

hello welcome back again ah

so i will begin by summarizing what we did in lecture uh two that is last time so uh one of the things that we did is to define drift velocity

so this is the velocity which the charge carriers attain when subjected to an electric field now what we did is to realize that the electrons in a conductor they are moving with great speed actually it's of the order of 10^6 meter per second but they move randomly now when they move randomly the net velocity of all the electrons taken together because velocity is a vector and if i am summing over vectors in random directions i get 0 but if i apply an electric field then there would be a net drift or a velocity which they will pick up with respect to uh what it was in the absence of the electric field in other words in that in the absence of the electric field the average velocity was zero but in the presence of the electric field the average electron velocity which will be in a direction opposite to the direction in which the electric field has been applied will be the drift velocity or v_d we had obtained a relationship between the drift velocity and the current density by saying that j is related to the drift velocity by $j = -ne v_d$ where n is the number density of electrons e is the charge and this j and the drift velocity have a relative minus sign between them and that is simply because we are talking about uh current the velocity of electrons whereas the current positive current is defined as the current in which the direction at which the positive charges move they we did do an estimate of the drift velocity for a typical conductor like copper and we found that it is very small its typically v_d magnitude is small we found it to be a few millimeter per second then we did a comparison of the drift velocities magnitude with other speeds which are characteristic of the conductor for example we have already said that the random speed the thermal speed of electrons is of the order of 10^6 meter per second which is of course a several orders of magnitude higher and there is another scale there which is when you switch on an electric field what is the speed with which the electric field gets established and we found since it is decided by the velocity of light the electric field is practically instantaneously established when we switch on an electric field

so drift velocity is very small the having done that we found that for a very large class of material a simple relationship exists between the current density j and the electric field e and this is known as the ohm's law we found that we can write $j = \sigma e$ or alternatively the reverse relationship $e = \rho j$ σ is called the conductivity and ρ the resistivity now what we did say was ρ and σ are basically material property that is the property which depends upon what material it is we also said that it could depend upon things like temperature and pressure but we have not said much about it today we will try to talk about that also as well

so the point is what is the resistance

so what we said is this that while resistivity or conductivity are material properties the resistance is a sample dependent property of course it depends upon the conductivity or resistivity but it also depends upon the sample geometry

so we define the resistance as R i should more properly say that resistance as seen between or as measured between two points across which we apply a potential difference ΔV and the resistance R between such two points is defined to be ΔV divided by

so in other words resistance is defined as the potential difference that must be applied across two points of a resistance in order to get a unit current and of course we know the unit of current is ampere and this is volt

so therefore resistance has the unit of ohms other than depending upon material

property like conductivity and resistivity the resistance depends upon directly proportional to the length of the sample and has an inverse relationship with the area of cross section we also provided an analogy between the conduction of electricity and heat conduction we found that there is a similarity there having done that we provided a microscopic view of ohm's law and we basically pointed out that there is a characteristic time which is defined as the time that is taken or time that elapses between two successive collisions between the electron and the ions or atoms in the medium and that is called the relaxation time τ is called relaxation time and we showed that the conductivity is given as $n e^2 \tau / m$ and we also found out that there is a relationship between the drift velocity and this relaxation time which is simply $v_d = e E \tau / m$

so not one thing that in spite of the fact that in typical metal τ is of the order of 10^{-14} to 10^{-15} seconds e is of course a small quantity but because of the fact that the number density is large and of course because m appears here in this expression of the denominator the number density in typical samples is of the order of 10^{28} per meter cube and

so therefore that explains why σ is not very small because well v_d is small because n doesn't appear there

so another thing which i have said but i would like to emphasize is that when we say resistance of a sample it is actually a vague statement it is a vague statement because we said that the resistance is proportional to length and inversely proportional to the area now the question is what is the length is that a standard thing

so the point to realize is this that very often whenever we say that resistance of a sample is

so much we understand that the potential difference has been across the applied across the longer of the sides and that's what we call typically as a length but supporting is supposing you applied the potential difference between the shorter side then of course the resistance will change

so that is uh these are the things that we talked about last time and let us proceed with further data

so let me define a new term which is called mobility dictionary wise when i say that something is mobile mobility is ability to move but of course in physics we have to be lot more precise i mean it's not ability to move but that's where the name comes from

so let me say qualitatively it is the ease with which a charge carrier moves inside a solid when an electric field is applied

so notice that mobility depends upon how easily the charges move inside a conductor in an electric field we will see that the mobility becomes actually lot more important in substances which are known as semiconductors but at the moment we are talking about conductors

