Electroceramics
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Lecture - 35

So, we again we will start a new lecture here, and I am just discussed the contents of the last lecture briefly. So, in the last lecture we started our discussion on diamagnetic materials with a emphasis on sort of qualitative treatment of diamagnetic susceptibility. And what we found there was that the moment or the magnetization which is created as a result of application of magnetic field opposes the applied field. So, as a result the susceptibility is negative, and this diamagnetic behavior is inherent to all the materials because all the materials have electrons. And as a result no matter what is that eventually the type of material diamagnetic character is always present. It is just that some materials have only diamagnetic behavior. That is why they are called as diamagnetic materials. But other materials happen to have other contributions such as paramagnetism, ferromagnetism etcetera dominating over the diamagnetic character. So, as a result diamagnetic behavior is shielded. And since this diamagnetic susceptibilities are very small in nature in number. They do not really show up.

So, the next contribution that we talked about was paramagnetism. And this paramagnetism happens in materials where atoms have permanent dipole moments. But those dipole moments are randomly arranged with respect to each other because of thermal energy. And this thermal energy allows these dipoles to be at random orientation with respect to each other. As a result the net magnetic moment of material is equal to 0. Now, when you apply field to such a material of course, there is alignment of magnetic dipoles in the direction of applied field. And that results in a positive magnetization and positive susceptibility.

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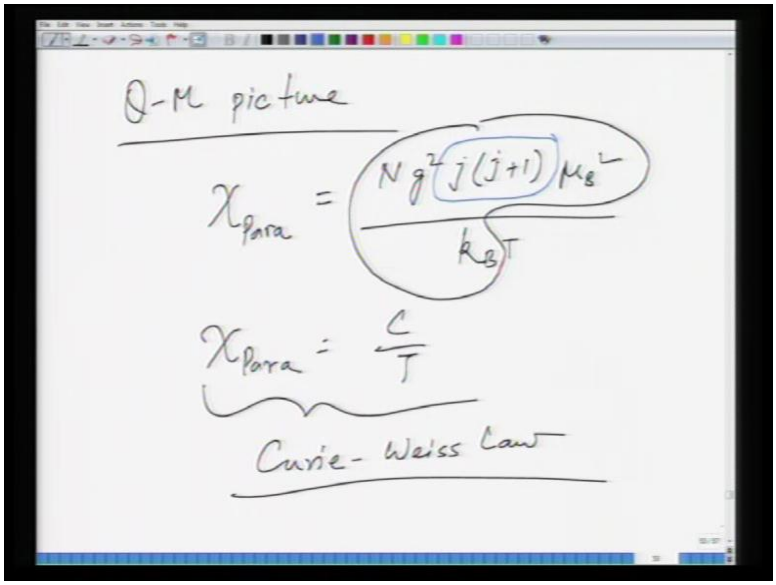

And so and what we found here was also that paramagnetic susceptibility was a temperature dependent entity and this has a temperature dependent of the sort. So, that is called as curie Weiss behavior and the behavior is something like this.

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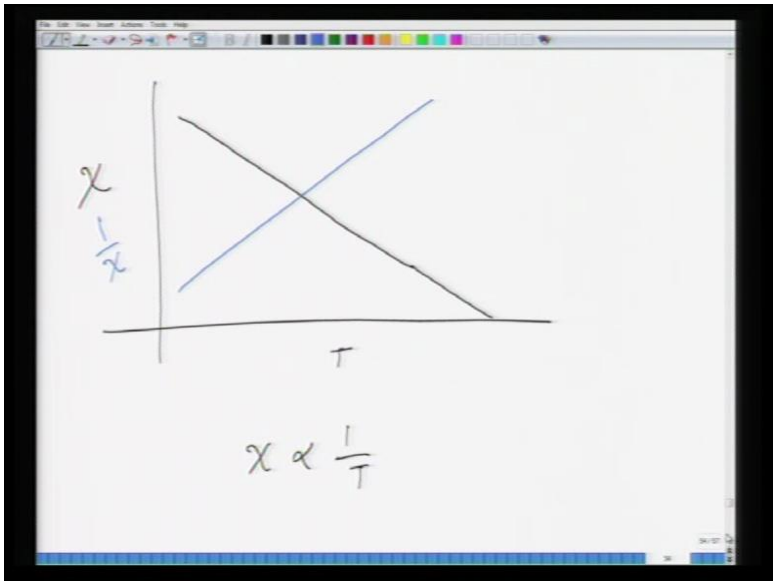

So, your one by chi starts from starts increasing as a function of temperature or chi decreases as the function of increasing temperature. So, this is how you need to depict the behavior of a paramagnetic material. Now, lastly we looked at because there is a quantum mechanical explanation. Because the quantum mechanics says that everything

has to be quantized. So moment also has to be quantized. And as a result and since you know that moment has contributions from orbit and spins a spin contributions in paramagnetic materials of interest such as transition metal elements. The magnetic moment per atom is spin dominated.

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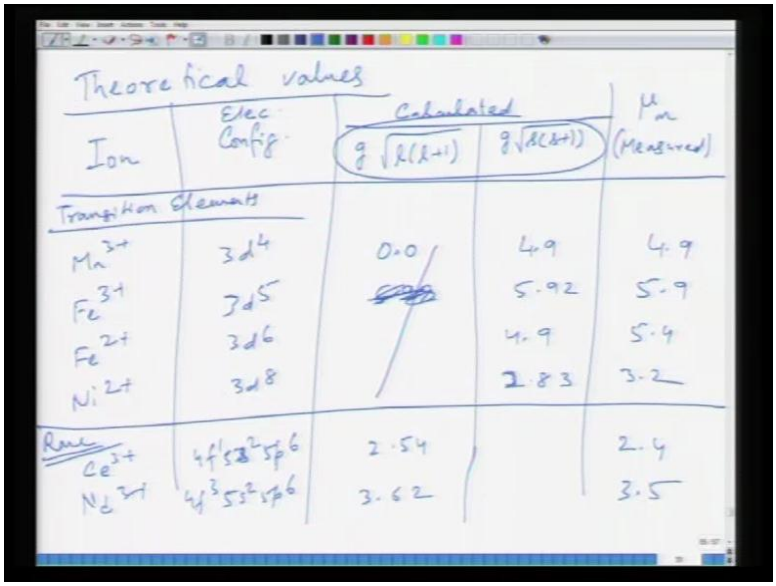

Whereas in case of rare earth elements since the orbitals are far off they don't get quenched. As a result orbital magnetic moment also starts contributing. So, the this factor which is g root j and j plus 1 its it contribute it takes contributions both from a spin as well as orbital. Whereas, from the spin contribution; spin contribution contributes mostly in the case of transition elements or d group elements and the measured and experimental values. They match pretty well to suggest that that is indeed the case.

