Materials Science
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Lecture 36
Superconductors

Right, so we had been looking at the conductors and resistors which are used by Engineers for various applications.

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Now we shall look at materials which are called superconductors their resistivity is almost 0 we try to understand these materials though we have limitations we will talk about those limitations the use of these materials.

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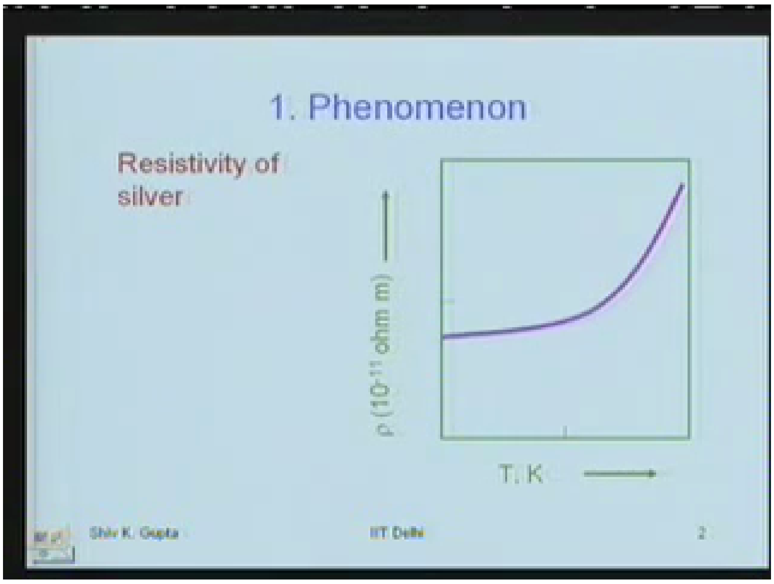

First of all I will talk about this Phenomenon of super conductivity before going to that let us look at the a very good conductor silver is one of the good conductors and how its resistivity changes as the temperature is lower and I have magnified the scale this time they are 0 kelvin this is 5 kelvin that is about 10 kelvin in a very small temperature range and this value is not 0 that is what I am trying to decay is in the range of 10 to the power minus 11 ohm meter but it is not 0 and this one of these for pure copper I showed you it was starting for almost 0 but scale was in the range of 10 to the power minus 8 or 10 to the power minus 9 ohm meter but now it is 10 to the power minus 11 ohm meter and you can see that it is not 0 still measurable as compared to what it is after about 10, 15 kelvin it is very small and that can be said to be close to 0. However it is not 0 and measurable quantity a small value minus 11 ohm meter is very important to understand.

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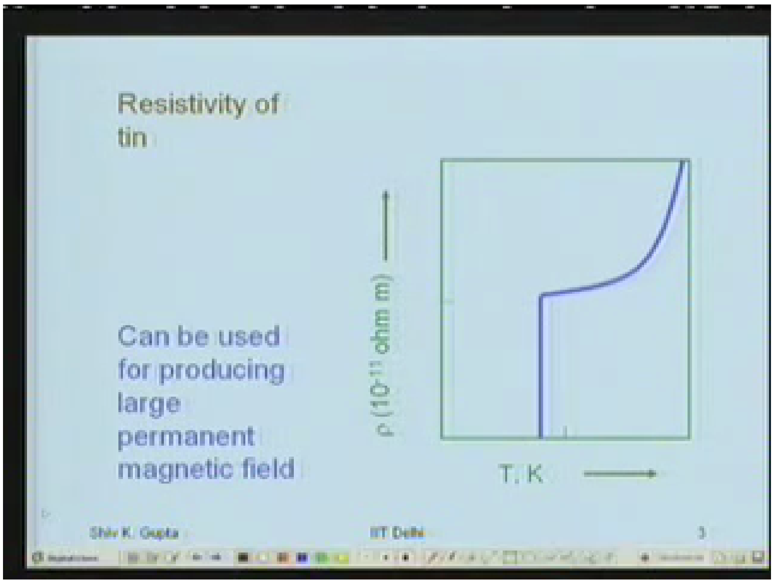

See what happens in another material which is tin here just below 5 it is about 4 kelvin the resistivity which was (())(3:16) in the range of 10 to the power minus 11 ohm meters suddenly becomes 0 once again I cannot say it is absolutely 0 for the simple reason that I have no means of measuring the resistivity below 10 to the power minus 20 ohm meter already something less than 10 to the power minus 20 ohm meter but I do not know what this value is, no instruments are available which can measure the resistivity of that nature.

So this is what I am calling 0 resistivity and this is a very small value, this is sudden drop at this temperature of about 4 kelvin which is close to boiling point of Helium. Now once you have material with such low resistivity as Engineers it comes to your mind immediately that we can use this kind of a material to produce magnets. Now if you make a coil like a solenoid and then pass the current through this it will produce a magnetic field well that is one can do and then you have to produce means the energy you have to spent is very small because resistivity is small, current once it starts to flow it will continue to flow it will not be dissipated I square R loss will be very negligible.

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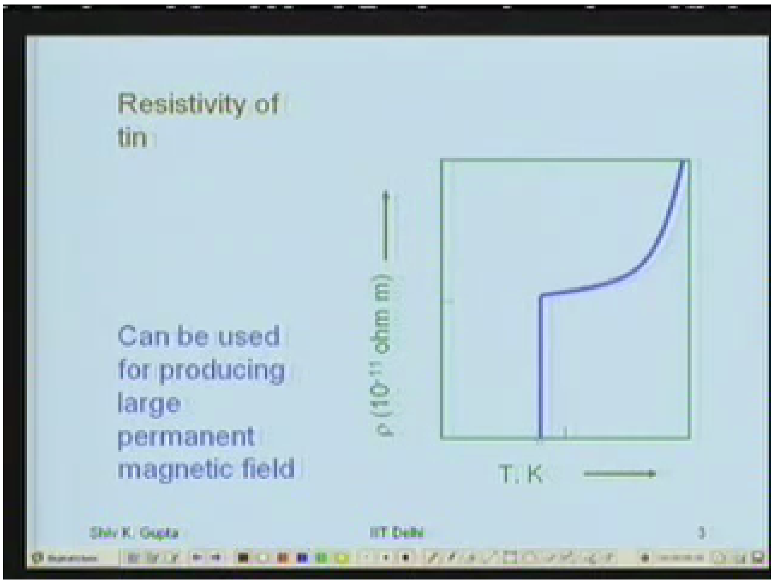

