

Lecture 30: GMR materials

Hello, welcome to the first lecture of week 8. In the previous lecture, which I finished in the seventh week, we were talking about magnetic materials and magnetism at nanoscale. There are other phenomena which have been seen in magnetic materials when they are made to combine with other types of materials. We will start talking about those systems in today's lecture and you will see that those kind of materials have large number of applications. So, we will start talking about GMR and CMR materials. What are these materials? Before I introduce the giant magnetoresistance materials or colossal magnetoresistance materials that is GMR and CMR, we must understand what is the concept of magnetoresistance.

So, that is what we will start today. Following the introduction of magnetoresistance phenomena, we will start with the first type of systems which show magnetic field dependence change in the resistance and those are called giant magnetoresistive materials or giant magnetoresistance materials. You will see that there are three types of configurations. First the alternate layer model which will show GMR phenomena or you can have matrix model for observing GMR or you can have the combination of the two to obtain a hybrid system to observe the GMR phenomena.

What is magnetoresistance? What do we understand by resistance? It is a phenomena which opposes the flow of charge carriers in materials. Generally, change in resistance is believed that it will occur whenever there is flow of charges. Now, this is an electric field dependent phenomena. Why should a magnetic field change the behavior more so the resistive behavior of a material if the order of magnetic field is changed? Why should that happen? Seemingly they are independent parameters M and P that is polarization or if I see the magnetic field and electric field. So they are independently seemingly so why should change in magnetic field be observed as change in resistance, but this has been observed.

Obviously, this opens a new field of applications for such materials. So you can change the magnetic field the resistance will change and you can make new kind of devices. So what is magnetoresistance? It is a phenomena where the application of a DC magnetic field changes the resistance of a material. Now is it a new phenomena or it was known? If you go through literature if you see books or if you see the relevant scientific publications you will find that this phenomena was actually known for many many decades and centuries and in ordinary metals also they were observed and this was arising due to the conduction electrons which were being forced to move in a helical trajectory about a magnetic field. So, Larmor frequencies these are the things which you have studied.

So as they process if you change the direction of the process then what is going to happen? You are going to change the magnitude of resistance being observed even in metals, but because to observe these phenomena in a way that they have appreciable magnitude or consequence on the end result either you were expected to have very high fields or you

needed to go to low temperatures so that you can minimize the impact of thermal energy and whatever change you are going to observe was basically coming in because of the change in the resistance owing to the application of a magnetic field and therefore at room temperature at the magnetic field strength which are normally available these phenomena were not observed or they were considered to be negligible. Now what have we seen? We have seen till now that the effect of magneto resistance will become evident only when the magnetic field is strong enough, strong enough for what? Strong enough to curve the electron trajectory. It needs to curve the electron trajectory within a length equal to its mean free path. So if the field strength is large enough that it can change the motion then the nature of collisions would change and therefore resistance would change because of the applied magnetic field. For example if you see even in pure copper and you go to very low temperatures let's say at 4K and you increase the field up to 10 Tesla and then you measure the resistance then the resistance has been found to vary by a factor of 10.

So it is not a small variation it is a large variation but you can clearly see the temperatures are quite low and the field strengths are quite large. What is the mean free path? If you go back to your gaseous system or kinetic theory of gases the mean free path was the path which was the average of all the path lengths between the collisions. What collisions? So if you take molecules of a gas then they never move in a straight line all along. So you will have the molecules of the gas interacting and if they come very near they enforce a phenomena which is called as collision and then they force the other to deviate from its original path while the atom or the molecule which is enforcing the shift in the path of the second molecule also needs to deviate from its path. This is what we had seen.

So they will change the speed and direction of each other. Now between every two collisions a molecule travels a path length. So you can see before a collision takes place the molecules are traveling a path length. If you take the average of all the path lengths then that is called the mean free path and the resistance of a material is the result of the scattering of electrons out of the direction of current flow because of these collisions. So two molecules coming together in the same direction but they cannot hit each other, they have a distance of closest approach and when that happens when the energy orbitals start to overlap or they are very near to each other and if they are of the same charges they will repel so then they move away from each other's path and then they get deviated and because you are forcing deviation this appears as the resistance.

Now we have to see that why resistance should change when you apply a magnetic field and by the magnitude of the change in resistance owing to the applied magnetic field you will find that there are two classes of materials which have been observed. So if you have change which is large enough to be observed then those types of materials are called as giant magneto resistive materials. But if the change is very large larger than the change observed in these giant magneto resistive materials then just to show that the change is much larger than the giant magneto resistive materials the term colossal was used and those kind of systems are classified under the subheading colossal magneto resistive

materials and the phenomena is colossal magneto resistance. So let us start with giant magneto resistive behaviors observed in certain class of materials. This was first observed and reported around 1988 by the work of Professor Peter Grunberg and Professor Albert Firth from University of Jülich in Germany and University of Paris Sude respectively.