so therefore we need a quantitative definition mobility by definition is a positive quantity and it is defined as the ratio of the drift velocity to the applied electric field notice that velocity meter per second electric field is of course volt per meter

so therefore this is the unit of meter square by volt second

so this is the quantitative definition of mobility and let us try to see how it is connected to the characteristic times remember that we had obtained this expression for the drift velocity which is $v_d = e E \tau / m$

so if you substitute it for the electric field this expression there the the drift velocity by this expression you will find μ will be given by $e \tau / m$ now this enables you to determine the typical values of μ remember this is 10^{-19} to 10^{-15} i'm just doing an order this is 10^{-14} or 10^{-15} and

mass of electron is 9×10^{-31}

so let's take it as 10^{-30}

so this is typically of the order of 10^3 to 10^4 meter per second sorry meter square by four second this is actually very small

so this is very important to realize that though i said mobility is the ease with which the electrons move in the presence of a semiconductor in the presence of an electric field the value of mobility in case of conductors is actually not very much

so usually this is measured in not in meter square by volt second but in centimeter square per volt second we'll do some calculation we'll see this is not very large for a substance like copper etcetera where mobility becomes much more important or in this semiconductor semiconductor devices solid state devices they require large mobility for their efficient working for example if you look at silicon at room temperature this has a mobility there are two types of charge carriers in silicon or semiconductors in general there are this electron mobility

so electron mobility is about 1400 centimeter square per volt second this is the electron mobility and there is a thing called a hole mobility that is the mobility associated with the vacancies in a semiconductor and that is for the case of silicon is about a third of this value about 450 centimeters per volt second now recall sigma expression

so sigma was $n e^2 \tau$ over m

so this is if you pull out either

so you find this sorry this is any square tower mass

so this turns out to be e times n times m and that is just taking my expression from here that my m is given by $e \tau$ over 1

so notice that the conductivity has a simple relationship with the mobility which is simply the electronic charge multiplied by the number density times the mobility now in semiconductors where both the electron and the holes contribute to conductivity this takes an expression of this type that is the charge n times the electron mobility plus the density of holes which is usually represented by p times the whole mobility we will be talking more about it then in our discussion on semiconductors

so let's look at the copper which we have been talking about remember we calculated in one of the examples the number density of copper was 8.5×10^{28} .

per meter cube and we had seen that sigma is 5.8×10^7 siemens per meter

so therefore my mobility is if you look at this expression sigma equal to $n \mu$

my mobility is simply sigma over any you substitute this

so this is 5.8×10^7 .

8.5×10^{28} divided by 8.5×10^{28} multiplied by 1.6×10^{-19}

6.4×10^{-19}

10^{-19}

so this is you can calculate the number but let us look at the order of magnitude in the denominator you have got 10^9

so therefore you take it up there

so you get 10^{-2} and there is a 5.8 .

8 by 8 .

5.8 and it works out to 0.42 .

0.42 okay meter per meter square per volt second which is 42 centimeter square per volt second i had already told you that the silicon for example has a fairly large electron mobility which is 1400 also now i can look at this data and in turn find out what is the drift speed like

so look at let us look at v_d expression

so supposing i apply let us say an electric field of 10 volts supposing i have e is equal to 10 volts i just now calculated μ to be equal to 4.

3×10^{-3} into 10^{-3}

so that gives you 4.

3×10^{-2} or in other words 4.

2 centimeter per second consistently giving us small number for drift velocity let us return back to ohm's law which we talked about

so what we said is the ohm's law is a linear relationship that exists between the applied voltage and the current

so the typical $i-v$ relationship if ohm's law is valid is given like this and this thing slope here is tan inverse of the resistance v is equal to i times r

so that is typical relationship most of the time the this relationship will have some deviation from linearity particularly in this region

so this is this is ohm's law and this is deviation from linearity now for a large range of current voltage relationship the linearity is valid and in fact most of the time in while we are at in our discussion of current electricity we will be assuming ohm's law to be valid but this is probably a good time to point out that this linearity is not true in many materials but more importantly another property in case of most of the conductors is that v_i relations that i have given you it is independent of the sign of v what i mean is that the current that flows the magnitude of the current that flows it does not depend upon the sign of v of course the direction will change but it does not depend upon the sign of v but

so does not depend upon what it means is that if you have a resistance and let's suppose you apply potential difference between the two ends with this side positive this side negative you get certain amount of current that if you change the polarity that is the potential difference u_h between the two ends instead of this being positive that being negative if you apply make this u_h negative that positive the magnitude of the current for the same voltage irrespective of its sign remains the same but this is not true particularly in when you go to semiconductors

so if you look at the current voltage characteristic of a typical diode like a silicon diode this is completely different from what you see in the case of a metal

so for instance for a silicon diode when you apply a forward voltage that is positive v the language that is used in diodes is if the diode is forward biased then what you find is that for certain values of voltage small values of voltage the current essentially remains zero and then suddenly there is a threshold after which it rises sharply this threshold for silicon is 0.7 volt

