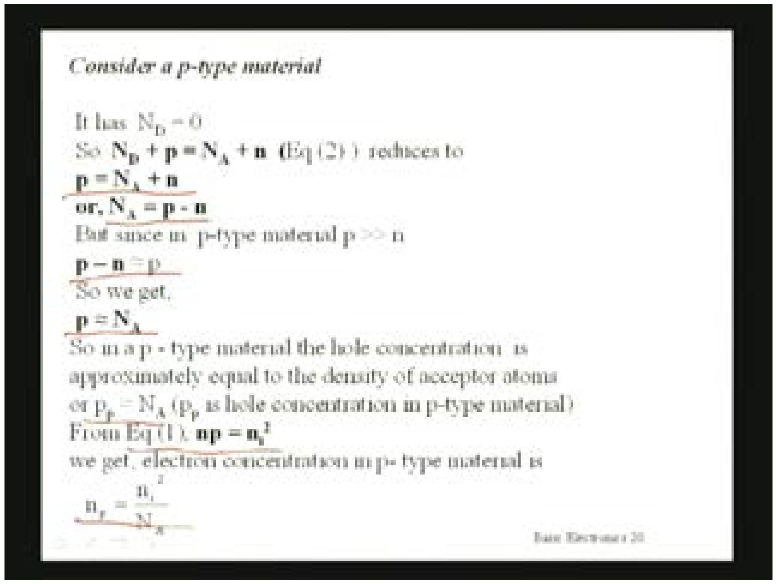

Here I am substituting in this equation n_p is equal to n_i square. I am substituting this p with N_A. Then I get this n equal to n_i square by N_A. The fundamental difference between a metal and a semiconductor is that metal is unipolar since current conduction is taking place only by electrons which are having only one sign that is negative sign.

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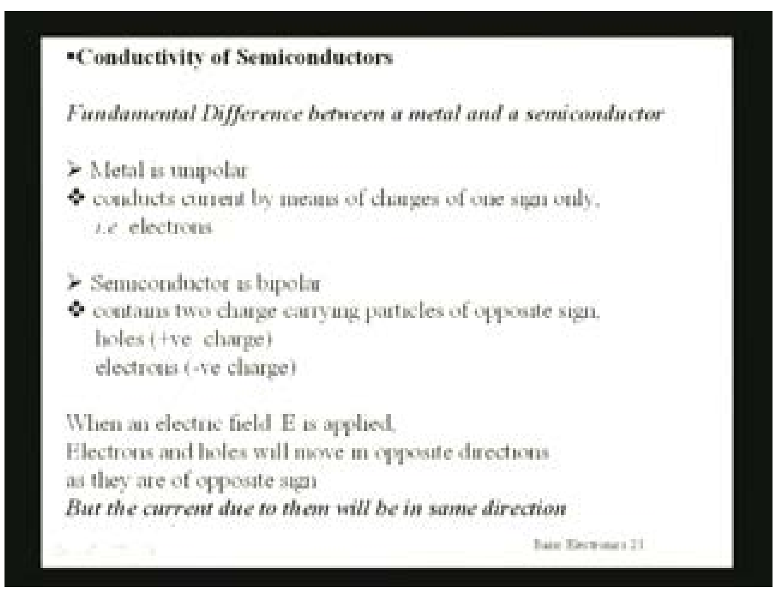

But in semiconductor there are two charge carriers having negative as well as positive charges which are known as electrons and holes. Semiconductor is a bipolar material. There are 2 types of charge carriers positive as well as negative. Holes are positively charged and electrons are negatively charged. Whenever you apply an electric field, E then your holes and electrons will move in opposite directions since they are of opposite sign but the current due to both these two components will be in one direction.

If you want to find out the current density after the application of an electrical field E, that is given by this expression. The current density J is equal to n times mu n plus p times mu p into q into E which is known as sigma into E. What are those terms? n is magnitude of free electron concentration, mu n is mobility of the electrons, p is magnitude of the hole concentration and mu p is the mobility of holes, q is the charge of an electron and sigma is known as conductivity which is given by this expression n mu n plus p mu p into q. For intrinsic semiconductor as n is equal to p which is equal to n_i that is intrinsic concentration, we get for intrinsic semiconductor if you want to find out the current density you will have to simply substitute n_i both for n and p.

