Materials Science and Engineering
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Lecture - 39
Electrical and Magnetic properties

Hello friends. Today's lecture, we will now go to slightly different properties. Till now, we concentrated mostly on mechanical properties of the material ok. Now, we want to see some other properties; for example, Electrical and Magnetic properties. So, today's lecture will be concentration on the understanding of these properties which are used in some of the application for materials. Of course, for mechanical engineer, it will not be that much interest ok, but knowing these properties will be useful for certain applications ok.

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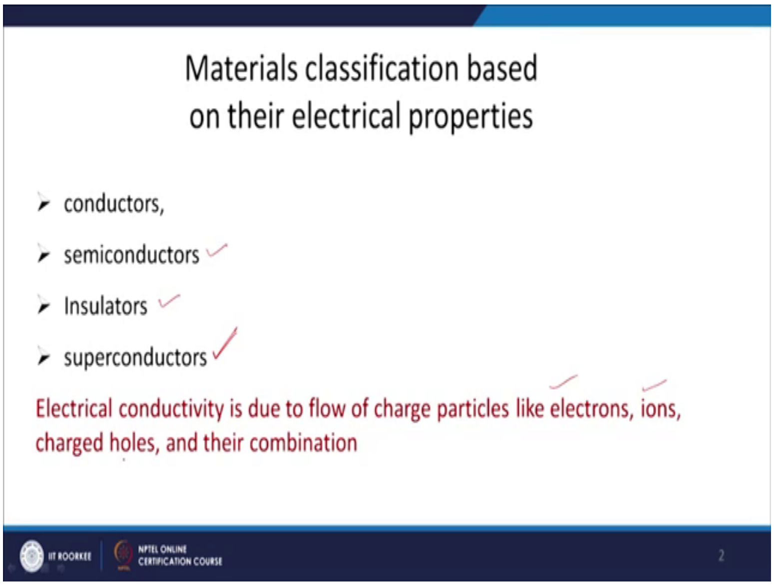

So, if we want to see the material classification based on their electrical properties ok, I can classify the material in terms of whether a material is a conductor which is all usually what all the metallic materials are there ok. For example, in our household application all the wires are made of copper which is a very good conductor ok; sometime aluminium is also used because it is much cheaper than copper ok. And then, one class of material which is a very important class in terms of electronic circuits and electronic applications and this is semiconductor ok.

So, understanding semiconductor is very important that is what we will concentrate more in this lecture. Then, there are Insulators ok. Of course, these are also important because if you have a conductor you have to have an insulation around that. Similarly, the insulators can be ceramic materials, for example, are usually insulator because the because of the covalent bonding or ionic bonding between the 2 atoms ok.

There are no free electrons for conduction. But sometime, this ceramic material can show a very important property which is called superconductors ok. Now, the electrical conductivity is due to flow of charged particles ok. So, any conductivity will be related to movement of charged particle.

These charged particles can be electronics or it can be irons also or it can be charged holes ok. So, when electron leaves valence band; it will it leaves behind one hole which can be considered as positively charged hole or it can be combination of all these 3 ok. So, the conduction will depends upon the moment of these charge particles. The electrical conduction can be explained using band theory that where the electrons are residing ok.

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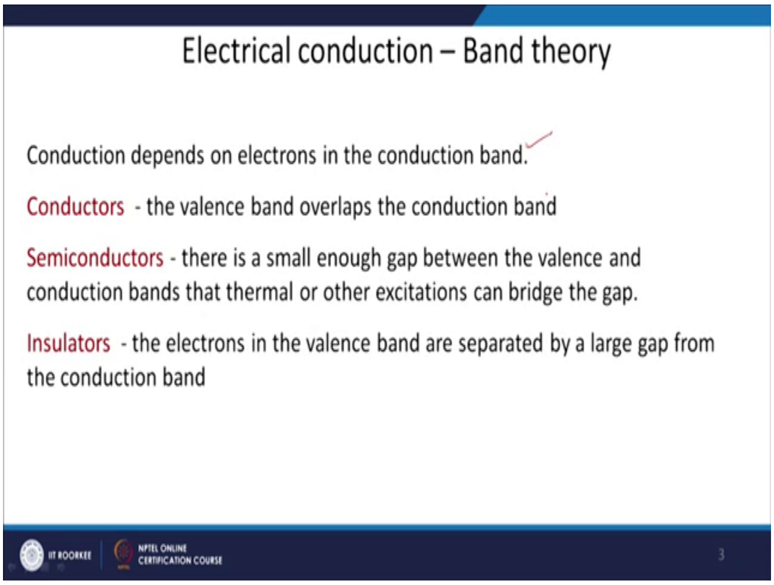

So, in Conduction depends on electrons in the conduction band, if the electrons are in the conduction band; then, you will have a conductivity, otherwise you will not have ok if the conduction is due to flow of electrons. So, the conductors are the ones which have valence band overlapping the conduction band.

