Advanced Ceramics for Strategic Applications
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Lecture -24
Superconductivity

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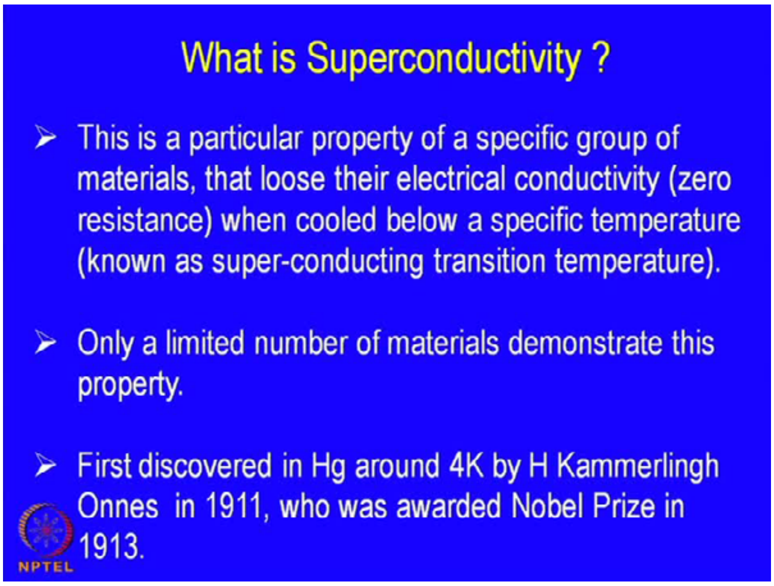

Today's topic is superconductivity. We have earlier discussed that ceramic materials are a wide spectrum of electrical properties starting from superconductivity to insulating properties. We have discussed semi-conductivity and insulating properties earlier. Today, we will take up the super-conductivity. First of all, what is superconductivity? How do we define this property? This is basically a statement of how we can describe the superconducting behavior of materials. This is a particular property of specific group of materials, not only of course ceramics there are large number of non-ceramic materials which do cause this particular property.

So, this is a particular property of the specific group of materials that lose their electrical conductivity or in other words, it becomes zero resistance state when cooled below a specific temperature and on a normal condition, normal temperature and pressure, they do not behave in this manner, but only when they are cooled at a very low temperature and normally below 100 K. Then, this material is supposed to be superconducting, so that the resistance becomes almost 0 or all practical purposes, it becomes 0.

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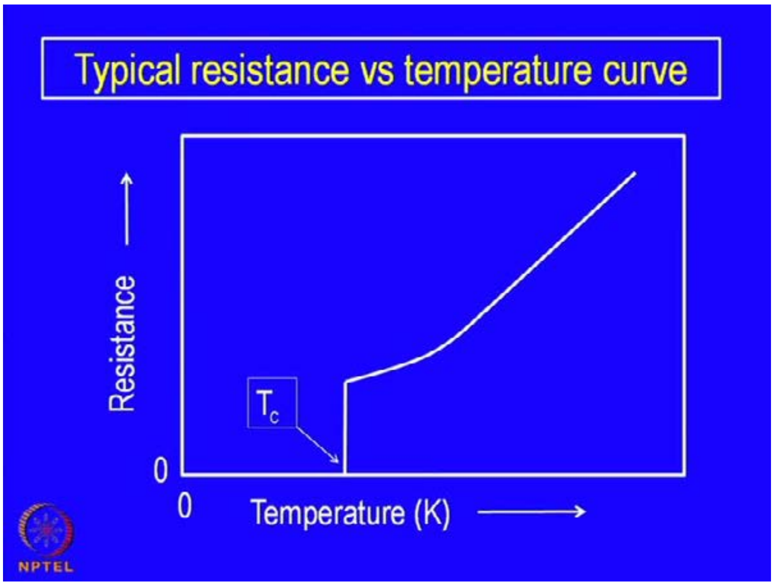

Only a limited number of materials demonstrate this property, not all materials demonstrate all material when cooled do not causes this property. Only a specific material becomes superconducting at a very low temperature. This particular property was discovered more than 100 years back, precisely in 1911 by a scientist named Kammerlingh Onnes who was of course awarded noble prize in 1913. So, it has been going on for a long time. It has been the property as known for fairly long time, even though we will see later many of the theoretical understanding is still lacking. This is the typical resistance curve.

We have seen earlier how the metals behave. We will see some of the curves today also, but this is the normal behavior of a metal. Its resistance decreases as we decrease the temperature and it tends to be 0. In fact, it does not go to 0. Even at 0 if we (( )) pull at, it has always a residual resistance, even at absolute 0 temperature, but there are group of materials when cooled upto certain point, very close to 0, of course then suddenly the resistance become 0. It comes to 0 is not a gradual change. It is a discontinuous curve here. So, there is almost a vertical line at certain critical temperature and that is called the superconducting critical temperature. So, this is the typical resistivity versus temperature curve for a superconductor.

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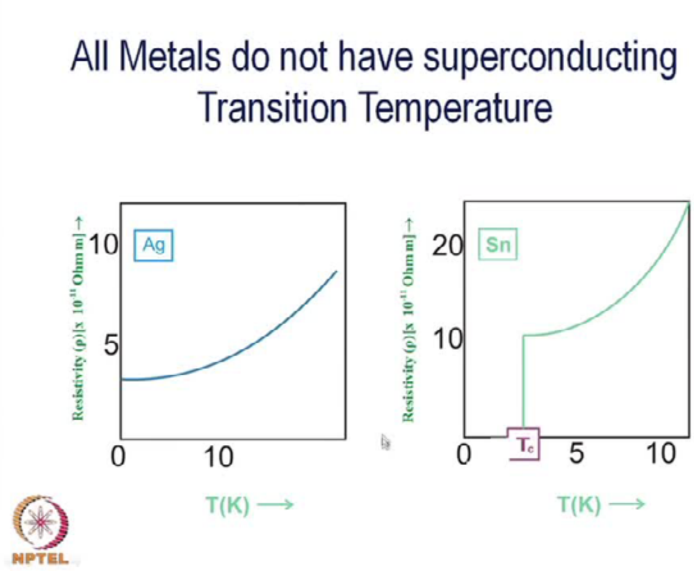

This is a non-superconductor versus super conducting resistivity curves of two different metals. One is silver, another is steel. As we have discussed earlier, silver is one of the conduct, highly conducting material elements and it has been used as a conductor in many different purposes. However, it is not that conducting. Its resistivity is relatively high whereas, so far as the superconducting property is concerned, silver does not show any superconducting property. Even at 0 degree kelvin, you have a residual resistance. It does not go to 0 whereas, a superconductive element like tin which has a superconducting transition at a slightly higher temperature or between about 2.5 to 3 degrees kelvin, you have a superconducting transition and suddenly, the resistance goes to 0. So, this is again a typical superconducting behavior of elements and so, although it is highly conducting the normal condition, but it does not have a superconducting property. So, it is related to something else. Its structure, its electron, phonon, interaction and so on.