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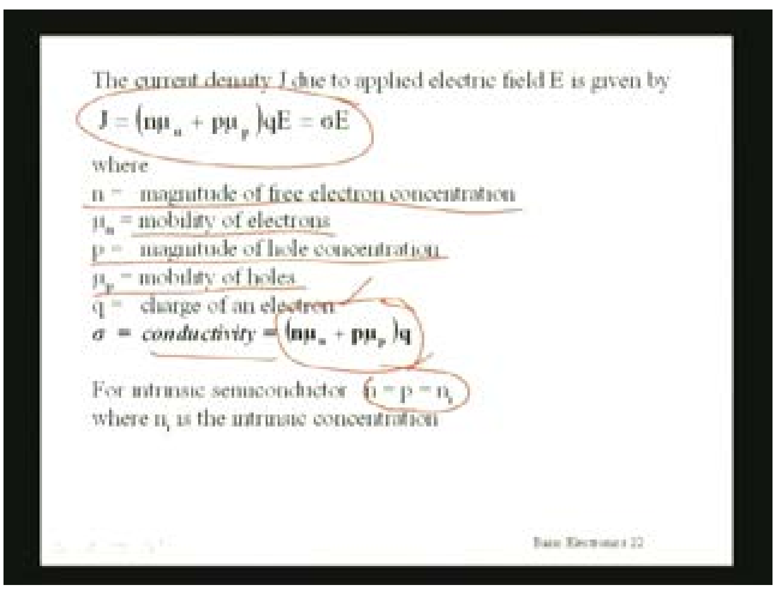

Let us take one example and see how you can find out the current density. Consider an intrinsic silicon bar of cross section 5 centimeter square and length 0.5 centimeter at room temperature, 300 degree Kelvin. An average field of 20 volt per centimeter is applied across the ends of the silicon bar. It is the silicon bar having a cross section of 5 centimeter square and you are applying an average field of 20 volt per cm. Now you have to calculate electron and hole component of current density, total current in the bar and resistivity of the bar; these three you have to find out. You are given that the mobility of electrons is 1400 centimeter square per voltage second and hole mobility is 450 centimeter square by volt second and intrinsic carrier concentration of silicon at room temperature, 300 degree Kelvin is generally taken as room temperature. Kelvin is small t degree centigrade plus 273 degree that gives you the Kelvin temperature. Here it is 300 degree Kelvin. You can find out at what room temperature this example is carried out 300-273. At 27 degree centigrade room temperature the sample is given and now at that temperature the intrinsic carrier concentration of silicon is given as 1.5 into 10 to the power 10 per centimeter cube. You have to find out electron and hole component of current density.

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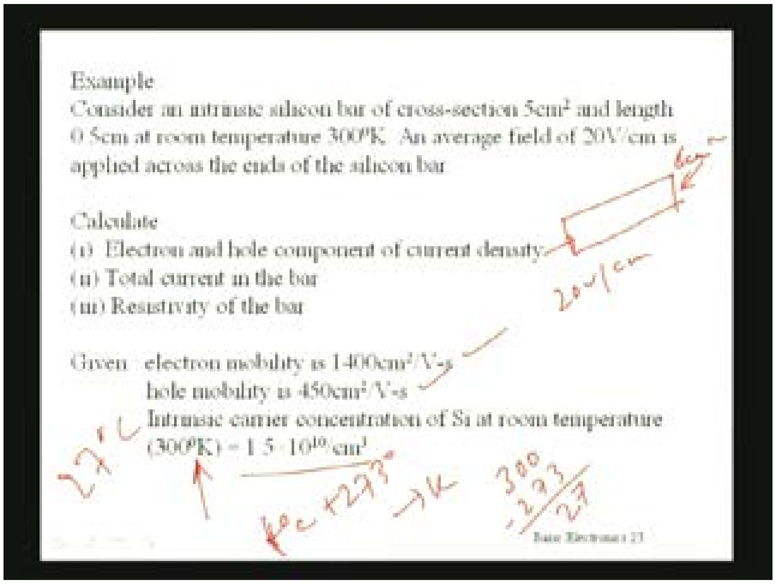

If we are to find out electron and hole component of current density we must use the equation J equal to n mu n q E plus p mu p q E. Now you have to see the data given to you. We know already n is equal to p is equal to n_i in an intrinsic semiconductor, since this is an intrinsic semiconductor and it's value is given in the data as 1.5 into 10 to the power 10 per centimeter cube. Electron mobility and hole mobility are also given. Electron mobility mu n is 1400 centimeter square per volt second and hole mobility is 450 centimeter square per volt second. But this charge of an electron is not given. It is supposed that you know this and its value is standard 1.6 into 10 to the power -19 coulomb.