So they were working independently and they were also talking to each other and they reported this kind of phenomena. It was reported that GMR that is giant magneto resistance materials or phenomena is associated with a large change in electrical resistance not because in the change of the electric potential but because of an applied magnetic field just like magneto resistive effect. So large change was observed. The large change in the electrical resistance is induced by the magnetic field in thin films which were composed of alternating ferromagnetic and non-magnetic layers. This was first observed.

Generally when you are seeing the GMR effect it was seen that the decrease in resistance takes place because the field induce alignment of the magnetization of the magnetic layers. And hence the origin of GMR is the dependence of the electrical conduction in ferromagnetic materials on the spin state of the carriers. So this is the reason why one observes the GMR behavior. So GMR phenomena can be observed in three types of configurations. The first where you have alternative layers of non-magnetic and oppositely magnetized ferromagnetic material or you have randomly oriented single domain ferromagnetic cobalt nanoparticles in a matrix made up of non-magnetic copper.

We will see about all these things in the coming slides. And hybrid as I said earlier is a combination of the two. So what it would be? It is basically cobalt nanoparticles in a silver matrix sandwiched between the nickel iron magnetic layers with alternative magnetization. So you have the hybrid systems. Let us start what is the alternate layer configuration to observe GMR? You will have the alternate layers of ferromagnetic and non-magnetic materials.

So you have a magnetic layer, then you have a non-magnetic metal, then you have a magnetic layer and then you have a non-magnetic metal. So what will happen? Now if you want to apply the field and you observe phenomena such that there is electrical conduction. What will you get? You are applying field and then trying to see the flow of current. What will happen? If you have these domains, you have applied a field, a very high field therefore I am taking the pole radius is quite small so that we can apply high fields. Now if the field is in this direction what will happen? The magnetic material which was having the domains aligned in the opposite direction will start to flip in the other direction.

So what will be the condition now? If we draw it you have a magnetic material, a non-magnetic metal, then a magnetic layer and then a non-magnetic metal, then you have a magnet material, non-magnetic metal and a magnetic material. Now the domains in the first was already aligned in this direction. In the third also after the application of the field they will flip in the opposite direction. You are taking a ferromagnetic material please note so

the orientation will flip. Now what you have? You have changed the orientation of the domains and therefore you have changed the way this material is going to oppose the flow of current because there has been reorientation in the domains and hence if this is the case what will happen? You will see certain change in the resistance because of the reorientation of the domains in the magnetic layer which was opposite in the to the direction of the first.

So if you plot $R(B) - R(0)$ by $R(0)$ as a function of B then you will find that the electrical resistance $R(B)$ relative to its original value that is at 0 field and if you take let's say iron chromium system then you will find that you will see a change in the resistance as you go on increasing the field strength. So for example if you go from 0 to 1.2 Tesla then you can clearly see that the change in resistance is quite significant and you have variation which is quite prominent. So what do you get? You get a strategy by which you can reduce the resistance of a system by changing a magnetic field and this is what was observed and this kind of phenomena was called as GMR, giant magneto resistance phenomena because a change was much larger than the magneto resistive behavior which is expected in materials but for that you need to go to very low temperatures or to very high fields but this was being observed at room temperatures at reasonably low fields compared to what is expected to observe magneto resistive behavior and the order of change was very high and this is an example for the iron chromium multilayered systems. So how will the change in resistance occur if you now play with the thickness of the layer? So what are we doing? We are playing with the thickness of the layers.

So you are playing with the thickness of the layers that means how much magnetic material is combining with the non magnetic metal. Ideally it should not change but you will find that the magnitude of change in the resistance actually depends on the thickness of the layer and in this case which you were talking about if you have the iron chromium layer or nickel chromium layer then it has significant modulation and if you plot the change that is ΔR by R_0 in terms of percentage then you will find that as a function of changing of iron layer which is in terms of nanometers. Very very thin layers nano means so very thin layers the change in the resistance is maximum when you are approximately at 7 nanometer thickness. Below that and above that the change becomes less. So this is what was observed and you will find that such magnitude changes were quite large in comparison to the magnetoresistive behaviors.