So, in case of conductors, what happens? The electrons the conduction band and valence bands are overlapping each other. So, the valence electrons in the valence band can easily go to the conduction band and when you apply any electric field, the flow of electron will start ok.

So, you have lot of free electrons there which are not bounded by the by the by the atom ok; they are not in the valence shell. They are free to move around because they are in the conduction band and as soon as you apply any electric field, they will move. Semiconductors are those which have small gap between the valence and the conduction band ok, but due to thermal exercitation, this electron can go from valence band to the conduction band.

So, you can increase the conductivity of the semiconductor by taking it to higher temperatures where the thermal energy or the thermal excitation will push the electron from valence band to the conduction band ok. So, this is one of the important difference between the conductor and semiconductors that the conductor or the conductors have lower conductivity at high temperature.

So, if you increase the temperature the conductivity of a conductor will come down. Whereas, in case of semi conductor when you take it to you higher temperate, it the conductivity increases because now, more electron can go to the conduction band. In case of Insulators, the electron can the valence band are separated by a large gap from the conduction band ok.

So, between valence band and conduction band, there is a very large gap and they cannot jump from valence band to conduction band. So, that is why insulators do not conduct any electric charge.

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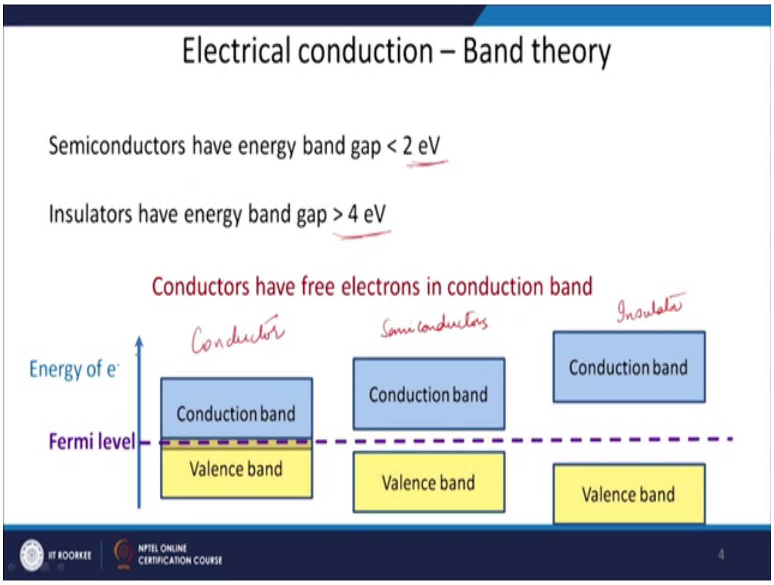

So, this is how; if you see in terms of a graph that how that these different bands are there. So, Conduction band and Valence band are there. So, in this case this is the case for conductor ok, for conductors the 2 are overlapping each other. So, the electrons in the Valence band can easily go to the Conduct band ok. And they can carry the charge when an electric field is applied.

Whereas, in Semiconductors, this is for semiconductors; there is a small gap between the Valence band and Conduction band, but the gap is quite small. So, that if you have any thermal excitation; electron can jump to the Conduction band.

So, at 0 Kelvin of course, no conductivity will be there ok, but at any high temperature this conductivity will start increasing. In case of insulator, so this is for insulator you will have a large gap between the two and it will not be able to for electron to jump to the conduction band ok.

So, if you want to see the energy gap in terms of some values, semiconductors have energy band gap of less than 2 electron volts; whereas, insulator have energy gap of more than 4 electron volts ok. In case of conductor, they are overlapping each other. So, there is there cannot be any gap between the two ok.

