Fundamentals of Power Electronics
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Lecture – 07
Review of Semiconductor Physics

Welcome back. So, today let us try to see certain facts about semiconductors and how they can be used to produce some useful devices, particularly we have to see how that would be useful for Power Electronics. Now when we talk about solids, a very good definition which really helps us relate the microscopic properties of a given material to the macroscopic or external properties and characteristics of a material, the definition of resistance is very helpful. Now, let us just see the definition of the resistance for a minute.

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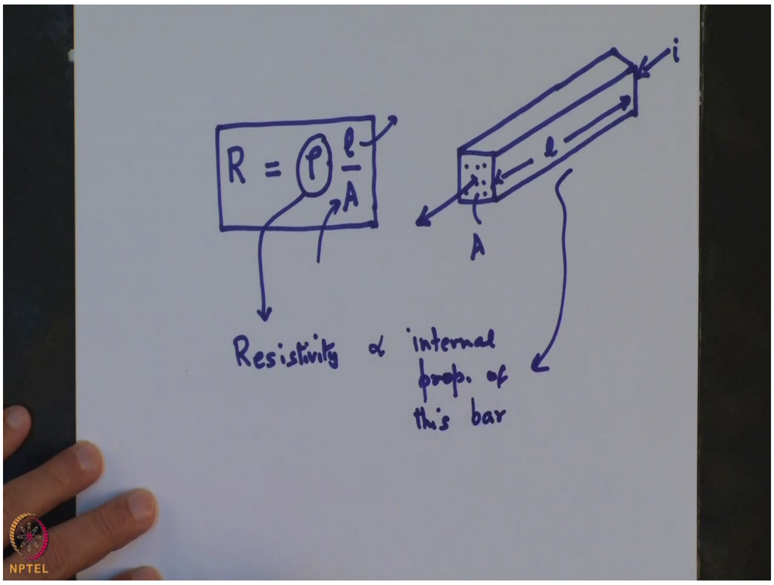

R is equal to rho l over A where, where I have just assumed that it is a rod let us say made up of some metal or maybe some other material semiconductor or maybe an insulator I do not know; I just taken a general example. So, this area what you see is A and this length is l. Now, if I want to determine what is the resistance offered by this? You know by this rod or this bar of rectangular cross section to a current that is trying to flow.

So, let us say there is a current that is trying to flow through this bar and come out like this, what is the resistance that would be offered to this current this particular expression for the resistance gives us exactly that. It actually tells us what is the resistance offered by this rod to a current that is trying to flow through it? As you can see area of cross section l, the length of this bar ok; these are the physical properties and these are all externally measurable observable properties.

So, looking at this definition we have constant of proportionality which is the rho which is also called as a resistivity. Now this resistivity is a function of the internal properties of this bar or the material which comprises this bar, which makes up this bar. Now talking about the resistivity and the resistance the solids, the solid material can be divided into 3 main types ok.

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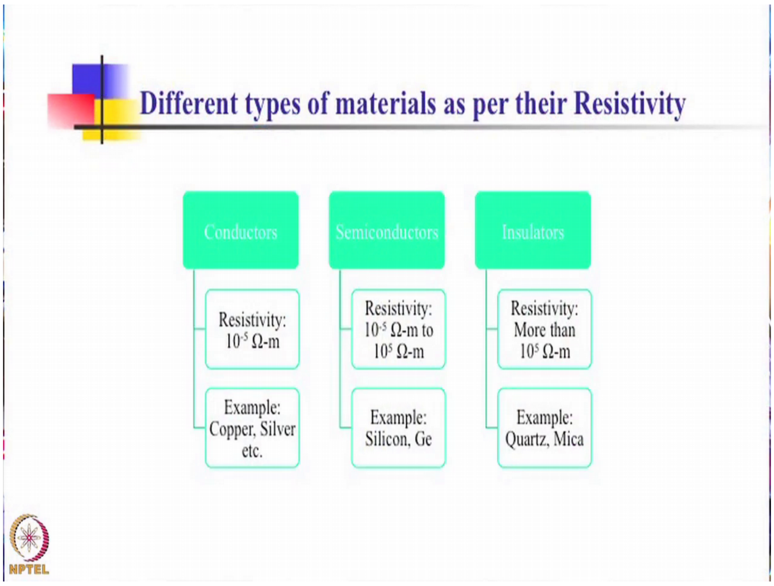

Different types of materials as per their Resistivity

- Conductors
  - Resistivity: 10^{-5} Ω-m
  - Example: Copper, Silver etc.
- Semiconductors
  - Resistivity: 10^{-5} Ω-m to 10^{5} Ω-m
  - Example: Silicon, Ge
- Insulators
  - Resistivity: More than 10^{5} Ω-m
  - Example: Quartz, Mica

And that is roughly you know based on the resistivity value ok.

