Materials Science

Professor S.K. Gupta
Department of Applied Mechanics
Indian Institute of Technology Delhi

Lecture 35

Conductors and Resistors (Continued)

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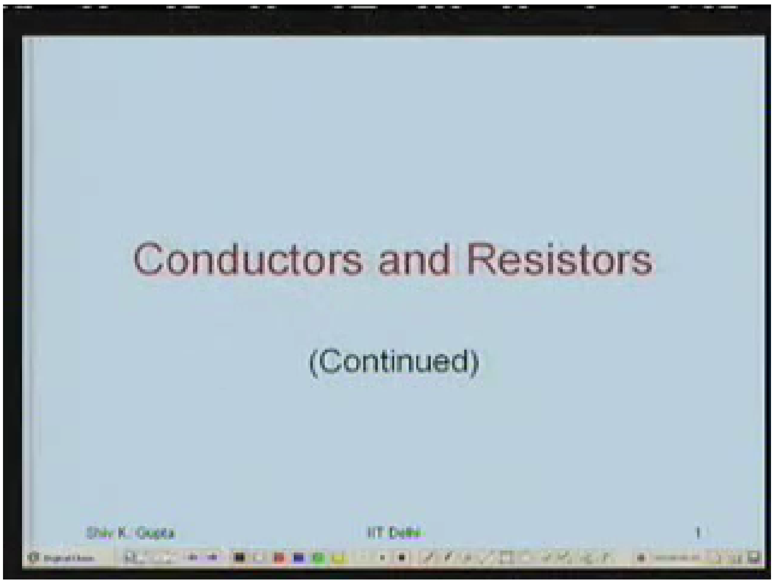

Well in the last class we were talking about the conductivity in metals and alloys what we call conductors and resistors, okay.

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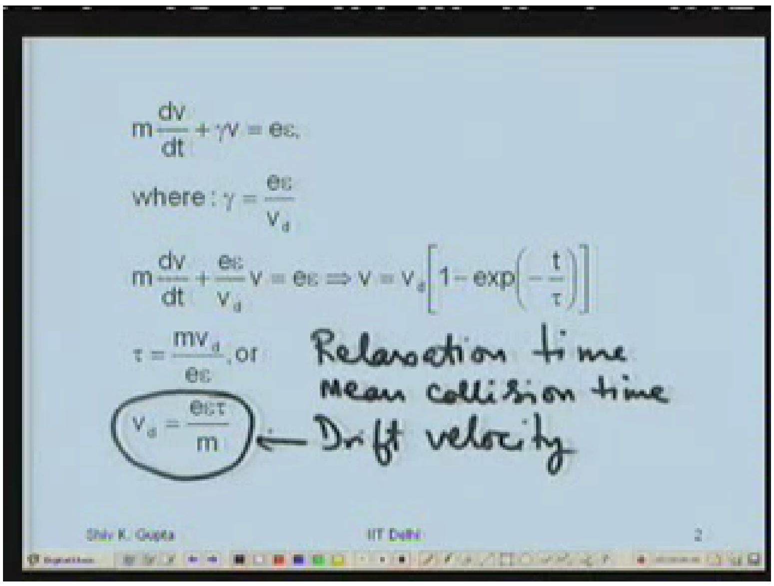

And we looked at the free electrons or free electron gas and we said that the motion of electrons can be (())(1:40) by Newton's Law, force is equal to mass into acceleration, force applied is the electric field applied onto the charge for the electron and mass into acceleration is this term but then we said that when we switch it on there is a constant current current does not continue increasing there is no acceleration going on.

So there must be a frictional force that is what we said is proportional to the velocity of the electrons and we said that in the steady state situation the acceleration is 0 so therefore gamma v is equal to this and we can get gamma value is equal to the where the velocity is the steady state velocity what we call the drift velocity or the average velocity of the electrons. Substitute that we have found the solution so this can be written as in the form of v equal to v d multiplied by 1 minus exponential of minus t by Tau, where Tau is m into v d divided by e epsilon which is called the relaxation time or the mean collision time or you can rewrite the whole thing again and call this the drift velocity or the average velocity.

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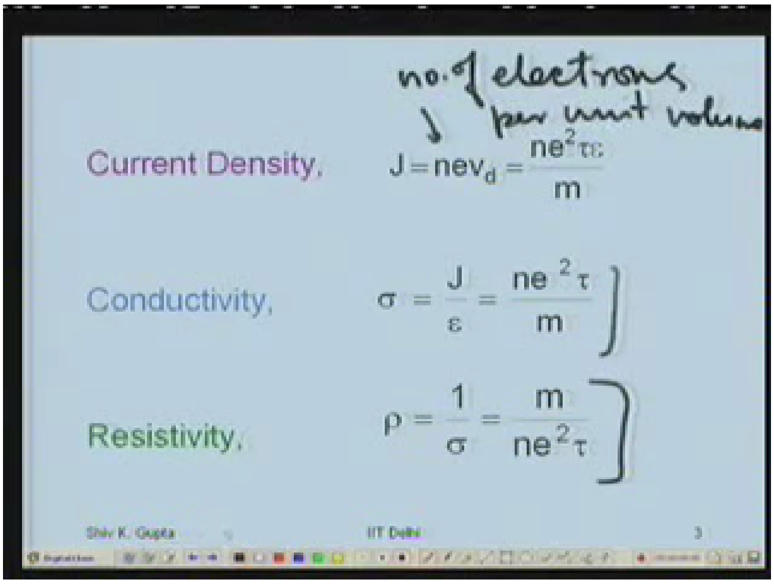

Now next is only some definitions which you have already used in physics rewrite that density of the current in these conductors called the current per unit area is given by J n is the number of electrons per unit volume which are travelling that means I am talking about the free electrons and e is the charge on the electron and this is the drift velocity the average velocity with which they are all travelling.

Now if I substitute the value the drift velocity which I gave in the previous formula substitute that e times epsilon times Tau divided by m it becomes ne square Tau epsilon divided by m and we define the conductivity as the current density per unit electric field applied we do that the epsilon from here can be taken on to the left hand side and it will be left this n times e square Tau by m that is the conductivity and the resistivity is defined as reciprocal of the conductivity 1 upon sigma is equal to m divided by n times e square Tau is the reciprocal of that that is the resistivity.