It is simple to find out this current density J given by this equation. In this equation there are 2 components, one is due to the electrons and the other is due to the holes. Electron component of current density we can find out from this part of this equation. You substitute each of these values and by an intrinsic concentration mu n q E, E is 30 volt per cm and each of these are substituted by the given values then we get this equation and finally the answer comes to 67.2 micro ampere per cm square. That is the electron component of the current density.

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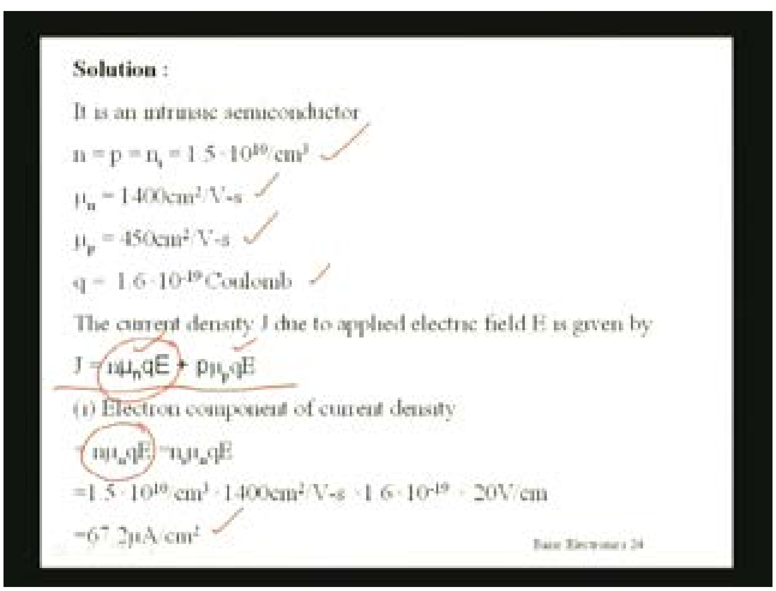

This current density is due to the electrons. Similarly you can find out the hole component of current density. That is p mu p q E. Here also you substitute all these given values and you find 21.6 micro ampere per cm square, that comes to be the hole component of current density. Another thing you have to find out is the total current. This is only current density. In order to find out the total current you have to multiply it by the cross sectional area which is given as 5 cm square. Current density mu A per cm square we have found out. Each of these hole component and electron component you have to add up. Then you will get the total component, total current density. 67.2 plus 21.6 is the total current density multiplied by the cross sectional area 5 centimeter square. Finally we get 444 micro ampere which is the current flowing in the silicon bar and finally the resistivity of the silicon bar which is inverse of conductivity. 1 by conductivity gives you the resistivity. Conductivity is sigma which is given by n mu n plus p mu p into q. So 1 by this whole term will give you the resistivity and substituting each of these values we get finally the resistivity of the silicon bar is 22.52 into 10 to the power 4 ohm centimeter.

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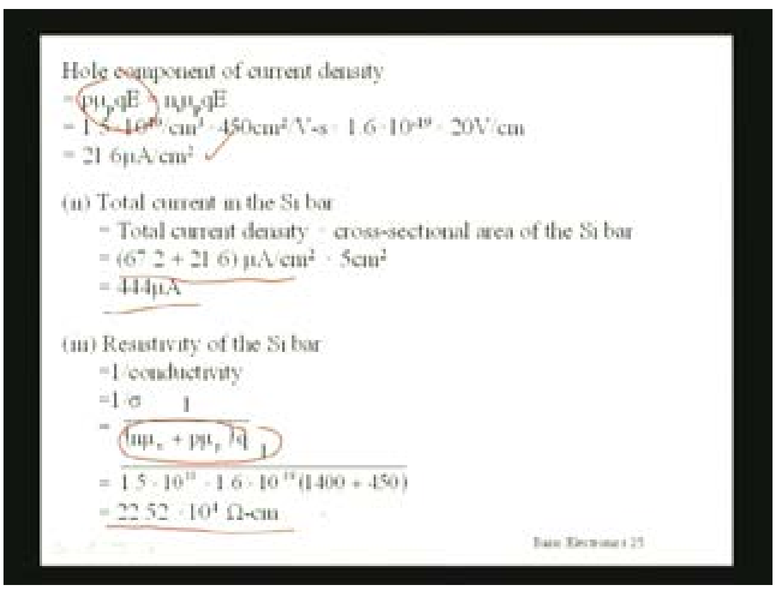

In these examples we have used only one equation that is the current density equation. The rest of the things are found from that.