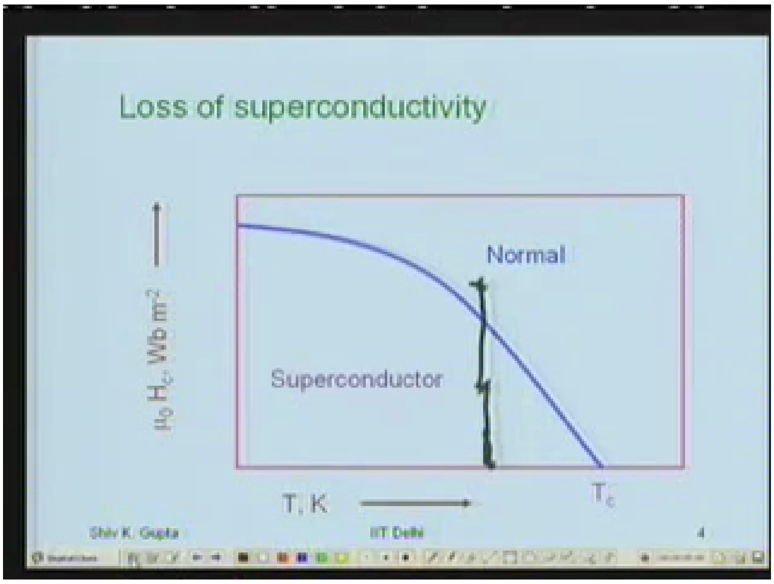

And that is what one does and if you do that one observes another problem that as the current through this solenoid or whatever magnet you are trying to make it passes losses its superconductivity that is shown here that magnetic field which is produced as effect on to the surface of the conductor as well and before when this value increases the material goes let us say I am below this temperature well I think I should define this T c because I have used it here.

This temperature where it suddenly goes to 0 or very small value is called the T c critical temperature, below this temperature material is going to behave like a superconductor and above this temperature it is going to behave like a normal conductor that is why it is called a critical temperature. Now so if I am below this temperature critical temperature at some temperature here let us say with the magnetic field produced is this much no problem it is a superconductor but if I cross this and reach a value like this it becomes a normal conductor is no more a superconductor.

That means this will depend upon how much current is flowing through the conductor, what is the capacity of the superconductor to carry the current, how much current per unit area of cross section it can carry is called the current density the critical current density is when it turns into a normal conductor which I show you again in the form of a critical current density flowing through the superconducting material.

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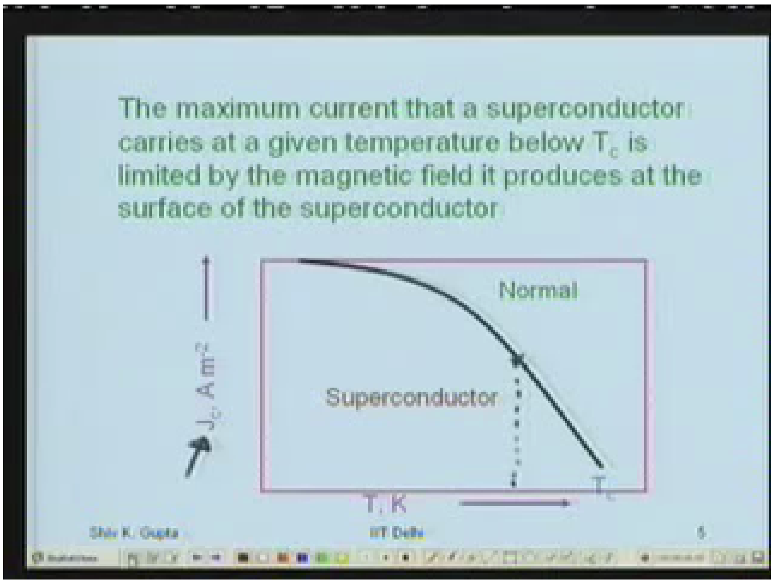

Same thing I have shown here here rather than the magnetic field produced here the current density critical current density c stands for critical and that is the critical value at this temperature that if the current flows from more than that it becomes a normal conductor and current remains less than that it is a superconductor.

So they causes a limitations on the current carrying capacity of this material all which means normal conductor if I that much current flows through this the magnetic field will be so produced that the material would have become normal conductor and we would not show the superconductivity means the resistivity would certainly come to a normal value in the range of 10 to the power minus 11 ohm meter it will no more be in the below 10 to the power minus 20 ohm meter, okay.

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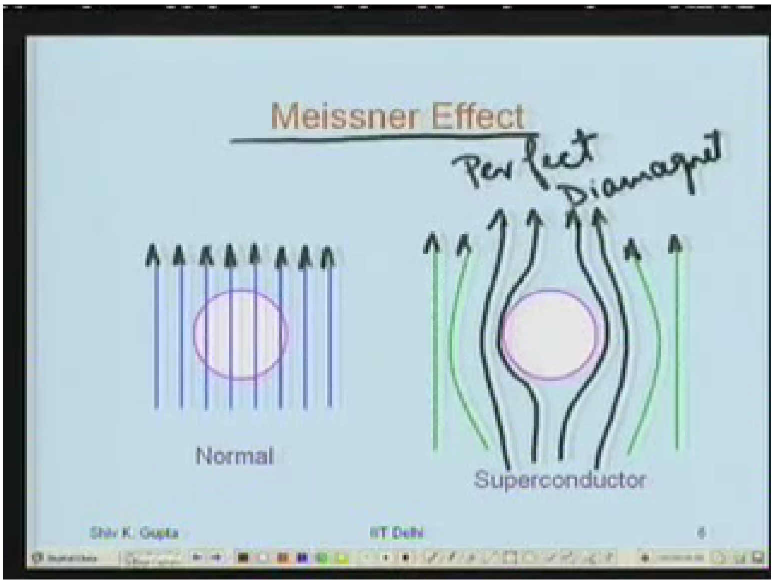

Now this is what I have talked about is the superconducting state of a material does not allow the magnetic lines of force to pass through it. However, there is always surface that is small thickness of the material where does it pass through this small surface is called skin and skin could range few times of angstroms upto 100 angstrom it could be. So around that thickness field can pass through but inside field magnetic field is not passing this is what shown here.

