

**Physics of Functional Materials and Devices**  
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**Lecture – 33, Week 8**  
**Spintronics and devices**

Hello, let us start. The final lecture of week 8. In this week, we have been talking to you about the magnetic properties of solids and various types of magnetic materials which are there. In today's class, I will introduce to you a very interesting concept and that is called Spintronics. We will see that these spintronics have large number of applications and many spintronic based devices are being fabricated using the concept of modulating the spin of the electron by applied magnetic field. Spintronics, if you look into definition, is basically a field whose central idea is the manipulation of spin degrees of freedom in a solid state system.

If you look into electron, you call it as up or down, plus or minus, the concepts are that the magnetic spin quantum number is plus half or minus half. So, you have two types of ordering in these spins. So, up spin or down spin that is what we know. If you write the magnetic moment of an electron with spin as  $s$ , it is equal to minus  $g \mu_B s$ , where  $\mu_B$  is the Bohr-Magneton,  $g$  is the electron  $g$  factor or the average spin of an ensemble of electrons which are manifested in the form of magnetization.

Now, the goal of spintronics is to understand the interaction between the particle spin and its solid state environments to an applied magnetic field and if there are modulations, then how these materials can be used for different applications. So, what are you going to understand? You are basically going to investigate the spin transports in electronic materials. If there is a spin, what is the dynamics? Is it slow, it is changing rapidly, what is the way it is static or it is dynamic and if it is dynamic, what is the way it is processing and if it is processing, it is processing around which axis. And if it is dynamic, then what is its relaxation processes, how it relaxes to stabilize in the minimum energy position. So, what is the relaxation processes which are involved? So, typical questions which would come into picture is what are the effective ways by which you can polarize a spin system.

And suppose you have actually managed to change the spin ordering of a system, is it permanent or it will remain as long as the field is there or it will sustain for some period even if the field is removed or the change from ordered state to disordered state is instantaneous if you switch off the applied field. So, there are various questions which can be asked which basically means how long does a system remember the spin orientation and how will you detect spin. Even if there is change in spin, can you detect the change in spin

using some experimental techniques. It has been seen that all these questions which I post have answers which are positive. That means, you can detect spin, you can modulate spin as well as you can have methodologies where the materials remember the spin ordering even if the field is applied.

And because of these answers you will find that the spintronic materials are finding applications ranging from sensors to spin wave based logics. You have various spintronic devices, you have MRAM, you have magnetic recording, you can have terahertz devices or you can even have SOTs devices. So, you must remember that the devices which involve spintronics will be doing what? They would be utilizing the spin degree of freedom of electrons or holes which can also interact with their orbital moments. The spin polarization is controlled either by the magnetic layers used as spin polarizers or analyzers or it can also be controlled by spin orbit coupling. So, these are the components or factors which would be controlling the spin polarization.

And if you have movement of spin it is you are not talking in terms of charge now, you are talking in terms of spin movement, then you will call it as spin waves. And if the spin waves are moving, they would be carrying what? They would be carrying spin currents. And using these concepts you can have the spintronic devices for data storing or even sensing electronic devices. In all these things you will find that you just do not want to detect the spin, but also you want to detect the change in the spin states. And you have large number of materials which are being developed fabricated where spintronic or the spin movement and its modulation is being observed routinely such as ferromagnetic semiconductors, you have organic semiconductors, organic ferromagnets, you have high temperature superconductors and you can combine these to obtain novel functionalities to spintronic devices.

So, let us see what is spin polarization and magnetoresistive effects. So, what is spin polarization? Spin polarization is the degree to which the spin of electron or hole is going to get aligned in a given direction. Basically, it is the intrinsic angular momentum of the elementary particle that is going to get aligned in a given direction. Now, this property may be related to spin, hence the magnetic movement of the conduction electrons in these materials which we just mentioned is going to give rise to spin polarized currents. Now, spin polarizations in terms or relation to electrons or holes or nuclei can be defined as  $\frac{X_s}{X}$ , where the ratio or the difference  $X_s = X_\lambda - X_{-\lambda}$  and X is the sum that is equal to  $X_\lambda + X_{-\lambda}$  of this spin resolved lambda components of a particular quantity X.

X may be referred to as a magnetic moment in the present case. Conventionally, lambda is taken to be up direction or positive, when the numerical value is plus 1 for spin up and it is taken downwards or negative value that is numerical value minus 1 for spin down states. This is with respect to chosen axis of quantization. This is conventionally which is being

followed now. So, spin up spin down you will have numerical values of lambda plus 1 or minus 1 respectively.

What is magneto resistance? Magnetoresistance is a term which is used to understand any change in the electrical conductivity due to the applied magnetic field. Why? Because mostly when you talk in terms of resistance, it is the change in the value of current if you have a resistive component in between. So, if the resistance of a material can be changed because of an applied magnetic field, then it is called the magneto resistance. The element which has all these effects will be called what as we had seen in the initial lectures of the week, it will be magneto resistors. So, magneto resistors are what? Are type of resistors whose resistance varies with the applied magnetic field.

And the effect was discovered way back in 1856 by Thomson. Mathematically you have magneto resistance MR which is defined as  $\frac{\Delta R}{R_0}$  which is proportional to  $\mu B^2$  where  $\mu$  is the electron mobility, B is the magnetic flux density and  $\Delta R$  is the change in resistance due to the applied magnetic field and  $R_0$  is the resistance at zero magnetic field. If you remember for example, we had plotted a curve for colossal magneto resistance the LSMOs and you had seen that you had plotted as a function of strontium concentration and you had obtained a curve something of this order and this was 40 percent. So, this is what we are talking about and the phenomena is magneto resistance. Now, if you have let us say that was in bulk, now you go to very small size part systems.