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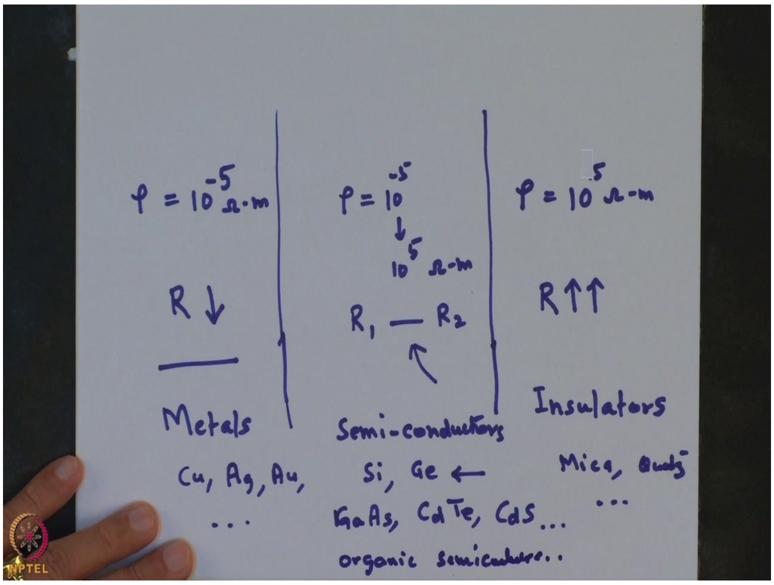

So, you have basically one particular category of solids which have extremely low resistivity. So, the rho is 10 raised to power minus 5 Ohms meter, this is the typical resistivity that we have for one category of solids there is another one whose resistivity is extremely high it is in excess of 10 raised to power 5 Ohms meter. And lying between these two ranges is another class of solids which has typically resistivity ranging from 10 raised to power minus 5 to 10 raise to power plus 5 and mind you the units are Ohms meter.

So, basically what we see here is that looking at the basic definition of the resistance we can see that any current or any charge carriers that will try to flow through the bar that we have considered in our example ok. It will see a very low resistance when it is passing through this particular category of solids it will see a very high, very very high you know resistance when the charge carriers are trying to flow through this type of solids. And here it is going to be in you know in the in the intermediate range in the intermediate category it will be the resistance will be actually modulated.

So, basically it will depend on some external conditions that will apply that there will be the charge carriers would experience a resistance that will vary between a certain range. So, maybe R 1 to R 2 between this range, now it is customary to actually call these solids which actually offer a very low resistance to the flow of charge carriers as metals and. It is very common for this the other extreme category of very high resistivity, very high resistance as insulators and in between these two, this intermediate category its common to call this as semi conductors some people also call them as semi metals; so, semi conductors.

Now, examples of metals of course, there are many copper, silver, gold and so on, insulators again mica, cards and so on and semiconductors as you will see there are many, again there are many examples. The most common being the silicon and the germanium which are the pure semiconductors in the pure form ok, but then there are also certain compounds like for example, we have the gallium arsenide or we have the cadmium telluride or we have the cadmium sulphide and so on. These are you know the inorganic compounds of you know which are having semiconductor properties and we also have organic semiconductors like several organic polymers which are there so organic semiconductors as well.

Now, to understand the properties in more details and then try to see what is the relevance and usefulness of the semiconductors, let us go back to a very fundamental concept.