In today's class we have learnt about intrinsic semiconductor material as well as extrinsic semiconductor material and their characteristics or properties we have studied and this semiconductor is the main component in all electronic applications and devices which is made of intrinsic semiconductor silicon or germanium and when it is doped with impurity atoms like pentavalent or trivalent materials then you get n-type as well as p-type extrinsic semiconductors. These will be used in all electronic devices. In today's class we have learnt about intrinsic as well as extrinsic semiconductors. How extrinsic semiconductors are formed from intrinsic semiconductors by doping them with p-type or n-type materials and we have also seen the characteristics or properties of these extrinsic semiconductors. This semiconductor is used as a backbone in all semiconductor devices and circuits. Let us try one example.

Consider an intrinsic silicon bar of cross section 5 centimeter square and length 0.5 centimeter at room temperature 300 degree Kelvin. An average field of 20 volt per centimeter is applied across the ends of the silicon bar. In part a, calculate number i, electron and hole component of current density; number ii, total current in the bar and number iii, resistivity of the bar. Part b of the problem is if now donor impurity to the extent of 1 part in 10 to the power 8 atoms of silicon is added find the density of minority carriers and the resistivity. The data given to you are electron mobility is given as 1400 centimeter square per volt second, hole mobility is 450 centimeter square per volt second, intrinsic carrier concentration of silicon at room temperature 300 degree Kelvin is given as 1.5 into 10 to the power 10 per centimeter cube and number of silicon atoms which are doped per meter cube is 4.99 into 10 to the power 28.

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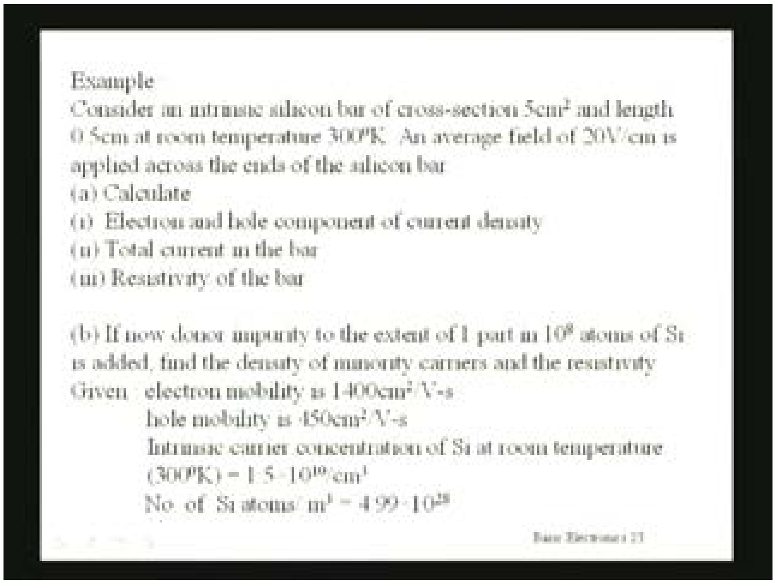

This last data will be required for the part b of the problem. Let us first of all do part a of the problem. It is given that it is an intrinsic semiconductor. The hole concentration and electron concentration is same which is the intrinsic concentration and it is given as 1.5 into 10 to the power 10 per centimeter cube. Electron mobility is given as 1400 centimeter square per volt second. Hole mobility is given 450 centimeter square per volt second and charge of an electron is not given but you should know this value which is 1.6 into 10 to the power -19 coulomb. With this data we will now find out the current density first. As you know the current density J is given by n mu n q into E plus p mu p q into E where E is the applied electric field and all the other data are given to you. This current density has 2 components one due to the electron and other due to the hole. Electron component of current density will be the first part; this part will be the electron component of current density.

