Materials Chemistry
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Module - 5
Lecture - 3
Spintronic Materials II Giant Magnetoresistive Materials

We have come to the second lecture of module 5. In the first lecture, I discussed with you along the same lines of, how a material can drop in resistance, specially in a rare earth oxide such as lanthanum manganite. How this particular unit cell displace a unique property of both becoming ferromagnetic as well as becoming metallic from a non magnetic, and insulating state. I call this as a genie inside the lattice, because two things are operative in a same single lattice. Now today, I want to talk along the same lines of loosing resistance in a different class of compounds called metallic multi layers.

And the way the material looses the electrical resistivity brings a unique nature of giant magnetoresistance, which can be used for a variety of applications. To draw your attention more, this metallic multi layers are presently used in our computer read heads, and it has brought about a tremendous revolution in the magnetic storage system. So, quickly let me go through, and tell you about the last lectures brief.

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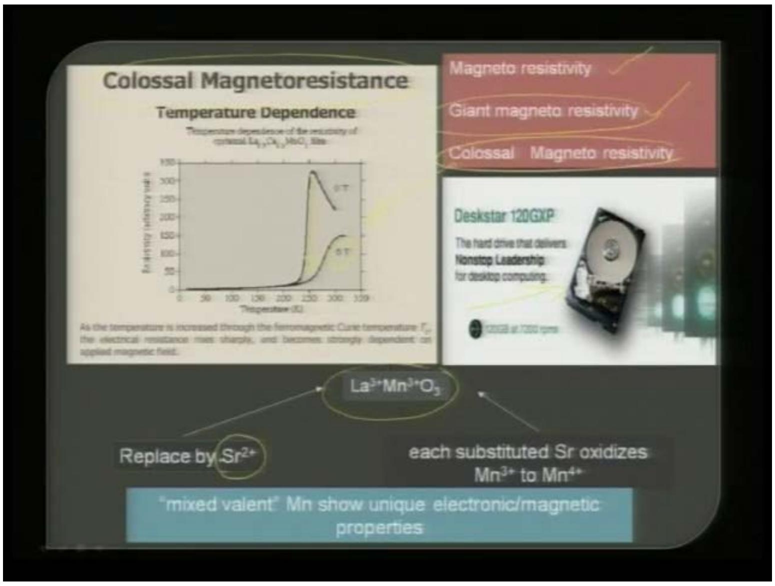

Here, we told that, the CMR oxide or Colossal Magneto Resistive manganese shows loss in resistance at the curie temperature, if you apply a very high field and this can be used for magnetoresistivity or giant magnetoresistivity or colossal magnetoresistivity. It is mentioned in different ways, and by enlarge colossal MR is referred to manganites, whereas giant magnetoresistivity is actually referred to multi layers. Now, this is the application that I drew your attention to that, it can be used as a read head and you can also write information using this sort of devices. So, the compounds, which show similar property, colossal MR property is compounds based on LaMnO 3, when substituted with strontium, barium or copper.

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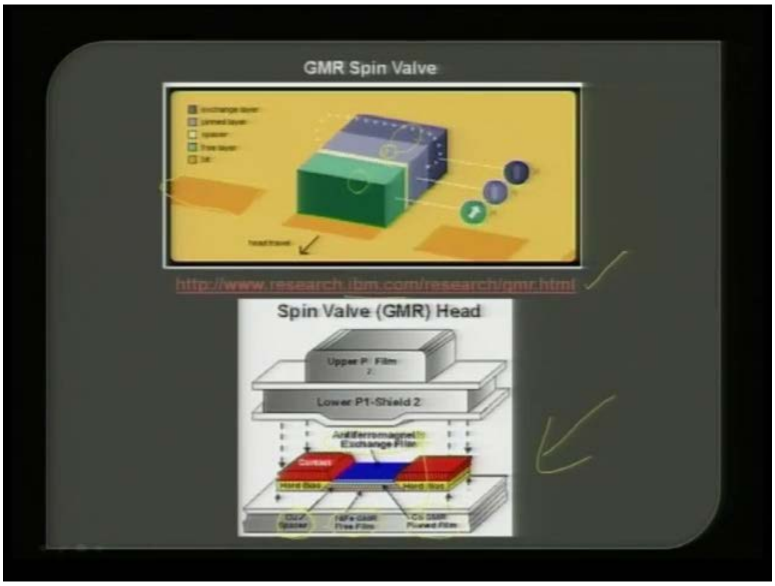

Now, what is important as per as the metallic multilayers are concerned, this is a typical multilayer that is made and it is presently used in our computer hard disk. And if you want to see the animation of this, you should visit this website, this is displayed in i b m dot com website, where they will show you, how the resistance varies with information and how that can be used for reading magnetic information. In this device, you would see, this is a bit that has to be read, we have a free layer which is this one.

This is a free magnetic layer and then you have a spacer layer in between and you have a pined layer, this is also a ferromagnetic layer, but this is actually pined to the exchange layer or antiferromagnetic layer. This is also shown in this viewgraph, where you have the copper spacer and you have the GMR free film, nickel iron which is called permalloy and this is there on the top and you also have cobalt, which is actually pined to a antiferromagnetic exchange film.

So, when you have a ferromagnet and a ferromagnet divided by a spacer and this ferromagnetic layer is actually pined by a antiferromagnet then this top layer alone is free to rotate. I will come to the physics of it later, but what happens is, in such a device system, the reading capacity of this head becomes much, much faster than the magnetoresistive head that is used now.

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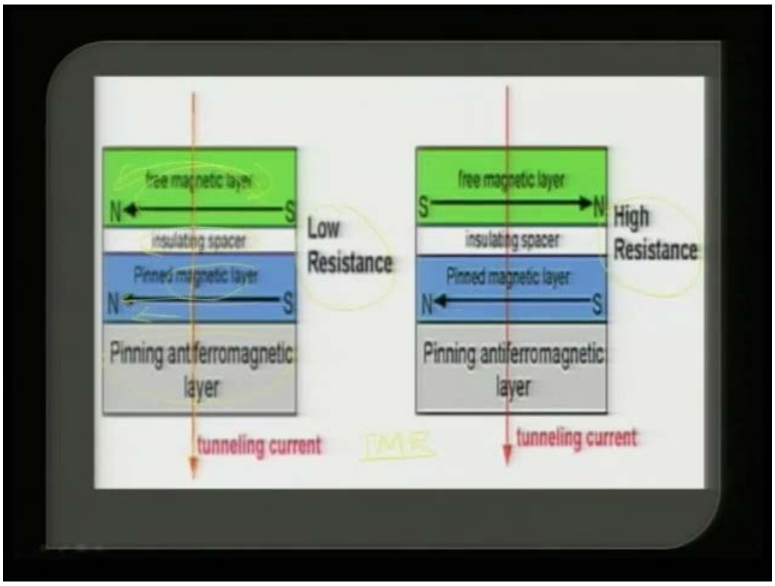

So, the implications are phenomenal, same thing you can do, you can pin with an antiferromagnetic layer, a magnetic layer. Therefore, this moment will be fixed, this magnetic moment is fixed and then you have a instead of copper in the previous case, you can put a insulating layer. If you can pin this magnetization in this direction then when you apply magnetic field, the magnetic field can either rotate this, in this direction or it can rotate in this direction.

So, this is free to rotate depending on the field of magnetization and in such case, when the moments of this ferromagnetic layer and this is aligned then the electron that is flowing across this layer will easily tunnel, whereas in this case, because these two ferromagnetic layers are in opposite direction then the tunneling of this electron becomes difficult. As a result, you have a high resistance case and a low resistance case, we will come to this later, this is called TMR devices, Tunneling MagnetoResistance. In the previous case, we talked about giant magnetoresistance, both have tremendous application.

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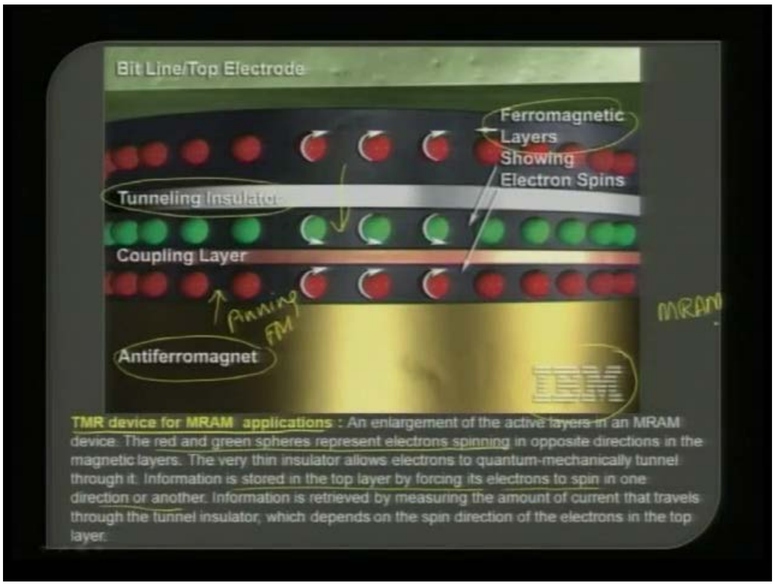

And this TMR device is actually used for magnetic random access memory devices, which is a major break trough in today’s technology. Because, an enlargement of the active layers in MRAM device is actually shown here and this is exactly the way a MRAM device look like, where you have a antiferromagnet and this is actually pinning. This is pinning a ferromagnetic layer, whose electrons have the pin in this direction and then you have a coupling layer like this and then you have the other ferromagnetic layer here.