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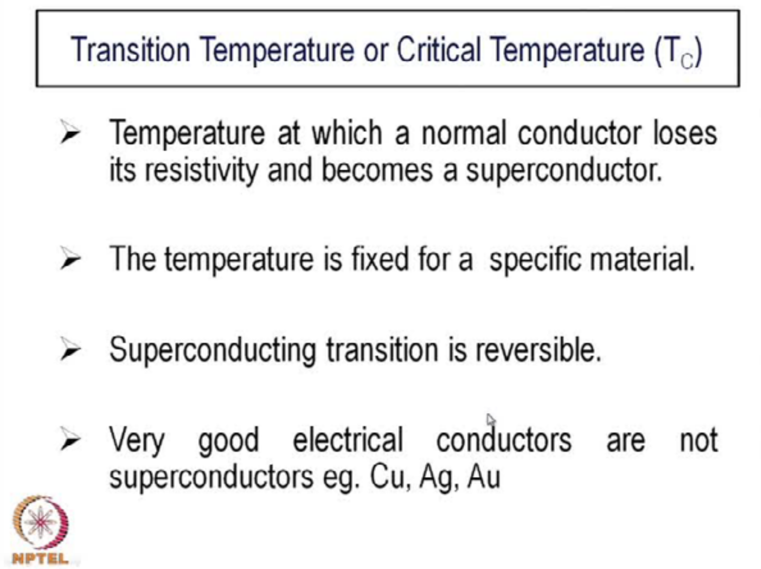

Few other statements. The temperature at which the normal conductor loses resistivity becomes superconductor. That is the definition of the critical temperature, T c. That is the T c is the temperature at which normal conductor loses its resistivity and becomes superconductor. That is how the T c, the critical superconducting critical temperature has been defined. The temperature is fixed for a specific material. So, it does not vary. It does not depend on the weight is cooled or the rate of cooling or rate of heating, it really does not change. So, it is very specific and characteristics of a particular material.

So, of course for different materials, the temperatures are different. As we will see later, it is reversible. That means, once you cool, you have a zero-resistance stepped, but if you come back or heat it up and cross the transition temperature, once again it becomes a normal conductor. So, it is a reversible phenomenon. So, it is basically a reversible transition which takes place at specific temperature, very good electrical conductors that has been mentioned earlier. The very good electric conductors are really not necessarily.

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Two categories

- Low T_C superconductors
- High T_C superconductors

Superconductors, most of the time, they are not so. For example, the three most conducting elements like copper, silver and gold, they do not become superconductors if you cool to very close to absolute 0. So, these are some of the characteristics of superconducting transistor or superconducting phenomenon. So far, there are two categories or two subgroups of superconducting materials. One is normally called low temperature superconductor and the other high-temperature superconductor. So, of course till very recently about mid of eights, most of the superconductors are basically low-temperature superconductors.

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Low T_c Superconductors

Superconducting Elements	T_C (K)
Sn (Tin)	3.72
Hg (Mercury)	4.15
Pb (Lead)	7.19
Superconducting Compounds	
NbTi (Niobium Titanium)	10
Nb_3Sn (Niobium Tin)	18.1

Till some ceramic superconductors were discovered around 1986 and that is the distinction. Now, we have a very distinct group of superconductors which are mostly ceramic super conductors, oxide way super conductor and they are called high T c superconductors compared to the low T c superconductors which are either elemental superconductors or intermetallic. Some examples to start with the low-temperature superconductors. These are few examples of low-temperature superconductors. As we have mentioned, mercury was a first element to be discovered in which the phenomena of superconductivity will be absorbed and then, few other elements like tin and lead also have been discovered later that they have also the superconducting phenomena or they behave as superconductor. The superconducting transition temperature has been given in the right. For example, tin as 3.72, mercury 4.15. These are all degree kelvin. Lead is 7.19. These are few elemental superconductors having a very low transition temperature.

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High T_c Superconductors

Material	T_c (K)
Nb_3Ge	23
$(LaBa)CuO_4$ **	34
$YBa_2Cu_3O_{7-x}$ (YBCO)	90
$Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO)	110
$(Tl\,Bi)_2\,(BaSr)_2Ca_2Cu_3O_{10}$	125

** Bednorz and Mueller (1986)

Later on, quite a few intermetallic compounds have been also found in the superconducting property. The important ones among them is niobium titanium. It is intermetallic compound and having a transition temperature of 10 degree k and niobium tin, another intermetallic compound, both of them of course. Niobium is a common element present. So, either it combines with titanium or tin. They do have superconducting property and this temperature is slightly higher 18.1. So, one of the highest one can say there are other. We will come to that. However, in 1960-1986, the first oxide base superconductors were discovered and till that time, niobium germanium was the highest. Although, it is been categorized under high T c superconductors, but really not high T c, except they have a much higher transition temperature than the rest of the groups shown earlier.