So, and y axis, if the energy of electron is there; so, this is what is the band theory to explain the conduction in different type of materials that why you have conduction in some material and not in some other materials ok. Of course, the theories much more you have to understand more of that how the electrons are positioned in an atoms and shares in sub shares and there is a spin associated with each electron and so on.

So, those are you have to go into much more details, if you are interested only in the electrical properties of the material ok. For our purpose right now, this much information is sufficient to understand that we can have different type of materials and how the conductivity of different materials can change as a function of temperature; for example, there are other ways also to change the conductivity of the material and that is what we will see in the next slides.

So, if you come to Semiconductor, we will look slightly in detail because these are more one of the most important materials. And in fact, all the electronic industry is based on the semiconductors that how you can manipulate the properties of the semiconductor.

So, if you look at the semiconductor, there are can be of two type; one is what we call is Intrinsic semiconductors ok.

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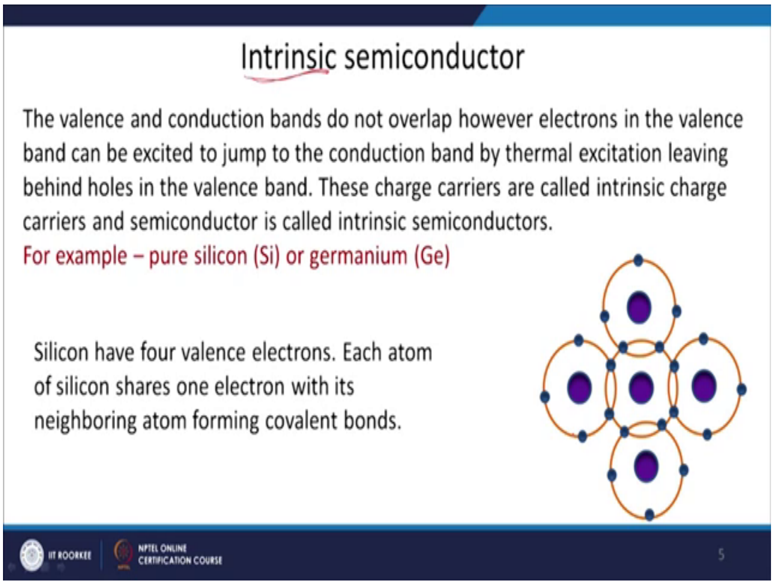

So, in case of semiconductor, the valence and conduction bands do not overlap ok. However, electrons in the valence can be excited to jump to the conduction band by thermal excitation leaving behind holes in the valence band ok. So, when the electron course from valence band to the conduction band, it leaves behind one hole in the valence band that whole can be considered as a positively charged particle ok. And electron is of course, and negatively charged particle.

So, these charge carriers are called intrinsic charge carriers and semiconductor are called intrinsic semiconductor. So, this kind of small conductivity is always going to be there in the semiconductor because of the thermal excitation ok. That is why this are called this is the intrinsic property of the semiconductor ok; that is why these are called intrinsic semiconductor.

So, all semiconductors will have same conductivity, if you are not at 0 Kelvin ok; any other temperature, there has to be some conductivity in semiconductor and in this condition it is called intrinsic semiconductor. So, for example, pure silicon or pure germanium will be of this type of intrinsic semiconductor type. Why they show this kind of property ok? Then, silicon have four valence electron ok, basically here it is shown ok.

So, 1 silicon atom is it at the centre and 4 are around it and they are sharing their valence electrons to fill the fill their outer orbit. So, please remember that I am not showing the full atomic structure of silicon here, I am just showing the outer orbital. There will be 2 more orbits in this which I am not showing it right now because, it will complicate the whole schematic here. So, only I am showing the outer valance shell ok; where, the valence electrons are orbiting.

So, 1 silicon atom is in the centre is sharing electrons with the 4; because and the outer shell, it is only 4 electrons. It needs 8 electrons to be stable that is why it is sharing 4 other silicon atoms ok; one-one electron to fill its shell with the 8 electrons and become stable. So, with this silicon atom another 4 will come here and like that it will be a sharing of electrons and covalent bonding will be there between the silicon atoms.

So, in normal condition, you will see that there is not going to be any free electron available for conduction ok, but as the temperature increases what happens that this electron make a get sufficient energy to jump from this valence shell and leave behind hole here and become free to carry a charge a when electric field is applied. So, it can move when an electric field is applied ok. So, because of thermal excitation, it can jump from this steel and go out ok. So, this is how the silicon arrangement is there and in this case, when a thermal excitation there is to be some intrinsic flow of charge will be there.

