

Physics of Functional Materials and Devices
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Lecture – 28, Week 7
Magnetic materials and their applications

Welcome to the third lecture of week 7. In this week, we are focusing on magnetic materials and how the properties of magnetic materials can be tuned for various applications. In this week, let us look into the field of magnetism from different point of view. We will talk about exchange interaction and how does this interaction impact the response in magnetic materials and how then you get materials which have higher response to an applied magnetic field and then you can classify these materials as ferromagnetic, ferrimagnetic or to an extent antiferromagnetic. Once you have a magnetic material, you can classify them as soft and hard magnets. What is the difference? This is what we will try to understand today.

You will realize that we have defined magnetic materials by the shape of the hysteresis loop which you obtained in the B-H curve or M-H curve. And as you change or tune the shape of the B-H or M-H curve of these materials, you can get large number of applications for these materials and that is what we will discuss in today's class. What have we seen? We have seen that there are certain atoms or elements which are highly magnetic such as you have various transition series elements of the periodic table which have unfilled inner energy levels which lead to a condition that their spins are unpaired resulting in a net magnetic moment. Let us quickly take an example of iron.

Iron has how many electrons? It has 26 electrons. Now for iron, write the electronic configuration by using the principal quantum number N, the magnetic quantum number M L, the spin M S and the azimuthal quantum number L. For d level with n equal to 3, how many electrons can be accommodated? You have 10 electrons in the d level which can be accommodated. So, if you write the electronic configuration for iron, what do you get? You get $1S^2, 2S^2, 2P^6, 3S^2, 3P^6, 4S^2$ and $3D^6$. Let us see how do we get it.

So, $1S^2, 2S^2, 2P^6, 3S^2, 3P^6, 3D^{10}, 4S^2, 4P^6, 4D^{10}$ and you will get 4 D, F 14. So, we know how the shells are filled in this order. So, you get $1S^2$ taking 2 electrons, then $2S^2$ taking another 2, $2P^6$ taking 6, $3S^2$ taking 2, $3P^6$ taking 6 and then $4S^2$ gets filled and finally, you have the remaining 6 electrons going in the $3D^6$ level. But how many electrons can be accommodated in the d level? There are 10. So, first you fill all the let us say spin up electrons in the 5 possible sub levels.

Using the Pauli's exclusion principle what do we know? That in a given orbit no 2 electrons can have the same 4 quantum numbers that is n , l , m_l and m_s . So, if this is m_s plus half you can have another electron with m_s minus half. So, you have the 6 electrons being accommodated in the d level. But what do you see? You see 4 electrons which are unpaired and because of these incompletely filled electron D shell what do you get? You get a net magnetic moment and because there are 4 electrons which are giving their contribution you have a strong magnetic moment coming in from the configuration which iron having 26 electron gives and that gives it is the character of ferromagnetic. Similarly, you can try for nickel, cobalt and manganese these are the 4 ferromagnetic materials and you will find that they have the unfilled orbitals and leading to net magnetic moment.

Based on the net magnetic moment what have we seen till now? We have seen if you have the magnetic moments So, arranged that they cancel each other then you have m is equal to 0 and you define those materials as paramagnetic. If all the magnetic moments align in the same direction and the magnetic moments which are aligning, they have nearly the same magnitude then you obtain a ferromagnetic material with m greater than 0. Then you have ferrimagnetic although you have 2 types of magnetic moments which are aligning one in let us say x plus direction the other is in the x minus direction, but the magnitudes of the 2 are different and hence you get a net magnetic moment which is less than the ferromagnetic material. And finally, you have the case of antiferromagnetic materials which where you have alignments in such a way that they are not random, but the magnetic moments of the grains or the domains or the particles are such that they are of similar magnitude, but they are aligning in the opposite direction and leading to the cancellation of the effect of each other and hence the net magnetic moment is 0 and that leads to the condition m is equal to 0. If you look into a paramagnetic material, what have we seen? You have the 0 net magnetic moment, but the application of a DC magnetic field aligns some of the moments in the direction of the applied field and then you can obtain a small net moment.

But in ferromagnetic materials what you see? You see that the domains are all aligned in the same direction and therefore, even when there is no DC magnetic field the whole crystal has a magnetic moment and behaves like a bar magnet which is producing a magnetic field outside of it and you get a hysteresis loop in the M - H curve. What do you get? You get M - S saturation magnetization, M - R the remnant magnetization and you get H - C that is the cohesive field. What is that field? That is the field which you have to apply in the opposite direction to take the magnetization back to 0. So, you get a hysteresis loop. I have told in the previous class that this dash line is what you get in the first cycle only.

From if you are continuously cycling the material that means, you are changing the frequency then you will not get the dash line from second cycle onward because the material is no more going to the origin it is going to the value which is slightly away from 0 and that gets repeated. So, you do not go back to 0. Based on the nature of these materials

you have large number of applications for them. For example, people believe that paramagnetic materials have no applications. No, they have because they are used in MRI, they are used in cryogenic and refrigeration.