So, you have the ferromagnetic layer and the antiferromagnetic layer, which is actually pinning then you have a tunneling insulator and then another ferromagnetic layer on the top. So, this is the way a MRAM device is actually used in IBM, the red and green spears represents electron spinning in opposite directions in the magnetic layers. The very thin insulator allows electrons to quantum mechanically tunnel across this interface and information is actually stored in the top layer by forcing it is electron to spin in one direction or other.

So, this is the free layer, where the flip can either be clockwise or anticlockwise, depending upon the configuration and depending upon the magnetic field direction. So, this is one of the major development in the magnetic storage, where thin layers of ferromagnetic metals are actually stacked across a nonmagnetic layer or a insulating layer, I will come to the details of it later.

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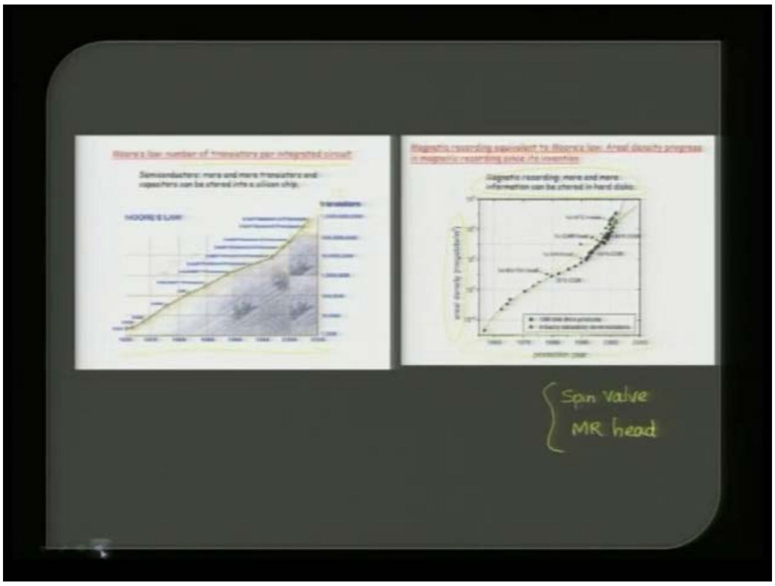

Now, according to Moore’s law, number of transistors increases per integrated circuit, as a function of the number of years. So, if you see, the transistors that can be accommodated in the integrated circuit has almost linearly increased and this is called Moore’s law. So, you can actually have hundreds and thousands of transistors stacked in a integrated circuit now and this is bound to keep going in the future years. The same analogy can be extrapolated for magnetic recording, which is also equivalent to Moore’s law.

The aerial density actually is keep increasing with the years, it is almost you see a linear dependency. Therefore, magnetic recording, more and more information can be stored in the hard disk, because you have a powerful read head memory device now and the current memory device that is used by IBM is called spin valve MR head. If you have opportunity, you can visit the IBM website to understand, how these multilayers are used to improve the aerial density. So, this is bound to bring lot of revolution into the magnetic recording market.

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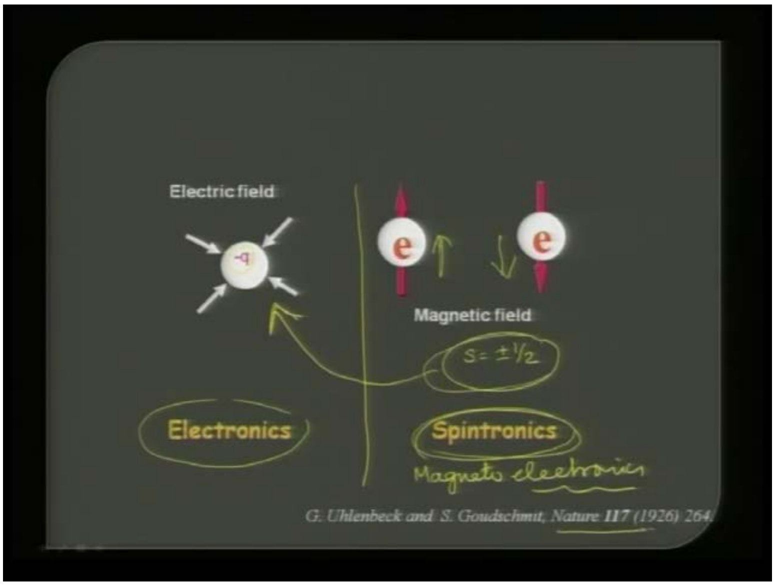

Now, what is fundamental to this application is, in the case of electronics, so far people have worried more about the charge. Charge and number of charge are very important for a semiconducting industry, whereas if you look at another missing link in this whole application, is the spin part of the electron. Electron has spin, either plus half or minus half and this spin actually can control the charge of the electron. So far, the spin part is actually forgotten, electronic industry has exploited the issue of charge, number of charge carriers.

But, never it has bothered about controlling the charges or the mobility of electrons with respect to spin part. Therefore, if you apply a magnetic field then either it will be up spin or down spin and depending upon the population of electrons that you are going to force then you can modify the electronic part. So, that is what is called as spin electronics or spintronics, it is also called as magneto electronics, because you are trying to control the electronic property using magnetic field. And this was actually proposed, the issue of spin part was proposed as early as 1926.

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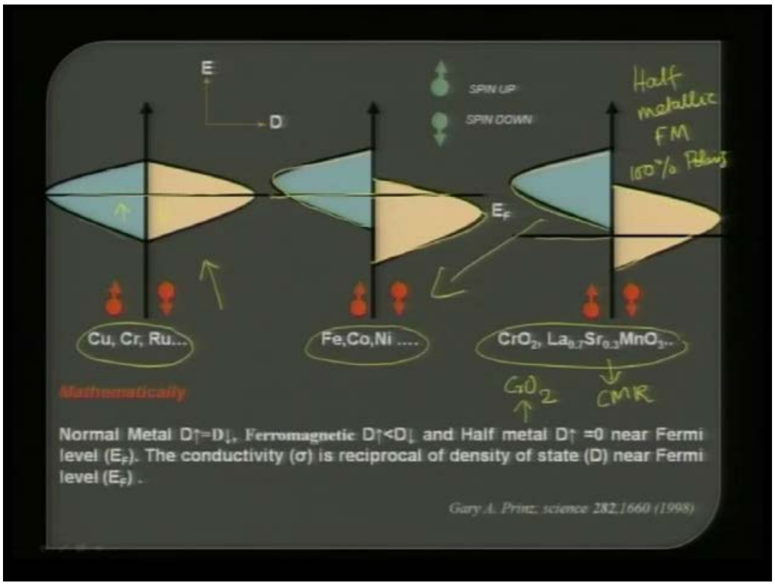

Now, if you take any metal in the periodic table, you can easily classify, whether it is a non magnetic metal or whether it is a magnetic metal or it is a ferromagnetic metal. Now, in the case of copper, chromium, ruthenium, we know that it is a metal, but not a ferromagnetic metal, why, because you have the number of up spin electrons and the down spin electrons, they are exactly having the same sub bands, spin bands across the Fermi level.

So, because they are equal then this can be actually called a nonmagnetic metal, because the number of up spin electron cancels the number of down spin electrons, therefore, there is no net ferromagnetic moment, there is no net magnetic moment. Whereas, in the case of iron, cobalt and nickel, as we saw in the first module, the whole thing can be explained based on molecular orbital theory, where you can see the spin up band has the spin band like this across the Fermi level and the spin down band has across the Fermi level band, which is lower than the spin up band.

As a result, there is a net moment, which makes this material ferromagnetic, now if you look at these compounds, chromium dioxide which is actually used in video tape and this is the colossal magnetoresistive CMR oxides. One of the interesting feature is, one of the spin up band here is actually well above the Fermi level and what matters finally is, the spin down band, which is cutting across the Fermi level. Therefore, the conduction can actually come from one of the spin bands, which is completely devoid of the Fermi level.