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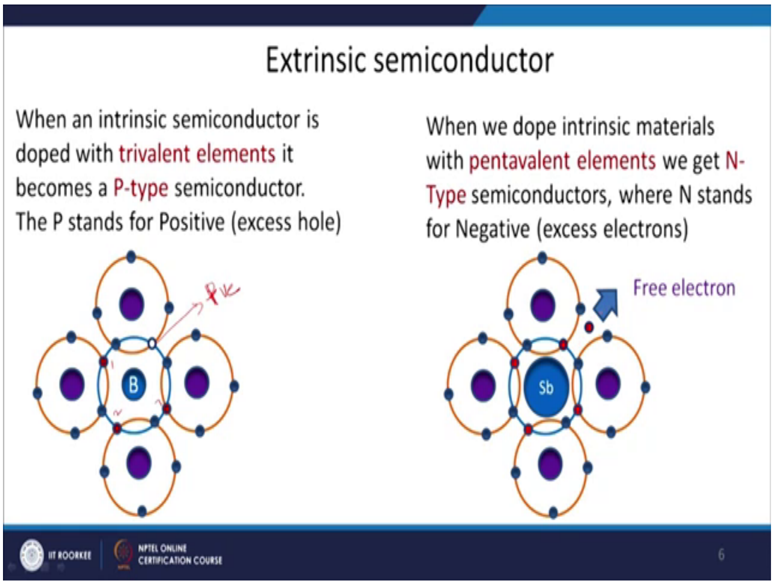

The extrinsic semiconductor are the ones where you add deliberately some doping agents or doping elements or with this is what we call is doping phenomenon of a semiconductor to add elements of either trivalent elements or pentavalent ok. What do we mean by trivalent elements? These are the element which has 3 electron in the outer shells.

For example, Boron; here is shown in the centre ok. It has this 4 let us say I will I think I have shown it by this red color electrons, these are 4 Boron. So, you have 1, 2 and 3 electrons of in the valence shell of the Boron ok. So, these are the 3 valence electrons, this is a trivalent element which has 3 electrons in the outer shell. So, when you add this kind of element in the silicon and this is what we call is doping. Then, what will happen is if the boron will replace the silicon atom and now what will happen?

Earlier, all the silicon atoms are sharing one-one electrons and their shell were getting full with all the 8 electrons in the outer shell ok. But now with the boron 3 electron will be shared by this 3 silicon atoms. But with the fourth silicon atom, it is no electron to share this. So, it is only having a hole present here ok. So, with addition of each boron atom, you will have 1 additional hole present here. Now, because it is not sharing any electron this hole is not bounded by if the bonding between the boron and silicon ok.

So, it is free to move and as soon as you apply any electric field, this hole is hole will move ok. And since, hole is considered as positively charged that is why this type of semiconductor are P-type. So, if you add trivalent element in semiconductors or silicon material ok; you will get a P-type semiconductor.

When we dope the same intrinsic semiconductor with a pentavalent element we get a N-Type semiconductor; where, N stands for Negative axis electrons ok. So, again you can see antimony is there which has five electron 1, 2, 3, 4 and 5th one is now 1 extra electron is there. So, 4 electrons is shared with the 4 silicon atom around it; 1 extra electron is there which is not shared with any electrons.

So, it is free to move now. So, we have increase the conductivity of the semiconductor by adding trivalent element here and this free electron when you apply electric field it will be free to free to move. So, these are called extrinsic semiconductor when you add deliberately some element into that to make it either P-type or N-Type. You need both P-type or N-Type to make diodes and so on to make a circuit. So, both are important now the Superconductivity is another type of property where the material does not show any resistivity to electrical flow ok.