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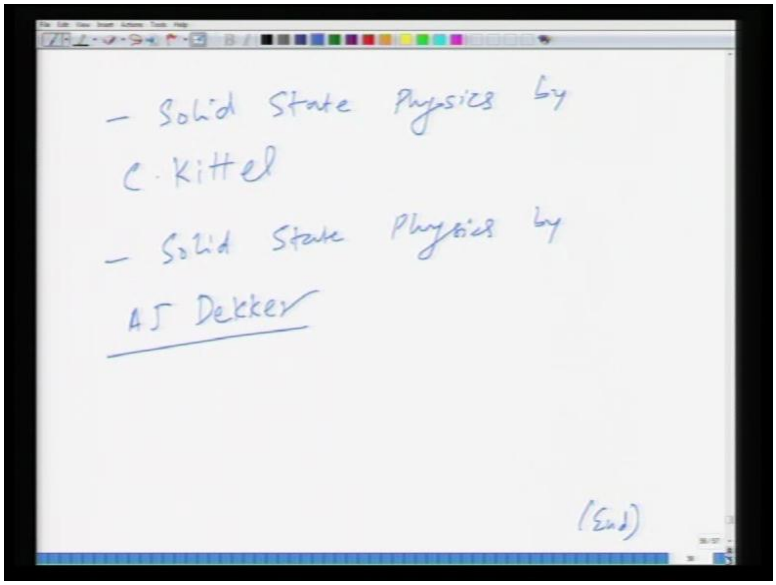

So, I also suggested couple of books which would be relevant for reading about magnetism. So, solid state physics by Charles Kittel and solid state physics by A J Dekker. These are the two good books which you can go through for improving the understanding on magnetism or as a supplementary reading in addition to this module.

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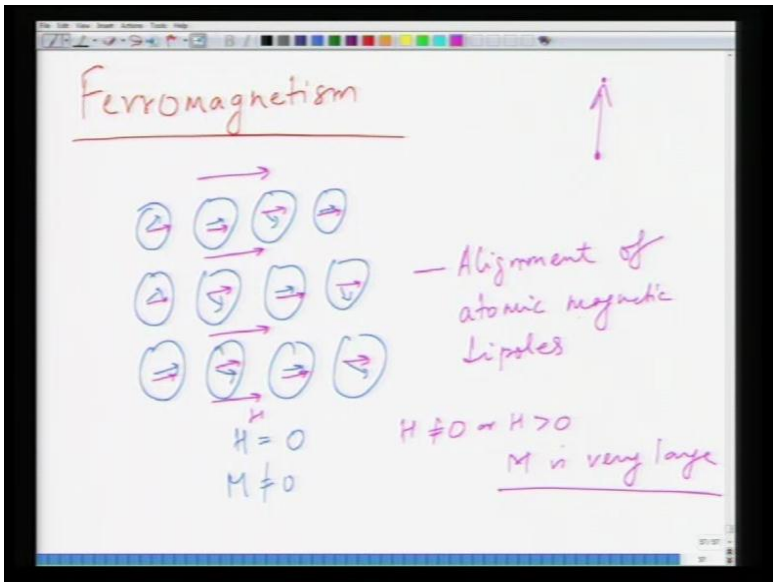

So, what we will do now is we will take up the case of another important class of magnetism. This is called as ferromagnetism and this ferromagnetism is a very interesting phenomena. It is been observed since long times since the times when the iron

is available iron oxides are available and these happen to and the pieces of iron have always have had this magnetic property. They have attracted each other, but the fundamental reasons of this behavior were not known. And it was merely an observation rather than a deep study of science into it.

So, basically this phenomenon happens in materials where atoms do contain permanent magnetic moments, but but that is also true about paramagnetic materials. So, what is the difference? Here the difference is while in paramagnetic materials the dipoles are magnetic dipoles or spins are atomic. Spins are randomly distributed with respect to each other though magnetic moments of the atoms are randomly distributed with respect to each other. Here, you have a alignment which gives rise to a non 0 magnetic moment even in the absence of applied field.

So, the picture is something like this. So, you have these for instance atoms and these atoms have magnetic moment which is which gives you a random sort of moment. But it is still it is not all it is not random enough to give you 0 moment something like that. So, it is a idealized picture. So, this gives you this is in the situation when H is equal to 0, but M is not equal to zero. So, there is a finite magnetic moment in the absence of applied field. Now, when you apply field to such a such a material. So, when let us say I depict by different color. So, if I apply field H to such a material then all the magnetic moments eventually apply align themselves in the direction of applied field.

I think two moment two moments have been drawn here. So, it should be corrected. So, so the picture now is. So, when H is not equal to 0 or H is greater than 0 then M is very large as well because all the moments align themselves in the direction of applied field. So, this state this color says alignment of atomic magnetic dipole this dipole term is only a analogous term to the charged dipole. But dipole essentially means that you have dipole you have two different poles. So, it is just that because you have magnetic magnetization magnetic moment vector pointing from this direction that direction. So, you have one pole or you have another pole. And in magnets its seen as north south as well. So, that is why it is called as magnetic dipole as well.

So, by analogy it is it's called as dipole. So, let us let us stick to this term magnetic dipole. So, alignment of atomic magnetic dipoles in one in the direction of applied field when the field is large. So, now, these materials typically they contain regions of again

just like ferroelectric materials. They contain these regions of ordered magnetization. So, or you can say ordered regions of single magnetization which are also again called as domains. And these domains happen to happen to be arranged in such a manner. So, that when there is no field there is a remanent magnetization. So, the we will we will look at the reasons for why domain exists and how do they grow and or change their orientation with respect of applied field a little later. But just like ferroelectric material also when you when you change the temperature for this material; then this material also go undergoes a curie transition.

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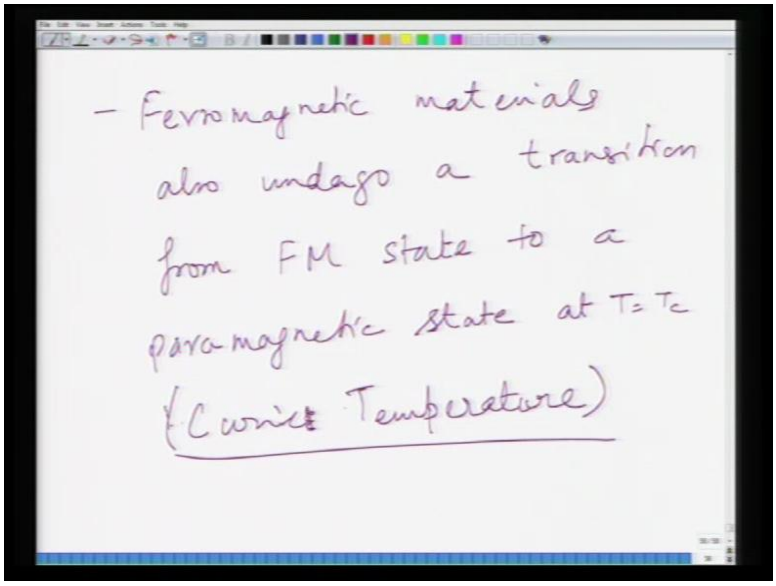

So, ferromagnetic materials also undergo a transition from ferromagnetic state to a paramagnetic state or you can say a nonmagnetic state because paramagnetic is nonmagnetic in the absence of applied field at a temperature T is equal to T c. And this is called as curie temperature.