In such case, this is called as half metallic ferromagnets, this sort of magnets have 100 percent polarization compared to the traditional ferromagnets.

These ferromagnets have 100 percent polarization, because in one of the configuration, the spin up band is actually 100 percent spin polarizing. So, this can be used for the GMR or CMR applications, so this is very important as we think about, what sort of material you want to use for tunneling magneto resistance. Because, if you want to tunnel the electron then if it is actually 100 percent spin polarized then it can easily tunnel, because there would not be any scattering process across the interface.

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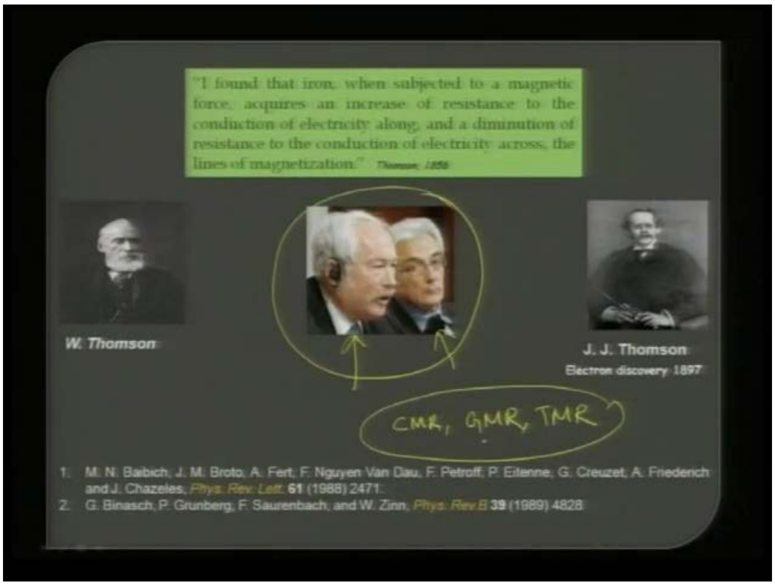

Now, I will have to register this issue that, the whole idea of CMR or GMR or TMR, all this came to prominence, because of the discovery of magnetoresistance by these two gentlemen, this is Albert Fert from France and this is Peter Grunberg from Forschung center Mulisch. Both of them found out that, there is a strange coupling mechanism happening, if you can maintain these metallic multilayers in a very, very thin dimension.

And they found, there is a huge response when you measure such stackings, when you measure the electrical conductivity. And they found, there is a huge loss in resistance in the presence and absence of field and that is what brings to effect the GMR spin valves, now what really they did.

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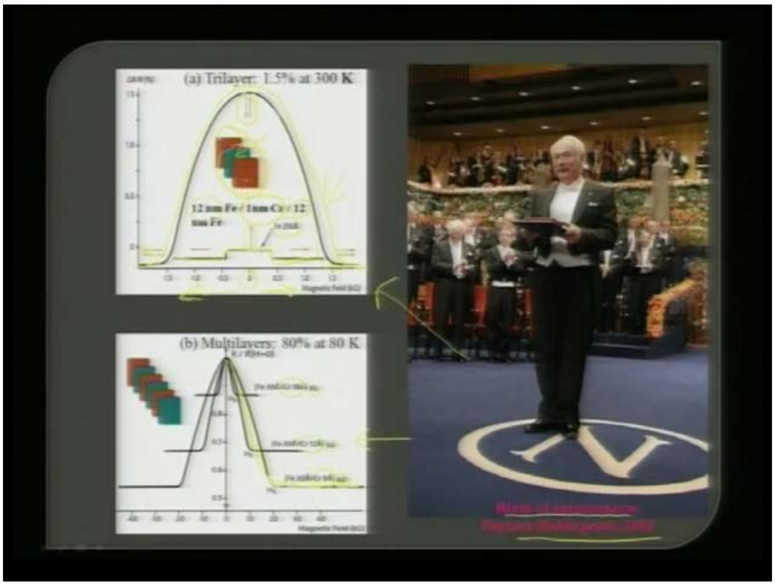

This is Peter Grunberg, who is receiving his Nobel prize in 2007, which marks the birth of spintronics. Also, I should say, because they emphasized on thin magnetic or nonmagnetic layers as small as 1 nanometer, the issue of nano technology became more prominent after the discovery. Now, what did Peter Grunberg report, in his report he said, if you take only iron of this dimension say, 250 nanometer and if you measure the resistance as a function of magnetic field in both directions, you see a very small change in the resistance, which is called anisotrophic magnetoresistance, which is of very low order.

Whereas, if you now separate the same amount thickness of iron, but you divide it as 120 nanometer 120 nanometer of iron and you put one single small layer of chromium, which is only 1 nanometer in this form then you can clearly see, this same feature which is supposed to be there, is now a more pronounced feature like this. So, what happens, when there is zero field here, when there is zero field, these two ferromagnets are actually anti parallelly they are coupled, they are antiferromagnetically coupled.

But, they are not actually antiferromagnets, the way they are coupled is of the opposite form, therefore we call this as a antiferromagnetic coupling. Now, as you sweep the magnetic field in both directions, you see that these two moments get ferromagnetically ordered in this fashion and at that point, the resistance is really low. And the same way, it happens if you flip it to the other direction, therefore there is a tremendous fall in resistance, as you sweep the magnetic field.

Suppose, you can keep reverting this at a very low field then it becomes a real magnetic switch. So, Albert Fert actually brought out this notion, he said I can try to make several of these bilayers, several of these bilayers instead of, just a trilayer and everywhere, I will try to change the spacer layer thickness, so that is what he did. If you have chromium as 1.8 nanometer or 1.2 nanometer or 0.9 nanometer, as you bring down the spacer layer smaller and smaller, you can see there is a tremendous fall in resistance and also the field sensitivity is quite bright compared to even this example.

So, if you make such bilayers repeats of 30 angstrom iron and 9 angstrom chromium and if you makes repeats like 60 times or 30 times like this then you see a tremendous fall in resistance. And that makes the application much more prospective, where you can now look for 0 1 switch. So that, you can write and read the magnetic information as a 0 1 bit, so this is the birth for spin electronic applications.

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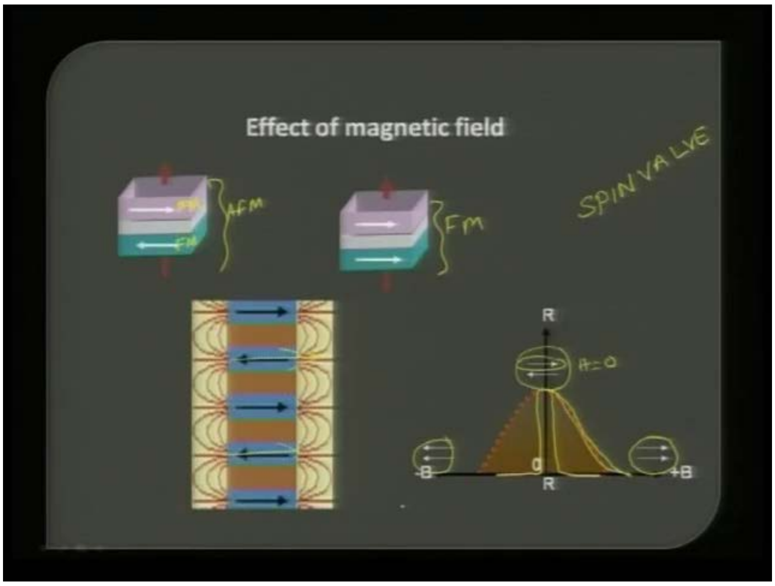

Now, what really happens is, this carton tells you that, if you have this ferromagnetic layer aligned in this direction and this ferromagnetic layer aligned in opposite direction, they are antiferromagnetically coupled, whereas in this case, they are ferromagnetically coupled. Now, in both case, you will see, when they are antiferromagnetically coupled then they have a different resistance, that is what we show here. Bu,t once you force with the magnetic field in this direction, all these antiferromagnetically coupled layers, they also go ferromagnetic.

So, as a result, you have a low resistance state and a high resistance state at H is equal to 0, which is important for magnetoresistive property. But, what is needed is, this saturation cannot take so much time, it has to saturate very sharply for applications, then only you can use such materials for 0 1 bit reading or writing. Otherwise, if you takes too much of a field saturation then that cannot really act as a very good device.

So, to transform this, people have made several structures and they have made something called spin valve, where the top ferromagnetic layer is more like a valve and the bottom ferromagnetic layer is actually pinned to a antiferromagnetic. So, even with small magnetic field like valve, you can rotate the moment of the top magnetic layer, so that is the technological challenge.