So, the first high-temperature superconductor actually in effect, it is here, but in between the first, this is the first observation of a superconducting phenomenon in an oxide base material lanthanum barium cuprate, lanthanum barium copper oxide. It was observed by Bednorz and Mueller in 1986 and in the next year, they were awarded the noble prize because before that there was no question of having superconducting phenomena in oxides. Nobody could really think that some of the oxides can also show superconducting behavior. Now, within few months, in fact the same family of oxides were lanthanum has been replaced by (()) and immediately, there is a big jump in superconducting critical temperature from 34 k. It immediately jumped to about 90 as a big jump there in between. Otherwise, there were gradual changes with different materials over a period of materials 75-80 years. Then, of course once the oxides could be found to behave a superconductor, then there are various different other oxides came, complex oxides many different substitutions took place within 10 year or so.

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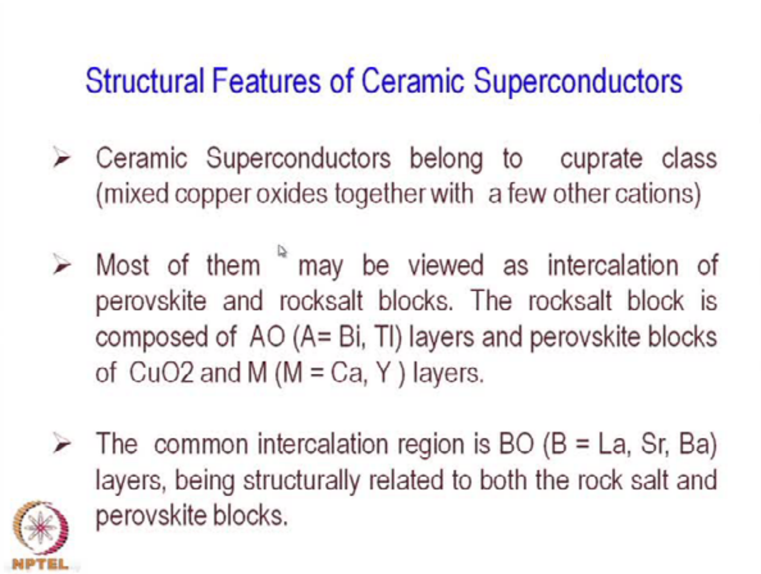

The critical temperature could be raised at that point of time. First there was a high expectation that superconductivity can be observed even at room temperature or higher than room temperature, but that has not been shown. So far, there is no room temperature superconductivity available, but the transition temperature has certainly increased quite significantly from around 4 degree kelvin to more than 125 or 130 degree kelvin. That is a big jump, no doubt, but it took more than 100 years of research to come across such a phenomenon. So, we will discuss some of these things later on, some more details of these compounds. So, these are basically ceramic superconductors. One can classify them as ceramics superconductors or high T c superconductors.

Well, if you look at the structural features of the oxides ceramic superconductors or high T c superconductors belong to cuprate basic copper oxygen block or cuprate block cuprate class of superconductors and they have a mixed copper oxide together, copper oxides together with few other cations. So, there is a substitution of different other cations or addition of different other cations in order, in addition to copper oxide. Most of them may be viewed as intercalation of perovskite and rock salt blocks. So, it is a complex structure again and you have a perovskite block as well as rock salt blocks and the rock salt block is composed of AO type oxides like A can be bismuth or thallium layers whereas, perovskite blocks can be Cu 2 OCEO2 and M can be an M. So, it is A in CEO 2. You can replace or add other oxides like calcium and yttrium. So, that forms the perovskite block. The common intercalation region is BO that is, B is lanthanum strontium or barium layers being structural related to both the rock salt and the perovskite blocks.

So, on one hand, we have perovskite block and other hand, you have another side we have a rock salt block and in between, you have oxygen layer, an oxide layer of either lanthanum strontium or barium. So, these are simple description, very simplified description of the structures, the super ceramic structure, superconductor structures.

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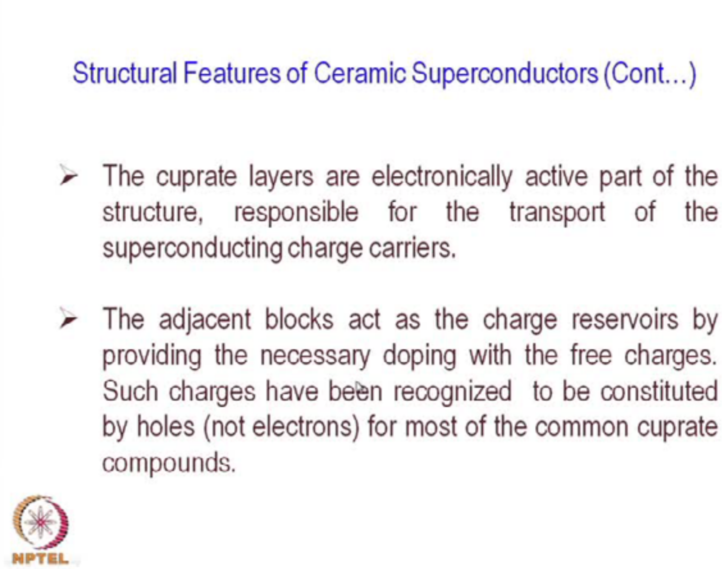

Well, we will come to this may be later basically how the superconductivity arises here. Of course, we have to have some electronic transport and basically, the transport takes place in layer form. It is not a isotropic material. So, in some direction, superconductivity is predominant or prevalent whereas, in other directions, particularly along the jet direction, there is early in any superconductivity whereas, the x y direction in the layer, the superconductive is prevalent. So, the cuprate layers are electronically active part of the structure and also responsible for the transport of superconducting charge carriers.

So, the superconducting charge carriers actually moves in a layer structure or in the x y plane whereas, in the jet plane or jet direction, there is hardly any transport. So, it is highly an isotropic property. In fact, in many of the other superconductor also, one can find this kind of behavior. The adjusting blocks act as the charge reservoirs by providing the necessary doping with free charges. So, the charge carrier actually is provided by the adjoining blocks which we have mentioned earlier. So, such charges have been recognized to be constituted of by holes well in normal superconductors. That means, low-temperature superconducting is the electrons, electron pairs. To be more precise, electron pairs moves and those are the charge species which carries the charge or give rise to the conduction process whereas, in case of high-temperature superconductors, it is believed that not the electrons, but the holes are more predominant charge carriers here.