So; however, the difference is while in ferromagnetism we talk about first order second order transition. Here we talk do not talk about that kind of transition simply because in Ferro electricity the transition is associated with the phase transition. There is a there is a change when you heat the material from a low symmetry to a high symmetry phase where as this is not a strict condition or this is not necessarily a condition for a ferromagnetism. So, this is not a necessary condition phase transition is not a necessary condition for ferromagnetism. That is why you don't associate it with the phase

transition as such. So, you just talk about a curie temperature which is a transition temperature form ordered ferromagnetic state to a disordered paramagnetic state.

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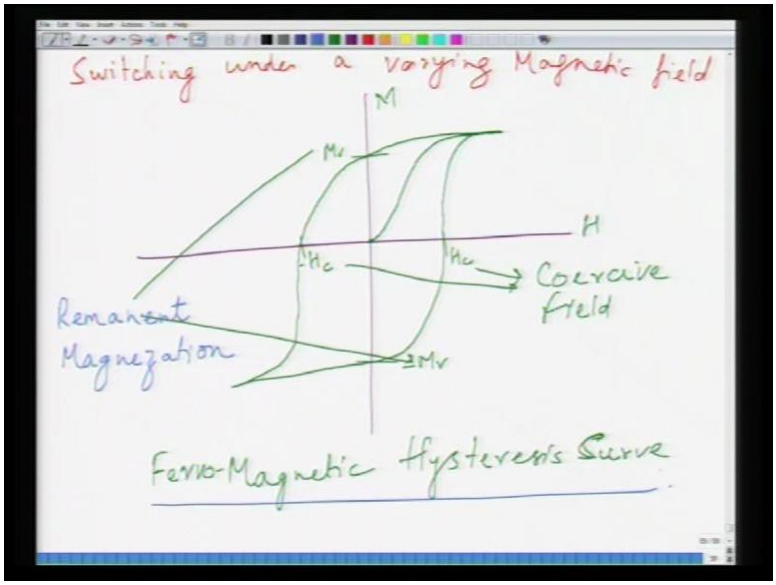

So, what happens in a ferromagnetic material also like a ferroelectric material, when you, so so what we are going to draw is basically switching under a varying magnetic field. So, what you have here is essentially material in the virgin state. Virgin state means as prepared state does not have any magnetization. And then this magnetization increases and then it saturates as the field increase increases large values. And then it comes down and it follows this kind of hysteresis. It is not looking very nice here, but the point is here these two values M r and minus M r. They are exactly equal and opposite to each other and similarly you have two field values at which the magnetization is 0. They are called as plus H c and minus H c. And this curve is called as a M H curve or magnetic hysteresis curve.

So, what you have? A hysteresis when you switch a ferromagnetic material under the varying magnetic field. So, you start from 0 magnetization in the virgin state and that is because the domains are randomly oriented with respect to each other giving rise to 0 net magnetization. When you increase the field eventually a point comes where all the domains are aligned in the direction of applied field. And you get a saturation magnetization. And once you have all the saturation, once you have alignment of all the magnetic dipoles along the direction of applied field you have nothing else to be aligned.

And so further entries in the field, does not result in any increase in the magnetization and we will decrease this magnetic field. At 0 magnetic field there is a remanent magnetization which means there are domains. So, there is a net alignment of domains along the direction of applied field or there is a net alignment of domains in one direction. As and those domains happen to be larger in number or larger in volume as compared to those which are oppositely oriented.

So, the net magnetization is finite and when you if you if you want to bring back material to this state. You need to apply an a additional field in the opposite direction. So, that you have volume of domains of one orientation equal to volume of domains of another orientation giving rise to 0, magnetic field 0, magnetization. And when and then when you want to achieve this state again in the opposite direction you need to increase the field further. So, that the domains of opposite orientation are larger in number or mono domain state occurs. And when you again bring the, bring the field back to 0. Then again you have similar state as you had at plus M r as minus M r and this cycle continues. And this is called as a magnetic hysteresis curve or ferromagnetic hysteresis curve to be precise. And this H c is called as again coercive field H c and minus H c and this M r and minus M r are called as remanent remanent. And the energy which is dissipated now because you have a hysteresis which means you have some energy dissipated. And this energy basically defines the nature of a energy dissipation, defines the nature of a Ferro magnet. Unlike the this term is not used in used for ferroelectrics. In general, but for ferromagnetic materials you have these this term which defines whether you have a soft magnet or whether you have a hard magnet and we look at it in the while.

So, what happens here is and of course, we are talking here in terms of domains as well we have not introduced. How the domains in these materials have formed and how do they switch. So, you look at that in a in a little while, as well this is what is the characteristic of a ferromagnetic material.

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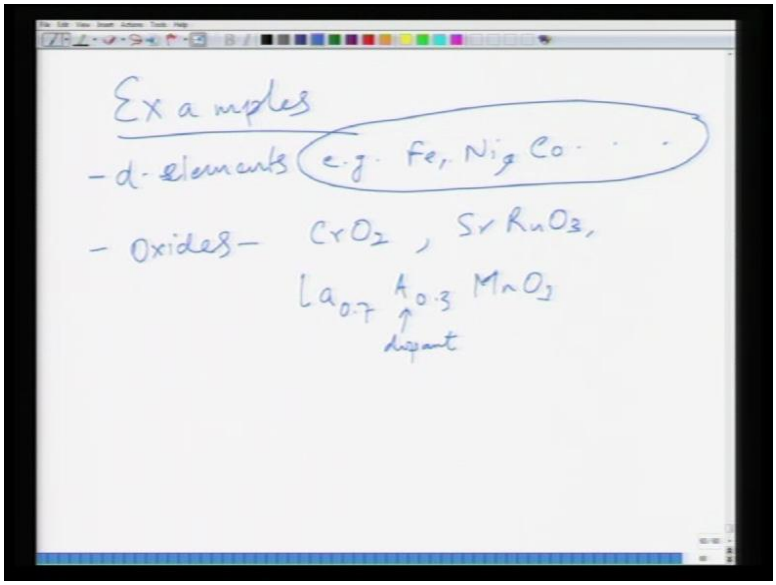

Now, examples of ferromagnetic materials are mostly d elements like iron, nickel, cobalt. All of these are ferromagnetic in nature. And then and the paramagnetic materials are different actually paramagnetic materials, are the early transitions metals like titanium and calcium etc which are in the in the in the top row. And then you have some oxides as well which are ferromagnetic in nature. So, oxides such as chromium oxides C r O 2 S r R u O 3 and some doped oxides as well. So, a is the do pant and doped manganites. Basically these happen to be ferromagnetic in nature.

So, there is a host of materials which happen to ferromagnetic in nature. But most important of them which have been studied a lot are these metallic elements which happen to which have of course, a permanent magnetic moment. And that is why we chose them as an example. But they do have strong ferromagnetic character. Now, comes a point first of all what these we have introduced the term domain. So, the question which comes now is how did how do these domains form in the ferromagnetic material and how do these domains move in the ferromagnetic material.

So, there are essentially, variety of reasons. We will look at this domains first in the in the context of switching and then we will introduce the physical explanation of what is the reason of forming domains in the ferromagnetic material. So, we will first look at the hysteresis behavior in terms of domain movement and in terms of the energy which is dissipated.