7 volt

so that is the type of scale we are talking about and this is this scale is about one or two volts in this case the current i is in milliamps now something interesting happens when you apply voltage in the reverse direction the direction of current of course changes but the current essentially remains zero for a very large value of voltage even for 50 60 volts or

so and then there is a particular value at which the what is known as a breakdown occurs

so this is called breakdown voltage and this reverse breakdown voltage is greater than 50 volts now if you now look at a typical semiconductor for example if you look at gallium arsenide and look at its current voltage characteristic there is something interesting you find

so first thing that you notice is that the current voltage curve in here my current is in typically in milliamps reason volts it starts with a linear rather

ohmic relation and then there is a departure from the linearity and it sort of passes through a maximum and at some stage something interesting happens it starts bending down

so let's look at that picture a little more carefully

so i have three regions here this is my region one and this region one is it follows ohm's law in region 2 is a nonlinear region and the last region that we have is a region where something interesting is happening that as voltage increases current instead of increasing as is normally the case it starts decreasing

so in other words this is actually a region which is showing negative resistance there is another thing that i would like to point out remember i said that when i say that resistance of a sample is

so much you should be lot clearer and point out that the resistance when i apply it across these points in a register but on the other hand we generally understand by length the longer side now in laboratory uses in many practical uses we need resistances whose values are standard and these are usually manufactured in bulk and supplied to the laboratories there are typically two groups of resistances the first one is what is called a wire bound these are made of alloys of material such as manganine constantine they are all alloys necrom wires the reason why these are used is because as we will see later the resistivity of a sample or in this case resistance because i am fixing the length and the cross section it also has a dependence on temperature now these are materials where the resistance is roughly independent of the temperature range they are fairly tolerant towards a changes in temperature and and these are used when you want a typical use resistance typically from fraction of ohms to let us say several hundred ohms more common are what are called carbon resistances which also has such study properties now in carbon resistance there is a color coding used to indicate what is the resistance if you go to the lab and pick up a carbon resistance you will find there are certain color bands there i mean typically a carbon resistance would look like this

so let me suppose this is the resistance there will be two lead wires across which you can apply the potential difference but what you will find is there will be different colors here i don't have all the colors but let me sort of draw some one or two that i have actually

so this is color coding of resistances

so let me explain how does this color coding work most of the time the resistances that you find in your labs have four bands

so there are four bands of colors and the way it works is this the colors that are used here are black i will explain some way of remembering the black brown red orange yellow green blue violet gray and finally white

so let me explain how this works typically these are four bands i have just shown you three but let me add another one out of this the first two they represent the significant figures

so let me explain what it means

so this is significant figure depending upon the color we assign a value which is black 0 brown 1 red 2 3 4 5 6 7 8 9.

so therefore suppose you wanted to have the first two numbers as 23 your first one band will be red the next one will be orange or for example 47 the first one will be yellow the second one will be violet now the third one is a multiplier the multiplier is basically 10 to the power whatever is the digit which represents this color i'll give an example to explain what happens

so for example supposing i wanted to write 230 how what will i do now this i will write as 23 into 10 to the power 1.

so 23 is red orange

so it will be red first band red next band orange and one is brown

so next band will be brown there is a fourth band which tells you what is the tolerance level and this fourth band is either silver which represents a ten percent tolerance or gold which represents a five percent tolerance or no color that is the band is missing actually missing band which represents a pretty bad tolerance which is 20 percent of course you would sort of wonder how does one ever remember such things when we were in school we were given a mnemonics to remember this

so i will repeat that you might have your own but the one that i learnt is a phrase like this bb roy of great britain has a very good wife good to remember it

so you realize all that happens is black blue brown red green orange great green blue then of course violet grey and white

so you could have your own there are if you look up internet you will find several but let me explain this by the following supposing you have a color combination of this type supposing you have a yellow you have a violet you have a red and a silvery these are the four bands then if you look at my table there yellow was four violet was seven red was 2 and silver of course i told you a tolerance

so we'll come to silver tolerance which is a 10 tolerance

so what it says is this this 2 represents 47 our third one represents 10 to the power 2

so 47 into 10 to the power 2 plus or minus 10 this is what is meant by tolerance

so this nothing but 4.