In normal conductor magnetic lines of force pass through the conductor like this while in a superconducting state the lines of force do not pass through the material. Say for example the one which is going close by something like this the lines magnetic lines of force will pass through. So material is behaving like a typical or a perfect diamagnet it is behaving like a perfect diamagnet even diamagnetic materials are not perfect diamagnets that means the susceptibility is minus 1, okay susceptibility is minus 1.

So all line of force repel and they are not allowed to pass through the superconductor and that is what is referred to as the Meissner Effect while this is happening and our conductor the lines of force are passing through you can also show the direction because they have a direction magnetic lines of force going from north to south you can show that.

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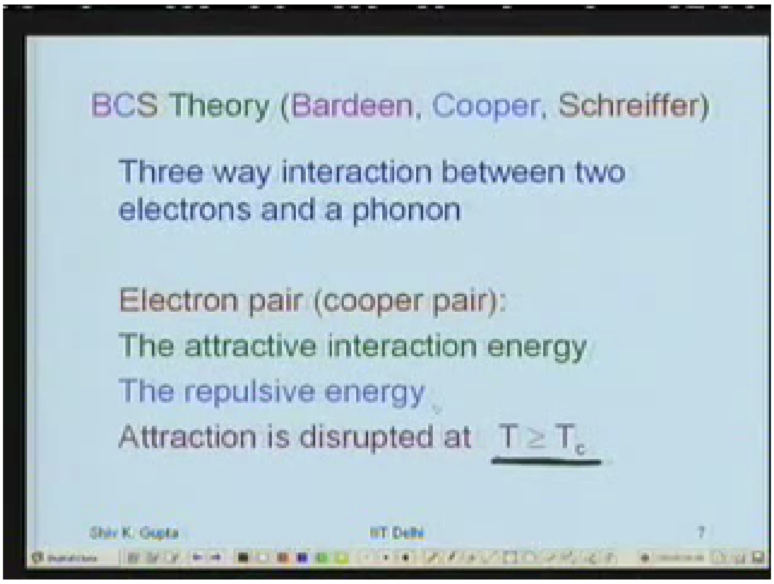

Now before we talk about the Engineering aspects of science really well we start with number of theories, why the material is behaving like this? The most accepted theory today is called BCS theory Bardeen, Cooper, Schreiffer name of the three scientist who work for it. they said that there is a three way interaction between two electrons and a phonon I am just making a very very brief and very very simple in Layman's language because the three things there is a pair form of two electrons, one with a positive spin other with a negative spin or we can say one with a positive movement other is negative momentum the pair is formed this pair is called the Cooper pair and this pair is attracted by the positive ion cores which are oscillating about their mean position a temperature get at 0 kelven they are oscillating.

So there is an attractive force because of this positive ion core and there is repulsion between these electrons because being the same charge. So the three things that there will be three way interaction interaction between electron 1 and electron 2 in the pair this is repulsive, electron 1 and the positive ion core attractive electron 2 and the positive ion core which is also attractive.

So this three way interaction is maintaining these two electrons as a pair. In other words the attractive force is more than the repulsive force between the electrons in the superconducting state is a very small difference is not a very large difference small difference. However that difference maintains the two together and these electron pair is the one which keep moving.

In other words if you look at this pair as a group if there is something which is attracting the one in one direction might be doing the same applying the force in the opposite direction of the other one because direction of motion is different opposite rather. But the net effect on the couple will be 0 one force acting in the positive direction, other acting in the negative direction, net effect on the group is 0. So that pair keeps moving as if no force is applied on to that as long as they appear in the form of a pair.

So that is what is called a Cooper pair and there is an attractive interaction energy because as I said with the positive ion core and there is a repulsive energy between them and attraction gets disrupted when temperature exceeds the critical temperature these are low temperatures that means I am talking about the low thermal energy which is disrupting this.

So that is what I said the difference between attraction, repulsion is very small but attraction is more than the repulsion while that is what is happening and this is I can summarize in simple words what the BCS theory is about, about T c the repulsion between the electrons is more than the attraction of the the positive ion cores now because they are also now oscillating with more vigorous nature you know and therefore they are not able to put the same effect on the two electrons what they were doing at a lower temperature.

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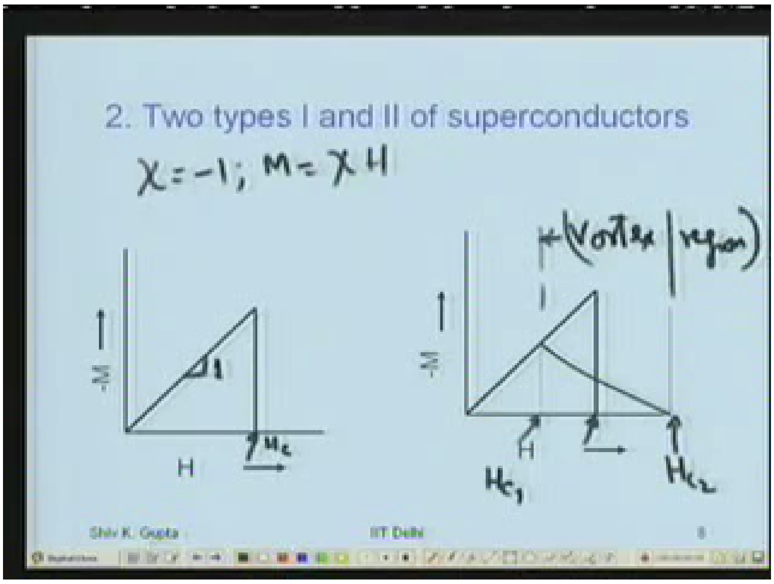

Now there are second thing about this phenomenon which I want to say is there are two types of superconductors one is called type 1 where I said there is a perfect diamagnet which susceptibility being minus 1, so M which is equal to Chi H we have plot minus M versus H slope is 1 it goes upto a critical field beyond which it becomes a normal conductor and susceptibility falls down close to 0 even if it is a dialectic material which is not going to be minus 1 its perfect diamagnet only in the superconducting state. So it comes to a very small value maybe minus 1 10 to the power minus 3 or minus 5, alright that is where it reaches which is close to 0 and there is a sudden drop and material becomes normal conductor it is a particular magnetic field.