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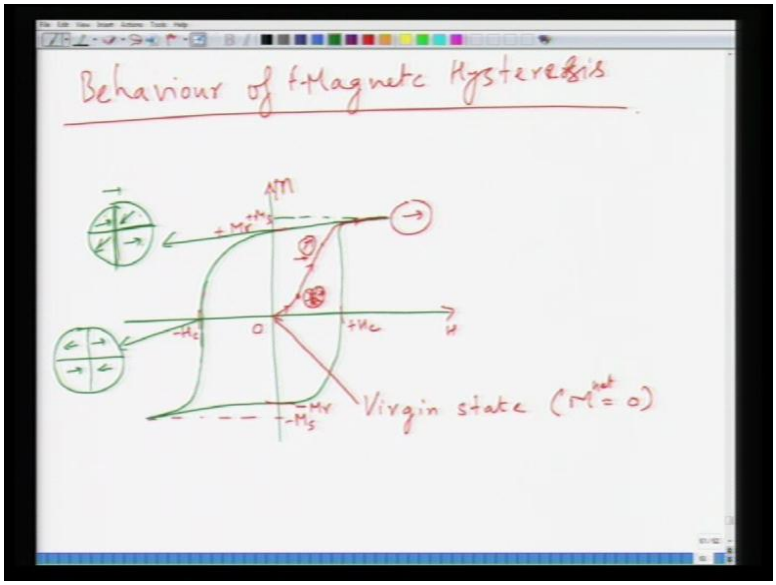

So, or rather behavior of magnetic ferromagnetic hysteresis now. So, we have said that you have a ferromagnetic materials like material like this and you have. So, this is how it looks like. So, you have plus M r and this is your M minus M r plus H c and minus H c. And this should be a straight line actually and this is called as saturation magnetization. So, plus M s and this is called as minus M s.

So, these are equal and opposite states and this is again has advantages in the in the in the form of their applications. So, you start at this point a or let us say o and initially what this point corresponds to a virgin state. And what this means is that M is equal to M net is equal to 0. There is no magnetization and then you slowly start increasing and then it goes like this. So, you have these different regions of domain growth. Here you reach you achieve complete alignment of domains like this. And here it may be at this point it could be. So, field is like these domains could be like that and at this point you would have let us say different regions. So, you would have situations like this. So, you do not have net you have very small net magnetic moment and so on and. So, forth this keeps going on. So, by depending upon the parameters of this hysteresis loop the behavior of magnetic field is defined.

So for typically, its defined in terms of ease of magnetization; and these ease of magnetization essentially is about the coercive field. Typically a large coercive field would mean that domains are not easy to switch which means you cannot re-orient the

domains without applying a large field. And that is why these large coercive field materials.

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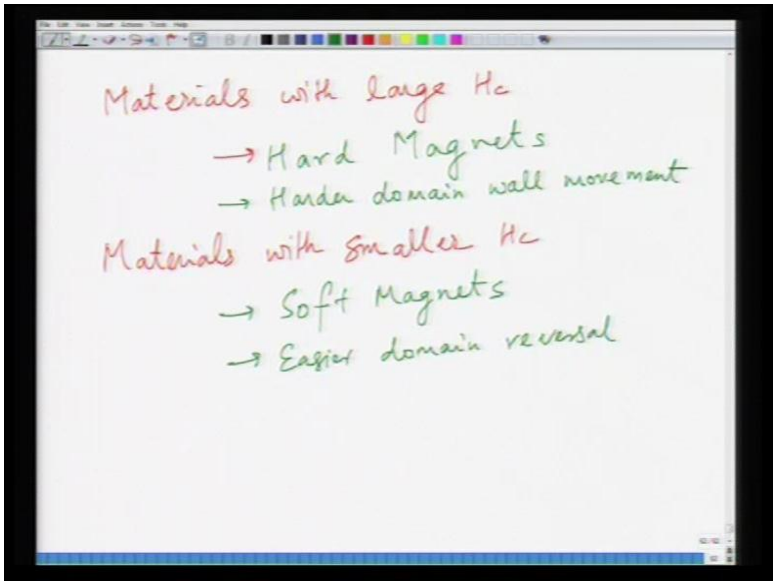

So, material with large H c they are called as hard magnets they have typically large magnetization. But they also have large H c. What it means is that essentially we because when you are going from this state. So, the domain structure at this point would be something like this. So, let us say it is a very simplified picture. So, this would be let us say this and then let us say this and something like that. So, you have a net volume of domains which are favorably oriented. Let us say this is the, this is the direction in which the original magnetization was done. So, this would be the total volume which is. So, this volume plus this volume minus this volume plus this volume gives you a finite magnetization.

Now, when you want to go to this state which means you have four equal quadrants. So, let us say you have a picture like this. And this means that net magnetization is equal to 0. Now how would this occur? This would occur by some sort of movement of domain wall. Now, how walls move that I will come to little later. It has to happen by shrinking of these domains which are favorably oriented or nucleation of or some other mechanism. I will I will not bring to I will I will, let us not talk about the term nucleation, but it has to happen by some movement of this domain wall which is the boundary between these two domains. And that basically determines and that basically

requires a particular force. And this some domain walls may require larger force some domain walls may require smaller force. So, the domain walls which require larger force for the for their movement are typically materials with higher coercive field. And domain walls which move easily at a small fields. They are called as we will introduce another magnet which is called as soft magnet.

So, materials with soft magnets and typically this would characterize harder domain wall movement and this would be easier domain reversal domain wall movement or reversal is the same thing. So, this is a typical difference between these two different kind of materials.

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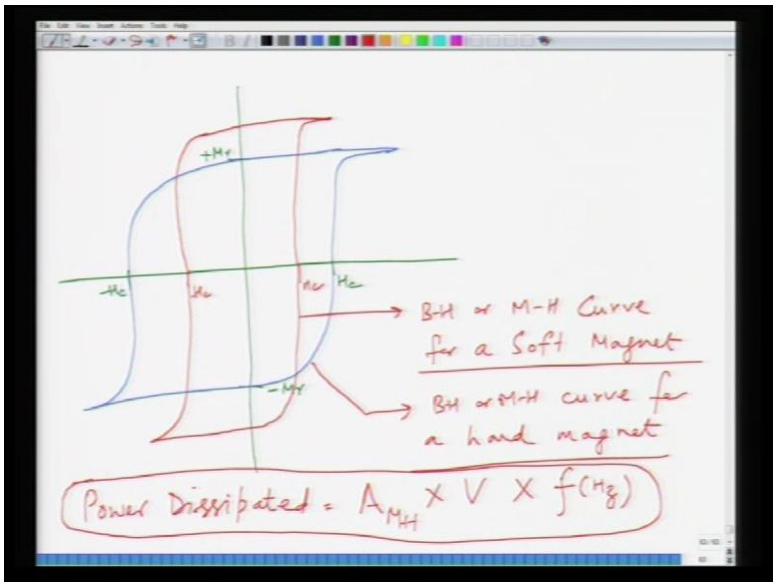

So, if I want to draw the magnetic hysteresis curve of two different kind of materials. Then if I draw it on the same plot, so if this is my, if this is my material with let me just draw two different lines. So, so this is one kind of magnet. And if I draw another one which is something like this let us say this was for sake of illustration. I am going to just make it slightly different. Then do not look at the magnitude of M r that is just for sake of illustration. But what is important here is this H c and this H c minus H c. They are smaller than the green one. So, this would be called as B H or M H curve for a soft magnet and this would be called as A B H or M H curve for a hard magnet all right. So, this is the typical differentiation the power which is dissipated no matter what the type of magnet it is. You still have dissipation of energy in the form of hysteresis. So, this power

which is dissipated is nothing, but a M H area of this M H curve multiplied by the volume of material and multiplied by the frequency in hertz.