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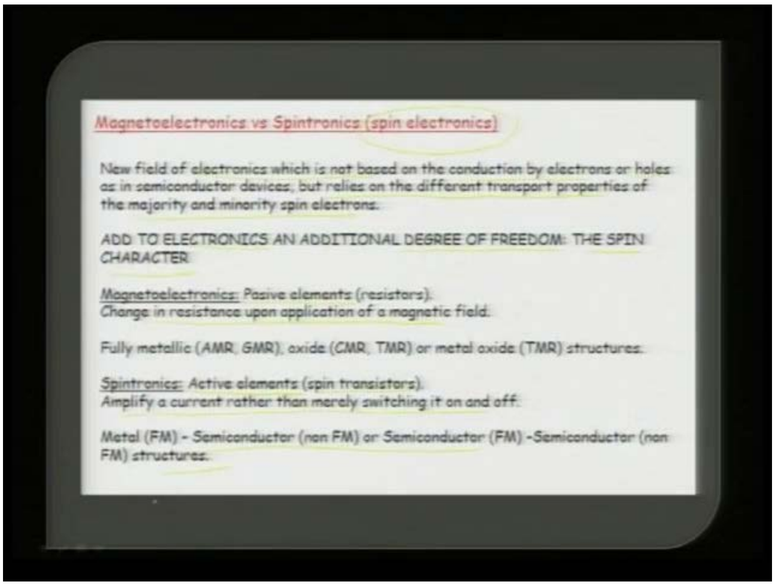

L et me run through some of the issues just to register that in your memory, this new field of electronics, which is not based on conduction of electrons or holes, but relies on the different transport properties of majority and minority spin electrons, actually forms the bases for spin electronics. Add to electronics, an additional degree of freedom, that is the spin character, so you are actually using the spin of the electron for governing the electronic properties.

So, in magneto electronics, you actually have passive elements which are resistors, change in resistance happens upon application of magnetic field, whereas in spintronics, you actually have active elements, which are spin transistors, this amplify a current rather than merely switching it on or off. So, what are such characters, you have a metal ferromagnet, semiconductor, non ferromagnet and then you also have a ferromagnet. So, this sort of structures can actually bring about the spintronic applications.

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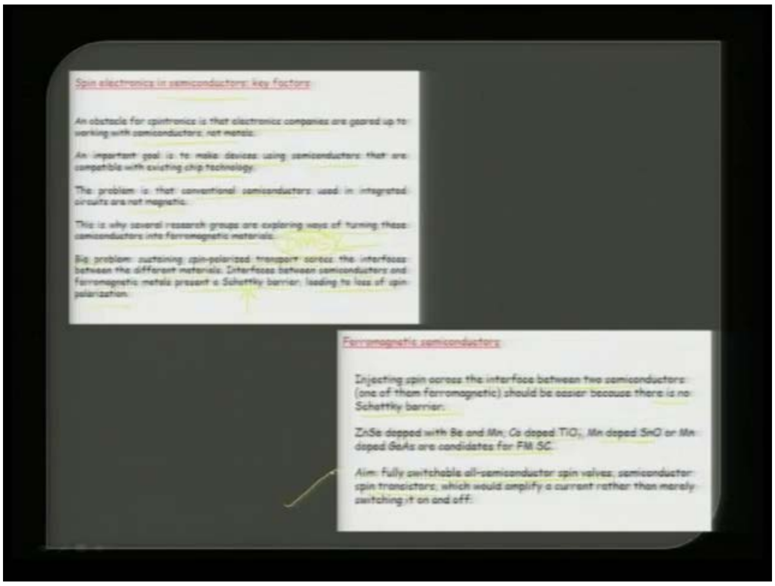

Another key factors that I want to emphasize is, spin electronics in semiconductors are also possible and obstacle for spintronics is that, electronics companies are geared up for semiconductors. They are traditionally, they know how to handle a semiconductor and to run the industry without any interruption. And important goal is to make devices using semiconductors, that are compatible with existing spin technology, chip technology.

The problem is that, conventional semiconductors use in integrated circuits are not magnetic, this is why several research groups are exploring ways to tune the semiconductors into ferromagnetic metals, which we call it as dilute magnetic semiconductors. So, another field apart from tunneling magnetoresistance comes into picture, which is called DMS field, where they want to retain the semiconductor technology.

But, just do a careful manipulation so that, you can make the semiconductor magnetic so that, you can tune the electronic properties, now controlling the spin part of the semiconductor. The big problem here is, spin polarized transport across the interfaces between different materials, because interfaces are very sensitive between semiconductors and ferromagnetic metals, presently they induce a Schottky barrier, that is leading to loss of spin polarization.

So, one has to overcome this Schottky barrier, which is the challenge if you want to realize DNA situation here. Ferromagnetic semiconductors injecting spin across the interface between two semiconductors, one of them ferromagnetic should be easier, because there is no Schottky barrier. ZnSc doped with beryllium, manganese or cobalt doped with TiO 2, manganese doped with SnO, they are all candidates for ferromagnetic semiconductors. What is the aim, you fully switchable all semiconductor spin valves are possible, semiconductor spin transistors are possible. So, there are tremendous scope that is lying, if we can generate newer materials.

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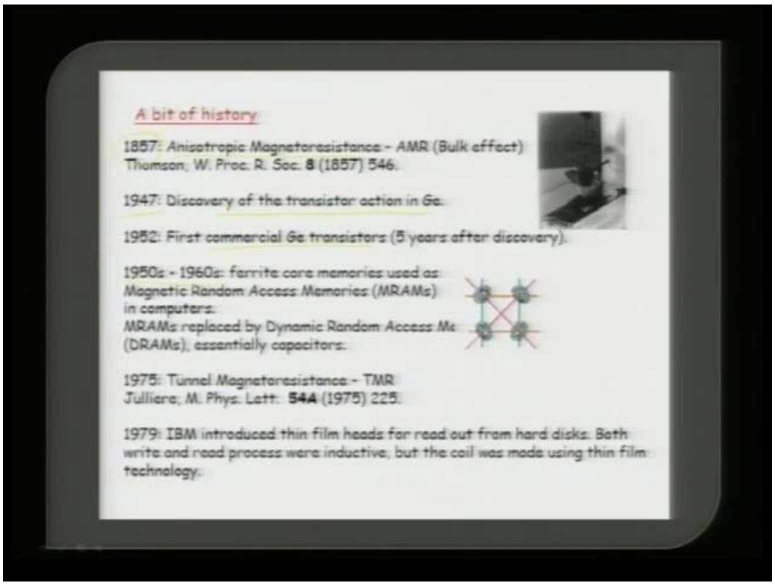

A bit of history in the anisotropic magnetoresistance was reported as early as 1857 and in 1947, there was a discovery of transit action in germanium, 1952 germanium transistors were discovered then 1950 and 60s, this random access memories in computers were broughtin in USA. Then 1975, first time a tunneling magnetoresistance response was reported by Julliere and 1979, IBM introduced thin films head, which is called MR read heads, which started coming and affecting the memory storage and that is where, we saw the computers coming into every home.

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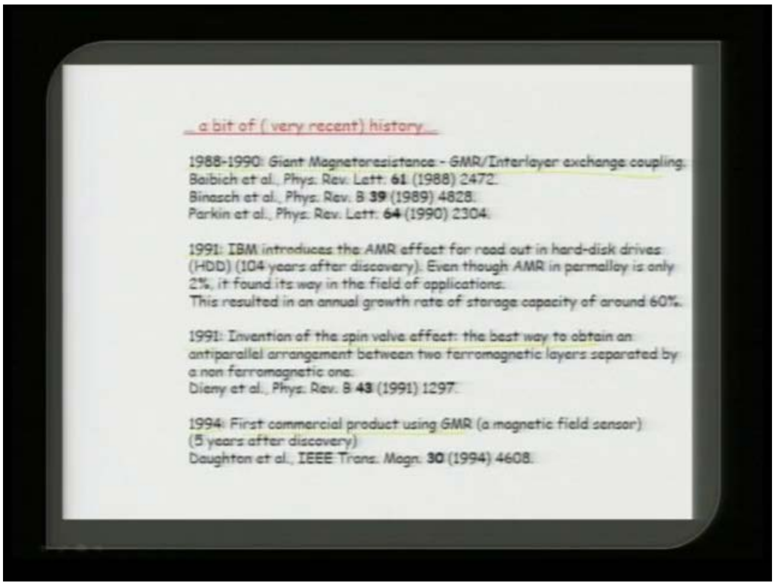

And a bit of very recent history, 1988, 1990, GMR was reported by both this Nobel laureates and 1991, IBM introduced the AMR effect for read out in hard disk drive. And 1991, the spin valve effect was also recognized, 1994 first commercial product using GMR, a magnetic field sensor was brought in.