Ferromagnetic we know it is used in storage devices. For example, for a storage device what is the shape of hysteresis loop which you will require is nearly a square shaped loop which you will require which states that the M_S and M_R values are not too different and h_c value is not very large. Why? If you have this kind of shape then the area under the loop is basically the energy you are losing per cycle. But if M_R values are quite low compared to M_S , then what will happen? You will be in a condition that small change in temperature or any kind of thermal agitation can flip the domains and then your magnetic bit will change. So, you need to have significant size of the M_R . So, that if the field is removed then also the bits remain aligned in the direction in which you had made them to align when you are storing 0 or 1 bit in the magnetic storage devices.

So, the typical shape is of a square like hysteresis loop for storage devices. Ferromagnetic materials are used for permanent magnets and we have seen they are used for transformer cores. Again, antiferromagnetic materials they are used in spintronic devices which you will learn in the next week. They are used in magnetic field sensors. How will they be used in magnetic field sensors? Let us take an example once again.

So, if you have an M-H loop till the fields are low the loop has a paramagnetic nature and it does not open, but beyond a critical field as I showed you have a butterfly loop opening and you have an indication that the field has crossed the limit for which you were defining the safety of a given device. So, as long as in this linear curve the M-H loop is being manifested you are ok, but the moment the loop starts to appear you can know that you have reached a value which is higher than let us say $H_{observer}$ or user defined value. So, you know what is the typical M-O or H-O values. Antiferromagnetic materials are used for magnetic shielding because they can absorb the magnetic field which is around or absorb the electromagnetic radiations which are falling on them and take the magnetic component and then absorb them. They are used in spin walls; they are used in spin walls.

Ferromagnetic materials are used as core of coils in microwave frequency systems and they are also used as ferromagnetic insulators in electrical circuits. So, just by tuning the materials you can tune the applications. Ok, I have a very simple question to ask. Suppose you want to transform a material which is ferromagnetic to a paramagnetic material. How can you do that? You can do that by changing temperature and giving thermal energy to the domains. So, that their thermal agitation increases and beyond a critical value the agitation is such that it randomizes the orientation and you can transform to ferromagnetic to paramagnetic kind of materials.

You can have conditions other than variation in temperature, you can have vibrations, you can have shocks which can drive these kinds of transformations and these kind of transformation from one type of material to the other are then analyzed as magnetic phase transitions. What happens in some of the materials when individual magnets or the domains or the grains are made to align? So, you have you are applying a DC field and you are asking the randomized domains to get aligned in the direction of the DC field. Now if the magnetic moment is large enough then what will happen? The resulting large DC field can force a nearest neighbor to align in the same direction. What do we mean by that? So, if there is a domain like this and then you have another domain which is slightly in the opposite direction. If the net magnetic moment of this domain is large then it will force the other domain to align its in its direction and what you will have been the alignment in the same direction.

This is what we mean that it can force the nearest neighbor to align in the same direction provided the interaction energy that means, the how these two grains or domains are actually interacting with each other is larger than the thermal vibration because you have $k \beta T$ as the energy being given to these domains and they are leading to the thermal agitation of these grains or domains. I am using the terms domains and grains interchangeably, but you should understand that we are trying to explain a phenomenon where there is a net magnetic moment in a small region and then how that region is getting aligned to an applied DC field and how the nearest neighbor is impacting its behavior. Now, if thermal agitation is large then even if they try to align the agitation will randomize their motion. So, the field or the interaction energy must be larger than the impact of the thermal energy then only the reorientation will take place. This interaction between the atomic magnetic moments is of two types.

One is exchanging interaction and the other is dipolar interaction. The exchange interaction is purely quantum mechanical effect and is generally stronger of the two interactions. What do we see? In case of small particles if you there is a DC magnetic field which is applied then for an electron its spin vector will align in such a way that is two projections spin up or spin down. So, plus is spin up for example, and minus indicates spin down. So, spin up and spin down.

And what do you get? You get a magnetic moment that is $\frac{1}{2} \mu_B$ plus or minus and you have this plus half and plus minus as the values of the magnetic or the spin quantum number m_s which can take the values of plus minus half and μ_B is the unit of magnetic moment. Now, you can explain the whole phenomena using quantum mechanics which takes into consideration the wave function of the electrons and then see how they interact with each other. The form of the wave function that meets the condition that is explaining the magnetic moment is given by equation 1. If you then calculate the total electrostatic energy, you will get the value of E given by equation 2. Now, if you see it has an integration term.