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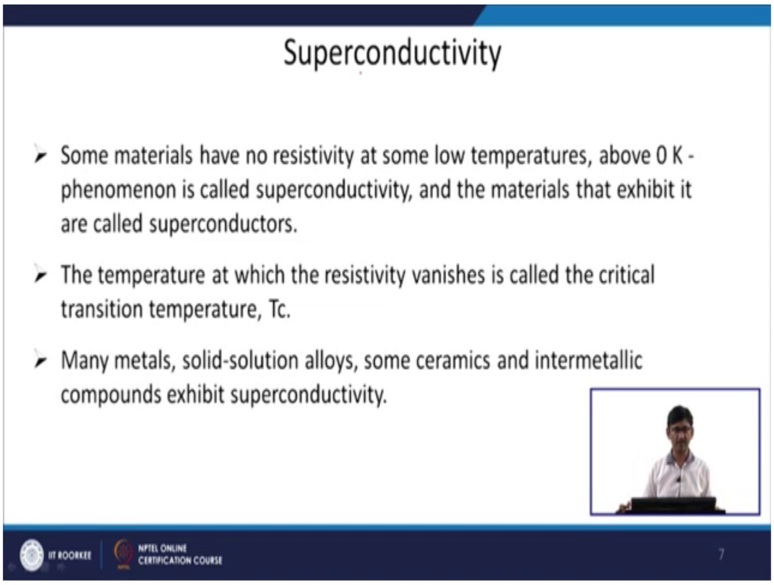

So, you can understand for any flow of electricity through normal metallic material ok, there is always some resistance is offered to the flow of electric current ok. And of course, this is significant resistance and you have significant power loss because of this resistance. So, superconductors why when people started thinking about that this superconductor does not offer any resistance to electrical flow ok.

So, and especially ceramics are some of these type of material which show superconductivity. So, these show super very nil resistance at some temperature, but these temperature are usually much lower. So, likely at liquid nitrogen and these kind of temperatures or below that they show superconductivity ok. So, the resistivity the temperature at which the resistivity completely become 0 is called the critical transition temperature, T c ok.

Many metal and ceramic and inter metallic show this kind of properties very important and these kind of maglev high speed trains you must have these trains, maglev high speed trains. They operate on this principle that when you have superconductor and you put another conducting metal over that. Then, it will kind of float over that ok. There are lot of theories about that ok. We are not going in to details of that, but these are same important class of materials.

Now, to have 0 friction movement of for example, in this case trains by having a superconductivity in the where the wheels are there ok. Then, coming to magnetic properties, the magnet is can be divided into different classes ok. A Dia-magnetise is very weak magnetise which exist in the presence of an external field ok.

So, when you apply the external field only then, you will see magnetise in the material and when you remove the external field; then, there will not be any magnetise. Then, there can be Para-magnetise slightly stronger than Dia-magnetic ok, in presence of external field dipoles line-up with the fields.

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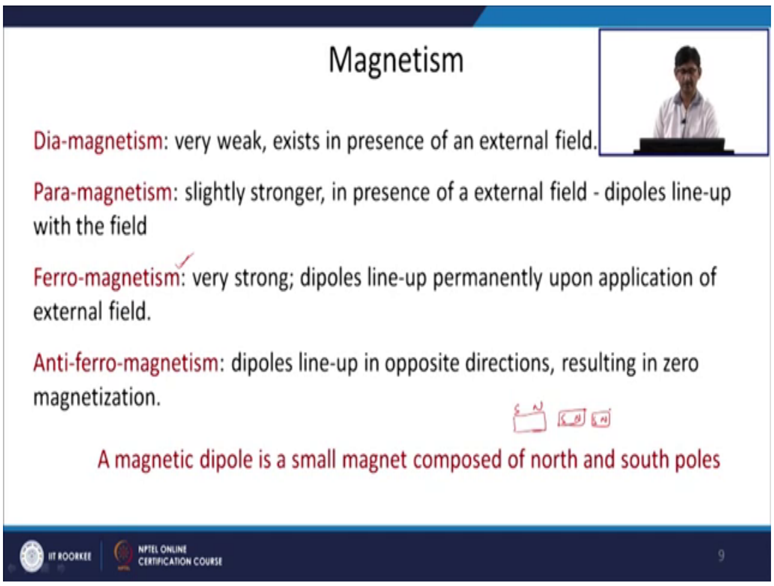

Again, in the presence of external field you will see some magnetic field be slightly stronger than diamagnetic. Ferro-magnetic is the one which you usually see in magnets whatever you use in your for example, in your music box ok, there will be some magnetise there going to be there and lot of for example, your fridge magnet you will have a magnet.

So, all these magnet are show Ferro-magnetic which is very strong magnetise they show because the dipole line-up permanently up on application of external field. So, when you apply the external field ok, they permanently show magnetise. So, Ferro-magnetism will always show magnet is once you have induced magnetise in that in that particular material.