But the second kind of superconductor which is called pair to superconductors where instead of this happening at a critical field like in the type 1 the process of becoming normal takes place over a range of magnetic field it does not take place at a single magnetic field value. So that is what is called the lower critical field we call it H c 1, upper critical field we call it H c 2.

Between H c 1 and H c 2 is called the vertex region and here this is how the a susceptibility is decreasing you know it starts to decrease from 1 goes down down down down and reaches almost 0 value at upper critical field. Between critical field 1 and between critical field 2 material is still going to behave like a superconductor, what is happening is magnetic lines of field are going through the material slowly.

In other words there is a volume of the material which is allowing the magnetic lines of force to pass through it is another volume which is not allowing it to pass through it and this volume is decreasing slowly as a critical or as a magnetic field is increasing this keeps on decreasing. It is the situation you can consider as two conductors in parallel one is a good conductor, other is a poor conductor what shall be the resistivity of such a material such a combination?

So the resistance you will obtain will be less than the resistance of the lower resistance is not it this is in parallel. So it will try continue to behave like a superconductor this material, right only thing is current carrying capacity might decrease because the volume through which the current can pass through the superconducting current can pass through is going to become smaller and smaller till you reach here.

So these and from the Engineering point of view this is the material which you can manipulate the vertex region and also the upper critical field becomes very high for such materials. Therefore, the current carrying capacity can also become very high for certain materials. H here it is in the superconducting state ya that is of course that is of course I have already said that the magnetic field produced at critical temperature small value is good enough to make a normal conductor but I am below the critical temperature I will need a higher value.

So it is always that where in a superconducting state I am below the critical temperature of the material when I am putting to use as a superconductor and that is some temperature we are talking about, no we cannot do that. So this is critical temperature we are below the what we are talking about is below the critical temperature whatever the critical temperature of the material that is a material property we will come to that we will talk about it.

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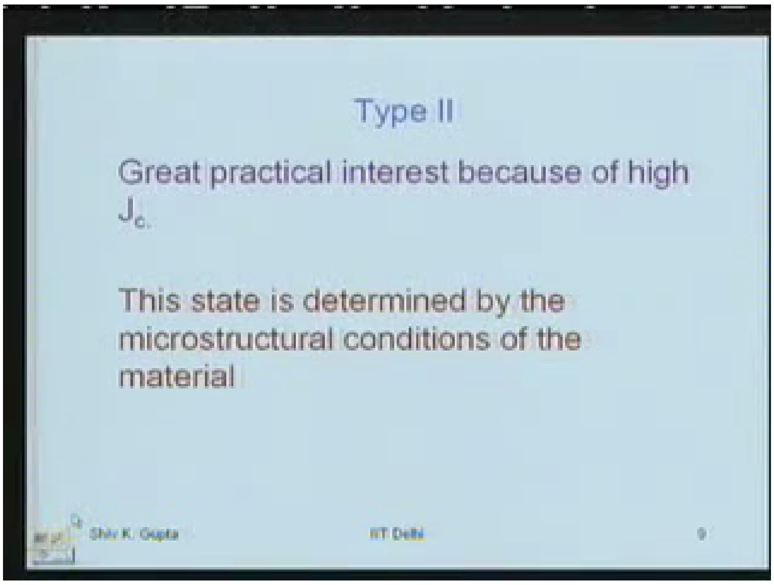

This is a type 2 superconductor is of great practical interest because of its ability to carry high current density or carry higher currents, yes yes they can lose below T c they can lose their superconductivity nature that is what I showed you with the how much current it can pass through the conductor or what magnetic field you put it in you know that they can make it normal conductor that can happen, yes even that T c small current passes through it makes it a magnet yes it will lose yes so only below T c that you can use it as a superconductor.

Now here the practical importance for Engineers is that I can manipulate microstructure at this condition of the vertex region is decided by the microstructure of the material, right.

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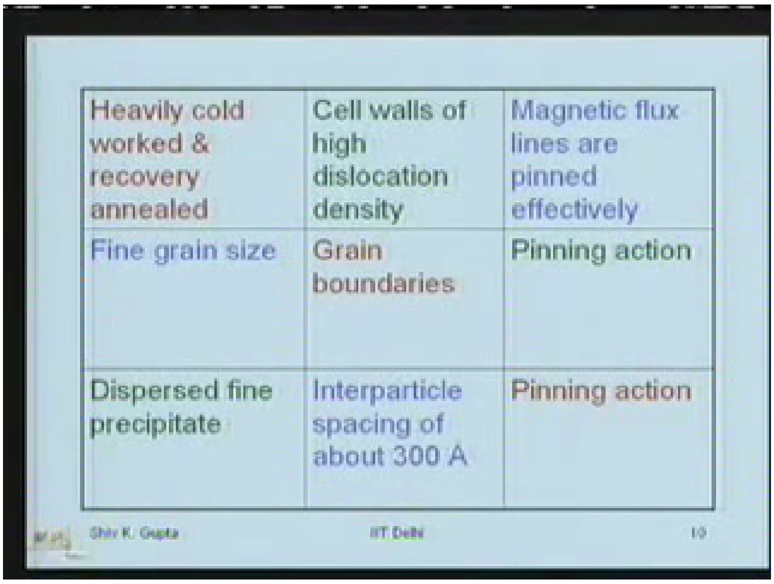

Heavily cold worked & recovery annealed	Cell walls of high dislocation density	Magnetic flux lines are pinned effectively
Fine grain size	Grain boundaries	Pinning action
Dispersed fine precipitate	Interparticle spacing of about 300 A	Pinning action

And microstructure how we manipulate that I have already explained in this course but let us see what are the features which can allow or not allow the lines of force to pass through the material. In a heavily cold worked and recovery annealed material what is structure? Heavily cold worked means high dislocation density when I do the recovery annealing only the dislocations of the opposite sign lying on the same slip plane they come close and get lost as a result I am left with mostly all dislocation of the same sign and they form the low angle boundaries like tilt boundary and the twist boundaries.