So these are the definitions and the terms which we shall be using resistivity and conductivity mostly the ones which we will be using and we shall use these terms or here it should be understood that n is the number of charge carriers per unit volume, okay this is charge density you can call it number of in this case electrons per unit volume and of course e is the charge and drift velocity I have already said that is the average velocity in the steady state.

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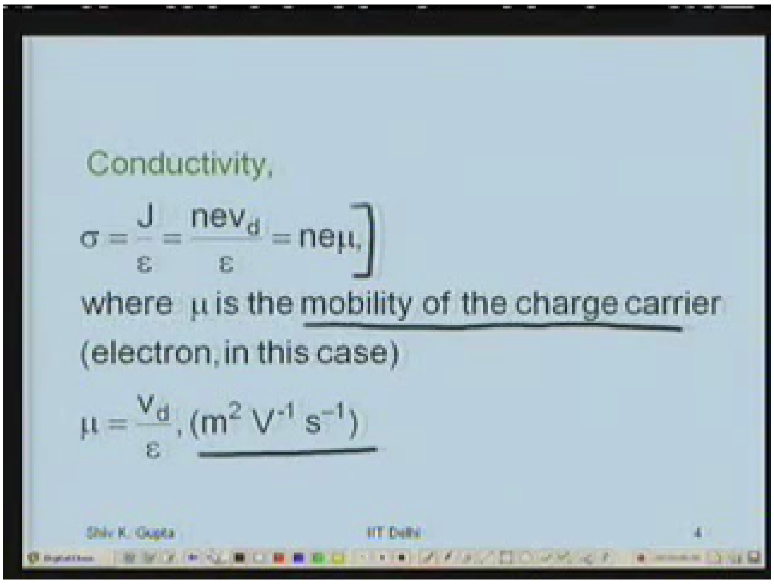

So conductivity as I just now said sigma is equal to current density per unit field and I write that as n times e times v d by epsilon, it is also written as we will be using this as n times e times Mu, where Mu is defined as the mobility of the charge carrier and you can see from here is nothing but drift velocity divided by the electric field and drift velocity is the units of meter per second, electric field or the units of volt per second, so mobility of the units of meter square per volt per second.

So conductivity can be said to be charged density multiplied by the charge multiplied by the mobility of the charge carriers in this case they are the free electrons. So in conductors they are the free electrons which are doing that and the mobility is defined like this they have sub definitions only.

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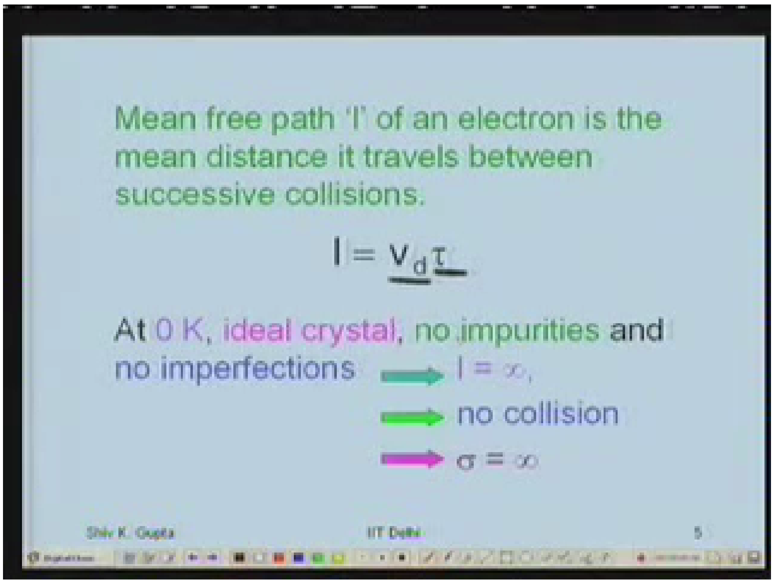

Now I come to the next term like I have since we are talking about in a cubic centimetre of the order of 10 to the power 23 electrons which are travelling or may be more than that. So I can talk only about the average things you know because some are getting accelerated, may be they get accelerated for a longer time other is getting accelerated for a shorter time and then colliding. So we can talk about only average things.

Similarly we talk about the mean field path of an electron which we say is the mean distance it travels between two successive collisions and again it is a mean one electron may be travelling 10 angstrom before colliding, another electron may be travelling 20 angstrom before colliding, some may be travelling a micron, okay. So there could be different lengths they will be travelling and we define this as the average distance or the mean distance as the drift velocity multiplied by the mean collision time the Tau again it is statistically we are defining this.

So there are three things here the drift velocity, the mean collision time and the mean collision distance more is the mean collision time more it is going to be mean distance or mean free path of the electron. At 0 kelvin in an ideal crystal where there are no impurities and no imperfections present I am talking about a very pure material at 0 kelvin. The mean free path is infinite there are nothing to interfere, there are no collisions taking place because it is a uniform potential at that point and no nucleus is oscillating about its mean position because it is at 0 kelvin so potential field is not getting disturbed and therefore what we assume the potential field is uniform and it is at 0 level so electrons among it begins to travel it keeps travelling and there is no collision and there are no impurities, no imperfections which can also disturb the potential field, alright.

Let me just ask how can an impurity affect the potential field? Let us say there is a solute atom sitting how it can affect the potential field? Its atomic number is going to be different from the matrix, number of positive charges of the nucleus and the electrons around it and what it contributes in the outer most orbit they are all going to be different and also its size is different.

Therefore, the potential field in locally in that region where this solute is sitting will be disturbed it will not be same. So uniform potential field is not there when it is present and it is the potential field which is going to attract or repel the electron which is travelling depending upon what is the charge, okay. So that is how whether it is attracting slowly, less attraction is there or more attraction is there it will affect the motion of the electron that is what we have talked about as a collision.

Similarly is the situation with imperfection, imperfections like of course the impurity is itself an imperfection where the dislocations, the grain boundaries which are there they are also going to affect the uniformity of the potential field because uniform (())(10:38) structure is no more there whenever the imperfection is present that is the singularity in the uniform or what is called periodic repetition which I started with in the perfect crystal that is not there so potential field is also disturbed is no more uniform and that is going to change the direction of motion of the electron and that is what I refer to as a collision when the electron is travelling.