For example, if you might have seen there are some time on the office table some jar is there to store the pins alpines and there is a magnet around it. Then, the alpine also start showing magnetism after sometime ok. So, under an external field they get magnetized and they remain magnetic even after removal of the external field. Then, Anti-ferro-magnetism are there dipoles line-up in opposite direction, resulting in 0 magnetisation.

So, in this case, if you apply the external field also, you will not get any magnetise this. So, these are Anti-ferro-magnetism. So, anti of what we have discussed just now. A magnetic dipole is a small magnet composed of north and south poles ok. So, basically for any magnet, we have already seen that you will always going to have some South and North Pole ok.

So, dipoles when we say magnetic dipole ok, basically we have talking about an arrangement were their arrangement in this fashion south and north. So, if all the dipoles are arrange in the same fashion then, you will have magnetism. So, in any ferro-magnetic material, we will now consider basically ferro-magnetic materials only here ok.

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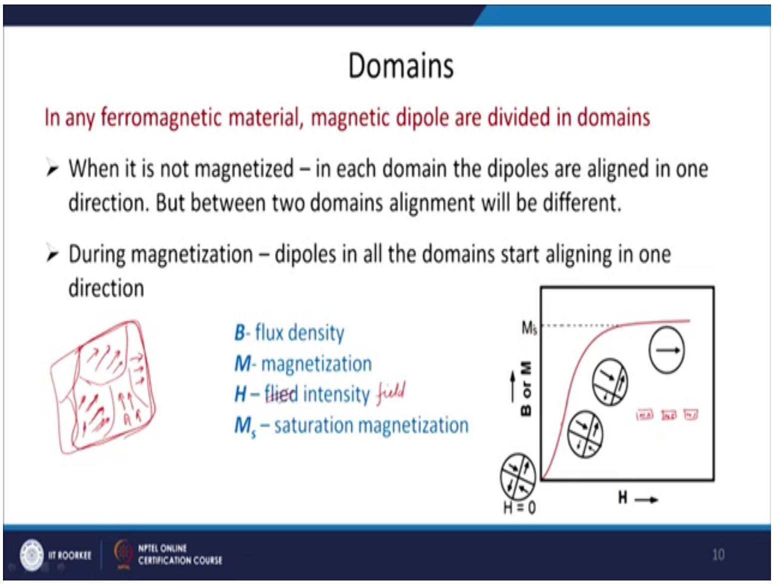

Magnetic dipole are divided into domains ok. So, if you take any material, there will be there will be some domains will be there ok, like grain boundaries or grains and material where the in one domain the dipole will have one type of alignment. In another domain, they may have a different alignment for example, again those type of north south dipole.

And may be another domain, they will have another alignment. So, on these are not grain boundary this are domain boundary. So, one domain can consist of; so, this can be domain can be within one grain. So, you can have one grain like that. And this one grain, you can have the domains like this within a grain itself.

So, they are not divided between the grain single grain can have multiple domains and in each domain you will have some alignment of dipoles. So, when it is not magnetized in each domain the dipoles are aligned in 1 direction, but between 2 domains alignment will be different ok. So, in a in a domain the alignment is going to be same, but if you compare between 2 domains the alignment is going to be different.

So, when it is not magnetized, in all this domain they are aligned in very random way ok. But when you do a magnetization ok; during magnetization dipoles in all the domain start aligning in one direction ok. So, when you do magnetization all these domains will start aligning in one direction.

So, which can be shown by a curve like this where it is called a B H curve; where, B is your flux density which is your and using the magnetic flux density in the material. M, you can say M also magnetization. H is the field intensity. I am sorry there is spelling is wrong here. So, field intensity is there H on the x axis. This is what externally we are applying on the material and M s is the saturation magnetization ok. So, what happens when you start applying a magnetic field on a material?

So, initially they have these domains and alignment of dipoles will be different in each domain and you started applying some magnetic field on this material for magnetization ok. What will happen that slowly the flux density in the magnetic flux density will increase in material as a function of h the external applied field intensity? So, you can see that slowly a domain are started changing. So, some domains are disappearing and as the H is increasing B is increasing, you reach a saturation point. When all the domain are disappeared and throughout the material you have only one alignment of dipole which is in this direction ok.