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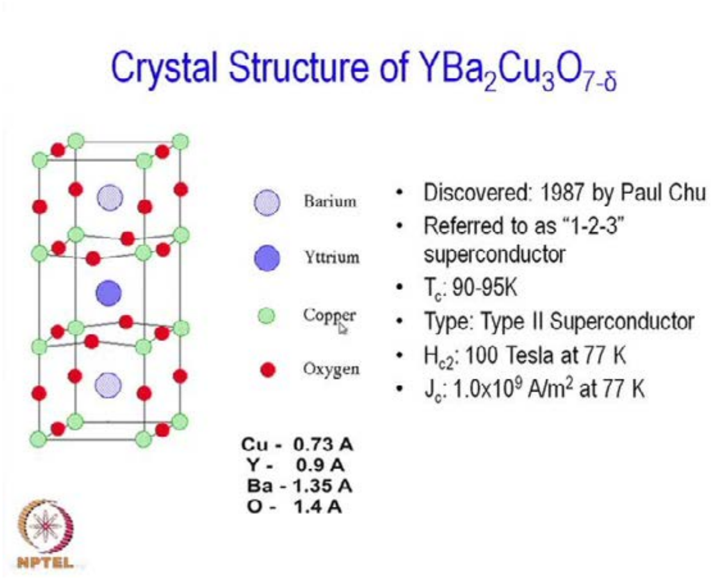

So, that is one of the difference between the high-temperature superconductor oxide base superconductors or ceramic super conductors compared to elemental or intermetallic superconductors which we have discussed earlier. Well, this is what we have described just now and this is a simplified form of the particular structure that is the yttrium barium copper yttrium barium cuprate and that is the formula, sometimes is called 1, 2, 3 compounds because of the ratio of the elements present yttrium is present in only one element, one atom, this is two atoms and this is three atoms. Copper is three. Sometimes, they are called 1 2 3 compound oral. So, it can be called YBa2Cu3. So, that is how it has been described in the literature and this is a formula. It is an oxygen deficient oxide. It is an oxygen deficient oxide, although oxygen deficient oxide is supposed to be electronically conducting, but in this case, it is very peculiar situation where you get actually whole conduction, whole conductivity rather than electronic conductivity.

Of course, there is a little bit of controversy about that. So, it was discovered in 1986. In fact, not in 87. Sorry, this is fine. This not the lanthanum barium copper, this is yttrium barium copper. This was discovered in 1987, but Paul Chu and as mentioned earlier, its transition temperature varies between 90-95 K and there are some other properties which will be more relevant when you discuss the other aspects of superconductivity. For the time being, one can say that it is a type two superconductor.

What is type II superconductor? We will discuss that in few minutes and there is a critical magnetic field as well as critical current. So, this is the order of the current. One can expect a superconductor of this type can carry without destroying the superconductivity. These are the typical blocks of different blocks we have described just now and then, you have this barium and this is yttrium and this is cuprate block. So, this is the cuprate block where you have oxygen and copper and one can see particularly at which are facing the yttrium ions. There is some distortion of the oxygen. So, there are not a completely flat planes or the crystallographic planes are not real flat planes, but there is some distortion here both on this. On this side as well as on this side. So, this is what is basically a kind of distorted perovskite kind of structure and because of the distortion, we have different blocks where one can get a symmetry of rock salt as well these are the ionic sizes of these different elements present here. Copper, yttrium, barium and oxygen, we will come to these figures later on.

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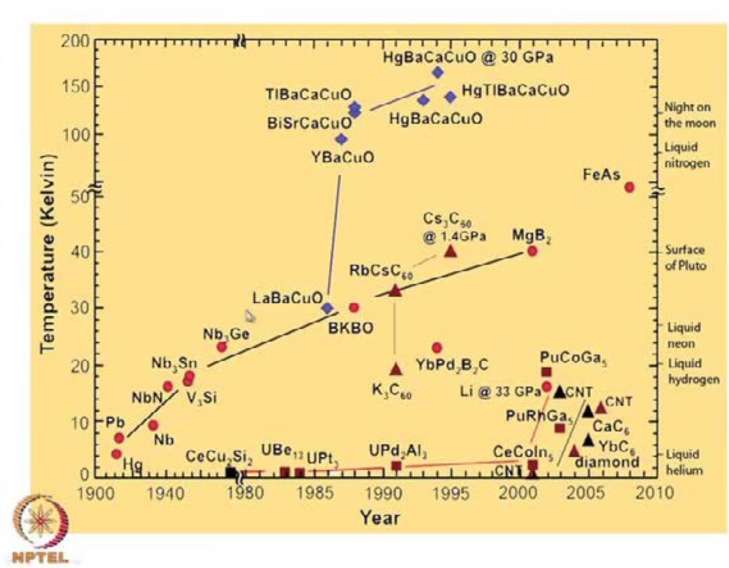

Now, this is a comprehensive picture of how many different compounds have been discovered so far and how over a period of 100 year show the transition temperature has improved in different compounds. This is the elemental superconductors which we have mentioned earlier. Mercury, lead, then niobium, niobium nitrite, niobium tin, benedium, silicon, niobium germanium and so on. There is another group of materials which has also been discovered at different points of time, but there transition temperature is very low. There is hardly any change of within 5 degree kelvin. So, there are even CNT some people have reported that there is superconductivity, the carbon nano tubes and then, there are more complex compounds, basically intermetallic compound. They are not oxides. These are carbides. Then, you have potassium C 60.

All kinds of different compounds have been shown to be superconductor, but the main group is here which are more industrial or application related materials. The highest in this area elemental or intermetallic compounds is magnesium diborite and then, very recently after 2000, 2007, his compound has also been observed. A intermetallic compound of iron and arsenic that is the highest DC is more than, slightly more than 50 k. However, there is a bifurcation here. These all are oxides.

These groups, the first started with barium lanthanum, barium copper and then, immediately by changing, substituting lanthanum by yttriuma, very strong and a very large jump has taken place. So far as the T c is concerned from 35 34 35, it is gone to about 90 and then, there are few other compounds in this range which has been observed to be slightly higher than T c and almost 150, one has reached 150, but this particular one has reached more than 150, but not at a normal pressure at about 30 giga percales. So, pressure also has an effect on the transition temperature, otherwise in normal pressure, it is around 100, 1300 and 3250. So, magnesium thallium barium, barium copper, copper oxide calcium.