So when the mean free path is infinite at 0 kelvin in a pure substance without imperfections without any impurities there will be no collisions and the conductivity would be infinite. Ya but we are talking about the average velocity of an electron we are talking about that what you are saying is possible, what we are talking about the average velocity of the free electron, okay and they are going to repel each other means they will maintain a distance between them they will always maintain a distance between them that matter because there are same charges.

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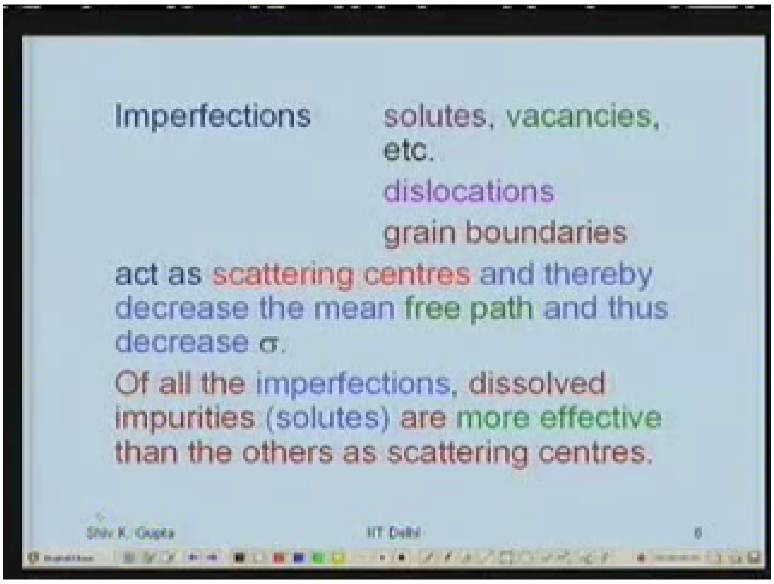

Imperfections is solid state solutes, vacancies, etc these are the point effects, dislocations which are the line defects, grain boundaries surface defects. So I have point, line and surface defects these are the imperfections I am not talking about the volume defects a blow hole in a material that will also affect all these act as scatering centres that means they divert the direction of motion of the electron that is why I call scattering and thereby they decrease the mean free path and since the mean free path is changed the conductivity reduces, mean free path is less, mean collision time is less, mean collision time is less the conductivity will be less we recall that ne square Tau by m what we have used so conductivity will come down.

Among the imperfection which I have talked about in this course, the dissolved impurities water solutes I am not talking about the un dissolved impurities even or the more effective or the most effective in scattering the electron motion or in increasing the resistivity or decreasing the conductivity of the electron than any other imperfection, they are the most deleterious most effective in doing so.

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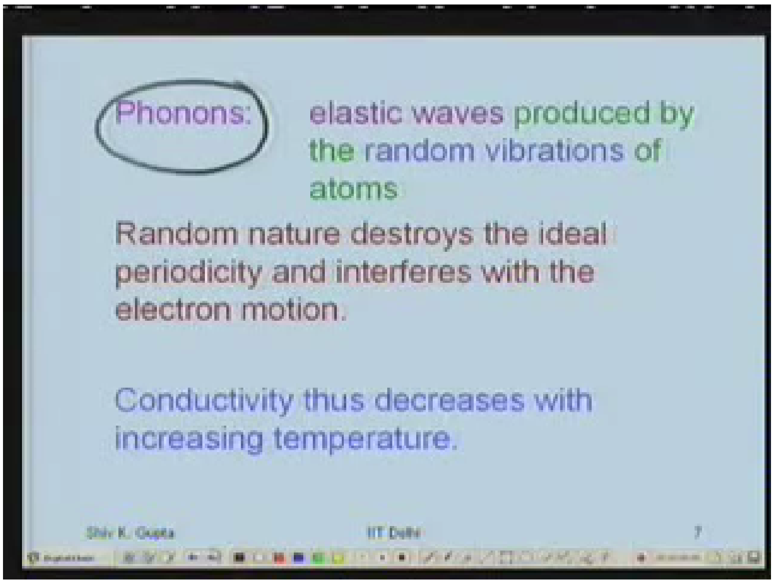

Now that is again on an observation besides these imperfections or the impurities which are causing the motion or the disturbing the motion the electron causing the collision of the electrons they are elastic waves in the solid which we refer to as Phonons what are these elastic waves? Positive ion core leaving aside the electron gas free electron gas they are oscillating about their mean position at temperature is greater than 0 kelvin whatever may the temperature it is only the amplitude will be changing frequency would be changing initially for lower temperatures but by the time we come to 200 degree kelvin and at higher temperature even frequency settles down to about 10 to power 13 per second.

So these are the ones which are oscillating about their mean position in random directions with random amplitude they among themselves are colliding and therefore the amplitudes are changing, energies are changing, right. So these are producing the elastic waves and this is the random vibration of atoms about their mean position, what we call Phonons other than the impurities which are present they are the Phonons these are not impurities they are Phonons.

And when something is oscillating which is producing the potential field in which the electron is travelling even that itself is getting disturbed the uniformity of the electric potential available is also going to be disturbed it will not be same that is what the (())(15:26) waves are doing. If you consider a electron travelling in a potential field and uniform potential field is the uniformity is lost, was the uniformity is lost at certain locations there will be more attraction, certain locations there will be less attraction.

So that is again is causing the collisions or causing the resistivity to increase and it is this random nature as I said destroys the ideal periodicity and interferes with the electron motion. Therefore the conductivity decreases with increase in temperature because with increase in temperature these random vibrations become more vigorous more disturbed, amplitude, oscillation, frequency, etc. So therefore with increase in temperature there is a more collision taking place and therefore less conductivity or more resistivity is produced. I will come to that I will come to that I have assume something in free electron theory and I am going by that I have to show you something more how to (())(16:43) till I think 25th.