This tilt boundary and the twist boundaries within the same grain are really sub grain boundaries and they form the cells what I call cells the sub grain boundaries of this cell walls cell walls of high dislocation density are produced by this treatment and these cell walls stop the magnetic flux do not allow the magnetic flux to pass through they pin it down and therefore the lines cannot pass through the material from one end to the other they stop it, right and that is why it makes the vertex general little longer.

Similarly if we after recovery annealed we just recrystallized it produce a very fine grain size just recrystallized I have lot of grain boundaries and these grain boundaries also have the same also have the same effect that pin down the (())(23:00) lines of field or magnetic lines passing through the material are stopped they are called pinning down they pin down and they cannot go across the material.

Similarly if in a material (())(23:17) matrix I can produce very fine dispersed precipitate which will not dissolve with time or temperature it will stay there in the material but the size of the particle should be a few 100 angstrom not more as stated here about 300 angstrom then it can also pin down the magnetic flux lines and this magnetic field will not be able to pass through the material if I have precipitates with small spacing between them you notice that here both the grain boundaries, the cell walls which are the also the grain boundaries are the precipitate which are so fine and dispersed the spacing is about 300 angstrom are going to strengthen the material.

These strengthening mechanisms are also working to increase the upper critical field the vertex region is expanded so this strengthening mechanisms in materials of this nature are also going to increase the superconducting behaviour of the material improve this means they are giving me upper higher critical field that is vertex region is becoming more. No if the magnetic lines are field at a value x is not able to pass through because of these features if these features are not there it will pass through at x but when the features are present x plus delta x is required so that C 2 has become more what can go through is not it that is what it is.

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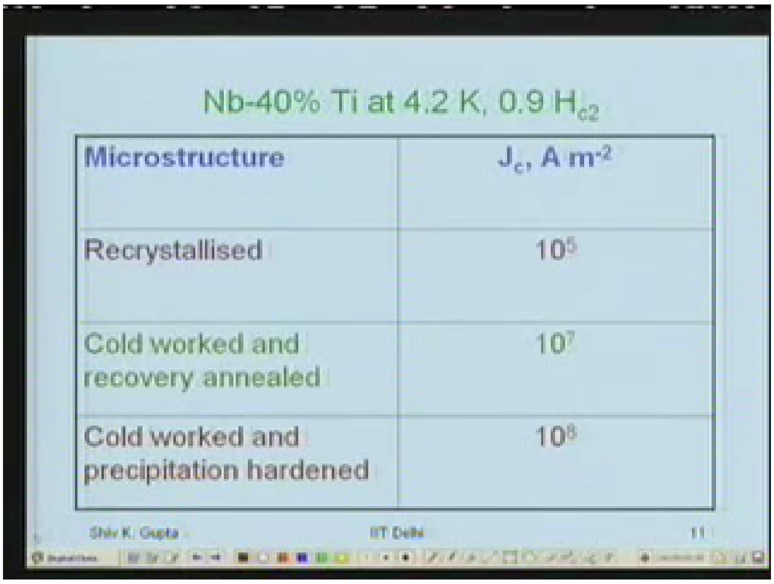
Nb-40% Ti at 4.2 K, 0.9 H_{c2}

Microstructure	J_c, A m^{-2}
Recrystallised	10^5
Cold worked and recovery annealed	10^7
Cold worked and precipitation hardened	10^8

Now here just I give an example of what was tried in an alloy of Niobium having 40 percent titanium in it at temperature of 4.2 kelvin which is just the boiling point of liquid helium and it is about the magnetic field which is applied is almost 90 percent of the upper critical field in that situation what is the current carrying capacity of these materials? She was asking so what happens when I am at the critical field almost no current can pass through yes so I have taken it 90 percent of the critical field some current can pass through and what is that value the current you can see that?

In the recrystallized state when I have just a fine-grained boundaries I have very fine grains 10 to the power 5 ampere per square meter is the current which can pass through this is the critical current density that means if I pass more than this it will become a normal conductor, less that this it is a superconductor. Cold worked and recovery annealed we have cell walls I have the fine cells formed within the grain, okay it is about 10 to the power 7 factors of magnitude two orders of magnitude difference between this and this.

And cold worked and precipitation hardened is 10 to the power 8 another order of magnitude increase so if this is can be done in Niobium titanium upper critical field is basically the current carrying capacity has gone up, ya it will be it will be only like that only because between Hc1 and Hc2 it is still a superconductor ya that will be for Hc2 ya.

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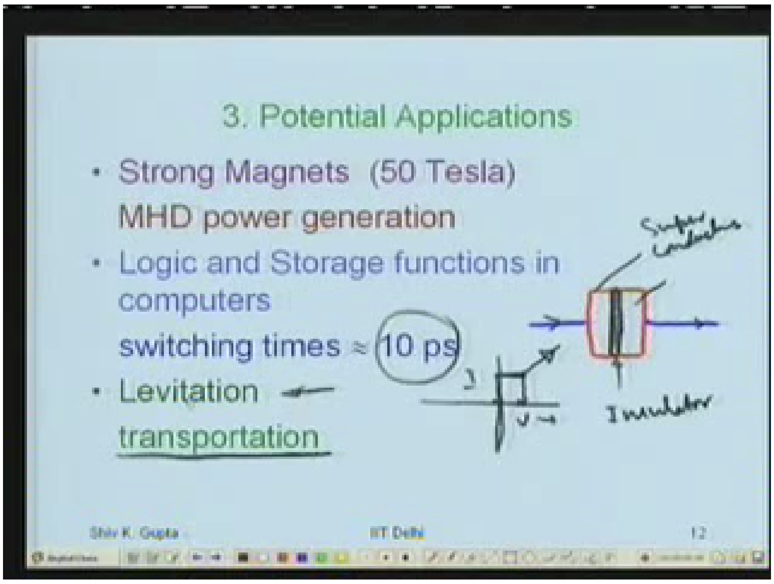

Third aspect of this phenomenon is I have talked I am going to talk about the potential application not the applications because we are not able to put them to use so far because certain constraints those constraints we will talk about. It is possible to produce strong magnets using this because they can carry high currents and the magnetic fields produced of the order of 50 Tesla the what is called the magnetic field intensity and this can be used in Magneto Hydro Dynamic power generation.