So, there will be lot of substitution in the basic cuprate structure. So, it started with these cuprates and then, more and more substitutions make the structure little more complex and of course, you have one increased T c. So, that is a very good sign that we are still on the path of increasing the T c and may be one can expect at some future time, one can expect a room temperature superconductor with some oxides. So, ceramic superconductors are believed to have a great future so far as the T c is concerned, but there are many practical problems, some of which will be discussing later on.

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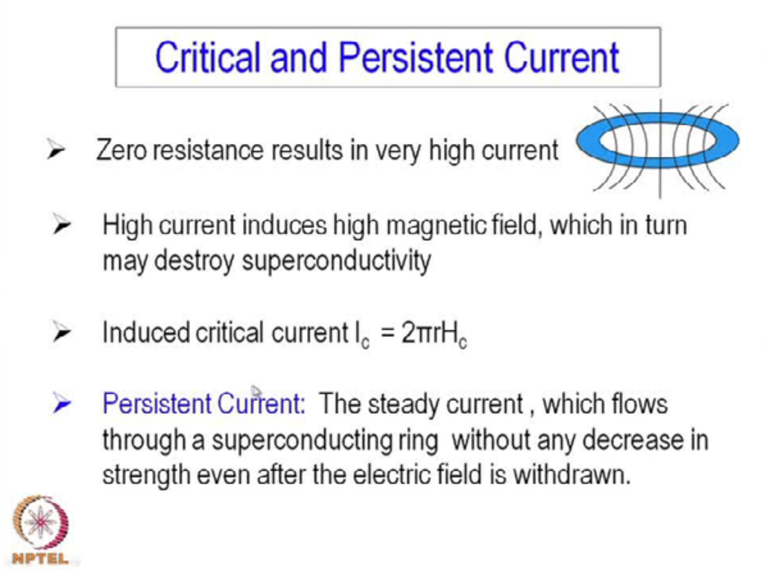

Well, there are certain additions to critical temperature. There are few other behaviors that must be understood and we remember, for example there are two critical parameters. One is the critical and persistent current. Since, we have seen that superconductors are having a zero resistance. So, zero resistance results in very high current. So, a very small applied voltage will give you a very high current in effect or theoretically, one can have an infinite current. So, that is the peculiar situation or very interesting situation for superconductors. So, high current however induces high magnetic field. So, high current means high magnetic field which in turn may destroy superconductivity. That is also another consequence that once you have a high current, there will be a high magnetic field and this magnetic field has an effect on the current itself, or the superconducting behavior of the material, the induced critical current is given if you have a coil of superconductor.

So, once we apply an electric field and current sets in that current, it will continue to be there even in the absence of the electric field. So, even after the withdrawal of the electric field, you can have a current flowing once it is induced in a superconducting coil of this nature. So, this is what we call the persistent current, the steady current which flows through the superconducting ring. It has to be a complete ring, of course not an open circuit one. A complete superconducting ring without any decrease in strength even after the electric field is withdrawn. So, once a current sets in by applying a small electrical field, one can withdraw the electrical field, but the current continues to flow and that is what we call the persistent current in case of a superconducting ring.

Now, this critical, there is a value of the critical current induced. Critical current is depending on the H c actually and also depends on the diameter or the radius of the ring. So, I c is equal 2 phi r H c is the critical field above which the superconducting property may be lost. So, that is what the critical current is. We will find out or discuss little more details what those values are and what exactly it means. So, there is a persistent current. What more important point in this slide is, basically the persistent current, the steady current which flows through the superconducting ring. So, that is a very important phenomena and observation that since, there is zero resistance, a very high current flows compared to many other conductors. Obviously, the current is much higher at a much lower voltage and not only that, even when the field is withdrawn, one can still have a persistent current in a superconducting coil. So, that is another very important phenomenon in super superconductors.

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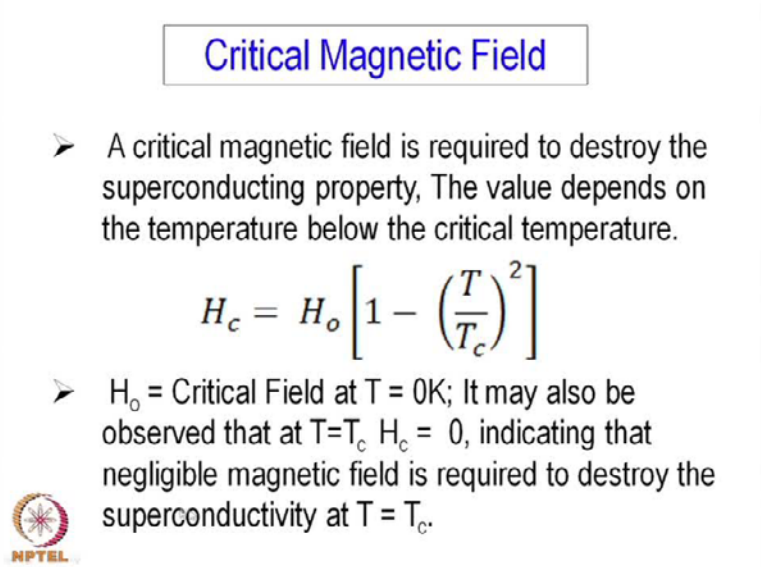

We have just now mentioned that there is a effect of magnetic field, in fact high current produces magnetic field and then, the same field also tries to destroy the superconductivity. So, it is a self-controlling phenomenon to some extent, so that the current really does not go to infinity. So, there is a realistic current which flow, real current which flows and which is kind of a steady current. The critical magnetic field is required to destroy the superconducting property. So, the value depends on the temperature below the critical temperature. Obviously, above the critical temperature there is no question of superconductivity, but even below the critical temperature, there is a possibility that the superconductivity can destroy itself and that depends on what kind of magnetic field it generates and what kind of magnet field it produces either by itself or a magnetic field is induced from the outside.