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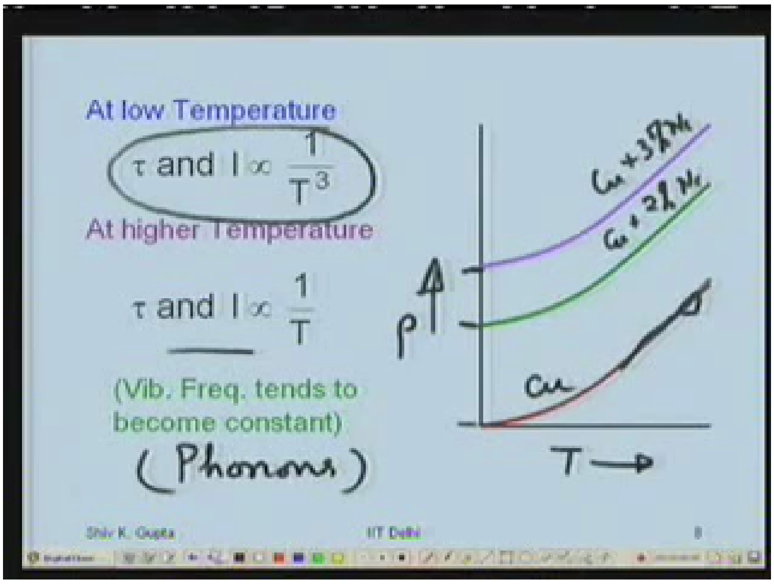

At low temperatures the mean collision time on the mean collision distance the mean free path are (proportional) reciprocal to the T cube it is not a linear variation like this is a cubic variation here in the for small values of I plot temperature on this axis and the resistivity on that axis. So that means conductivity will go as reciprocal of T cube and the resistivity which is reciprocal of that will go as T cube so it is T cube variation for resistivity.

But at higher temperature it becomes linear that is what it is higher temperature it becomes linear straight line see it becomes straight line there and those temperature ranges were the vibration frequency tends to become constant that is what I said 10 to power 13 per second that is what happens only at lower temperature this is varying as T cube.

What I have shown here is the first one is pure copper and this is for copper having I recall correctly 2 percent nickel and this is for copper having 3 percent nickel. So if I take pure copper this is how it varies the temperature initially it is a nonlinear variation the T cube variation that at higher temperature it is a linear variation. But as I change the impurity the resistivity itself goes up even at 0 kelvin and that difference remains same at higher temperatures it does not change obviously we see that there are two kinds of contributions one is because of the temperature and that variation temperature variation is because of Phonons I talked about two things.

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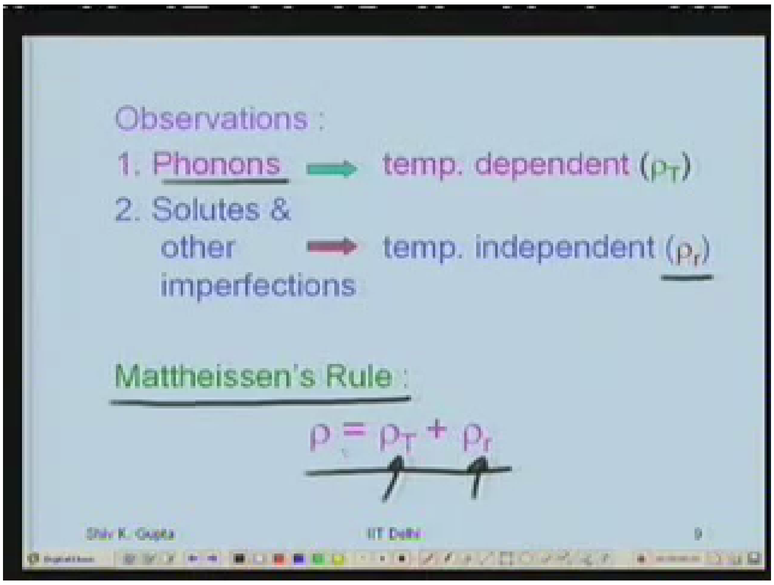

In second one is because of the impurities it is 2 percent this change and 1 percent extra half of it per percent impurity added there is the increase in resistivity and the two things can be added linearly that is what we call Mattheissen's Rule. The temperature dependence is comes because of the Phonons and solutes and other imperfections give temperature independent variation what I call resistivity this is called the residual resistivity because at 0 kelvin this resistivity would be there when everything is perfect no imperfection it should be 0 because I said conductivity should be infinity.

But I find some resistivity at 0 kelvin that is what is called the residual resistivity and is temperature independent and then there is temperature dependent which initially varies as T cube and then at higher temperature goes linearly. So I can add the two contributions linearly like this and that is what is called the Mattheissen's Rule this is temperature dependent and this is the residual due to the imperfections or the impurities. Imperfections means mostly it comes because of the solutes which are present in the material.

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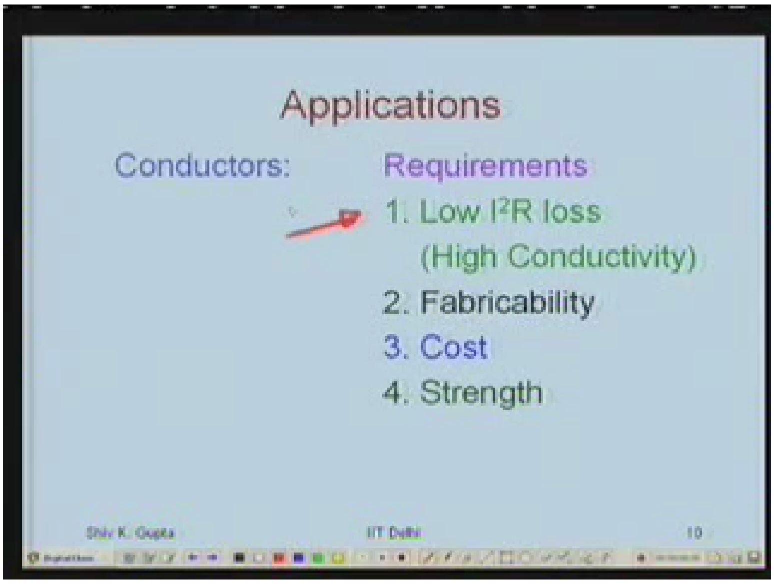

Or after having had a look at what we have observed and we try to analyse this using the free electron theory I am an Engineer more worried about the applications of conductors and resistors. In the applications of conductors I want to conduct electricity therefore I do not want any power loss during the transmission and therefore what I am looking for is a low I square R loss that would come about when the resistance is less that means the conduction is more or conductivity is more resistance and resistivity are related through the geometry of the conductor, okay that you know.

Secondly whatever conductor I use I should be able to fabricate it in the form of a wire or in the form of a strip whatever I want to use it or in the form of a bar therefore it should be fabricable and it should be convenient it should not be very expensive material that is the cost and then it should have enough strength it should not break or it should not swap. So therefore I want the material which satisfies these conditions to be used as in conductor.