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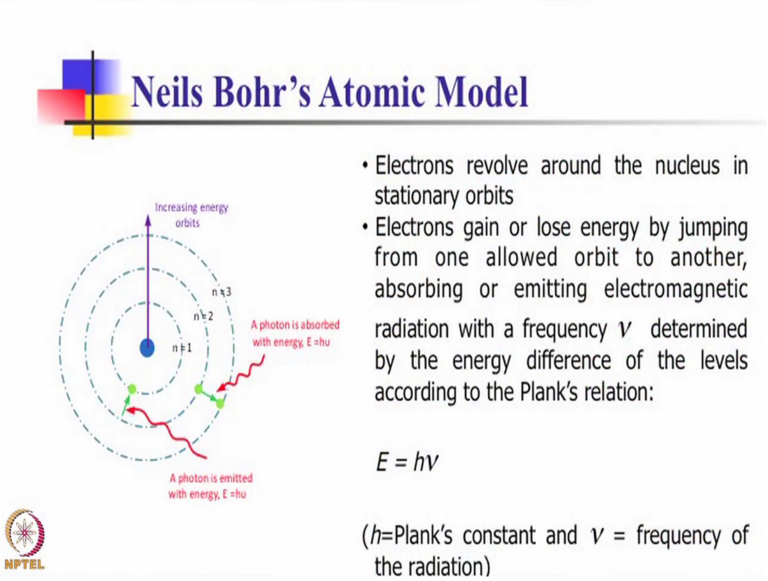

Neils Bohr's Atomic Model

- Electrons revolve around the nucleus in stationary orbits
- Electrons gain or lose energy by jumping from one allowed orbit to another, absorbing or emitting electromagnetic radiation with a frequency ν determined by the energy difference of the levels according to the Plank's relation:

$E = h\nu$

(h=Plank's constant and ν = frequency of the radiation)

The concept of Neil Bohr's atom ok.

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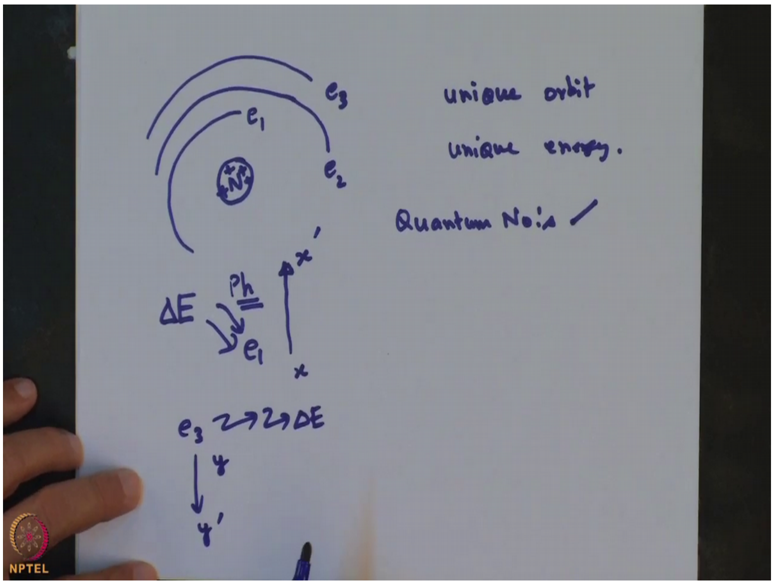

So, we all know from what we have studied in our earlier classes that as per the Neil Bohr atom the atoms nucleus lies in the center and is having all the positive charges of protons inside. And around this nucleus are revolving several electrons ok, just like the earth revolves around the sun these electrons are revolving around this nucleus and if I just mark these electrons as e 1 e 2 e 3 then I can see that each of these electrons they occupy a unique you know orbit.

They occupy a unique position, a unique orbit around the nucleus which uniquely determines the energy of these electrons. So, unique energy and we all know from our past knowledge that you know we can uniquely define each of these electrons which are revolving around a nucleus by using the concept of quantum numbers. So, we all know that there is principle quantum number, there is azimuthal quantum number and so on.

So, each of these electrons can be uniquely represented by a set of these four quantum numbers. So, each of them has a fixed energy, now when an electron let us say e 1 gets some energy from outside. So, let us say you know there is a packet of energy which has come you know and hit electron e 1.

So, let us say a photon, you know which is the fundamental particle postulated by Newton as you know what the light consists of the dual nature of light people know that light has dual nature it has both the particle nature as well as the wave nature as proposed by Huygens you know and the other scientists.

So, let us say that the light is falling on this atom and let us say there is a photon which has got an energy which is more than a certain threshold energy associated with this electron.