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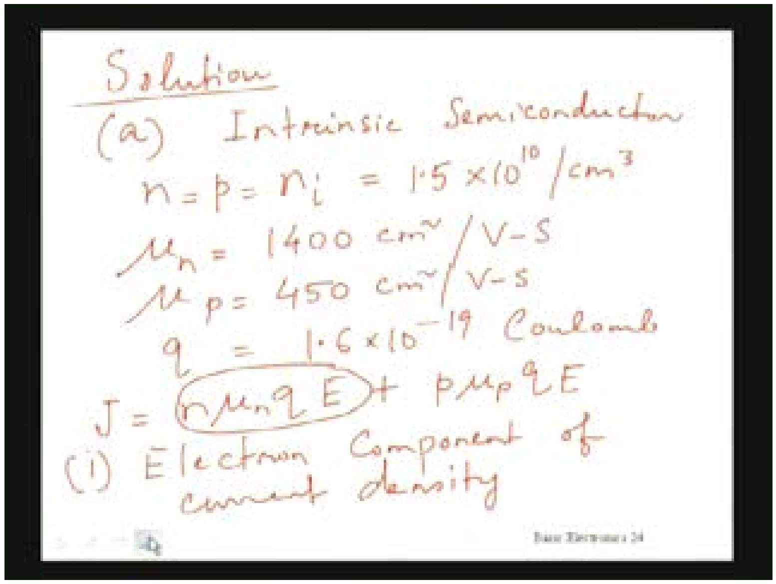

You just put down the values and you know that electron concentration is nothing but intrinsic concentration. So it will be n_i mu n q into E. Now substitute the values which are known to you. Each one we will substitute. n_i is 1.5 into 10 to the power 10 per cm cube and electron mobility is 1400 centimeter square per volt second. q charge of an electron is 1.6 into 10 to the power -19 coulomb and the applied electrical field is 20 volt per cm. All these are in cm that you must be careful because centimeter is the unit in all the data. If you calculate this value then we are getting 67.2 micro ampere per centimeter square. Part one of the problem a, is now 67.2 micro ampere per centimeter square.

Now in part 2, hole component of current density has to be found out and that is the second part of the equation J which is p mu p q into E and that can be replaced by n_i mu p q E because n_i is the intrinsic concentration that is equal to the hole concentration as well as electron concentration in intrinsic semiconductor. Substituting each of these values n_i is 1.5 into 10 to the power 10. Then mu p is 450, q is 1.6 into 10 to the power -19 and E is 20. We now calculate this and the result is 21.6 micro ampere per cm square.

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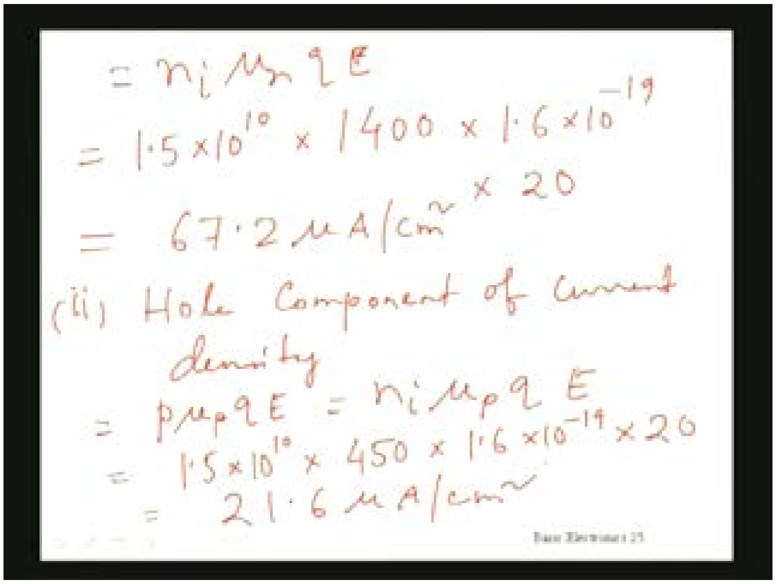

That is the hole component of current density. Third part of the problem says that you have to find out the total current in the silicon bar. In order to find out the total current you have to multiply the current density J by the cross sectional area. The total current in the bar is equal to the current density into the cross sectional area of the bar. Current density is the total current density due to the holes as well as electrons. We have to sum up these two 67.2 plus 21.6 micro ampere per cm square and multiply it by the 5 cm square cross sectional area and that gives the result as 444 micro ampere which is the total current and the next part of the problem is resistivity. This is part iii and this is part ii.

Part iii is resistivity of the silicon bar. Resistivity is 1 upon conductivity and conductivity, sigma is n mu n plus p mu p into q. You substitute all these values which we already have because n and p is nothing but n_i. n_i can be taken out; n_i into q then mu n plus mu p which will give you the resistivity and that is equal to 22.52 into 10 to the power 4 ohm centimeter.