So, you expand the square of the wave function and what you will get? You will get two terms which will define the energy. The first term is the Coulombic interaction between the two charged particles whereas, the second term defines the exchange interaction which primarily represents the difference in the Coulomb energy between two electrons with spins that are parallel and anti-parallel. So, how these two up and down spin electrons are exchanging energy is what is being manifested by the exchange interaction term. And you also have a term which is the term that is called the dipole-dipole interaction because you can have an interaction in a lattice which is made up of magnetic ions and it has a shape of

$$\frac{\mu_1 \cdot \mu_2}{r^3} - 3(\mu_1 \cdot r) \frac{\mu_2 r}{r^5}$$

where r is a vector along the line separating two magnetic moments μ_1 and μ_2 and r is the magnitude of distance. So, you have a typical dipole-dipole interaction and what is the impact is given by the term shown in equation 3.

Now, if you now have a material, if you change the size of the grains, the size of the particles then obviously, you will be changing the values of μ_1 and μ_2 and therefore, you will get different magnitudes of M because of the applied H field and that is the typical way to make new magnetic materials. If you see how do we define M , the magnetization is defined as the total magnetic moment per magnet volume. It is basically the vector sum of the magnetic moments of magnetic atoms in a bulk sample divided by the total volume of the sample. It increases at the Curie temperature. What is that temperature? This is the temperature where the sample becomes ferromagnetic and magnetization continues to increase as the temperature is lowered further below T_c because you if you reduce the temperature what are you doing? You are basically reducing the thermal agitation.

Higher is the value of T , what do you get? $k_B T$ is the thermal energy, k_B is constant, T is being reduced, you have less thermal energy. If you have less thermal energy the thermal agitations become less and therefore, the impact of the applied magnetic field is much larger or the impact of the nearest neighbor which can have higher magnetic moment would be higher on the next neighbor and therefore, you will have a alignment in the direction of the domain or the grain which has a higher magnetic moment because it will impact the neighbor much more and thermal energy has been reduced because we have reduced the temperature. Because of this you have magnetization which is a function of temperature and that is given as

$$M(T) = M(0) \left(1 - CT^{\frac{3}{2}}\right)$$

where C is a constant magnetization at 0 degree Kelvin is $M(0)$ and T_c is the temperature in Kelvin and you then define the ratio of M and H as the value of susceptibility. So, how? If you have high field and low change that is low impact what will be the value of χ ? χ

will be small. For ferromagnetic materials the χ values will be high or low in comparison to diamagnetic materials it would be larger because for the same field you will have more magnetization appearing.

So, based on this discussion we had till now you can use ferromagnetic materials to make or obtain two classes of systems one as soft magnets the other as hard magnets. The soft magnets are what? They are the materials which have small coercive forces and they can be easily magnetized and demagnetized. Whereas, you have the second class of materials which are hard magnets these are materials which have large coercive forces and are called as hard magnets because they cannot be easily magnetized or demagnetized. So, if I compare in terms of the hysteresis loop what would be the shape of soft magnet and hard magnets what do you think? You will clearly see that you will have these materials which are soft magnets would be small coercive forces means what? Therefore, you have magnetic materials which are hard magnets they have large coercive fields. The exact in this figure you may see that there is some shift in the origin this is just because I am just drawing by hand.

So, it is not the case you should have a symmetrical shape of the hysteresis loop. So, this is just a representation not the exact nature because I am just drawing by free hand and hence there is some modification in the figure. But you have a symmetric shape the point one should understand is that you have small coercive forces in soft magnets, but large coercive forces in hard magnets. For example, you can have soft iron-based materials which will give you soft magnetic materials and you can have steel-based materials which can give you hard magnetic materials. The properties which would be associated with soft magnetic materials would be then greater permeability greater retentivity, but smaller hysteresis loop area and this means if you have a smaller hysteresis loop area, area under the loop is telling me what? Is telling me the energy loss per cycle and if the area of the loop is small what is it telling me? It is telling me that you will have smaller energy loss during cycling of the material.

In comparison to soft magnets hard magnets would have smaller permeability, smaller retentivity, larger hysteresis loop area, but they will also have larger energy loss during cycling and this is what you have the hysteresis loop variation which we already discussed earlier. These magnets are used at various places and the choice of application is defined by the nature of the hysteresis loop. For example, you have electromagnets here what you will get? You will have the electromagnets which will have high magnetization at low magnetizing field. So, you will have high initial permeability and low hysteresis loss. Which of the two materials will you use? You will use soft iron or steel? These properties are manifested by iron.

So, you will use soft iron to make electromagnets. You will use the properties of soft iron to make the cores of transformer, armatures of dynamos and motors. And can you list the

applications of hard magnets? With this I will conclude today's lecture and you have seen the magnetic materials which are paramagnetic, ferromagnetic, ferrimagnetic or anti-ferromagnetic from a different point of view. And you have seen how you can have magnetic phase transitions, what is the driving force of phase transitions in these kinds of materials and how you can use these properties in various applications. These are the references which you can go through to obtain more knowledge about this field.

And I thank you once again for attending today's lecture. Thank you very much.