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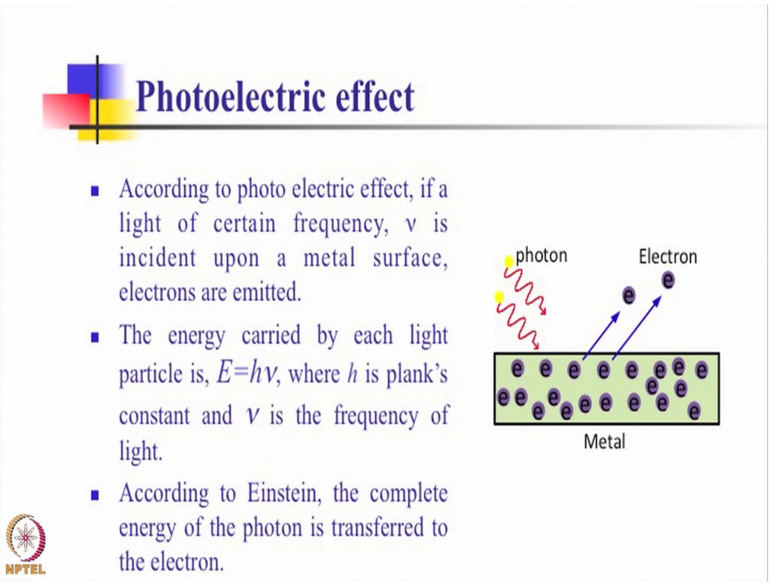

Photoelectric effect

- According to photo electric effect, if a light of certain frequency, ν is incident upon a metal surface, electrons are emitted.
- The energy carried by each light particle is, $E=h\nu$, where h is plank's constant and ν is the frequency of light.
- According to Einstein, the complete energy of the photon is transferred to the electron.

So, if that energy is transferred to e 1 this e 1 will move on to a higher energy orbit ok. So, it will absorb this energy. So, let us just say this is delta E which has been imparted to e 1 and e 1 will just move on to from position x to x dash, a new orbit that corresponds to the you know a new different energy which is a higher energy than what e 1 was associated with at the previous location.

Likewise, if let us say e 3 loses energy ok, it will fall. So, it actually this e 3 it actually loses energy. So, let us say delta e it will fall down from its original location y to y dash to a lower energy ok, now both these energy transitions what we have seen from lower energy level to higher and from higher energy level to lower the transition from lower to higher energy or from higher energy to lower energy.

So, this is what is the concept that we get from the from the Neil Bohr's atom the model that he postulated ok. Now, the point is that the way we look at the Neil Bohr's atom model you know it is like an isolated atom we are looking at, we are not talking about the interaction of these electrons with you know some of the other electrons that might be present in the vicinity.

And this is what really happens when we talk about solids and maybe liquids and gases because then you know we are talking about several atoms which are coming closer to each other of course, in gases this closing in or the distance between the atoms is very large in liquids it is really relatively less as compared to the gases. But still very much higher than what it is there for solids, but for solids you know we have many of these atoms they come very close to each other and they form a crystal structure.

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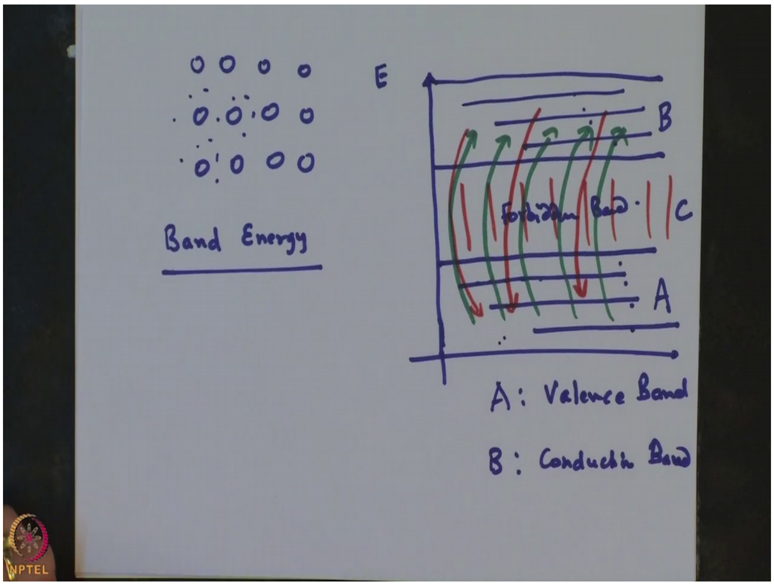

Now, we know that how these various atoms are arranged as you can see in space occupying very fixed locations and a pattern which is repeating ok. Now, these are the atoms and now if we consider each of these atoms having the same model as what we discussed sometime back about the Neil Bohr’s atom then we find that it is not possible you know for us to really, see what is happening because there is some electrons you know which are revolving around all these atoms and we do not know how they will interact and its extremely complicated.