The effect of this is going to be using as using a copper which we use for reducing the power use turbine and you have make the coil of copper let it rotate and when it rotates it produces magnetic field and the magnetic field current flows through this and all that kind of thing or else you like to make a transformer allow the current to pass through the coil and produces a magnetic field then you can take it to the secondary and from the secondary you can take it you can step up, step down whatever you want to do.

This kind of there is going to be some resistance or resistivity of the copper I square R heat loss is there and one has to use lot of water to cool this coil so the coil does not melt or does not oxidize so we keep it cool lot of water is required to be used for cooling this copper wire, it should be in a few kilo litres may be per hour or something you have to use but this value comes down because I square R loss becomes very small R is very small for superconductors and that heat loss is less and therefore you have to do less cooling you do not require big water pumps to let the water flow through the tubes and the cooling coils that is not require that is an advantage and you can if we are in a position to have a material which can be used for this it can be done.

It can be used for logic and storage functions in computers because the switching times could be as small as 10 picosecond a small let us say application we can put it is this is an insulator very thin layer and this is are the two superconducting materials very thin layer may be in the range of 10's of angstroms let us say call I think Josephson junction and once the conductivity means current begins to flow its main insulator this layer has been made so thin that electrons which pass through this superconductor before they can collide and fall down they cross this region and go into the other region and it keep flowing this kind of the material but this current should be a certain value for less than that it is not able to so if the behaviour would be something like this.

For current let us say apply the voltage, this is the current for the current value upto this nothing happens or the voltage you applied this but beyond that it behaves like this. So when you reduce this voltage which you applied at this this current will keep flowing because it is superconducting current I will come down to 0 only when you completely reduce the voltage. So it is working like a switch at this voltage just working like a switch that is what I said and the switching timings can be as small as 10 picosecond that is 10 to the power minus 11 seconds.

And I told you that even this is more than the mean collision time in conductors what we talked about is of the order of 10 to the power minus 13 second even this is more, 10 to the power minus 11 stands hundred times more than that, right but you cannot have better than that. This is possible to have this application of the superconducting material but I should be able to have superconductors which can work at the temperature where I am using them.

Then another kind of application is Levitation we produce a magnetic field and any object which you put there (())(33:32) material the magnetic field it will be floating that is what is called Levitation and that can be exploit it in transportation high speed trains the bullet train you have heard of that kind of application it can be put to train would be floating over the magnetic field only when you have stopped the magnetic field it will only fall down so it can travel at very fast speeds but that kind of Levitation is required at the temperature we are working ambient temperature while that is the restriction which we have only the application of these materials.

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Then it is also possible for me to use it for long distance transmission (())(34:15) and I square R loss will be almost nil, alright.

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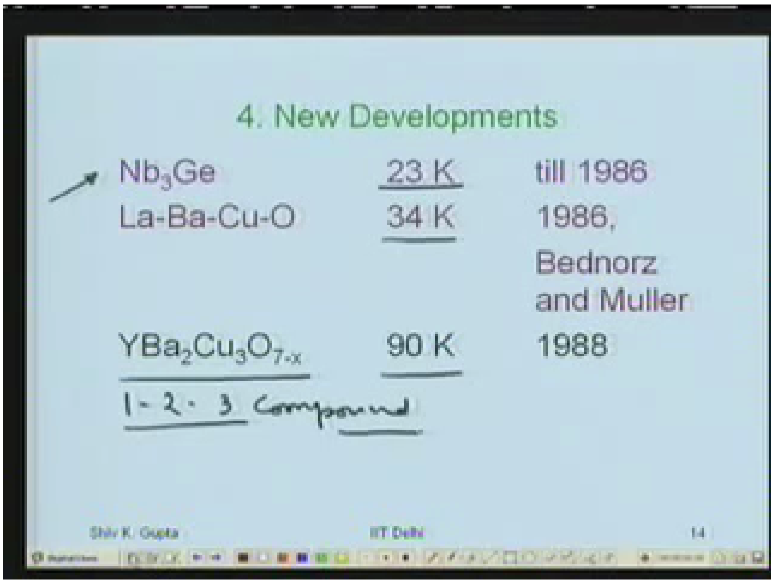

We will have a problem of temperature that is what I am going to show here where we can use it one of the material which we know I showed in example on Niobium titanium alloy, it is a Niobium germanium alloy give us the critical temperature 23 kelvin this was our knowledge till 1986 of course I showed you the first one tin which was at 4, kelvin this is 23 kelvin.

Then in 1986 oxides which are normally supposed to be insulators Lanthanum Barium Copper Oxide produce 34 kelvin it is a noble price winning discovery, okay that is a great jump from 23 kelvin to 34 kelvin but then in 2 years time came another material which is called 1-2-3 compound of course we have number of such compounds similar compounds here the critical temperature is 90 kelvin and this is a kind of a breakthrough we have come down from boiling temperature of the liquid helium to the boiling temperature of the liquid nitrogen, okay which is about 78, 90 is higher than that, okay.

So we have come down to this temperature of 90 kelvin and Yttrium Barium Copper Oxide is called I said 1-2-3 because Yttrium is only 1, Barium are 2 and Copper are 3 why it is called 1-2-3 compound, oxides have their own problem but if it is there 90 kelvin liquid nitrogen can be made available in abundance and probably can be used.