So, depending on what kind of magnetic field is generated, there is a critical magnetic field which is H c which can be expressed in this manner 1 minus T by T c square multiplied by a constant term which is specific to that particular material and H 0 is the critical field at T equal to 0. We will see the next curve what exactly it means. So, this is magnetic field. That is the critical magnetic field even below T c, it does not mean that at T c, at below T c, the temperature below T c all the time, a superconductor will remain as a superconductor. That superconductivity can be lost depending on how much current it is flowing and how much of magnetic field it is generating.

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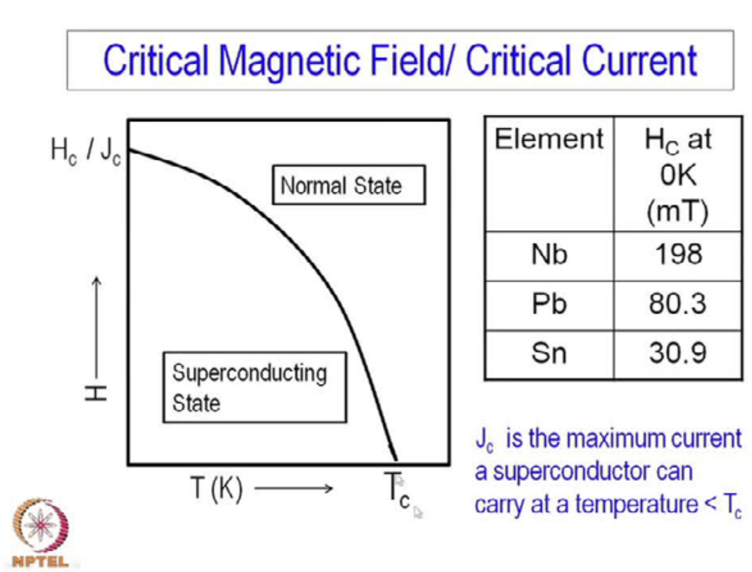

So, we can go to the next slide saying this is the relationship between the T c and the magnetic field. So, this is the critical magnetic field of course. That means at T c, this is the critical temperature exactly at T c, you cannot get a very high current because the H c, the critical magnetic field is very low whereas, if you go down the temperature, critical magnetic field increases and finally, reaches another highest value at T equal to T 0. So, this is the magnetic field below which it is a superconducting state. So, it is not our definition of superconductivity. Maybe it may have to be modified to some extent. So, you have to introduce. Also, it is not the temperature effect only, the magnetic field effect is also important. So, only at zero magnetic fields, we have seen at a particular temperature that there is a certain change of resistance and it becomes 0 whereas, if there is a finite magnetic field applied, then the T c further decreases. So, this area, the H versus T curve, this area is actually a normal state. So, any material which has a normal T c with zero fields, here the T c may decrease to this, provided magnetic field is higher as here.

So, there is a relationship between temperature and the magnetic field which we have given here. The critical field is H 0 1 minus T by T c square and that is what H 0 here is shown from this curve, this becomes H 0. So, at T equal to 0, this is actually H 0 and for all this, either T and H c, there is a critical current. So, the critical current also decreases as we come closer to the T c, but critical current increases as we go beyond T c or towards that zero degree kelvin. So, there is relationship between the temperature, the magnetic field and J c. J c is termed as the critical current which can flow in a superconductor without changing it to the normal state, otherwise a superconductor will become non-superconductor if those values exceeded. These are some of the values of critical field in low-temperature superconductors. For example, niobium. It is only milli tesla at zero degree kelvin. This is H c zero degree kelvin is only 198. That means, this value is about 198 milli tesla lead is about 80.3 milli tesla and T is about 30.9 milli tesla. So, for different materials, this value is, H c values are different. So, if you exceed this particular value, the material becomes non-superconductor irrespective of the temperature and therefore, this is the maximum current a superconductor can carry at a temperature less than T c. In fact, this is more or less similar variation. Also you will get J c. That means, as you decrease the temperature, you have a higher J c. If you are closer to the T c, then you have lower T c. So, that is the maximum current which superconductor can carry without changing over from the superconducting state to the normal state.

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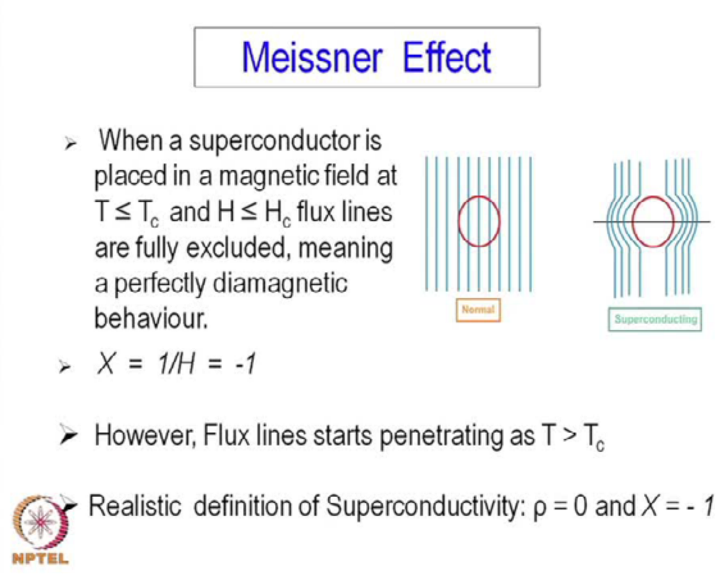

So, if the current is more than this value, the superconductivity is lost. So, there is a relationship between temperature, magnetic field as well as the current which can carry well. There is another very important property of superconductor that is known as the Meissner effect. When a superconductor is placed in a magnetic field at T less than equal to T c and H less than equal to H c flux line, the magnetic flux lines are the lines of forces are fully excluded from the superconducting material. That means, if it is a normal material, then either paramagnetic, let us say paramagnetic in particular. So, the line of force actually crosses through the material. So, this ring is actually, it is a sphere or a plate. One can say, it is actually supposed to be a superconducting material or there is a superconducting transition. So, in this state, there is, no these are normal material and not a superconducting material.