So, the best way to look at this situation that arises when the solids are formed that is when the atoms come closer is by way of the concept of band energy ok. Now when we say band energy what we mean is that lets say we just talked about solids what we mean is that we will just you know try to define, we just try to kind of ascertain the charge carriers and their energies and put them in various categories.

So, let us say how we can do that. So, in the band energy concept if I have the energy which is plotted here in the y direction then I can if I just maybe divide this in certain zones. So, let us say I just define this in these 3 zones and I just say that you know this is a zone which is having further divisions ok.

Now, this is energy your y axis is energy. So, basically you know you are talking about various energy levels here, likewise in this band which I am not yet mentioned what this band is though I am sure many of you can guess. Again you know, let us say there are several sub energy levels and there is this band here which is in the middle of these two bands ok, which is let us say does not have any charge carriers it does not have any electrons or holes ok.

So, this band what we are calling which is sandwiched between the top and the bottom band is what is called the forbidden band which basically means that none of the charge carriers electrons and holes are going to occupy this band ok. Now all the electrons if you look at you know basic diagram here where we have shown you know. So, so basically there are these atoms which are very lying very close to each other and we know that is say only electrons here are sticking very close to the their parent atom and sticking very close to it.

So, let us just say that those electrons which are very close to their parent atom and not free to move, let us say they are lying in this in this band ok; let me just call this as A band this is B and lets call this as C. So, C is the one which is forbidden you have seen a is let us call this as valence band.

So, these are basically this band will contain all the electrons which are you know kind of stuck with their parent atoms they are bound to them and they are not free to move likewise B, the band which is shown at the top here with the higher energy level is called a conduction band is called the conduction band. And this consists of charge carriers which have been actually transported from close to the atom, they somehow found some energy maybe thermal energy which then helped them to kind of jump over on to this band.

So, all these green lines they are showing how the charge carriers when they are in valence band ok, but when they are imported energy they somehow find energy they are actually transported, they are actually all going into the conduction band and there in the conduction band they exist as free charge carriers and they are free to move.

So, basically you know this is the basic concept of semiconductors and as we go along we will understand this even better. Now you know inside the semiconductor you know these charge carriers they are in constant motion back and forth. So, they will find some thermal energy, some of these carriers will actually be able to jump over this forbidden band and will now become a free charge carrier when it goes to the conduction band and when they collide they lose energy they actually then fall back. So, I could probably say that they are coming back here back to the valence band you know where they combine with poles and get neutralized. So, this process is all the time on.

At temperatures greater than the absolute 0 temperature it is possible that some of the electrons they find enough energy to break away from their covalent bonds and become free. Now electrons from vicinity may then come and occupy these missing electron positions and similarly we may have more electrons coming in and occupying this latest missing electron positions and the process goes on. So, it would seem that as electrons are moving towards one direction the missing electron position which we have also called as whole is moving to in the opposite direction.

Now, thermal equilibrium the densities of electrons and holes are same, let us say this density is ni then you know this is governed by a very important relation.