So, this gives you what is the power which is dissipated inside a ferromagnetic material and typically and naturally the larger the power dissipated. You would tend to think that the material is more material is a hard magnet. So, soft material soft Ferro magnets have a smaller power dissipation as compared to hard Ferro magnet.

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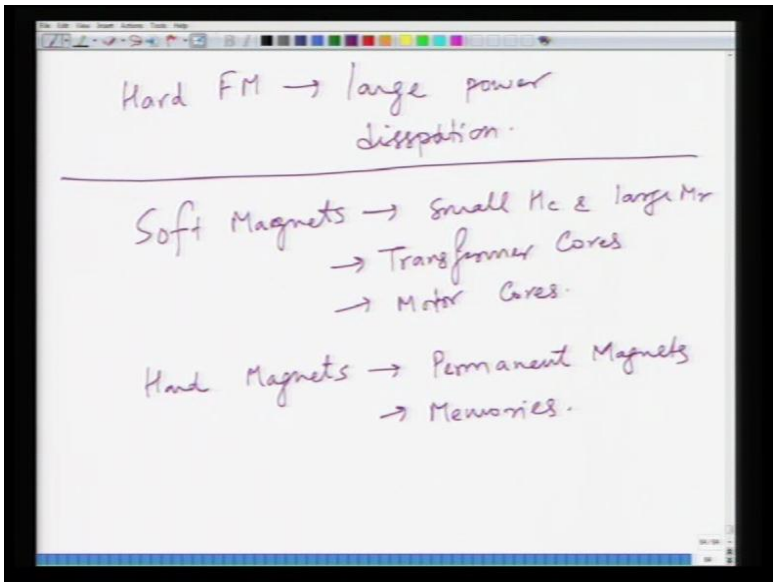

So, in general hard Ferro magnets have larger power dissipation. And these soft magnets as a result the soft magnets with small H c and reasonably large M r tend to be used in cases where the loses where the losses must be smaller power dissipation must be smaller. As a result they find applications in transformer cores and motor cores where the energy dissipation due to a c fields is low. And hard magnets on the other hand find application in find application in those areas where you want the magnetization to be reversed with difficulty where the domain reversal has to be difficult. So, they find applications in permanent magnets memories because you do not want to relate to be lost. So, you want to retain that particular state which is. So, I did not I did not introduced this. But just like a ferromagnetic material these states which are plus M r and minuses r M r can also be use as 0 in one state of memory in a binary memo read data. So, if you have that kind of memory device you then you do not want your data to be erased which means you want that 0 or one state of the memory to be preserved. When

you do not want to when you are not doing anything purposefully. So, as a result hard magnets are used in applications where you do not want domain to be reversed easily by small fields and soft magnets; of course, in applications where energy dissipation is in issue. So, this is the kind of picture which emerges of ferromagnetic material. Now, what we will look at ferromagnetic material in a little bit more fundamental detail.

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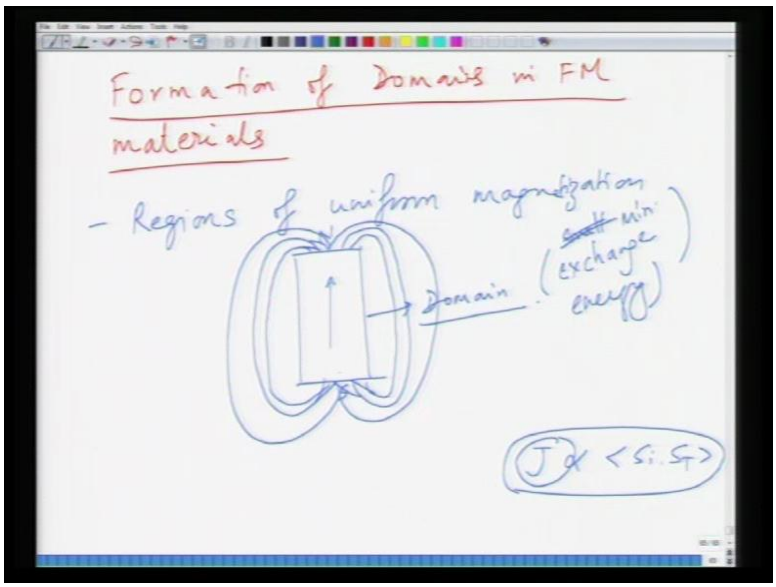

So, the first in first thing in that line is the formation of domain in these materials. Now domains again as we know in Ferro from our discussion in ferroelectrics that they are regions of uniform magnetization. So, you can have a state like this. So, let us say this is north this is south. So, this would be say if this whole volume of this material has magnetic dipole pointing in this direction. Then this is a mono domain state. So, this is a domain; so but just like in again refer back to ferroelectric material.

All those are reasons here are different than ferroelectric material, but again it is energetics. So, now when you have this mono domain state, now this mono domain state hund's rule allows the spins to be aligned in one direction and then because of certain reasons all these atomic spins are also aligned in one direction. They of course, obey Pauli's exclusion rule, but there is a term called exchange energy and this exchange energy is essentially without violating the Pauli's exclusion rule. It allows all these spins in one direction. That is called as a spin up direction.

And this is and for a certain ferromagnetic materials the exchange energy which is which is nothing, but product of different kind of spins. So, this exchange integral is proportional to sum of spin movements of all the atoms. And this exchange energy happens to be minimum for ferromagnetic material when the spins all the spins are aligned in one direction and that is what makes one domain. So, this domain essentially is as a result of this small exchange. Or let us say minimum exchange energy.

Now, so you can have throughout the volume of the material all the domains are aligned in all the spins are aligned in one direction. That is fine, but what is the problem with this because when you have such a situation then you have very large surface magnetization energy. And this is called as magneto static energy. So, you have very large flux line those are surface of the material. So, as a result you have as a result you have very large surface magnetic energy or magneto static energy which makes this structure unstable.