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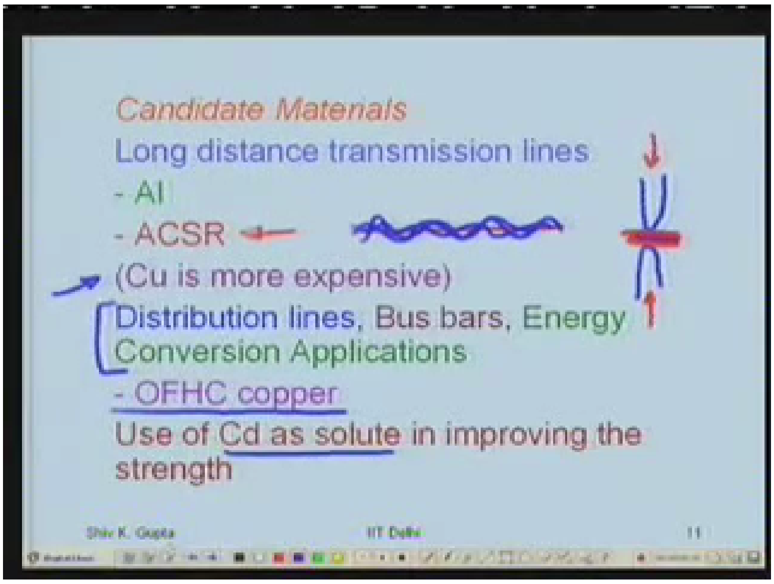

We shall look at some of the candidate materials for this application one of the applications of the conductors is a long distance transmission like from the power house to the town you have the people leave and there you have substations from substations it goes transmitted to the residences or the buildings or the institutes so wherever it has to go to it is a long distance transmission lines we use these days aluminium sometime we were using copper but the availability of the copper as the demand of conductors increased and the availability of the copper decreased small limited quantity on the earth crust.

So therefore we have gone onto the aluminium though I told you earlier the conductivity to aluminium is slightly less it may not be very bad if you consider per unit weight per unit volume it is probably the case but in per unit weight it may not be very bad and the problem with aluminium as compared to copper of other matter silver and gold the three very good conductors which we talked off its strength, its elasticity modulus of elasticity is also low for this.

So as a result what happens is when a long distance transmission cable let us say overhead cable I talk off is placed there is a sagging of the wire because of its low modulus, gravity is acting so it sags and therefore the distance between two poles has to be decreased so there is a shorter length and the sagging is less because after all you do not want it to come down so low that is just above your head therefore the distance between two poles has to be decreased in that means a cost in laying the overhead transmission line.

To reduce this cost of laying the overhead transmission line we have found out another conductor it is called aluminium conductor steel reinforced I have tried to change its modulus because modulus of material cannot be changed but making a composite you can slightly try to improve upon it. So in the centre there is a steel cable or steel wire over which one can have this aluminium coin going over like this, okay.

So you can make aluminium cable and in between there is a steel wire which will improve the modulus and therefore sagging will be less and you can increase the distance between poles again because making a pole itself is lot of cost and that cost is reduced and also the distance between two poles is increased may be you can cross the riverbed the width of the river you can cross if required.

And copper is more expensive besides being expensive its availability is less on the earth and therefore we cannot get it. Whatever cross section you need for conducting through the aluminium you can have but however you can see that here we have the two conductors in parallel so resistors will be lower than the bad of the lower one, okay. So that is not the problem that is not a problem this is how I try to improve the modulus and the bit of strength and the conductor.

I cannot use some other strengths in mechanism which I have discussed we will we can discuss this later where why cannot use the other strengths in mechanisms because modulus certainly I cannot do by those mechanisms and secondly even the strength I would not like to increase by those techniques. The reason is that all those techniques are going to increase the resistivity of the material alright because they are going to increase the imperfections and all imperfections are going to increase the resistivity.

Now the other application possibly for conductors is distribution lines from one room to the may be the switch board to the room and from the room maybe to the switch (())(27:29) etc. Bus bars, energy conversion applications like fans or your motors things like that where you are trying to convert the electrical energy to mechanical energy. Here I cannot use aluminium one reason is melting point is low, secondly with small spark on the heat its get heated, it gets oxidized for more anyway aluminium always has an oxide here on top it is a very reactive material.

So therefore I cannot use aluminium there we use copper it is called oxygen free high conductivity copper OFHC oxygen free high conductivity copper. Well sometimes still we need to improve the strength of the copper which we are using and we do that if possible to use cadmium and solution strengthening is obtained by adding cadmium a small addition like half a percent cadmium does not increase the resistivity very much while it increases a strength a lot. All other impurities were added to copper they decrease the conductivity or increase the resistivity very much.

So therefore I can probably make use of this and that is what we exploit you know an application in manufacturing process you might have learned about spot welding. In spot welding you have one copper electrode and second copper electrode and you have the job in the middle which you want to weld, okay. Now this welding is done by putting this in between the two electrodes and these electrodes are then pressed because of this resistance heating here there is a fusion taking place at the middle here junction because of that heating some fusion takes place and there were joining occurs that temperature wise it is also find by these electrodes and copper becomes soft any material becomes soft on heating and can be formed and that is what we try to gain by adding this half a percent cadmium to these electrodes increase the strength of the copper does not deform means by applying the pressure if copper itself distorts I may not be able to apply the pressure here, the pressure may not reach there. So that is what is gain by adding half a percent cadmium to these electrodes.