7 kilo ohms plus or minus 10 percent occasionally but not in your labs you might find a band with five of them in which case what happens is the same principle is true but the first three figures then represents the significant figure

so you realize this will be useful if you want to represent bigger or higher values of resistance having said that i did mention that the resistance depends upon resistance of a sample depends upon temperature let us see why and how now the typical variation of resistivity of a sample with temperature has been found to be roughly linear now since is a linear curve you can take any point as your reference now if you take any point as your reference let me call this sum temperature t_0 and let's say the corresponding resistance is ρ_0 then i can represent over this entire length $\rho - \rho_0 = \rho_0 (\alpha (t - t_0))$ alternatively ρ is given by $\rho_0 (1 + \alpha (t - t_0))$

so therefore look at this relationship this is your resistance at some temperature t_0 reference α is called temperature coefficient of resistivity and of course t is the temperature at which you want to find out what is the resistance like

so basically what we are trying to tell you is this that the like you know when you apply a temperature you have thermal expansion you have for example the length changes Δl okay

so in thermal expansion what we do is to say that the length changes Δl is equal to $\alpha l \Delta t$ a very similar relationship here

so $\alpha = \frac{1}{\rho_0} \frac{\Delta \rho}{\Delta t}$ alternatively ρ is given by $\rho_0 (1 + \alpha (t - t_0))$ and if you realize that this is the change in the resistivity when the temperature changes by $t - t_0$

so this quantity can be written as $\frac{1}{\rho_0} \frac{\Delta \rho}{\Delta t}$ now this is the definition of the temperature coefficient of resistivity and sometimes in

some material depending upon the temperature range this relationship may not remain valid in which case you should probably add corrections like β into t^{-1} minus p_0 square plus γ into t^{-2} etcetera etcetera

so then for for a material such as copper for instance versus temperature if you do it their variation is like this

so there is a wide length range in which the linearity is valid but of course there are some corrections here

so this is typically copper ρ_{300} is a much better this is copper if you look at ρ_{300} this is actually much better is almost linear but if you look at some semiconductors the behavior is different basically it goes like this now let us look at why is this happening

so forgetting about whether it is actually linear or not i understand here that the resistance or resistivity increases with increase in temperature why does it happen in order to understand remember how did resistance arise we said as temperature increases my charge carriers ah have a higher velocity because of thermal velocity is becoming more more importantly the ions in the solid they also start vibrating

so as a result the frequency of collision increases and this is very similar to the example that i gave you that if you are randomly moving around in a room where there are chairs now as long as the chairs are static you would be still moving randomly but suppose in the process chairs also started moving randomly then of course your probability of collision becomes much more and it is because of that that the resistance increases because as the probability of collision increases the relaxation time decreases further now what happens in a semiconductor once again i must tell you i occasionally bring in semiconductors

so that you can relate to such things when a complete discussion of semiconductor is taken up in later lectures

so in semiconductors this is not the primary mechanism what happens in semiconductors is the number density of charge carriers to begin with is low now as you increase temperatures the number of charge carriers increase and that is the predominant contribution to increased conductivity in case of semiconductors which means the resistivity decreases in fact this is a the best way in which you can distinguish a conductor from a semiconductor

so the reason is this supposing we say we ask the question what is a good cut now you would say well good conductors are those whose conductivity value is high but then that's a loose definition because how high is high is it 10^7 to the power 7 is it 10^8 to the power 8 is there a sharp number the answer is no but but this is a clear cut distribution if you look at the way the resistance of a sample increases when you increase the temperature if the substance happens to be a conductor then the resistance will rise with the increase in temperature in other words the conductivity the the conductance will decrease but if you have a semiconductor as you increase the temperature the conductivity increases the resistance decreases

so this is a much better way of distinguishing

so let me then take an example and work out a few things with which takes care of some of these explain some of these things in detail earlier i had talked about drift velocity of copper i will just change because copper aluminum etcetera are typical good conductors actually silver also is but then one doesn't play around with silver that much because this of its expense

so let me take aluminum now an aluminum has three valence electrons and at zero degrees centigrade it has a resistivity of 2.8×10^{-8} ohm meter

7 into 10^8 to the power minus 8 per meter its temperature coefficient which we represented by α is 4.

3 into 10^8 to the power minus 3 per degree kelvin or per degree centigrade

doesn't make any difference because as you know i am talking about units of temperature

so it doesn't matter one degree kelvin difference is also one degree centigrade difference

so first thing that we do is we want to calculate the resistivity at room temperature let me take the room temperature this is winter season to be let us say 25 degree centigrade i told you anything you can take as a reference

so therefore ρ at 25 degree centigrade is ρ at 0 degree into $1 + \alpha \times \Delta t$ and Δt is the change in temperature which is 1 plus so 4.