So, as I told you all the in all the case the alignment is same north-south, north-south, north-south and so on ok. So, now, when all the alignment of the dipoles is in the same direction; so, one end will be a south pole; another end will be in North Pole and you will ever magnetization in the material. So, when is the whole material is one alignment; then, you have reached the saturation.

Now, you cannot do anything else ok; you can keep increasing the external field, but you cannot go beyond that all the dipoles are one alignment. So, you have reached the saturation point. So, this is my saturation magnetization ok. Now, once you do that what happens when you again bring down the magnetic field ok? That is of interest for us because that actually bring about phenomenal called Hysteresis that is important for one material application.

So, the Hysteresis what do you mean by Hysteresis ok?

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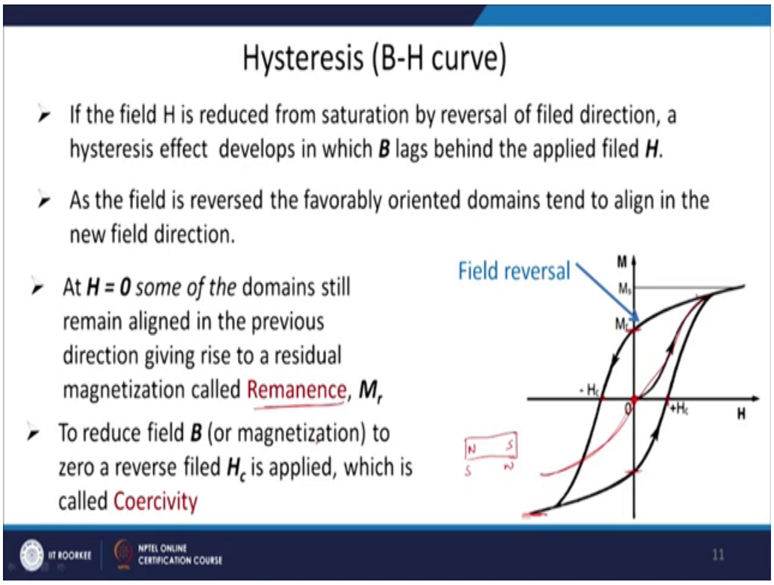

When you are starts the from this point ok, when the material was not magnetized ok, you applied a external field and you start at the magnetization process and it reach the saturation magnetization ok. Now, you are reversing the field ok. So, suppose you apply field such that given component suppose something like this.

By applying an external field, now this is what is the dipoles are aligned such that you get this 2 poles in the material and now you have reversed the external field. What will be have will happen? That dipole will again align in the different direction and the north has to become south and south has to become north. So, all the domain has to align in a in the opposite direction now ok. So, we are reversing the field now here ok.

So, you can see that we started from 0 for external field when the flux density was 0 ok, but while reversing what we have seen that when my external field is 0 is still there is some magnetization in the material is left; that means, all the domains could not get align into the opposite direction ok. So, there is some remained flux will be there though my external field is 0 now ok. So, this remained flux is called of course, remanence be because this much has remained in the in the material because all the domains could not get aligned in the opposite direction when we reverse the field.

So, have a while reversing at H is equal to 0, sum of the domain still remained a line in the previous direction which we did while magnetizing which give rise to residual magnetization which is called Remanence M r ok, that much will remain in the material to leave.

To get rid of this magnetization and we have to now go into the negative direction of the electrical field and this is this how much negative we have to go will be given by H c. So, to reduce the field B or magnetization to a 0 ok. So, now, we have come to the 0 flux the flux density in the material ok; reverse field of H c is applied.

So, negative of this external field is applied which is called Coercivity. So, basically are coercing the material to bring down the flux density to 0 ok. So, you are you are coercing the material because you are coercing it, this is called Coercivity and this much negative energy is negative external field you have to apply to bring it down to the earlier state from where we started. So, these are the 2 very important properties of any magnetic material that what is the Remanence value and what is the Coercivity value ok. This happens during the field reversal.

So, again you can go into the negative direction as you went into the positive direction here. Again, you will reach the saturation. Now, the hole all the domains are reversed and they are aligned in the reverse direction. So, again you will reach the saturation point and when again you start applying reversing the field ok, you will see that same Remanence field will be there same Coercivity will be there. That means, some positive external field has to be applied to bring it to 0 flux density again and then, it will go back to the saturation ok.