Can you please tell me or write an answer which we will discuss during the live sessions why there should be variation as a function of thickness in the resistive nature of the material or why the resistance should change as we change the thickness of the layer of the ferromagnetic material. Please note or I will give you a hint it is a very simple answer if you have very very small or thin layer then the material which is sitting over the non magnetic metal is quite low and then the impact should be less and if you have large deposition of this layer then what will happen the changes would be minimized because you are going through a insulating layer to a metal layer and then again the insulating layer. So what you are doing is that you are increasing the insulating layer and so the impacts would again be

minimized. So I have given the hint we will discuss more about this question when we have our live sessions. So what have we seen till now we have seen that the effect is because of the electron scattering on the orientation of the electron spin with respect to the direction of the magnetization.

So as you change the direction of magnetization the electron spin orientation changes and therefore the scattering magnitude and the nature changes. If you have electrons whose spins are not aligned along the direction of the magnetization obviously more scattering will take place and then you will see higher resistance and as you the alignment is in the direction of the magnetizing field then the scattering will be reduced and hence the value of resistance will come down. This is what we had seen in the previous curve also. Now the conduction electrons with spins aligned opposite to the magnetization they are more strongly scattered at the metal ferromagnet interface. So, you have an interface above is the ferromagnetic layer and below is what? Below is the non-ferromagnetic metal.

So this is the interface we are talking about. At this point you will have the conduction electrons with spins aligned in opposite directions they will obviously get more strongly scattered. So, if you have spins of the metal which are aligned in this direction and if the spins of the ferromagnetic layer is in the opposite direction then when they interact at the interface you will see more scattering and you will have higher resistance. Therefore because the two spin channels are in parallel the lower resistance channel determines the resistance of the material. Then comes the next example which was discovered and then you had the observation of magneto resistance in these kind of systems.

We have seen about nanomaterials and how their properties can change when you reduce the size. So if you have single domain ferromagnetic nanoparticles what are we basically talking about? Let us say we are talking about the concepts of elongated grains. So very small particles that is nano sized particles of ferromagnetic system. Now these are randomly oriented in non-magnetic matrix. So you have the randomly oriented ferromagnetic cobalt in the matrix of copper.

So you have copper having cobalt nanoparticles dispersed in it. And now they are randomly distributed. If this is the case you will obviously expect that the field which these nanoparticles are generating they will be in random directions. But still there would be interfaces which would be formed. Now when you have such kind of homogeneous system then what is going to happen that the magneto resistance would be isotropic because it would be similar in all directions and it would be seen throughout the system.

Now in this case let us apply the field. Let us apply the field. What will happen? The DC magnetic field will rotate the magnetization vector of what? Of the ferromagnetic nanoparticles and it would make them align in the direction of itself. That is the ferromagnetic nanoparticles will have to align in the direction of the field. This would do what? The consequence would be that this will lead to the reduction of the resistance

because the spin vector would be made to align in the direction of the field and then the resistance of the system would be much lower.

So you can have isotropic phenomena. So the logical way forward would be to make a system which combines the advantages of both the examples discussed earlier and that led to the discovery or fabrication of hybrid systems. So, what are hybrid systems? They are consisting of nanoparticles in metal matrices sandwiched between metal magnetic layers. So you had the nickel iron layers and cobalt dispersed in silver layers sandwiched between the other nickel iron layer. You can see the direction of magnetization in these layers were opposite to each other. Now you can combine the advantages of both the systems discussed earlier and obtain large change in resistance by modifying the applied magnetic field.

Let me ask you a very simple question. How can you make new GMR materials or combinations? Obviously answers are very simple. Make new matrices having different dispersed ferromagnetic nanoparticles. This is one thing. Then vary the thickness of layers.

Then vary the size of the nanoparticles. For example, you can go from let's say 5 nanometers to 100 nanometers. If you move let's say even at a step of 5, so you go from 5 nanometers to 10 and then you reach up to 100 nanometers. You have nearly 20 combinations which you can have. So you make 20 new types of combination and you can have these being used in matrix configuration and you get new types of GMR materials or response. Now you have these materials but you change the nature of the matrix.

I don't want to disperse this in copper. You disperse in some other metal. Then the response character will change. Along with that now you use different combinations to combine it in a hybrid system. You will get difference in the response characteristics. So it is a very easy method to obtain new GMR materials by changing the combinations and because of this the phenomena of magnetoresistance is still extensively investigated.

You can still devote lot of time to develop new alternate layer model based GMR, matrix model based GMR or hybrid system models which combine these two. So I hope you have seen that the lecture has covered various magnetoresistive materials and we will be talking about the application of these materials in the next lecture in detail. These are the references which you can follow to obtain more information. I thank you for attending lecture 1 of week 8. Thank you very much.