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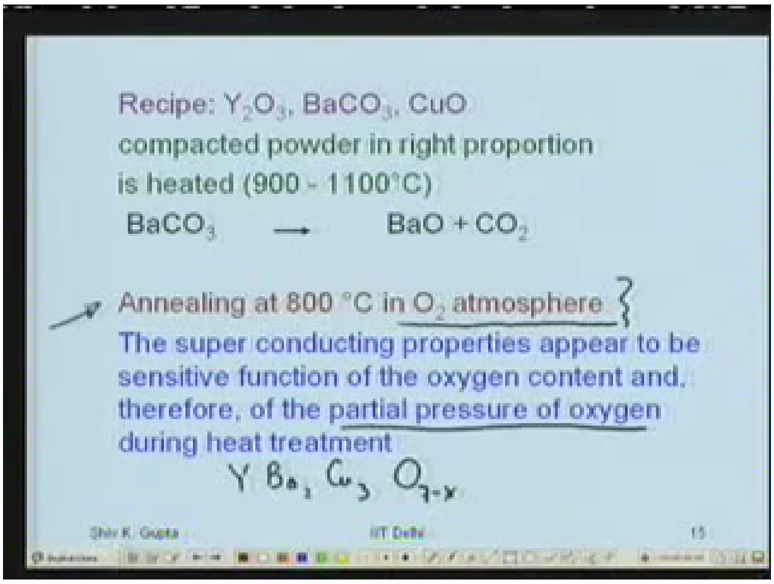

Let us see what are this 1-2-3 compound how do we make it and what is its structure and how can I use it, well the recipe for making Yttrium Barium compound the number of things which are patents and therefore they are not available still by enlarge you need Yttrium oxide Y 2 O 3 like Al 2 O 3, Barium carbonite and copper oxide you have to mix them in the right proportion in the form of powder compact them and heat it between 900 and 1100 degree centigrade I do not know what exact temperature it is. Barium carbonate decomposes in this temperature range to form Barium oxide and Carbon di Oxide. So because I do not want Carbon di here I need Oxygen, Nitrogen, Barium and Copper so this is Carbon di Oxide goes away.

Then it is annealed at 800 degree centigrade it mind it and underscore it Oxygen atmosphere partial pressure of oxygen is a must what is that value I do not know that is necessary for it to happen then it is annealed at that temperature the sintering causes and the coming to the right composition takes place. Now this superconducting property in this material this oxide which is made seems to be very sensitive function of the oxygen content.

And therefore of the partial pressure of oxygen during heat treatment that is the heat treatment I am referring to annealing at 800 degree centigrade from there it is taken to the room temperature very rapidly and kept there and you can use it below room temperature as superconductor so this is what is important the partial pressure of oxygen and you will recall that why I said was the composition of this is Yttrium Barium 2 Copper 3 Oxygen I said 7 minus X X is a fraction X is a small fraction so Oxygen is less than 7 but from here you would notice that you would get more Oxygen then you need. So that is partial pressure of oxygen is required to maintain the correct composition which is superconducting in nature.

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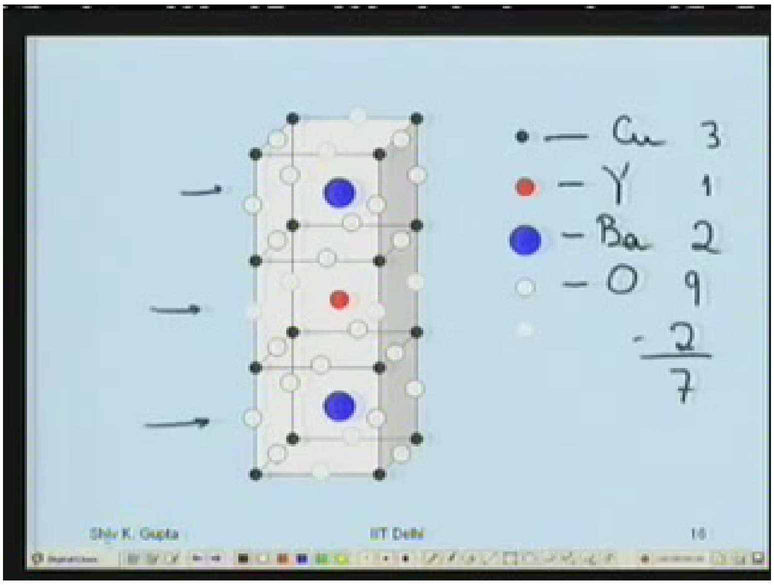

This is the crystal structure this crystal structure I am showing as is actually orthorhombic to be very frank with you A is different from B and C is very long but A and B are not very different so just to show you this I have made the unit cell I has composed of 3 cubes sees about 3 times of A and B, A and B are slightly different from each other but it is orthorhombic really speaking.

So here I have in this one cube consider any cube for that matter there are 3 cubes, cube number 1, cube number 2 and cube number 3. I have the positions the eight corners of the cube each cube, I have the locations the body centre of the cube, I have the location which are the edge centres of the cube I am not using any face centre, right this is copper which is at each corner each corner of a cell cubic cell which I am showing gives you effectively 1, I have seen there are 3 cubes 1, 2, 3 so 3 copper Yttrium Barium Copper oxide 1,2,3 I need 3 they are 3, alright.

This is Yttrium the centre body centre of the middle cube is only 1 among 3 there is only 1, so this I have got 3 this I have got 1 this is Barium body centres of the 2 cubes other 2 cubes where Yttrium is there other than that Barium Barium so there are 2 of them in 1-2-3 Yttrium Barium Copper 1-2-3 agaya now we will see the oxygen all the edge centres are oxygen if all the edge centres are oxygen what happens in a cube each edge centre gives you what? 1 by 4 and that 12 such edges they give me 3 and 3 cubes like this 9 so I get 9 I need 7 minus X if I take the Yttrium Barium Copper Oxide there should be oxygen should be 7 needs 7 minus X.