3 into 10 to the power minus 3 into 25 degrees now you can see what this is this is already this is ρ 0 and this is 25 into 4 roughly

so it's 100 into 10 to the power minus 1

so it is 1.

one roughly one point one and there is a little bit zero seven five etcetera

so so therefore if you look at the resistivity at twenty five degrees it will simply 1.

1 times that which simply makes if this was uh 2.

7 and you add another 0.

2 it's about 2.

so 2.

7 into 1.

1

so about 2.

9 into of course 10 to the power minus 8 per meter return back to properties of aluminum aluminum has an atomic mass of 27 and it has a mass density of about 2700 this makes our calculations little easier we do the same calculation as we did in case of copper

so we find out how many number of atoms are there in aluminum and that is clear because i have a mass density which is the mass of 1 meter cube then i divide it by the atomic mass but i take care to see write it in kg number of atoms is 6 into 10 to the power 23 the avogadro's number

so this is roughly this is 2 6 into 10 to the power 28 per meter cube now if i assume that aluminum contributes 3 all three of its valence electrons to the electron gas then my n will be three times that which is 1.

8 into 10 to the power 29 per meter cube

so this is this is your electron density you should be always careful what we need for calculation of conductivity is the electron density here we are talking about mass density that is what is its weight per unit volume or mass per unit volume

so this is what we have got and

so if you look at σ i use my usual $n e^2 \tau$ over m formula and substitute the conductivity values and you find that this is of the order of the τ is of the order of 7 into 10 to the power minus 15 seconds you have calculate the mobility which is σ over $n e$ i will not repeat this calculation because we have calculated the σ and then n we have got and then e of course is given if you do this it works out to 12 centimeter square per volt second the corresponding mean free path is obtained by multiplying this number with the typical value of the electron velocity thermal velocity which is 2 into 10 to the power 6 this is about 14.

4 nanometers or

so so basically what has happened is this

so as temperature t increases we have the following relationship for conductors

the resistivity ρ increases in other words if you take a sample of a fixed dimension of course then the resistance R also will increase σ naturally decreases now the collision time or relaxation time τ power decreases because there are more kinetic energy of thermal kinetic energy and the mean free path λ also decreases all this is of course applicable for conductors let me give you an example of how this temperature dependence of resistance or resistivity can be used to determine the temperature of an unknown heat bath for instance we have a platinum resistance thermometer whose thermal element has the following values of resistance at t equal to 0° degree centigrade the resistance R of the sample is 5 ohms and at t equal to 100° degree centigrade resistance is 5.

4 ohms this is the property the calibrated values and when the same thermometer is put in a heat bath of unknown temperature the resistance becomes 6 ohms the question is what is the temperature of this heat bath now the first thing is we know that the resistivity ρ is related to at any temperature it is related to the resistivity ρ_0 at a certain reference temperature by $\rho = \rho_0 [1 + \alpha \Delta t]$ where α is the temperature coefficient of resistivity and Δt is the change in temperature from this reference temperature in this case we take the reference temperature to be 0° degree centigrade and Δt is 100° degrees now since we are talking about a particular sample the resistance obviously follows the same rule because the dimensions have to be multiplied on both sides

so resistance R also follows $R = R_0 [1 + \alpha \Delta t]$

so if you substitute the given values 5.4 ohms is equal to 5 ohms here into $1 + \alpha \Delta t$ is 100 and if you solve this equation you find out the value of α to be given by 8×10^{-4} per degree centigrade now i substitute this equation $R = R_0 [1 + \alpha \Delta t]$ and take if α is taken to be 6 ohms

so i have 6 is equal to $5 [1 + 8 \times 10^{-4} \Delta t]$ that's $\alpha \Delta t$ this is the new Δt and if you solve for this i get Δt is equal to 250° degrees centigrade since my reference temperature with respect to which i had my 5 ohm resistance was 0° degrees

so the temperature of the heat bath is 250° degrees according to this method one thing that we observed is that the reference point can be anything and that is because of the linearity of this relationship okay let me conclude this lecture by saying that copper at 0° degrees has a resistivity of 1 .

7×10^{-8} ohm meter i am asking what should be the temperature at which its resistivity will double look at this i have $R = R_0 [1 + \alpha \Delta t]$ well α we have just now found out from the previous example we did find out for platinum but the value of α is known and

so therefore i can substitute it here all that i am asking is what should be the temperature at which my R will be equal to two times zero you could work this out and we will continue with this next time you