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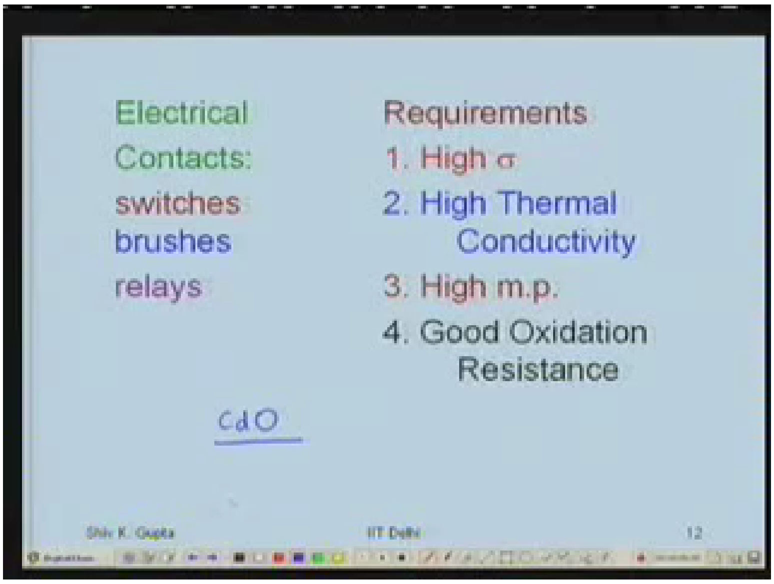

While then the other applications like electrical contacts for example switches very narrow one, brushes, relays this is just to make contacts you know. Requirement is again high very high conductivity at the same time I need high thermal conductivity why do I need high thermal conductivity then there is a switch you switch on and off if you are able to switch off the lights you will be able to see there is a spark because when two opposite polarity electrodes are brought together at some distance there is a spark produced between them, right.

And when you make a contact the spark will go off or similarly when you break by the time you reach here there is a spark, when you break it away the spark goes off but there is that means there is intermitted formation of spark and the heating of the two surfaces and that is why I need heat to be dissipated otherwise heat will get accumulated there particularly brushes and relays which are on and off very frequently they are doing so there will be lot of heating taking place in the contacts and the heat must be taken away.

And the material which is used should have high melting point otherwise with small whatever the heat generated this will just melt it effuse it and the material should have good oxidation resistance because after all this is happening in the atmosphere and atmospheric oxygen if it can oxidize the surface the material oxide is a very bad conductor and there will be no conducting conduction taking place and I think the material we use is copper again that means there are the contacts required very delicate and very sensitive places where like like in spacecraft or the aeroplane where the matter of life and death is possibly or the loss of property is possible we use silver and gold contacts.

And silver contacts can be further because it is lower melting point than the gold and copper but silver though expensive more expensive than copper but cheaper than gold is used and we try to increase the strength by adding cadmium oxide as a precipitate. Cadmium oxide if there is a heating taking place in silver decomposes before the melting of the alloy silver during this decomposition it absorbs heat it is under thermic process and thereby the heat is lost, temperature reduces so silver never melts that is what is done this is the dispersion hardening Cadmium is not soluble in silver so dispersion hardening caused by addition of cadmium oxide.

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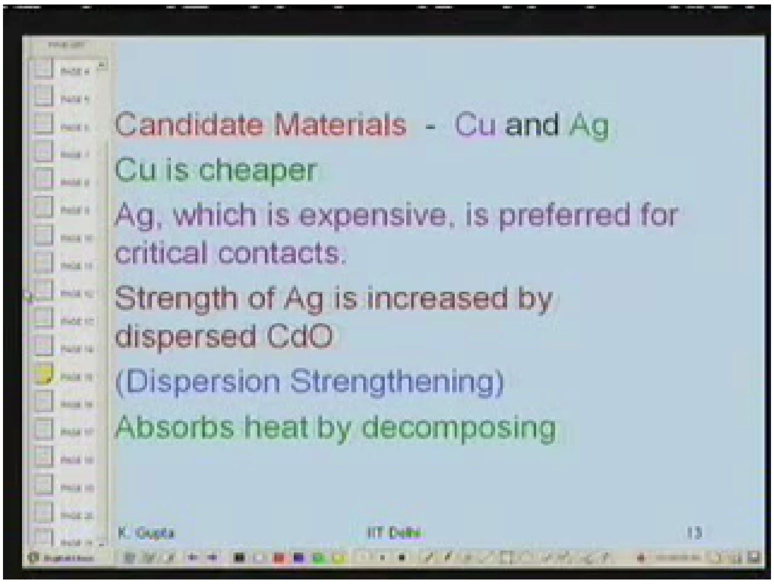

That I think I have listed here these candidate materials which I have just talked about copper and silver, gold is quite expensive for that matter but still it is used and some of the of course the computers the chips when we make we are making contacts there with the help of gold at the back of cheap. Copper is cheaper of course and silver is expensive preferred for critical contacts and strength of silver as I said is increased with the help of dispersed cadmium oxide and it absorbs heat while it gets decomposed.

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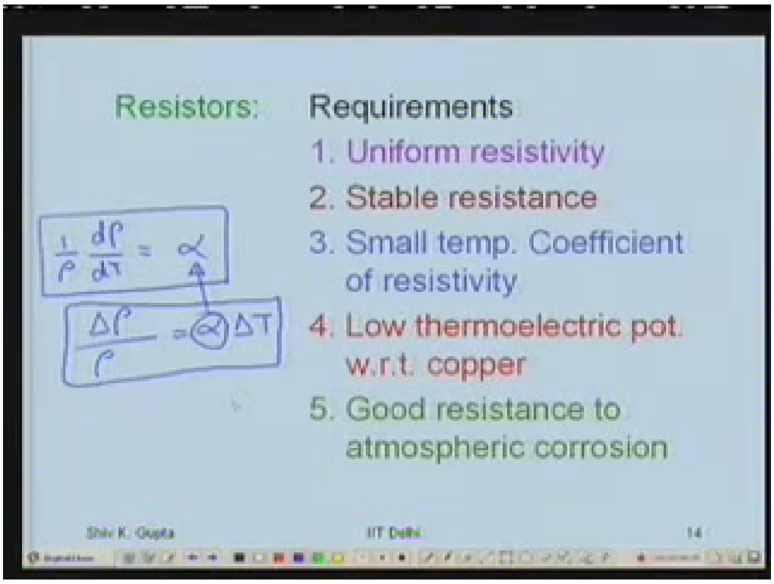

Now coming to the resistors this is another application of the materials in this category which engineers have to put them to when I am using something as a resistor it must have a uniform resistivity by uniform resistivity what I mean is in 1 meter length here or next meter length here the resistivity should be the same it should not be different. And this uniform resistivity requires the structure of the material is metallurgically stable means micro structure is stable micro structure which is not changing with time and you have seen what are the some structures do change with time.