You can see that in each of the cycle ok, you are losing some energy. So, there is a energy loss in each of this cycle because it is not following the same, if it would have followed the same curve, maybe it would have gone like this and again as you reverse the field it will go like this; then, there will not be any problem, then it will not lose any energy in the this process of magnetization demagnetization and so on ok.

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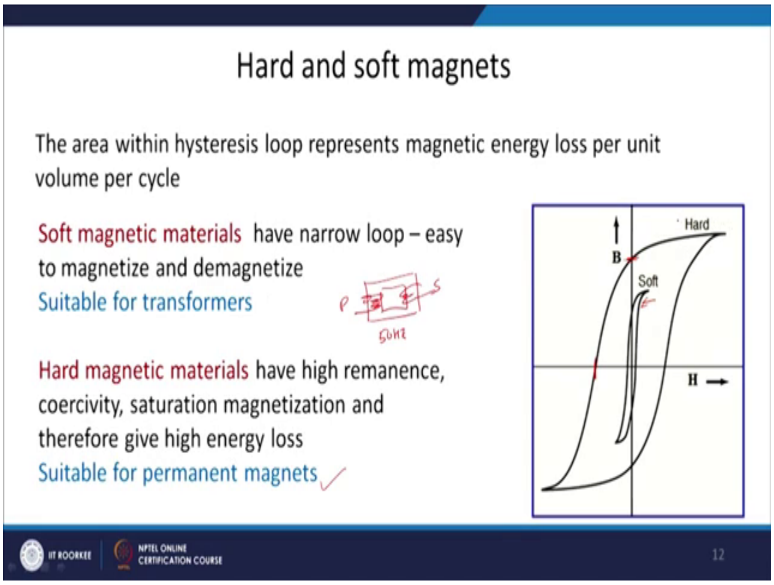

Now, depending upon this Hysteresis loop ok; so, the area within the Hysteresis loop represent magnetic energy loss per unit volume per cycle. So, in each cycle you loose area and energy given by the area of this loop because this much extra energy you have to apply to bring it back to 0 and then take it to the negative side and so on.

So, in each of this cycle, when you do the magnetization demagnetization; then go in to the negative direction ok, you lose certain amount of energy which is equal to the area of this loop. So, now, depending upon this area of the loop, I can define 2 types of material; one is Soft magnetic material, another is hard magnetic materials ok. Soft magnetic materials have narrow loop ok.

So, this is a Soft magnetic material; that means, you can have easy these are easy to magnetize and demagnetize. I can easily magnetize them and demagnetize them because you will have smaller remanence you will need smaller coercivity and so on ok. So, it can be easily done and these are actually that is why important for transformers ok.

So, you can understand in transformer ok, you have Primary winding say for example, suppose you have a transformer like this. So, you have Primary winding here and you have secondary winding here and in the Primary winding an alternating current is flowing which has a cycle of 50 hertz ok; that means, 50 times it is becoming positive and negative ok.

So, my this core material will also get this whole cycle will be repeated 50 times in a second 50 hertz means 50 times this Hysteresis loop is being you are doing in the material ok. So, any and each cycle you are losing certain energy ok. That means, there is a big loss of energy during the when the you are stepping down on stepping up the voltage using transformer that is why the transformers are covered with oil ok.

They are they are submerging oil to take out all this all this heat and you must have seen on the transformer outer surface also there are fins to increase the surface area. So, that this heat can be dissipated and sometime you must have seen that the transformer also burn up because there is so much heat is generated.

So, you can understand the importance of hysteresis loop that I have to have material which has a smaller Hysteresis loop and these are called soft magnetic materials. A lot of good research goes in the making of these type of material; one of the most important material which is used for this transformer applications are Silicon steels which contains around I think 2 to 3 percent silicon and they show this kind of soft magnetic properties ok.

Now, hard magnetic materials are also important ok. They of course, high remanence ok, they have high higher Coercivity, saturation magnetization will also be higher and that is why they have higher loss of energy, but for materials where you do not want to keep changing their magnetization condition these are important. So, in permanent magnet we will use hard magnetic materials.

Because in this material once we have magnetized it, we want it to remain like that ok. So, if it has a higher saturation magnetization; then it is good the magnetic field which is which it is going to generate will be of higher value ok. So, for permanent magnets we want to have hard magnetic materials.

So, with that we have covered 2 very important class of material. Electrical magnetic materials and we have seen few properties of these materials which are of great importance to our day to day life ok. So, with that I would like to say.

Thank you.