So what happens is these are the location like it is 1 and 2 here than in this 1, 2, 3 and 4 here and this again 1 and 2 these locations do not have oxygen I made this dotted these locations do not have oxygen how may are these locations 4 and 4, 8 by 4 makes it 2, so 2 of the oxygen are not there so that makes it 9 minus 2 7 oxygen so the location is used that 2 of them here, 4 in the middle here, 4 here then this is none here than the 4 here, the 4 there and the 2 here those are the locations for the oxygen used.

But in this unit cell which is the orthorhombic unit cell oxygen you will find this is the edge centre, this is an edge centre but on this edge long edge you have 2 of them one here, one there one here, one there as you see one here, one there, right and if you look at this axis this axis you have in this face in the middle of the face these 2 locations same way at the back I see. So these are the locations of the oxygen which makes it 7 but I need 7 minus X, X is a fraction some of this oxygen should not be there they should be providing vacant space or vacant location for oxygen. You will find that there is enough space for oxygen to be sitting there but those are not utilized by oxygen. So this is the crystal structure of the 1-2-3 compound.

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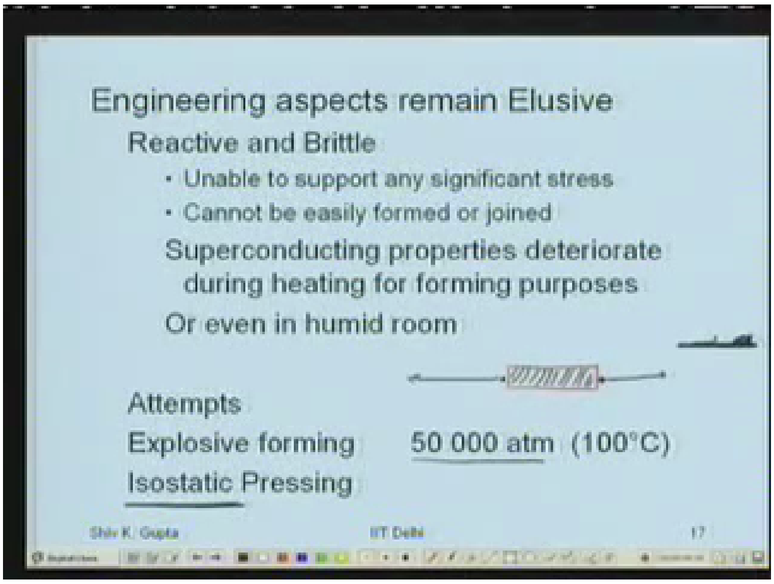

Now why we are not knowing all this having the material Yttrium Barium Copper Oxide we are not able to exploit even we cannot use it even for small simple application what talk about the transmission (())(44:52) the long cables to carry the current over miles and miles of distance this is because these oxides are very reactive and very brittle materials. It is brittle it is able to support any significant stress on it that is the brittle is within the elastic region it fails and its formability is very poor joining is still more difficult.

After all when this conductor has to be connected to something you use copper wire how do we connect it with the copper wire means joining is not easy, how to solder it will be the oxide, how to graze it with that oxide is difficult. So forming giving it the shape the oxide in the form of a wire or let us say if you are making switches some kind of strips forming is difficult because it is a brittle material (())(46:01) to deform plastically.

Secondly what we find is it is a reactive material superconducting properties deteriorate during heating which I may do for forming applications sometimes during forming the heat which is generated you know that and crystalline solid is deformed, dislocations move any dislocation comes out to the surface energy is lost this energy is shown up by the material as heat, its temperature of the material rises you do not believe me take a piece of ion may be ion nail heated with the hammer few times touch the nail you will find that has become hot because the dislocation which goes out to the surface losses that energy may be square by 2 per unit length of the dislocation line and that energy is goes waste as heat and that is material absorbs that heat and temperature rises.

So that heat which is generated during the forming operation or which is sometime required if you want to do it at a little alleviative temperature deteriorates the properties superconducting properties may not be superconducting at all that is very important. So reactive that even in a room with small humidity oxide lose all its character as a superconducting material small absorption of height water the oxide the humid atmosphere will make it a insulator which is which it is insulates oxides are all insulators and it is not a superconducting material at all.

Now we have it is not that we are keeping idle we have realized this material how do we go about using this material to the number of attempts have been made and some attempts have been made very successfully one of them is the explosive forming in explosive forming pressures of the order of 50000 atmosphere are generated and this is done in such a sudden manner the temperature rise is not more than 100 degree centigrade temperature does not rise explosivities so it is done in a very sudden manner.

And these stresses in the material are generated because of the explosion that shock waves created and this shock waves produce this stresses inside the material do that then what is possible is you can attempt it, this is the copper casing in the copper casing you fill your superconducting powder or oxide material and put in a chamber where you do the explosion because the pressure generated this will get compacted and the copper casing get joined automatically to this oxides.

Now outside you can put your conductor wires because copper you can join with the copper wire with the help of solder and when you do the soldering again the temperature does not rise it is beyond 183 degree centigrade you know that is the detecting temperature you may go about (())(50:01) degree or too more about that and then the material can be joined and can be used as a part of a circuit that is attempt has been made and this has been successful thin copper casing and material inside so gets automatically during that pressure that kind of pressure.

And similar thing can be done with Isostatic pressing it is not explosive forming but isostatic pressing, isostatic means it is the pressure is same in all directions like what you have in let us say liquid medium at any point you will find the pressure to be same in all directions that (())(50:50) is done and when the forming is done the isostatic pressing similar effects are produced like in the explosive forming, okay and it is possible for us to not only once I encase it in copper the it is got joint to the copper automatically, secondly I am avoiding its coming in contact with the normal atmosphere the ambience.

So it is unable to come in contact with the ambience that means the humidity is not going to affect it because it is encase already in a some kind of a copper shell has been encased and it is not in contact with the atmosphere at all. So that is kind of thing I have been tried but it has to be exploited for applications which require a large amount of this material in the form of wire, in the form of strips and so it is a conduction effect can be or the conducting component can be made out of this material, right so these are the limitations with which we are still working and we hope that soon we are able to come up with something which can be used at room temperature without requiring the use of liquid nitrogen.