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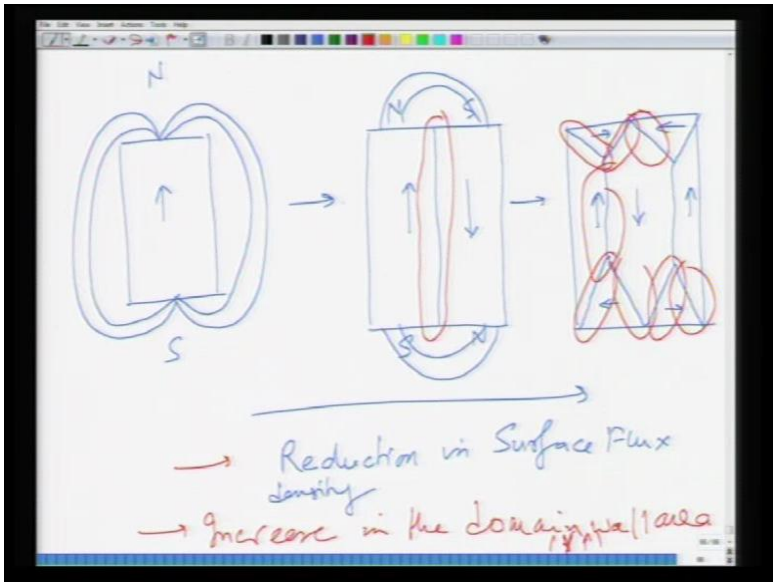

So, what happens rather is you have this state in which you have single magnetization and this has consequences in terms of large surface flux. Now this tends to break this single domain state into or rather more stable state. So, let us say if I have two regions of the material. Now, with one region spin up, one region spin down. Now, what I have is I have this north, this south, this south and this north. So now, I can have the flux lines only on this side.

So, the surface flux density has gone down which means the magneto static energy of the material has gone down. I can make this slightly more different if I have a situation like this. So, let us say this is spin down this is spin up and this again could be spin up and you can have different regions. Here again you can have let us say you need to have you need to always have this consonance. In terms of let me just make some changes here. Let us say situation is something like this. So, this is spin down. So, what you are going to have here is this spin left spin right and this would be is spin right spin left and this again you have north south, north south combination and this gives you much smaller.

So, as you go from this configuration to this configuration this configuration reduction in surface flux density. But what you also have here is although you have reduction in the surface flux density or decrease in the magneto static energy. But what you have also you have introduction of these. What you call? As these regions which are nothing, but domain walls and domain wall as we have seen before is a surface. So, what you have here is on one hand you have reduction in the surface flux density. On another hand you have increase in the domain wall area and this requires a positive energy surface energy.

So, as a result gamma requirement gamma is the typical term for surface energy that gamma increases. So, one needs, so the stable domain configuration is something where the net free energy term which includes these two term adopts a minima. And that would be the stable domain size and the analysis would be based on a on a similar line as against the analysis that we did for ferroelectric material. Basically you have to integrate differentiate that free energy term with respect to the domain size. And find out a stable domain size for a given combination of surface energy and the surface flux density.

So, there are varieties of material which there are variety of energies which affect I have I have given you very simple representation of this energy this energy balance. But there are variety of energies which affect this kind of scenario and these energies which…

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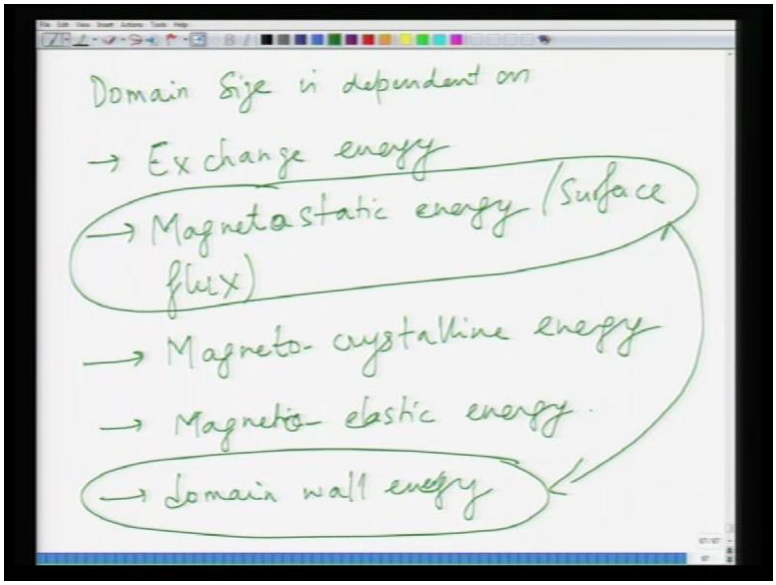

So, basically domain size is dependent on variety of these energies. And basically the balance between these energies because some of these energies are positive some of these energies are negative. So, of course, you have exchange energy and you have basically magneto static energy which is v. Because of the surface which is essentially due to surface flux density. And then you have you can also have magneto crystalline energy. And this force is the, this basically energy is due to the coupling of magnetic moments with respect to the crystal lattice. So, the that the direction of magnetic moment is coupled to the lattice. So, any change in the lattice structure or parameter forces the change in the magnetization. So, as a result hard and easy access may arise.

And then you have magneto elastic energy and which is due to changes in the lattice parameter as a result of spin orbit coupling. So, both of these are essentially coupling of structural parameters with respect to magnetization. For a given material they are constant for a given material exchange energy is also fixed. So, what is actually varying is this energy. And finally, you have domain wall energy. So, combination of these two energies essentially governs the size of the domain in a similar fashion as it happened in the ferro electric materials.

So, so essentially multi domain state requires many interphones. But this configuration essentially thermodynamically stable simply because it leads to overall reduction in the free energy of the system. So, essentially this, so once you have a stable domain

configuration. What you have is a multi domain state and this multi domain state as we as we have discussed it is dependent upon the combination of various energies. Most importantly the magneto static energy and the domain wall energy. So, these two decide the size of the domain in a given material because other energies are nothing. But function of the material itself and they fairly remain constant.

And the nature of this now the question another next question is in case of ferroelectric material. When you went from one domain to another domain there was a there was a change in the polar vector. But this domain wall was a very narrow domain wall. There was not that the domain wall was wide of the width of the domain wall of the order of aha lattice parameter or may be two lattice parameter or three lattice parameters. In case of magnetic materials the domain wall has a slightly different nature.

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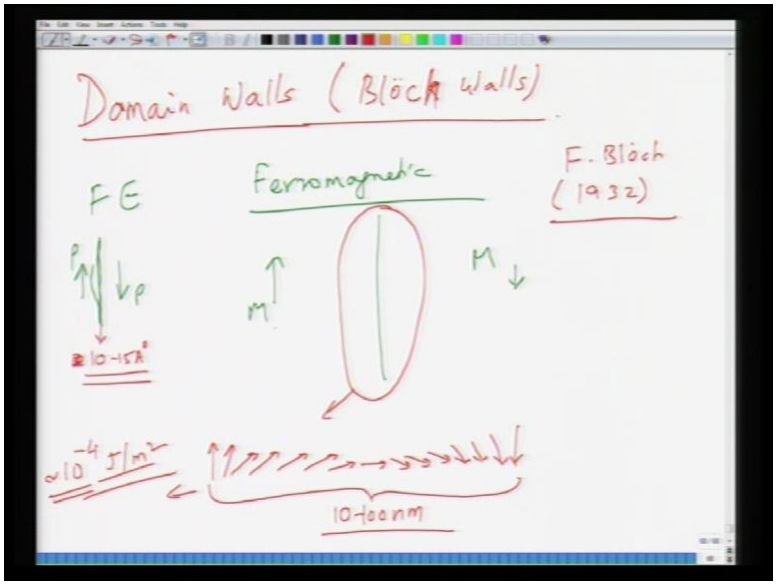

And that is why and in these materials these are called as often bloch walls after the F bloch who in 1932 proved that magnetization cannot change discontinuously at the domain boundary. So, unlike in ferroelectric materials if you remember in ferroelectric materials; if you had region of a polarization like this then the this was a domain boundary. And you had next region a polarization like this the at the domain wall. The ferroelectric polarization p changed abruptly.