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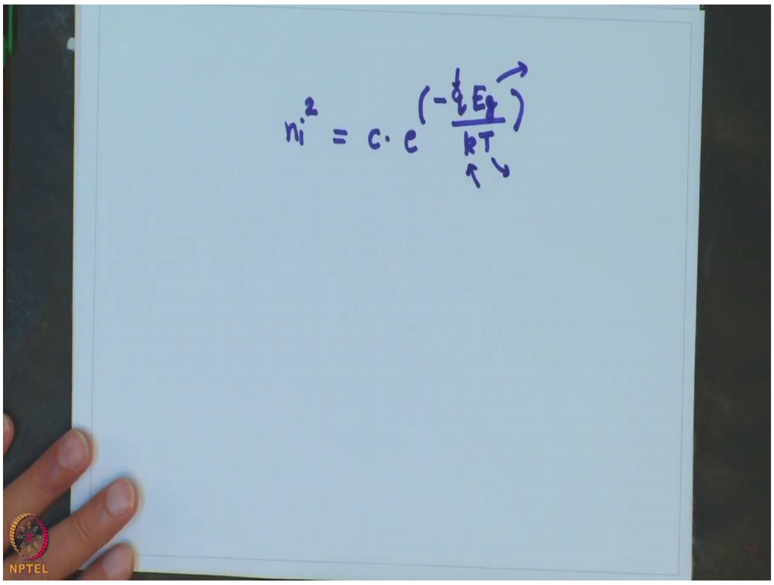

$$n_i^2 = c \cdot e^{\left(-\frac{\cancel{q}E_g \nearrow}{\overset{}{\underset{\uparrow}{k}}\,\underset{\searrow}{T}}\right)}$$

Which is n i square, which is the square of the density of either the electrons or the holes is equal to c where c is some constant of proportionality e raise to power minus q E g by k T where E g is nothing, but the band gap energy and is equal to 1.1 electron volt for silicon q is the magnitude of the charge of the electron k is nothing, but the Boltzmann constant and T is the temperature in degree Kelvin ok.

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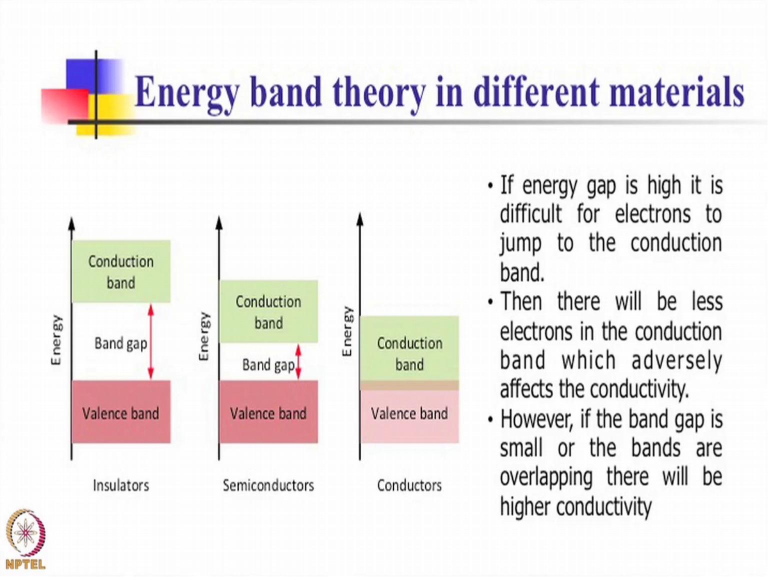

Energy band theory in different materials

- If energy gap is high it is difficult for electrons to jump to the conduction band.
- Then there will be less electrons in the conduction band which adversely affects the conductivity.
- However, if the band gap is small or the bands are overlapping there will be higher conductivity

So, what is the situation though in the conduction band with this. Now, it is observed that in metals even at room temperatures there is a huge amount of charge carriers which are there in the conduction band which we have marked as B and that is why the metals copper, silver, gold and so on. They show an enormous conductivity even at room temperature and once you have applied an external electric field these charge carriers they will just flow as per the field and will not be, you will not be able to control them, there is no control ok.

Now, if you look at the insulators which is the third category ok; let me consider you will find that the conduction band has very few charge carriers and in fact, they will hardly be any charge carriers and hence when you try to apply an external field there are no free charge carriers to move around and that is why you will see an insulator conducting very less current; it will hardly have any current. Now semi conductors on the other hand which lie between the first in the third categories of metals and semiconductors they actually have a very unique property, they actually present you know as we will see now under certain conditions very unique opportunities to you know allow controlled flow of charge carriers, we can actually control these carriers ok. So, let us just see now how this is achieved and how useful semiconductors are formed.