So that it should be in the stable form the resistance should be stable that means and its temperature coefficient of resistivity should be small temperature coefficient of resistivity what is the temperature coefficient of resistivity? Ya we define this as I will (())(35:55) temperature coefficient of resistivity we define as okay this is the temperature coefficient of resistivity that is rate of change of resistivity or a fractional change in resistivity per degree rise in temperature fractional change d rho by rho is becomes the fractional change and we can also write this as if in experimental measurement d rho by rho is not possible so delta rho by rho can be written as alpha delta T.

You measure the change in temperature, corresponding change in resistivity, then measure the resistivity and this is the temperature coefficient of resistivity alpha so this should be small what does it mean? When there is a variation in temperature the ambient temperature the room temperature there is change in resistivity is the least possible value, if it is large the resistivity change would be large.

During the year you know even in Delhi the room temperatures changing from 4 degree centigrade to 44 degree centigrade and if the alpha is lost there will be large change in the resistivity of the material. So performance of the conductor in winter will be different from then it is in summer, or performance during the noon time will be different from what it is in the evenings so that is going to happen if alpha is large.

Then low thermoelectric potential with respect to copper any resistor is connected in a circuit with the help of copper conductors and with respect to that this thermoelectric potential should be small otherwise there is additional potential developed or the loss of the energy. Good resistance to atmospheric corrosion since you are using these resistors in atmosphere only ambiance it should not be corroding with time if it is corroding then of course again the corrosion layer which is produced is insulating layer and will not be conducting.

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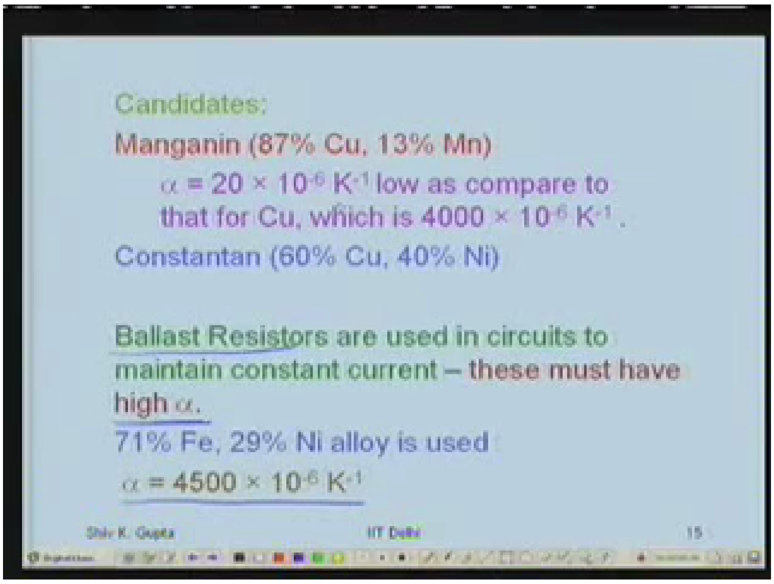

So the candidates for resistors are Manganin is the one which is a copper manganese alloy 87 percent copper and 13 percent manganese, its coefficient of thermal expansion is 20 10 to the power minus 6 per kelvin as compared to copper which is 4000 is equal to minus 6 per kelvin is very small. Then the next candidate material is Constantan 60 percent copper, 40 percent nickel these are the two kind of resistors you are used if you have used in the school physics laboratory.

Then there are Ballast resistors these are used to maintain constant current in a circuit and for these you must have high alpha because if there is a increase in current there will be I square R loss will be more more temperature more temperature means more resistance more resistance means low current so current will be stabilizing. So in such applications I need a material with high alpha and the candidate material there is 71 percent ion, 29 percent nickel alloy which has an alpha value of 4500 10 to power minus 6 per kelvin which is more than that for copper.

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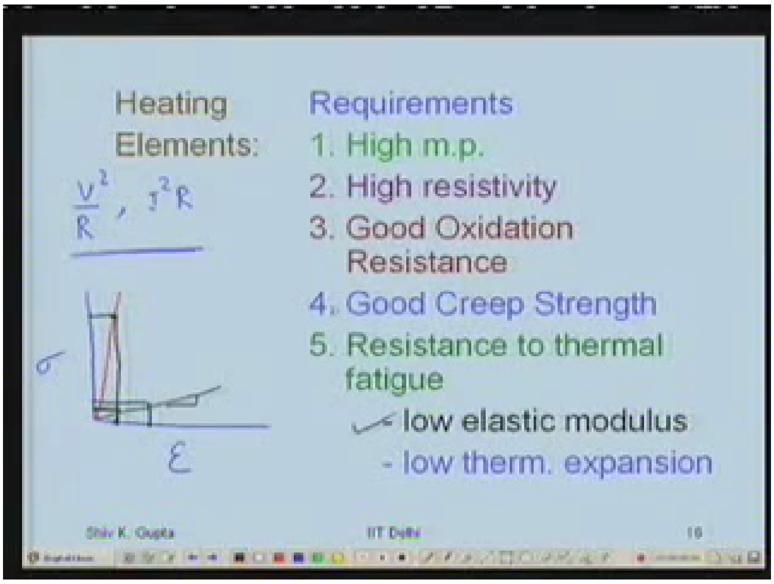

Then resistors are also used for heating elements I square R loss I need R to be high how high yes please since it is going to be heating and we have seen the heaters they become red hot the red hot the melting point is low it will melt so high melting point I said and I said high resistivity how high resistivity should I have? Ya this is this is a problem which cannot be worked out by differentiating and saying it should be so and so how much value I need.

Look it carefully if I use the constant voltage the power loss is V square by R the R is large it will be less and the same thing is I square R, so R is large I square R will be there is the constant current, right. So I cannot have the resistivity as high as it becomes the semiconductor or it becomes a insulator I still I am talking about the conductor which I said I have the range of 10 to power minus 9 ohm meter to 10 to the power of minus 3 ohm meter. So there is a higher side means it will be near about 10 to the power minus 3 ohm meter resistivity should be, okay that is one thing which you should be careful with.

It should have good oxidation resistance because heating element is going to become (()) (41:29) hot and it should not be oxidizing at that temperature. It should have good creep strengths because temperature is high you are working just below the melting point of the material may be and then it should not be creeping with creeps it is going to cause problems and may be it breaks.

Resistance to thermal fatigue because heater is switched on, switched off, switched off, switched off during the heating the wire or the resistor expands when you switch it of it cools, it contracts, heating means expanding cooling, spending cooling thereby there is also the stress developed in the material that causes the fatigue and the fatigue is now a thermal fatigue this is caused by the temperature.