So, the magnetic lines of force cross or penetrate through the material. However, if this material gets transformed to a superconducting material situation becomes like this. All magnetic lands of force are excluded from this material. They repel superconductor material. Superconducting material repels all the magnetic lines of force. So, it goes, grows, by passes it and then, goes. So, this is what we call a magnetic lines of force or flux lines are fully excluded meaning a perfectly diamagnetic behavior. This is what happens when there is a diamagnetism. Diamagnetism has been defined as the susceptibility. The susceptibility is less than 0 is negative, but it is not always 1.

So, other diamagnetic materials, the valve is not exactly minus 1. It may be slightly more than that, but it is minus, sorry it is negative, but close to 0 whereas, in case of superconductor, the value is per exactly minus 1. That means a complete exclusion takes place in other diamagnetic material. Some lines of force, a fraction of lines of force can go through or penetrate through the material whereas, in a superconductor, nothing penetrates and that is what is called a perfect diamagnetism. However, flux lines starts penetrating as T is more than T c. So, this happens when it is completely superconductor, but if the temperature goes beyond T c, then of course there flux line starts penetrating and it does not remain as a perfect superconductor diamagnetic material. So, that is also another important aspect of superconductivity. So, this is particular effect or the behavior of diamagnetic or the observation of the diamagnetism in a superconductor is known as the Meissner effect according to the scientist who discovered it. So, the realistic definition with this discussion, there is a strong correlation with the magnetic field.

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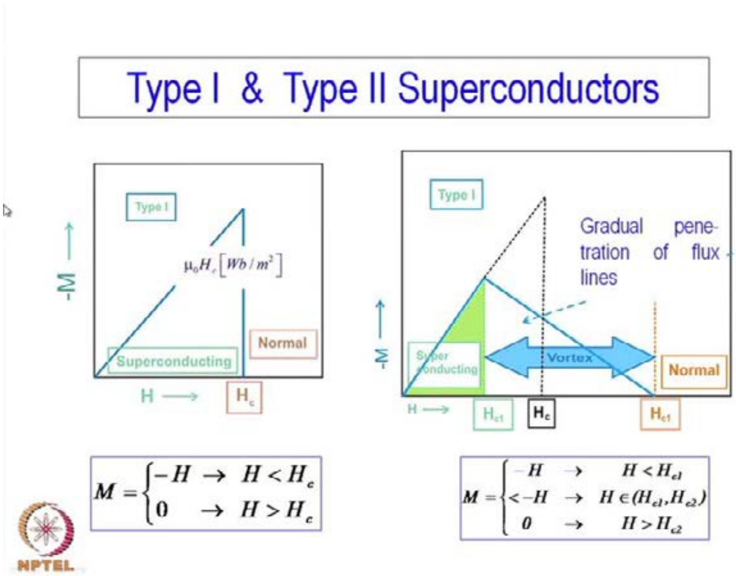

So, a better definition of superconductivity are not only must have a zero resistance, the row must be 0, but also x, the magnetic susceptibility should be minus 1. So, these are the two parameters fully describes the superconductor. A superconductor must have a zero resistance as well as a susceptibility of minus 1. So, these are how one can modify your definition to some extent and of superconductivity. Now, with this background, let us try to classify the whole range of superconductors. One, two, other subgroups from different angles, not just from T c point of view or high T c or low T c. These are how it behaves in presence of magnetic field. There are two types and they are normally called type I and type II superconductors and there magnetic behavior is the following.

This is what is type I superconductor. What has been plotted here is the magnetization against magnetic field and then, you can once again see two different regions. One is the normal region, another is the superconductor. This is a particular temperature. This is at a particular temperature. This is what happens of course below T c. So, below T c if you have a zero magnetic field, the magnetization is multiplied by minus 1 as you can see the magnetization when minus H equal, it become M equal to minus H. That means, linearly proportional when H equal to H c, less than H c, sorry so this is H c value, critical value of H c which we have discussed earlier. So, below H c m equal to or the magnetization is proportional to the magnetic field, but with a negative sign. That means, it has a complete exclusion of the magnetic lines of force. The susceptibility is absolutely minus 1. So, it remains superconductor. Therefore, it increases exactly proportional or exactly equal to the value of the magnetic field. At certain point, it becomes 0. So, at H c, there is a critical magnetic field. Suddenly the susceptibility becomes 0. So, from minus 1, its susceptibility drops to 0 or the magnetization which was equal to H, suddenly minus H actually equal to 0. So, there is a certain drop. So, once again just like T c, there is a transition.

So far, as the behavior of the material is concerned at low field, it is superconductor whereas, at high field, it is non-superconductor normal material. So, once again there is a transition, very soft transition takes place. It is not a gradual transition in this magnetic field, it is superconductor. Of course, these kind of plots can be drawn at different temperatures. These values will be different, but they will be always below T c. There will always be a H c critical magnetic field below which becomes superconductor, above which it is non-superconductor. So, this is what we call the type I superconductor, the kind of behavior actually characterizes this particular type. That means, there is a sudden fall of magnetization or the characteristics of the material and exactly at T H c, there is a sudden change of superconducting non-superconducting. There is another group of material and these are primarily absorbed in the whole range of different low-temperature superconductors which we have discussed.

So, in the low-temperature superconductor, this is another variety. In this case, it is not a sudden change like this, but a more of gradual change takes place and finally, of course it becomes normal. So, there is a superconducting state at low magnetic field under the high magnetic field in one non-superconducting state, but in between is a kind of dual phase region what we call a vortex region. So, in this region, magnetic field, there is slowly penetration of the lines of force. So, there is a gradual penetration of flux lines or magnetic lines of force gradually starts penetrating H a into the material and there is gradual change of magnetization.

So, unlike here, there is a sudden change from a high-value. Suddenly, it drops to 0 whereas, in this case, in type II superconductors, they do not suddenly change. If it is a type I superconductor, you would have followed like this line and then, suddenly H c, but this does not happen. That is why it is given doted. So, this does not happen. It happens only in type I whereas, in type II, this particular phenomenon does not happen. Instead, it follows this curve or the straight line. So, this is again a straight line behavior and if you have a superconducting phase, non-superconducting, purely superconducting phase, purely non-superconducting phase and then, this is a mixed phase.