So, the domain wall width was insignificant. It was very small of the order of lattice parameter or two where as in case of ferromagnetic material it was proven by energy calculations that this magnetization M in one region cannot abruptly change at the boundary into another region. So, this boundary happens to be a region which is fairly big. So, this boundary when you look at it microscopically it is something like that. So, you go from one to another magnetization it slowly goes like this. So, this is how it varies in nature and this is just this domain wall width. And this domain wall width happen to be of the order of ten to hundred Nano meter and which is much bigger than the domain wall size in ferroelectric materials and ferroelectric materials. We are talking of domain wall size of the order of couple of lattice parameters and which is a typical lattice parameter would be some somewhere like four to five angstrom. So, this would be somewhere like ten to fifteen angstrom in size in ferroelectric material where as in ferromagnetic material if you look at the difference. So, this is like one nano meter and here we are talking talking about an order or two magnitude higher wide domain. So, there is a gradual change of magnetization at the domain boundary unlike in the ferroelectric material. And this actually results from the change in the way these domains the domain reversal takes place.

In case of ferroelectric material we looked that the new domains nucleate which are in the direction of applied field and they grow at the expense of these older unfavorable oriental domains. Here what and here what happens is that you have growth of previously slightly the most favorably oriented domains. And the expense of the old domains the, so there is no nucleation phenomena it is only the growth of old domains which further realign them themselves in the direction of applied field. And as far as the energy of this boundary is concerned these boundaries can have energy anywhere around ten to the power minus four joules per meter square. This is the domain wall energy incase of ferromagnetic materials. So, this is after F Bloch who prescribed this theory in 1932 that the magnetization in a ferromagnetic material cannot change abruptly at the domain wall. It has to it has to be a gradual process and this was based on the theoretical calculations he made on these on the ferromagnetic systems.

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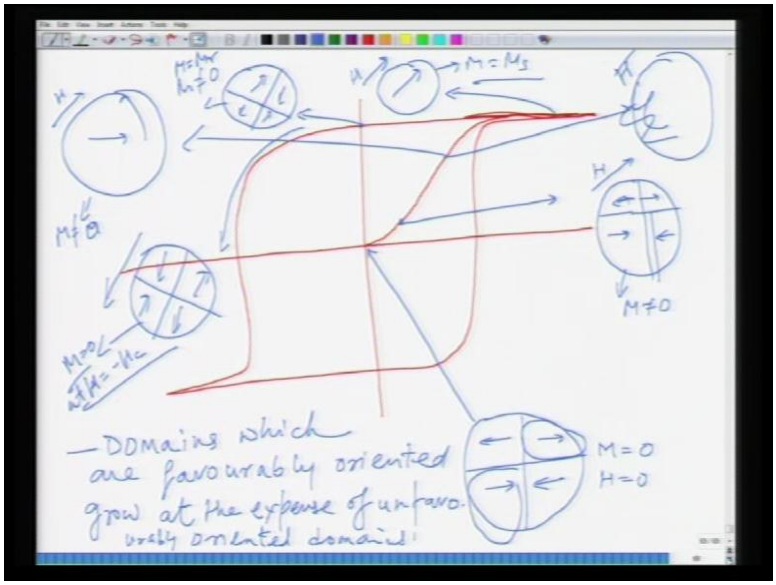

So, in the ferromagnetic material the way domains grow is. So, you have a situation. So, let us let us draw. So, this is the ferromagnetic loop all right and. So, this is the virgin state of the material. So, let us say the domain structure at this point is something like this if I draw different color. And at this point what you had was a domain structure like this. So, let us say this is in this direction, this is in this direction and this is in this direction, this is in this direction. So, the net M was equal to 0. Now what happens in these materials is that when you start applying the field. So, let us say the field initial initially the field was field is always in this direction. So, let us say the field is in. So, this is when H is equal to 0. Let us take somewhere around this point. So, the field is is in this direction and if we just look at this picture what happens is the most or just for the sake of illustration. I will make the field slightly in different direction. So, let us say the field is in field is in this direction ok.

So, what happens here is if the field was in this direction then the most favorably oriented domain was this domain and this domain. So, what happens is these domains grow at the expense of these other domains. So, what you have here is what you have here is you have the growth of these domains at the expense of. So, this domain for instance gets bigger and let me just and this domain gets smaller. So, so as a result you have M which is not equal to 0. Now let us say when you reach somewhere here. So, you do not have any nucleation of new grown domains. Rather what you have is growth of the old domains itself the most favorably oriented old domains. So, when you reached

this point for instance then you have let us say. So, your field was in is this direction oops. So, I will l do that here may be. So, this is your domain structure. So, if your field was in this direction, but the domains were aligned in this direction.

Now, since the field was in this direction, this these domains also now have to align rotate in this direction. So, when you come to this point then field was in this direction and the domains were also in this direction. So, this is how the domains move in these materials.

And when you come to this point then these favorably oriented domains they remain some of these other do. So, they tend to flip back because now the field direction is field intensity is changing. So, as a result now you have some domains of other kind which are forming. So, you have other domains which are forming. So, as a result you have M not equal to zero. So, M is equal to M r and here you had M is equal to not equal to 0. And this was the situation where M was equal to M s. So, from M s to M r there is a slight drop because of formation of oppositely oriented domains.

And this happens by gradual filliping of the gradually filliping of some of the magnetic dipoles in this otherwise mono domain region. And the whole system continues until you reach whole process continues and the formation of now when you change the field back to this direction the field direction is happened in this direction. So, the domains of, so there are some domains in this direction some domains in this direction. So, this gives rise to M is equal to 0 at H is equal to minus H c. And this whole process continues in the similar fashion. So, here the difference with respect to ferroelectric material is domains which are favorably oriented grow at the expense of unfavorably oriented domains. So, it is only a growth from the rather it is it is not a process of nucleation. So, there is no nucleation in growth from the unlike in ferroelectric material do that is the crucial difference with ferroelectric materials here in terms of domain growth and ferromagnetic materials.