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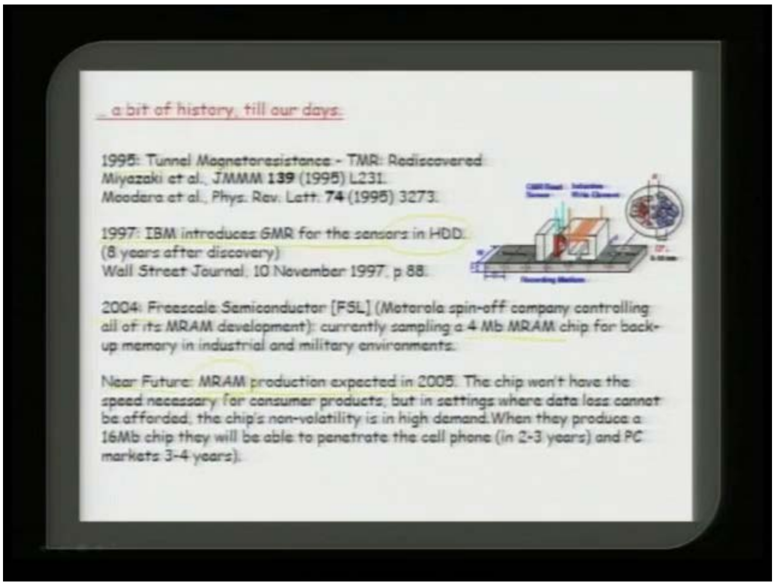

And a bit of history till our days, 1995 tunnel magnetoresistance was rediscovered and in 1997, this is the most important stuff GMR, using GMR property, IBM brought it is first hard disk drive. And in 2004, we have free scale semiconductor, they currently sampling a 4 megabit MRAM chip for back up memory in industrial and military environments. In near future, you have MRAM production expected in 2005, which is already set into action. Now, in 2010, we have a generation of MRAM devices, which are coming into market. This was actually a forecast several years back, but this is actually turning out to be a reality in 2010.

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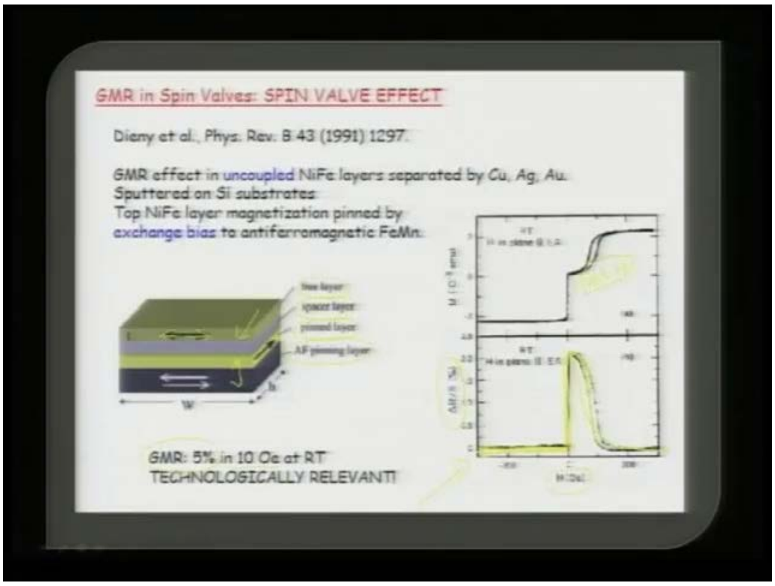

Now, GMR in spin valves is typically of this nature. I have already shown you a cartoon impressing upon the importance of it. So, you actually have a antiferromagnetic pining layer, which is pinning a ferromagnetic layer, therefore that moment is fixed. And then you have a spacer layer and a free layer, this free layer can rotate either this way or it can rotate this way freely, changing the overall resistance of the device. So, typically if you want to look at the device, the device will have a hysteresis, M versus H hysteresis like this, where in one direction you see the loop and the other direction is actually pinned.

If you measure the resistance as a function of field, you can see, when this ferromagnet is actually pinned, it is coming this way and then this free layer can rotate very sharply. In other words, you can achieve saturation in even with 10 or 20 Oersted, because this is a free layer and this can easily rotate to align in the direction in which it wants. So, you can get this field sensitivity in spin valve device, which is of fundamental importance for technological applications.

And in this cartoon, what we see here is GMR upto 5 percent, at just 10 Oersted, which is less than the field that is generated by the magnets, which we try to put on the refrigerator. So, even with such a low magnetic field, you can actually make this switch operate, therefore it can be used for a magnetic sensor applications.

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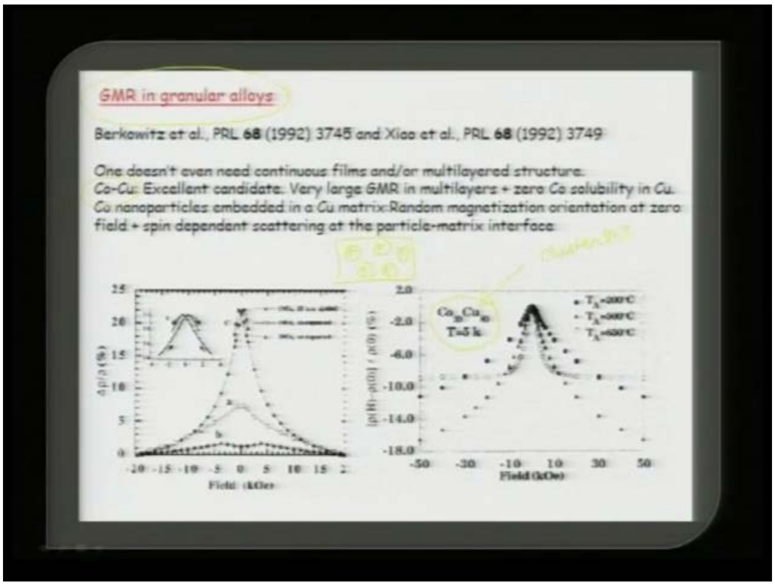

GMR can also be found in granular alloys, granular alloys means, those which are like cobalt, copper. If you co sputter or co deposit cobalt and copper, you would see that, cobalt and copper are not miscible. So, in a copper matrix, cobalt will actually form a cluster like stuff, instead of forming a continues layer, cobalt will form clusters. And depending on the cluster size of this cobalt in copper matrix, you can see resistance varying and that is what you see here.

This is cobalt in copper and you can see as a function of temperature, the magneto resistance changes. And also one can change the GMR property based on the cluster size of cobalt metal, so this is another way, GMR property can be exemplified. Now, let me tell you briefly, what really makes this useful for magnetic read head applications.

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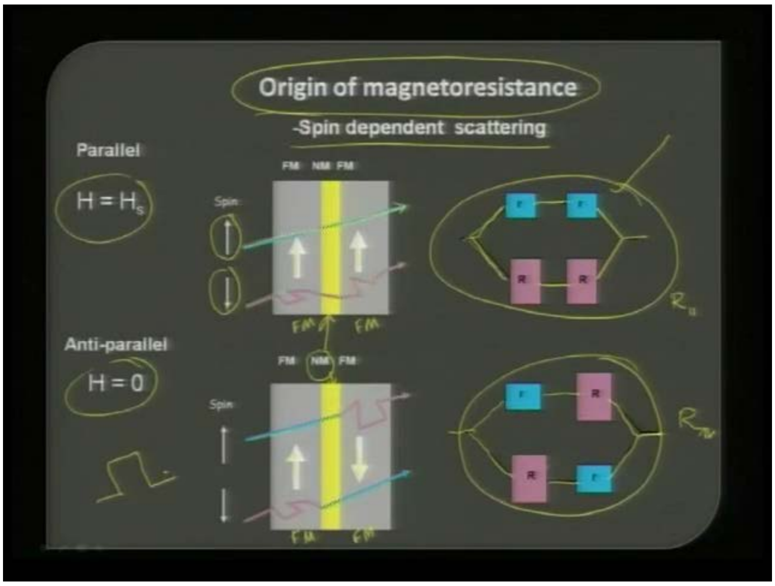

This is origin of the GMR and the principle that acts in this GMR is called spin dependent scattering, spin is getting scattered at the interface between a ferromagnet and a metal, and a metal and a ferromagnet. So, we can look at this situation in the following way, there are two models given, in these two models you see, in this model, this is a ferromagnet and this is a ferromagnet, where the moments are aligned in same direction. And in this, it is a ferromagnet, this is a ferromagnet and it is aligned in opposite fashion and this is the nonmagnetic layer, which is a metal.