This is basically a dual phase in terms of phase diagram kind of thing. So, there is this particular area, this particular region between this value of h, this value of magnetic field and this value of magnetic field is called vortex region. So, gradual penetration of the magnetic line of force or flux line, do gradually penetrate to the material. As a result, you have two different critical magnetic fields instead of one critical magnetic field called H c. Here you have two different critical fields. One, where the penetration starts and the magnetization drops from minus 1. So, this is called, lower one is called the H c 1 and I am sorry.

I think there is a mistake. It should be H c 2. This should be H c 2. This is not H c 1. This is H c 1 and this is H c 2. So, there are two critical magnetic field here. One is H c 1, another is H c 2 whereas, in type I, there is only one magnetic field. This mathematical represents equation has been plotted here like this or describe here, M becomes minus H when H equal to H c 1. So, H c 1 is when this is their the same equation is valid equal to minus H. If it is between H c 1 and H c 2, this becomes M i. This is not H. It is a different value of H. So, it has a gradual change with the slope. The slope is to be increased, has to be introduced. So, H is a function of H c 1 and H c 2 and then, if it is beyond H c 2, actually if it becomes H c greater than H c 2, then it is 0 here. It is beyond H c, it becomes 0.

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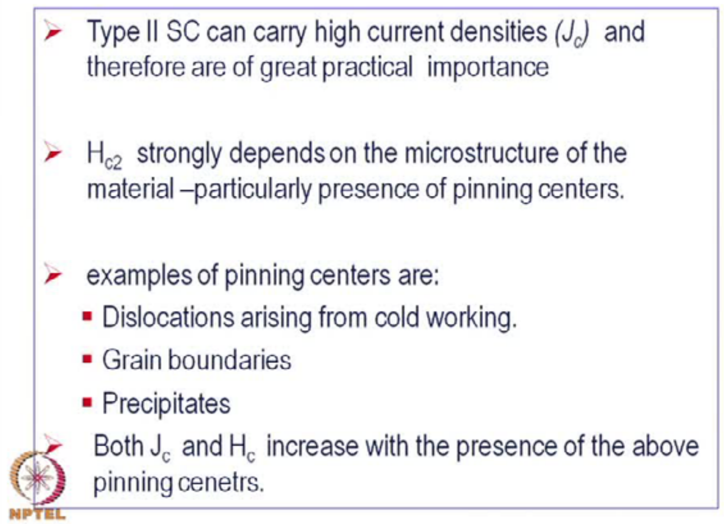

So, these are the reasons. These are the inter comp reasons between the two types of superconductors. In fact, this is not type I. Again, this is type II. This part is looks like type I, but the whole is type II. In fact, it should be corrected is type II. The behavior here that of type II, not type I. Type I is this one and type II is this to this one. So, these are the distinction between type I and type II superconductors.

Let me see, what is next? Well, there are some characteristics of type II. In fact, type II superconductors are more useful from practical point of view because type II superconductors can carry much higher current densities and therefore, are more useful for practical applications and they can be modified also to some extent. So, because there is a sudden change, the type I superconductors are not preferred. Type II superconductors are preferred because there is a gradual change. So, there is no catastrophic failure. Even if the local magnetic field or local J c, the critical current increases for some reason. There should not been a catastrophic failure in type II. The catastrophic failure is less, chances of catastrophic failure is less and therefore, type II superconductors are more preferred. Not only that the current density is relatively high, H c 2 strongly depends on the microstructure of the material.

So, once you refer to the earlier picture, this value is not a fixed value for any particular compound or element. It depends on many extrinsic properties of the material. So, one can modify, one can manipulate this carve, either it can be here or it can be there. So, this manipulation can be possible with type II superconductors whereas, that kind of manipulation is not possible with type I super conductors. So, this H c II strongly depends on the microstructure of the material, particularly the presence of pealing centers as you have said between H c 1 and H c 2, the lines of magnetic lines of force starts penetrating.

Now, it is the repulsive action which actually retention superconducting property. So, if you can avoid penetration of the lines of force through the material, then the H c 2 will increase. Therefore, if you can modify the microstructure and design the microstructure in such a way that you do not allow the penetration to take place, magnetic lines of force to cross through the material, then there is a possibility that H c II, both H c and H c II and J c can be increased. So, by control of the microstructure of the material are the property is the intrinsic property, but extrinsically, the materials can be modified. So, the examples of pealing centers for the magnetic lines of force like this dislocation arising from cold working particularly from metallic materials or intermetallic materials are some amount of is not so brittle, but in general, intermetallic materials are quite brittle. So, you cannot generate too much of plastic deformation.

However, in elements, one can introduced lot of plastic deformation and plastic deformations means, we have seen earlier. It is basically the introduction of dislocations. So, by introducing of plastic deformation or cold working material shows that more and more dislocations can generate and then, dislocations can act as appealing centers. So, it actually obstruct the penetration of the magnetic lines of force and thereby increases the H c 2 value, the critical value. So, it becomes more useful as similarly we have large number of grains. So, in between the grains of grain boundaries, those grain boundaries can also act as pealing centers.

It actually helps in micro pealing the lines of force and therefore, the penetration becomes difficult. Then, you have precipitates like fine precipitates in a metrics of one particular material. One can have a second phase precipitates and those precipitates can also act as pealing centers. So, that kind of a manipulation of the micro structures, one can increase both the H c value is C 2 in particular and then, that also increases the current carrying capacity. So, J c basically provides information what is the current carrying capacity of a particular conduct here. This is very similar to other conductors. Every conductor has a current carrying capacity beyond which it heats up so much that there is a failure, there is a structure gets disrupted. So, every material has a current carrying capacity.

So, in this case, therefore, superconductors J c is the current carrying capacity are that in other words called the critical current. So, both J c and H c can increase in the presence of above pealing centers. We will see some actual values, how they can be changed by introduction of this kind of pealing centers, right. So, the time is more or less up. So, we can finish this for the time being, and we will continue the discussion in the next class.

Thank you. Thank you for your attention.