Then a phenomena which is called as tunnel magneto resistance is a magneto resistive effect that occurs in magnetic tunnel junctions which is a component that is consisting of two ferromagnets separated by a thin insulator. So, you have two ferromagnets separated by thin insulating layer. Now, these are ferromagnet based electrodes. Now, you have what you have the tunneling currents and the magnetic field intensities. Now, if you have this you can see that the order of alignment in the two ferromagnetic electrodes are different.

So, what has happened if you apply a field in this direction what have you effectively seen that the ordering in the two electrodes are different. Now, if an electron tries to move in whose spin is aligned in this direction it will be able to move through the top layer easily. Then it will move through if the polarization is taking place in the insulator in the same direction as the applied field, but when it comes to a junction below what will happen it will get scattered because you it will interact with electrons which are aligned in the opposite direction. That is the spin of the electrons are aligned in the opposite direction and then there would be scattering taking place and the current will fall immediately. So, you can see that you will have scattering.

You have spin filters. Now, in certain applications that you need to filter the electrons with one spin and you want to remove the electrons of the other spin alignment. So, either you

can take spin up or spin down electrons. Such filtering is not a trivial exercise. Since, the spin dependent interactions are often quite weak.

We had seen earlier that if you wanted to really see magnetorheistic effects then either you had to go to very very low temperatures and you had to go to very high fields and there are only you are going to see these effects. At room temperatures or near ambient temperatures which are used for various devices there you will see that the spin dependent interactions are quite weak and hence the effect would also be quite low, but you want to filter the spins. Spin filters or spin walls then come into picture and they can be used to easily undertake these exercises. They are used to study the magnetization dynamics and spin and angle resolved photo emission spectroscopies of various materials. And recently couple of years back you can get the publication mentioned in the reference that the spin detection using a spin filter to separate the spin orientations according to their energies also is possible.

Then you can make spin transistors. The spin transistor with memory or logic functions is another application for the MR effect. This is a typical arrangement of a spin transistor. So, what is happening if you take the emitter side the base and the collector side. So, what you see you will have the voltage applied across the magnetic tunnel junction is usually small of the order of 0.

5 volt and the spin dependent scattering occurs the Fermi level. So, when you have the interface then that is where the scattering takes place. If the electrons with the same spins are moving forward they will pass through if the electrons with different spin ordering are trying to pass through they will get scattered. In contrast, the collector electrode in this spin transistor collects the hot electrons and the energy difference between these hot electrons and the Fermi level is usually of several volts. So, you have a magnification and therefore, you have the transistor action appearing.

What will happen at the emitter end? You will have the injection of electrons which can get strongly scattered depending upon the base electron. If it is forward biased the scattering would be low if it is reverse biased the scattering would be high basically what you are doing you are changing the polarization state of the spins. And finally, once you have these spin polarized electrons which are tunneling through towards the collector electrode again you can have scattering or you can have collection at the collector electrodes. So, you can have the same ordering of the collector electrode as that of the spin polarized electrons. So, the scattering would be low and you will get high current going through.

Therefore, the spin polarized electron injection into the semiconductor can be realized with semiconductor in this case the gallium arsenide. Then comes an interesting application that is spin diodes. What are those? Again simple design these are two terminal devices whose electronic or optical properties depend on the spin polarization of the carrier. If you go

back to your original knowledge there you were just talking about the biasing based on the potential or the current which was flowing. In spintronics what you are doing? You are playing with the spin wave and the spin current flow that is the basic difference you are finding between the electronics and the spintronics.

In 1976 this kind of diodes were actually fabricated and reported. What happens? If you apply a magnetic field now you have mobile carriers and recombination centers. You will reach an equilibrium spin polarization state due to Zeeman splitting. Once you have reached equilibrium state what will happen? The current in the p-n junction would depend on the recombination state that is if the rate is quite high you will get very low currents and if you have rates which are low you will get high current. That means, the current in the p-n junction depends on the recombination rate which is going to depend on the relative orientation of the spins of the carriers and the centers.

So, the trick would be what? You can modify the current and you can have decreasing current by what? By changing the spin polarization of the electrons or the centers and then you can either increase the current or you can decrease the current. And in 1976 Solomon actually got around 0.01 percent of the saturation current at small biases where the recombination in the space charge region basically dominates. So, this was observed quite some time back, but it is only late 1980s onwards that the field of spintronics have really taken off and you have now finding large number of application for such devices. So, I hope in this lecture without going too much in detail because this topic is slightly at the research level and may not be easily understood by many of you.

So, we have kept it simple, but you should also know what these magnetic systems which are now coming up means that is why we gave you the introduction to spintronics. You can have large number of materials which can be combined to obtain spintronic devices. They can then lead to various kind of filtering actions or transistor action or polarization action or resistive actions and then you can use them in the different electronic devices or circuits. And in today's lecture I have just mentioned a few of these spintronic based devices more in detail. If you want to read more about these spintronic devices, then you can look into these publications which focuses on spintronics and you will get more idea about the field of spintronics.

With this we come to the end of lectures of week 8 and next week we will start a new topic. I thank you once again for attending the 8th lecture 4. Thank you very much.