Now, you have both situations of a spin up electrons spin down electron, spin up electron when it is going from this layer to this layer, as you are measuring the current you see, because these two are up spin in this direction then there is no scattering, it will just go cross this interface. Whereas, this spin down will get scattered little bit here and then it will go through, again it will get scattered here. So, if you try to translate this to a resistivity model, for the spin up, there is low resistance path way, which is like this.

But, for a spin down, the resistance path way actually comes out like this, which is bigger, because in both cases it is getting scattered, therefore resistance in this form is a high resistivity issue. So, in one case, you have a low resistance and in other case, it is a higher resistance, whereas when you come here, for spin up, it gets easily to this stage and then it gets scattered here. Therefore, you have a lower resistance and a higher resistance, same thing happens for the spin down also, here it gets more scattered and then it gets easily transmitted.

Therefore, if you draw this resistivity model then you see in both cases, there is higher resistance in either way. Therefore, in overall if you see, this resistance is going to be very high compared to this, this resistance when the ferromagnets are aligned antiparallel, in this case ferromagnets are aligned parallelly. So, what happens is a short circuit, therefore resistance is lower when these two are ferromagnetically aligned.

And when they are ferromagnetically non aligned, they are antiferromagnetically aligned then you have a higher resistance and that is what is called GMR or Giant MagnetoResistance, in the presence of field and in the absence of field, you see difference. So, when magnetic informations are actually to be read, you have a low resistance case or a high resistance case, which can actually flip as a 0 1 0 1 bit and this property is, what is important for reading magnetic storage.

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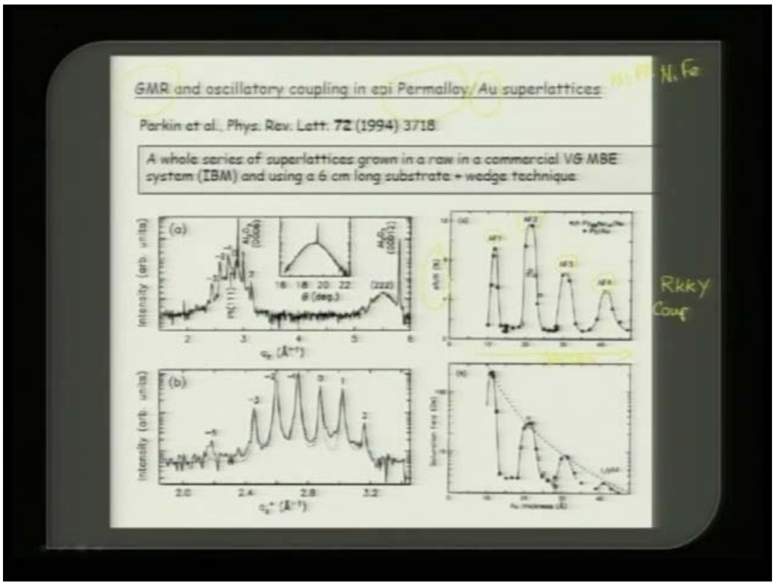

One thing that we need to understand, if you want such GMR property to be there and if this is purely a spin dependent scattering then I will come to the previous one once more. So, if this has to go through without scattering, this interface has to be very, very sharp, there should be no roughness. If there are physical defects also, scattering will occur, therefore you need to know how to make thin layers like this.

So, spin dependant scattering is one of the important issue and the next issue what we see here is, as you increase the layer thickness of the spacer, in this example it is gold, which is used has a spacer layer. And permalloy, which is nothing but nickel iron, I will write it here, nickel iron is the permalloy and in this case you can see, as you vary the thickness of your gold spacer layer, the magnetoresistance varies like this, like oscillation. What does it mean, at some thickness it is showing GMR property, at some thickness it does not show GMR property.

So, you can see several maxima is coming, antiferromagnetic situation 1, antiferromagnetic situation 1, antiferromagnetic 3, antiferromagnetic 4. So, if you keep on increasing the layer thickness of gold, you should actually see more and more of GMR or lesser and lesser of GMR happening. But, what happens, suddenly you see maximum GMR and then there is no GMR property and then there is GMR property and then it comes down, so keeps on varying as a oscillatory fashion.

And that is because of the physics involved in it, which can be interpreted based on RKKY type of coupling. Therefore, this is very important, so you need to know, what is the thickness of the nonmagnetic layer, that you are depositing. So, this thickness of the nonmagnetic layer is oscillatory, it can show maximum GMR at 2 nanometer, but at 4, it may not show at all and at 8 nanometer, it might show again. So, that is purely because of the exchanged coupling, which can be explained based on RKKY type of stuff.

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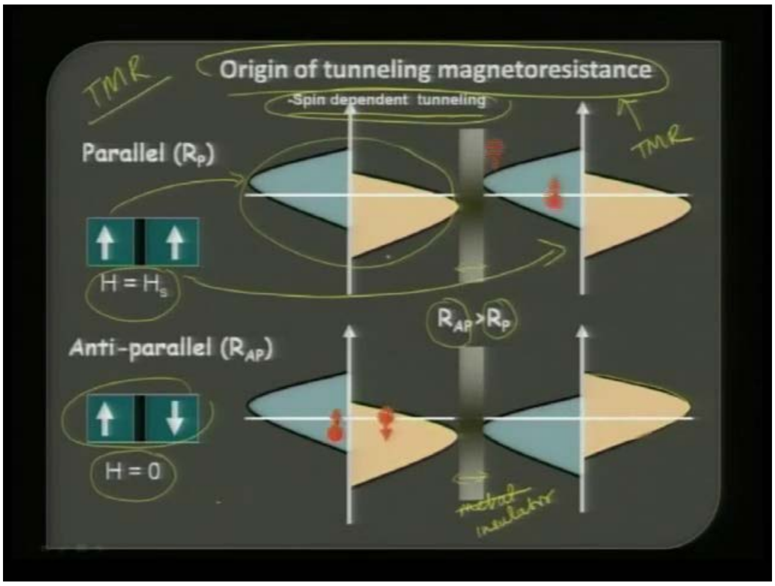

I will come to this issue of origin of tunneling magnetoresistance in a few minutes from now. So far, I told you about the origin of giant magnetoresistance in metallic multilayers and the issue that I have emphasized there is, that of spin dependence scattering. Therefore, when you make such very thin films, the interface has to be extremely flat, otherwise the electrons can get scattered, not just by the moment, but by the interfacial roughness.

Therefore, maintaining such flat layers is very important, for which people use molecular beam epitaxy as a very convenient tool to make such flat terraces. And if you are wanting to know, whether your material is flat enough then you use scanning tunneling microscopy to study, whether it is atomically flat. The other origin of TMR device, which we call it as tunneling magnetoresistance, this is not only based on interfacial scattering, but it is based on spin dependent tunneling, where the spin sub bands of the ferromagnetic layers and this ferromagnetic layer is very important.

The spin sub band of this ferromagnet and the spin sub band of this ferromagnet is important, so let me take it out. So, this spin sub band represents that of the ferromagnetic layer here and this spin sub band determines that of this one. So, when two ferromagnetic layers are aligned then the spin sub bands are also same, so what would happen, the up spin electrons can easily hop to this one and same is true for the down spin electrons, they will happily go across the insulating layer.

In this case, this is a small barrier, it will tunnel through the small barrier to the other ferromagnetic layer and this is the situation when you apply a magnetic field. Suppose, you do not apply a magnetic filed, H is equal to 0 then you would see that, this up spin electron is going reluctantly to this spin sub band, because they are antiferromagnetically coupled. As a result, the position of this up spin band here is different from the position of the up spin band here.

So, energetically they are not favorable, therefore it is going reluctantly, same is true for the down spin band. In this case, it is positioned here, whereas in this case, it is positioned here, therefore energetically it is not favorable, in both cases, you see a reluctance in the transfer of the spins up or down spin. As a result, in the antiparallel configuration, resistance is greater than the resistance in the parallel configuration and this is not based on the spin interfacial scattering, this is based on spin dependent tunneling.

And one more thing that is important to note in TMR devices, this should not be a metal, this should be a insulator and this insulator should be thin enough so that, this quantum mechanical tunneling can be effective. So, this is called as Tunneling MagnetoResistance TMR and this property what is happening here, is a spin dependent tunneling.