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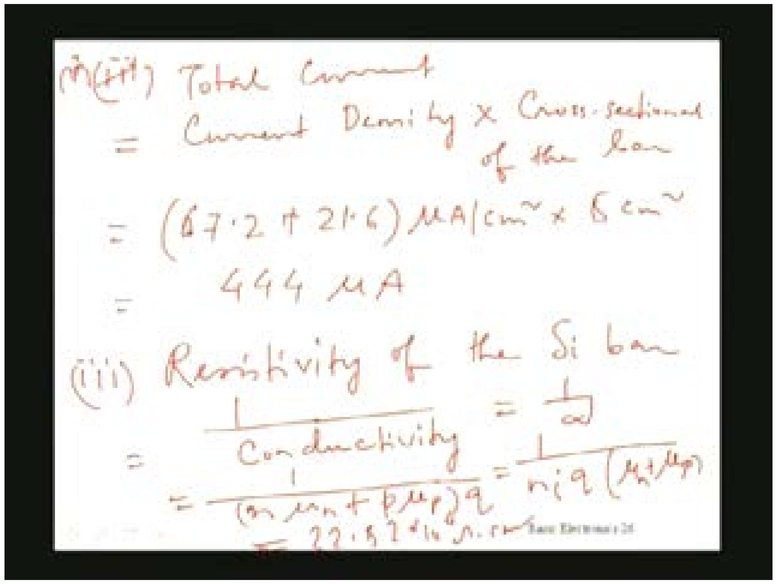

Now coming to the part b of the problem in which you have to find the resistivity of the doped semiconductor as well as minority carrier concentration. If you look into the problem it is doped and the doping impurity is an n-type of doping material. Donor impurity is 1 part in 10 to the power 8 atoms of silicon. In part b of the problem you are doping silicon with donor atom. The concentration of the donor atoms N_D will have to be found out and we have been told that the doping is 1 in 10 to the power 8 atoms of silicon. We also know and it is given in the problem that number of silicon atoms per meter cube is 4.99 into 10 to the power 28. We are doping 1 in 10 to the power 8 silicon atoms. What will be the donor concentration? Donor concentration will be 4.99 into 10 to the power 28 divided by 10 to the power 8. This value is 4.99 into 10 to the power 20 atoms per meter cube. You have to be careful. This is given in meter cube. This concentration is given in meter cube. But other data in part of the problem were in centimeter cube. Be careful about this and you have to divide wherever necessary to have conformity in the units. What will be this majority carrier density n_n which is almost equal to N_D in n-type semiconductor? We can write it as 4.99 into 10 to the power 20 atoms per meter cube.

Now we have to find out minority carrier density which is asked. Minority carrier here will be holes. Minority carrier density that is hole density we have to find out and we know from our previous discussion that p_n, the minority carrier density in n-type of material is n_i square divided by N_D. When you replace you have to see because n_i in our example, if you look into the problem is given as 1.5 into 10 to the power 10 per cm cube. But here you see that N_D is per meter cube. So we have to bring conformity by multiplying or dividing accordingly. Now I will find out this hole carrier density that is minority carrier density. That is 1.5 into 10 to the power 10 per cm cube is given divided by 4.99 into 10 to the power 20. But this way it will be wrong if I do like this because this is in per meter cube. So I have to bring this numerator to the same unit as in the denominator. I will have to bring this centimeter cube to meter cube. So 10 to the power -2 we will have to multiply, to get it into meter. So it will be 1.5 into 10 to the power 10 divided by 10 to the power -2 into 3; that becomes 10 to the power -6. Then it will be in per meter cube. There is a square and in the denominator it is 4.99 into 10 to the power 20. So all are now in per meter cube here in the denominator also.