Now, as we expect you know all our electronic circuits for which eventually we are going to use many of these devices made up of semiconductors, we expect them to actually be operating at room temperatures ok. Now the semiconductors at room temperature, I am talking about in their pure form ok, silicon germanium many of those. They actually have few charge carriers available or present in the conduction band at room temperature ok. In fact, at absolute 0 minus 273 degree centigrade ok, you know in principle there is the 0 charge carrier in the conduction band of a semiconductor material. Now what do we do? Now that is at this point and here that we introduce what are called impurities in these semiconductors ok. So, what let us understand this phenomenon of adding impurities in the semiconductors.

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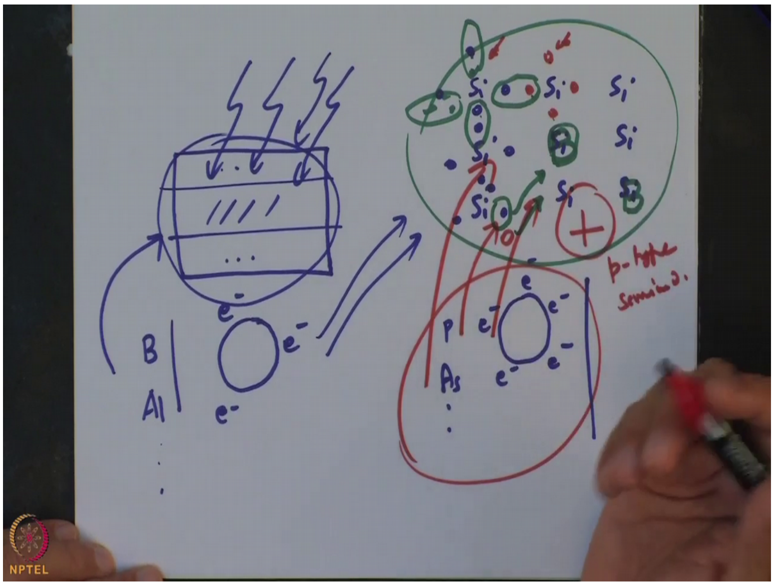

So, I have let us say a solid, a semiconductor solid block and we know from the band theory that you know there is there are you know 3 layers, 3 levels the valence band d and the forbidden band where no charge carriers can be present. They are not allowed to occupy any of the energy levels here and the conduction level, we know this. Now, what we do with some technique we try to bombard, the semiconductor solid ok, with an impurity there are many trivalent or pentavalent impurities. Now what I mean by this is trivalent like for example, boron or aluminum.

So, if you look at their outermost shell, you know if we talk about the now you just talk about the Neil Bohr’s atom as an isolated atom and if you look at these elements in which are many more actually in this group, then what will happen these guys they have three electrons which are there in the outermost shell. And if you are trying to basically bombard this material with what are called pentavalent impurities, pentavalent means something like phosphorous and arsenic and so on these guys they have 5 electrons in their outermost shell ok.

So, let us this is the situation, now what happens when we bombard this trivalent impurities here on the sample? What happens, let us see that now this particular sample ok, the original semiconductor which is not ideal created at all you have not mixed anything with it is a pure semiconductor we also call pure semiconductors without any you know adulteration, without any mixing as an intrinsic semiconductor. So, we have this piece of intrinsic semiconductor and we know that let us say we are talking about a silicon semiconductor here. So, we are going to have this is the situation silicon silicon silicon silicon silicon and silicon silicon silicon and we can see that the outermost shell of these silicon atoms they have 4 of these electrons and they form covalent bonds, you know they form covalent bonds with their neighbors.

So, let us just see the case of this and this atom, these two atoms. So, you can see that there are 1, 2, 3, 4 electrons around this silicon and there are one 1, 2, 3, 4; 4electrons across around this silicon. So, what these two atoms do they are their neighboring atoms of this crystal structure they form what is called a covalent bond ok. There are other types of bonds also as we know ionic bond for example, but that is not what we are discussing here they are not relevant to our semiconductors.

So, likewise you know this silicon atom it can form a bond here, with a neighboring which is at the bottom below this can form a covalent bond there, likewise it can form a covalent bond here and likewise it can form a covalent bond here. So, it is basically you know these two electrons, these two electrons, these two electrons and these two electrons they are shared these are constantly interacting, they are just back going back and forth and they are just. So, this is a theory which has been given you know for the covalent band which are formed. So, this is how you know the intrinsic semiconductor or silicon semiconductor structure would look like.