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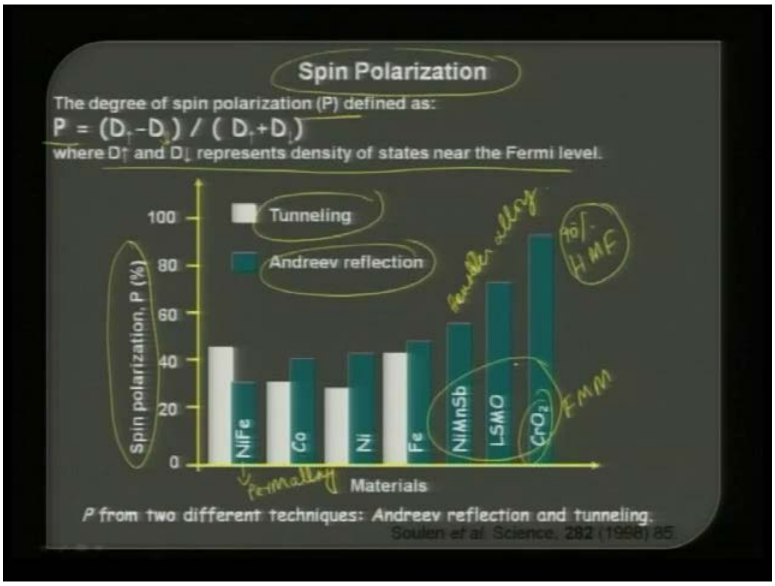

If we have different spin bands then the first question that I would like to know is, what is this spin polarization of this ferromagnets what I am using. And the definition for this spin polarization is, spin density of the up spin states minus density of the down spin electrons divided by the density of the up spin plus density of the down spin, where D plus and D minus represents a density of states near the Fermi level. Now, to measure this spin polarization, there are two methods, one is tunneling technique and the other one is Andreev reflection method.

In both cases, we can try to measure the spin polarization of the ferromagnets what you are using and for example, this is permalloy, nickel iron permalloy. In case of tunneling experiment you see, spin polarization upto say 40 percent, whereas in the Andreev mode, you see it is around 35, same is true for cobalt and you can measure for nickel, iron. And you can measure for nickel manganese antimony, this is called a Heusler alloy, Heusler alloy or lanthanum strontium manganites, that also shows upto 75 percent of spin polarization.

But, the best one to show is CrO 2, which is a ferromagnetic metal, which seems to show spin polarization upto 90 percent or so because it is a half metallic ferromagnet. So, these are good candidates for using this as a electrode for tunneling magnetoresistance devices. So, one of the important criteria is that, one of the spins should be a majority spin and if it is 100 percent spin polarized then tunneling magnetoresistance can be more pronounced for such applications. There are other several other models or several others trilayers, which have been tried.

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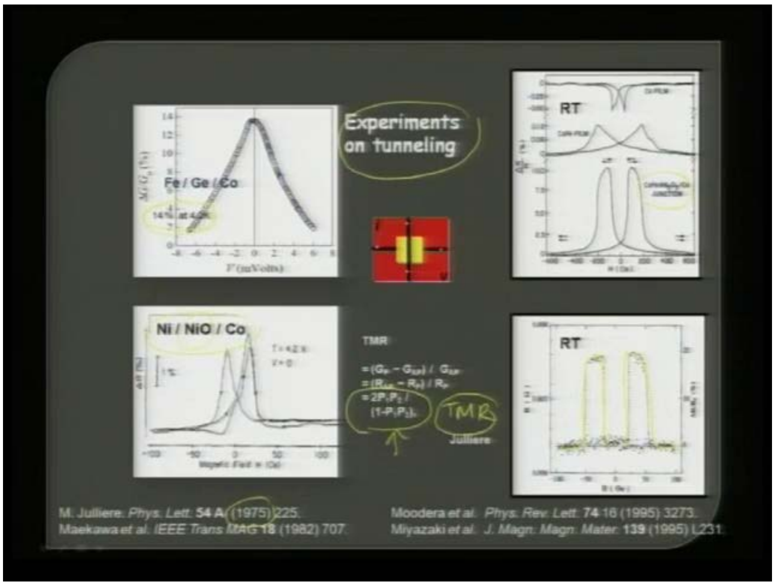

There are experiments on tunneling for a very long time, as early as 1975 Julliere, he found that in iron germanium cobalt, you can get upto 14 percent at 4.2 K. But, this is interesting, because he was the first one to report the tunneling magnetoresistance, nevertheless the numbers are not very attractive, because you have to get this sort of huge values at room temperature. Now, there was another report, where they have used nickel, nickel oxide is a antiferromagnetic compound which is a insulator and nickel cobalt layers show magneto resistance like this.

And TMR is actually tunneling magnetoresistance, which is explained in terms of spin polarization as 2 P 1 P 2 by 1 minus P 1 P 2, that is the order of TMR and this P 1 P 2 is the polarization of the first electrode and the second electrode. So, the TMR values entirely dependents on the spin polarization more than the thickness of the metallic layers. Because, that thickness becomes more prominent for giant magnetoresistive devices, for a TMR devices, it is the polarization which is more important.

You can also get very nice TMR response, if you actually have a permalloy alumina cobalt junction, where alumina is used as a tunneling barrier, because alumina is a very good insulator, so it is possible to get TMR devices like that. And this is again another example, where you can clearly see that, there is a very nice saturation for a spin valve junction operating on a TMR property. So, you can actually get this sort of a response, if you can try a variety of trilayer or a bilayer devices. In a typical TMR device, you can see how many magnetic signatures happen if you record the magnetic hysteresis.

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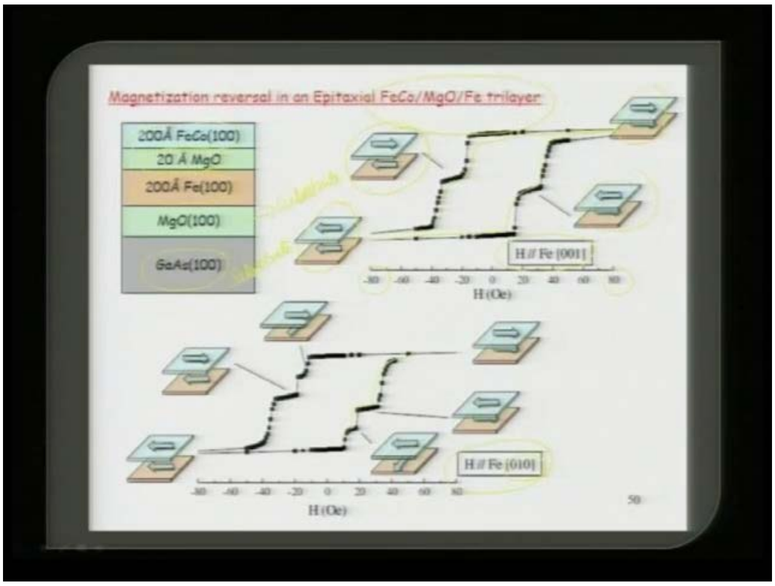

If it is a typical TMR device then you are supposed to see this sort of a staircase like magnetic hysteresis and that staircase like magnetic hysteresis has something to say. The device that is shown here is that of gallium arsenide based device, where this is the substrate and this is a MgO layer that is deposited, also to provide the substrate template. And then you have the ferromagnetic layer ion in 200 angstrom that is, 20 nanometers and then separated by a 2 nanometer MgO and then you have 200 angstrom FeCo.

In such a situation, you can see, if this layer and this layer are ferromagnetically coupled, you see the saturation reaching very fast. And as you come down at this dip staircase, you can see that, the lower one is antiferromagnetically coupled and then you can come down further, the top layer gets rotated, therefore you see again a fully ferromagnetic layer at say, 80 Oersted. So, at 80 Oersted here and 80 Oersted here, in both case it is ferromagnetically coupled, but in the staircase area, you can see that they are antiferromagnetically coupled and this is a true property of a trilayer TMR device.

So, in any TMR device, you should see a staircase like property, which is a signature that you have made the device. And the same is true, actually if you measuring it along this access and if you measure it along this axis, you see here a double staircase phenomena will come. That is because this moment is actually rotating, this spin is actually rotating, therefore you see a double staircase situation, if you are going to measure it along 0 1 0 plane.