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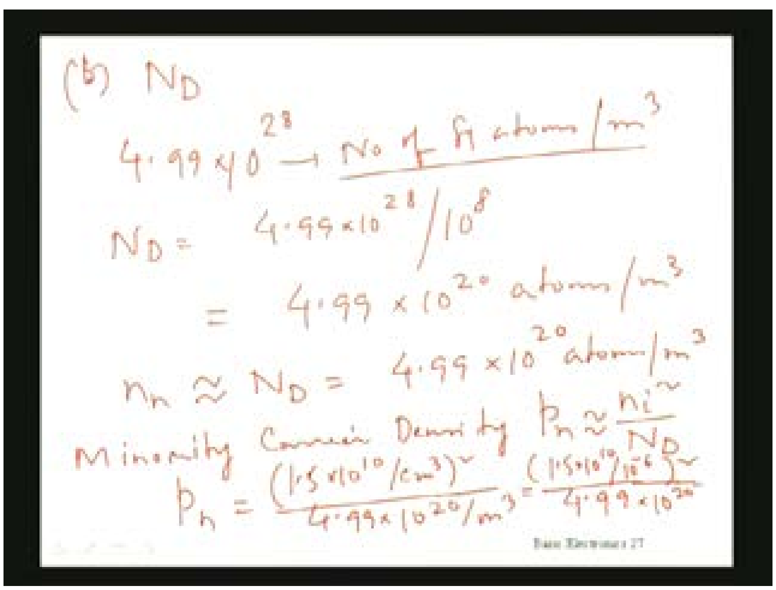

If I calculate this, then I get this value as 4.51 into 10 to the power 11 holes per meter cube because I have brought it into meter cube. The hole concentration now is 4.51 into 10 to the power 11 holes per meter cube.

Next part I have to find out the resistivity. Resistivity is 1 upon conductivity. You just replace these values. Sigma is equal to n_n mu n plus p_n mu p into q. Here n_n electron concentration is 4.99 into 10 to the power 20 into mobility of electron is 1400. Electron mobility was 1400 cm square per volt second. So I will convert everything to meter units. I will have to multiply 10 to the power -4 with 1400 plus the hole concentration I have found out 4.51 into 10 to the power 11 per meter cube into the mobility of holes is 450. Again I will multiply by 10 to the power -4 to bring it into meter square unit. The whole thing I'll have to multiply by q which is 1.6 into 10 to the power -19 and this calculation gives me the whole denominator will be 11.1777. So I will get 0.08946 ohm meter.

Now I can convert it to ohm centimeter just to see the difference how the resistivity changes when you are doping an intrinsic semiconductor. If I convert it to centimeter multiplying by 10 to the power 2 then I get it as 8.946 ohm centimeter. You compare what was the resistivity when you had only intrinsic semiconductor and that intrinsic semiconductor had a resistivity we have done in part a of the problem and that was 22.52 into 10 to the power 4 ohm centimeter that was of the intrinsic material. Now when we doped it with a material then that doping material is donor so that doping has brought down this resistivity to 8.946 ohm centimeter. If I find out how much ratio it has brought it down dividing this by 8.946 ohm centimeter, then I find that after doping 25,173.26 times the resistivity of the material has been brought down.

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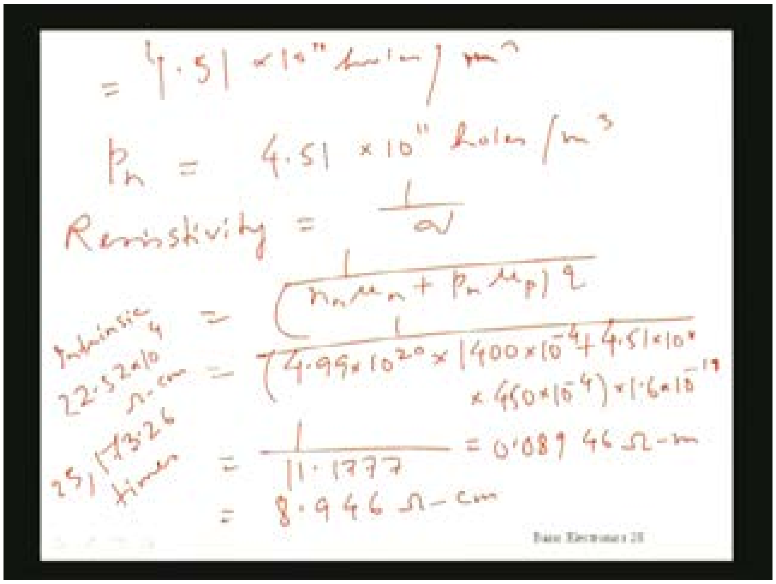

This effect of doping an intrinsic semiconductor by an n-type or a doping agent is very important because it has brought down the resistivity means it has increased or enhanced the conductivity so much. This example illustrated the effect of doping an intrinsic semiconductor by an external n-type impurity atom that we have learnt today.