To avoid this I need low elastic modulus let us see carefully what I am talking about this is the stress and this is the strain. Let us say I have a material with a modulus like this if I have a material with this modulus or I have a material with this modulus on increasing the temperature because thermal expansion let us say this is the strain developed in the material. So this material will develop this much stress while this material will develop only this much stress, this as a lower modulus and that as a higher modulus I need a low elastic modulus so the stress developed in the material is the least because fatigue below a certain level of stress no fatigue effect can be seen that is called the endures limit of the material.

Similarly low thermal expansion if there is a high thermal expansion strain developed will be this much, the low thermal expansion strain developed will be this much so stress developed will be here while it will be here. So stress developed will be more if there is a high thermal expansion so I want low coefficient thermal expansion you should not expand very much, okay. So these are the requirements on the heating elements.

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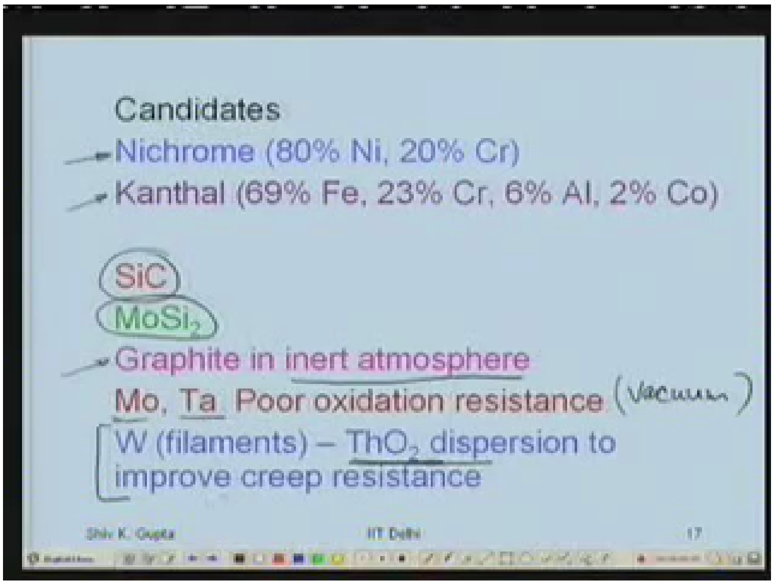

And then the candidate materials which we have more commonly used in the market is the Nichrome which is 80 percent nickel and 20 percent Chromium alloy and this can easily be used upto 900 degree centigrade without problem the room heaters, etc, etc are using or your hot plates are using normally Nichrome because you do not want to go to 900 degree centigrade even. If you want an industrial furnace you need Kanthal (())(44:17) upto 1100 degree centigrade, this is 69 percent Ion, 23 percent Chromium, 6 percent aluminium and 2 percent cobalt alloy and does not creep because you can see the large number of alloying additions added there and gives a solution strengthening is taking place in that material.

For one to go to still higher temperature like 14, 1500 degree centigrade Silicon carbide is the one which below 700 degree centigrade is a semiconducting material and the another semiconducting material Molybdenum Disilicide is also called Super Kanthal and it can go upto 16, 1700 degree centigrade easily. Then you may want to 17, 1800 degree centigrade range we have to use Graphite and Graphite since it is a very reactive material about 400 degree centigrade it will become Carbon Monoxide, Carbon Dioxide I must use the inner atmosphere we want to use the Graphite as a heating element.

Then it is about to go to still higher temperature like 24, 2500 degree centigrade may be I have to use Molybdenum, Tantalum, etc that they have a very poor oxidation resistance they have to be used in vacuum or inner atmosphere and also these materials are very expensive you can use them in small quantity so small when you are doing the research you want to have that kind of temperature in a small volume you can use this kind of fatigue elements.

Then Tungsten is also used for still higher temperature where Tungsten filaments are used with Thorium dispersed in that to increase the strength, it improves the creep resistance of the material in (())(46:05) have been using Tungsten filaments which are being dispersed with Thorium and improve the creep resistors of Tungsten. Tungsten its melting point is 3400 degree centigrade white (())(46:26) condition it is still probably in the (())(46:29) state.

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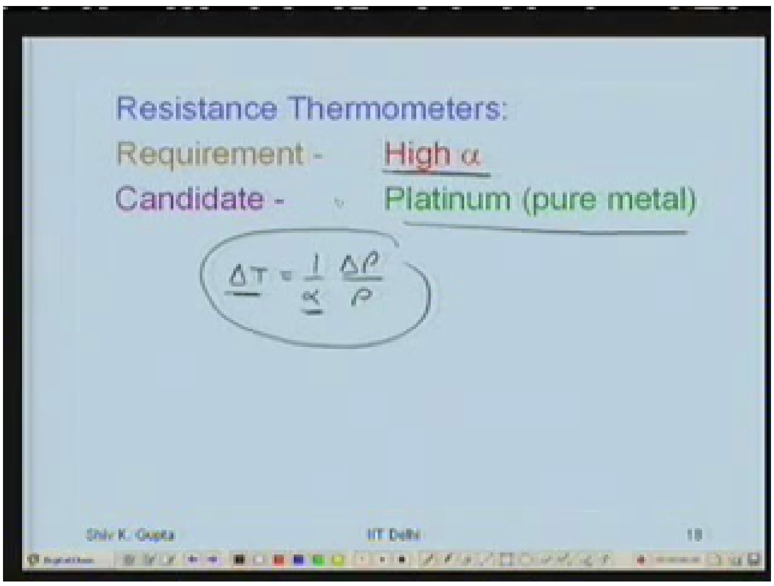

Then last applications which I am going to refer to the thermometers measuring temperature basically making use of these conductors, resistors for measuring temperature I can measure temperature more accurately the requirement is temperature coefficient of resistivity should be high that is now I just now showed you that I can measure delta T, alright so accuracy of delta T would be high if alpha is high accuracy means delta should be as small as possible it will be small if alpha is large, okay and that is what you can measure and we use pure metal platinum for this coefficient temperature coefficient resistivity is pretty high for this and can be used the temperature range in which we use this is low temperature range, okay it is not used at room temperatures and Graphite is also used for measuring temperature as a thermometer again at low temperatures, alright I think I shall end with this the conductors and resistors we shall start with semiconductors in the next class.