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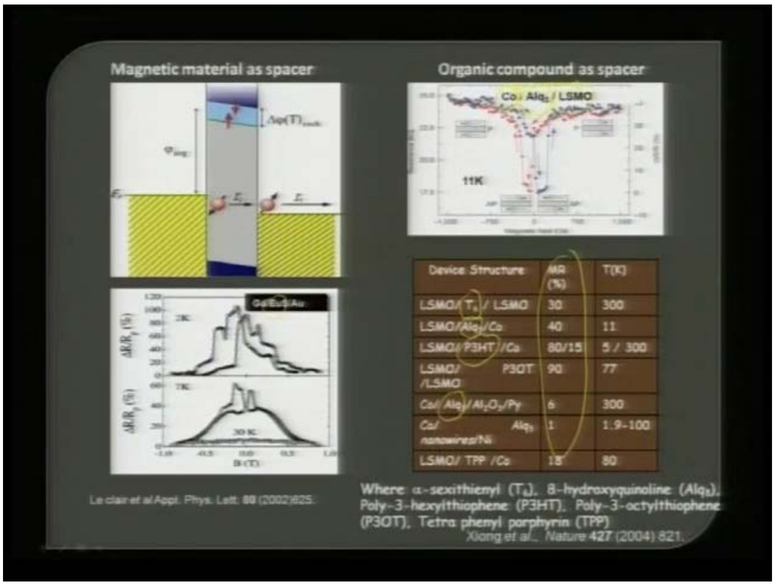

Now, this TMR device can also be extended to other cases, one of the problem that we face is, when electron goes or tunnels from one ferromagnetic layer to another ferromagnetic layer, the electron is scattered because of short or long time scales then the spin that the electron carries from here to here will be lost or will be minimized. The effect will be minimized, because of the nonmagnetic layer, why, because if you are using a nonmagnetic metal or if you are using a heavier metal ion then there will be spin orbit coupling that is contributing.

As a result, there will be a spin orbit coupling happening, as it goes from here to here, so it is better for us to replace this metal with the organic layer, because you have this spin relaxation times are of a very larger scale, because there is no metal in organic compounds. So, the electron can take it is own time to carry its spin memory from here to here without any scattering. Therefore, the recent TMR devices, they are trying to replace the spacer layer from a insulating inorganic layer to a organic insulting layer.

In such case, you can actually extent the spin memory of the electron going from this ferromagnet to this ferromagnetic layer by extending the length scale. So, lot of work is going on to understand that, I will come to this issue later in one of the slides. So, you can make several such organic molecules to measure the GMR, I will come to this issue shortly from now. So, you also can make other structure like europium sulphide, which is a nonmagnetic chalcogenide, people have explored and it shows TMR device like this.

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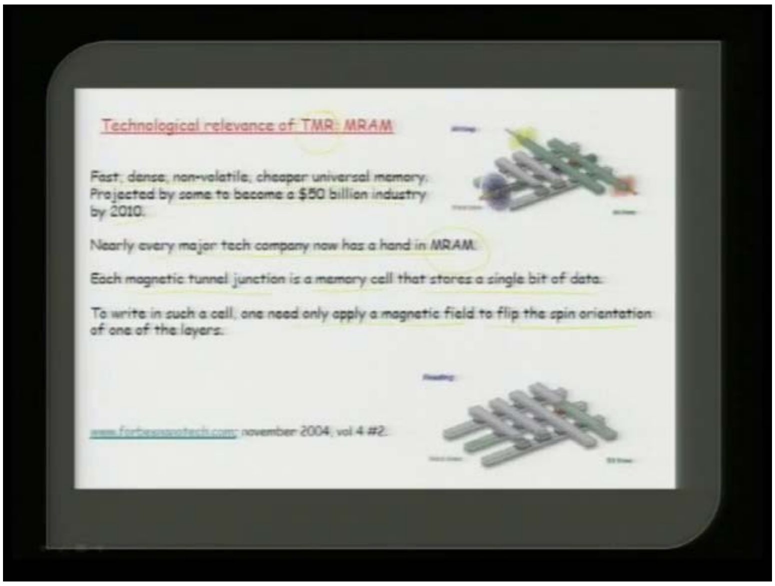

Now, what is the importance of TMR, as I told you earlier the technological relevance of tunneling magnetoresistance is to produce magnetic random access memory. Their fast, dense, nonvolatile, cheaper and this is projected to become a 50 billion dollar industry by 2010. We are almost realizing such a market trend as far as TMR property is concerned, nearly every major technological company now has a hand in MRAM, not only that, there are good ferroelectric devices, which are coming, which are also useful for integration in MRAM.

So, along with the ferromagnetic research, there is also ferroelectric compounds, which are essential for MRAM, which makes this very, very challengiing venture for most of the industries. Each magnetic tunnel junction is a memory cell that stores a single bit of data. So, to write in such a cell, one need only to apply a magnetic field to flip the spin orientation of one of this layers.

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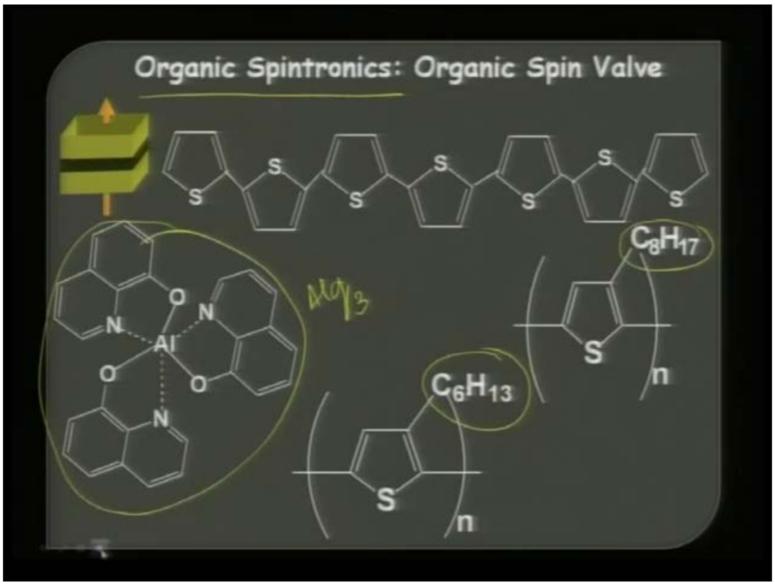

For the tunneling magnetoresistance involving organic compounds, we call this as organic spintronics, because several of these compounds can be used. This is a sixethiophene, which is used here and you also have thiophene molecules substituted with this sort of substituents, which makes it more interesting. Or you can also use the well know Alq 3, it can also act as very good organic insulator in this TMR devices, where organic spintronics can be demonstrated.

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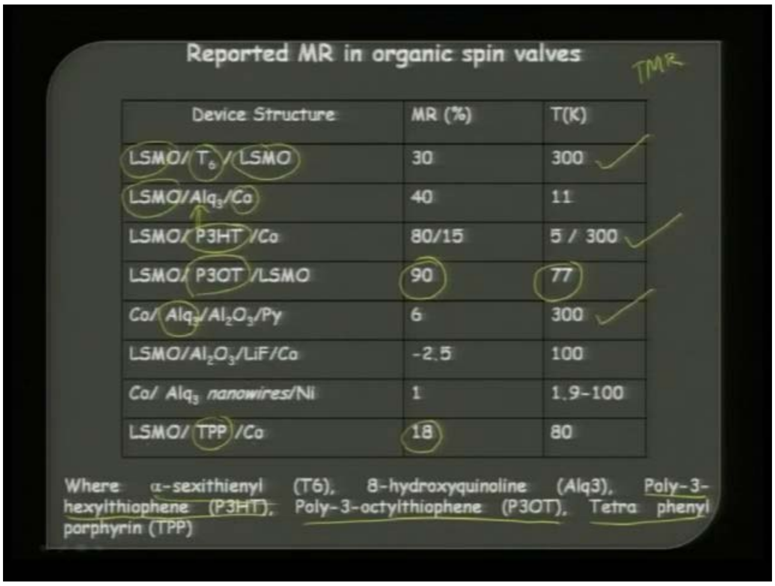

As I told you, I am showing a enlarge view of the table, which I referred earlier, I can actually take two ferromagnets and now, put T 6, which is sexithienyl or you can take two ferromagnetic electrodes and you can put a organic molecule like Alq 3 or P3HT you can put. P3HT is here that is, poly 3 hexylthiophene P3HT or you can use P3OT or you can also use phenyl porphyrin, phenyl porphyrin can be used here, where ferromagnet and another ferromagnet is there.

MR ratio of the order of 18 percent can be achieved using porphyrin and MR ratio upto 90 percent can be achieved using P3OT, but at lower temperature. What is important is, these three device configurations, where you can achieve TMR property to a greater extent at room temperature, that is important. Because, for fundamental applications, you need TMR properties at room temperature, where you can clearly see, organic molecules are coming into picture.

P3HT is used, thiophene is used, so it is very challenging issue as of now, to make lot of device combinations for TMR junctions. I will try to discuss, how other organic layers can be used in this sort of device applications. May be in the next lecture and see, how the magnetoresistive devices can be improved with various combination of these interlayers, I will stop here.

What we have seen in this lecture is that, making magnetic multilayers of different sort with spacer layers brings about a enormous change in the resistance in the presence and absence of magnetic field. And this can be extrapolated to many devices having spaces as oxides, spaces as nonmagnetic metals, spaces involving organic molecules and different magnetoresistive property can be observed and this is of importance for application, so I stop here.