Now, on on on that you bombard you know your trivalent the boron or aluminum, what would happen? If you have actually many of these atoms bombarding here at this place is that these atoms they will go and maybe they will dislodge one of these or many of these at different places silicon atoms. So, what basically you will have is a B coming in here, a B coming in here ok. Now what will happen that when the B comes here because it is one electron shot it has got three electrons in its outer orbits, it is actually having an affinity to have another electron.

So, basically what happens that it actually will pull out one electron from some atom you know in its vicinity, now that when it moves and it completes you know the boron’s valency requirement, but it does it at the expense of basically extracting one electron. So, this electron let us say move here and when it moves here it basically leaves out what is called a hole.

So, as you can see these electrons gone there leaving a miss missing electron position of the hole. So, many of these atoms of the boron trivalent impurity when they are actually when they actually replace the atoms which are originally sitting in the intrinsic semiconductor, they actually generate many such missing electron positions of the holes in this entire; in this entire structure ok. So, such atoms like the boron these are called acceptor atoms or acceptors or this is called an acceptor type impurity because it accepts an electron and generates a hole.

Now, when many of these traveling atoms are added to this structure this structure becomes rich in holes and we because the hole is missing electron which we associate with a positive charge. Therefore, this entire structure becomes rich in positive charge carriers and is called a p type semiconductor.

It is an extrinsic semiconductor now, but a p type semiconductor an extrinsic one, the one which has been adulterated which has been mixed with impurities or in terms of semiconductors we call them as doping. So, it has been doped, an intrinsic silicon semiconductor has been doped with trivalent impurity to generate p type semiconductor material. Now likewise in the same way it is easy for us to see that if a pentavalent or a atoms with 5 electrons in their outer most shells when they are going to be mixed with the intrinsic semiconductor ok, then at that time we are going to have the atoms which will go and sit and replace the original silicones, they are going to have one additional electrons.

So, these are called donors they actually are able to very easily donate their electrons and you know these electrons then become free to move, just like we have the holes becoming free to move in the p type semiconductor. Here we have electrons which are free to move, just because these pentavalent atoms have acted as donors and have donated several electrons in this material ok.

So, this kind of semiconductor this is called an n type semiconductor, even after doping the thermal ionization process you know which causes the breaking of bonds is not disturbed. You know this is because the doping concentration is much less you know compared to the intrinsic semiconductor concentration therefore, even after doping the product of the thermal equilibrium densities or the electrons and holes which you know we now define as n naught and p naught. So, their product n naught p naught it still remains equal to the square of the intrinsic densities of the whole and the electrons.

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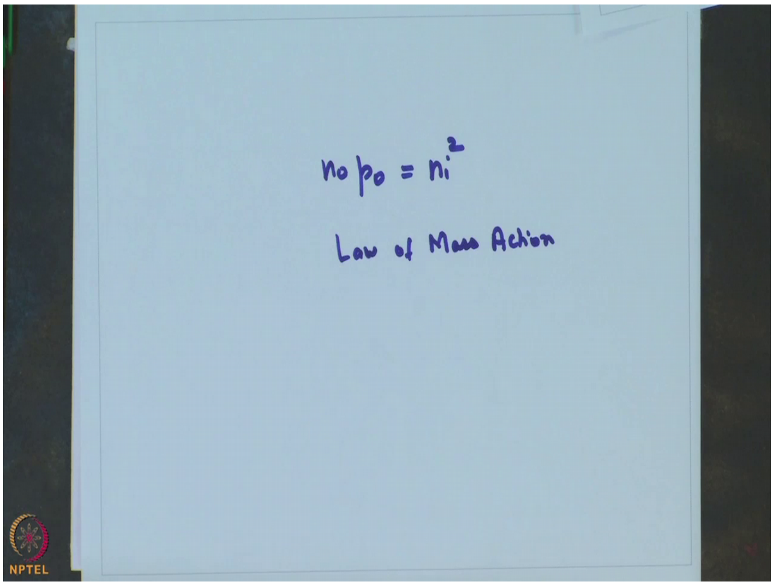

$$n_0 p_0 = n_i^2$$

Law of Mass Action

So, we could actually write n 0 p 0 equal to n i square, now this is a very important relation and it is also called the law of mass action ok. So, we will see now in the next lecture what more we can do with these semiconductors and how we can form some useful devices with them.

Thank you very much for your attention.