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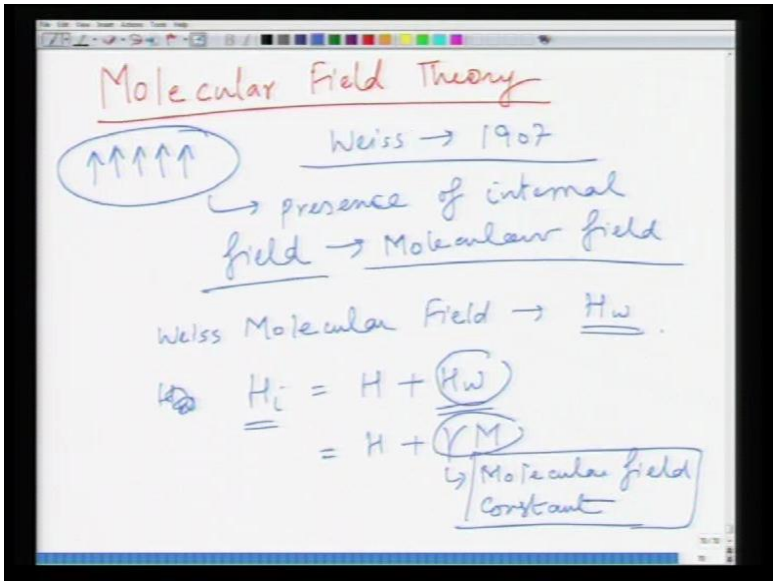

Now, what we are now going to look at is essentially the microscopic region for magnetization in ferromagnetic material. And for this we will look at what is called as molecular field theory. And this comes from the fact we are saying that each of these atoms have permanent magnetic moment. So, nickel has a permanent magnetic moment iron is permanent magnetic moment. But what is that which leads to this ordering of spins because what we are saying is that all these spins are aligned in one direction giving rise to a domain. So, what does what does lead to the formation of this single domain state and what is the effect of ordering on the magnetic moment of this material? And this ordering is in the in the very crude language you can call this an neighbourhood effect which essentially gives rise to a internal field as postulated by Weiss earlier in 1907.

So, who postulated that this alignment of magnetic moments in this uniform region is because of neighborhood effect or because of presence of some internal field. And this field was also called as at that time molecular field and this molecular field just like as we saw in ferromagnetic materials clausius. Just before the clausius mossoti relationship you have a internal you had ainternal field. So, on the on the same linesa molecular field was conceived. And this field was thought to promote this alignment of spins in one direction giving rise to a ferromagnetic interaction.

And so, this molecular field or internal field is called as Weiss molecular field and this is denoted as H w and so, let us say this H w. So, the internal field inside the material now will be the applied field plus this molecular field H w. So, you have the field which is applied typically if you take this internal field equal to 0. The total field which which the material experiences internally will be only applied field. But if you have some internal extra field present because which leads to alignment which was called as molecular field then the whole internal field gets modified as H plus H w. And this H w was defined as some constant gamma multiplied by magnetization and this gamma is called as molecular field constant. And this gamma multiplied by magnetization is a extra effect which is present in the ferromagnetic material.

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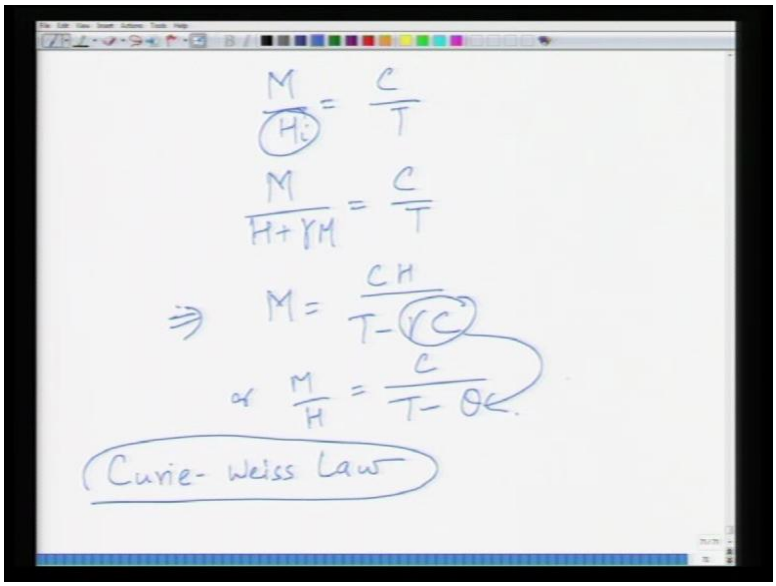

So, when you replace this h. So, you know that M by H is C by T. So, this H is the internal field in this case. So, you replace this M divided by H plus gamma m. So, let us say this is H I and this H I is equal to applied field in paramagnetic materials is equal to c by T and if you rearrange this what you will get is M is equal to c H divided by T minus gamma C or M divided by H is equal to c divided by T minus theta. So, this is theta and this has a of course, a unit of temperature because this is nothing, but C divided by T minus some T c or theta. And this is called as you know the curie temperature and this whole thing is called as curie Weiss law. So, the curie law which was followed by paramagnetic material has been modified into curie Weiss law with the introduction of this molecular constant which is a wise constant also into this susceptibility expression.

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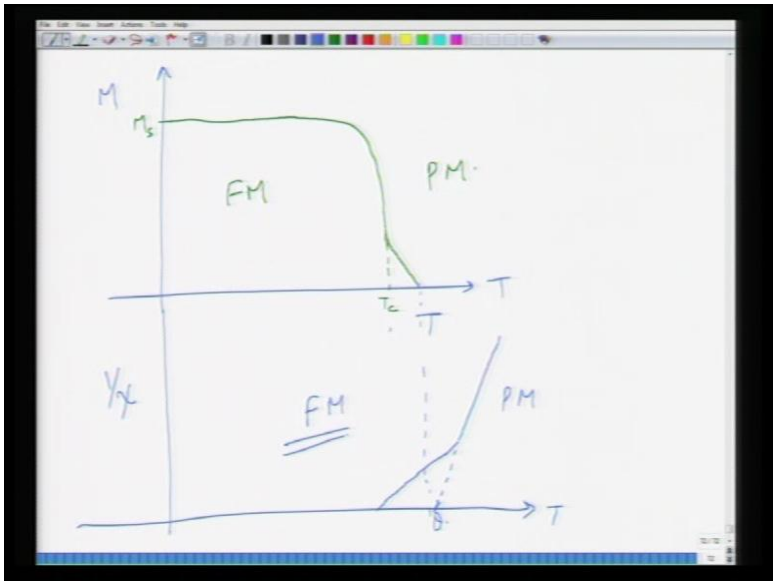

So, as a result when you plot this magnetization versus temperature for a ferromagnetic material this shows a following trend. So, you have magnetization starting at M s and this magnetization drops to. So, you would expect a transition temperature and this because of curie Weiss behavior it dies of slowly near T c. So, this is the ferromagnetic state and this is this is the paramagnetic state. And in contrast if you if you if you plot the susceptibility. So, this is temperature and if you plot one over chi. Now, one over chi has a behavior which is something like and this is called as theta.

So, this is your paramagnetic state and this is your ferromagnetic state. So, this is the behavior of. So, M s it starts of almost flat then it drops near the T c and then near the T c it dies of slowly leading to 0 magnetization where as one over chi. It is it is a signature of basically phase transition to a spontaneously ordered phase ordered in the sense of ferromagnetic ordering. And so, you might have these susceptibility drops of fairly rapidly up to theta as the temperature is decreased and it slowly dies of near the theta. So, this is how you depict the ferromagnetic to paramagnetic transition and this would correspond to a (( )).

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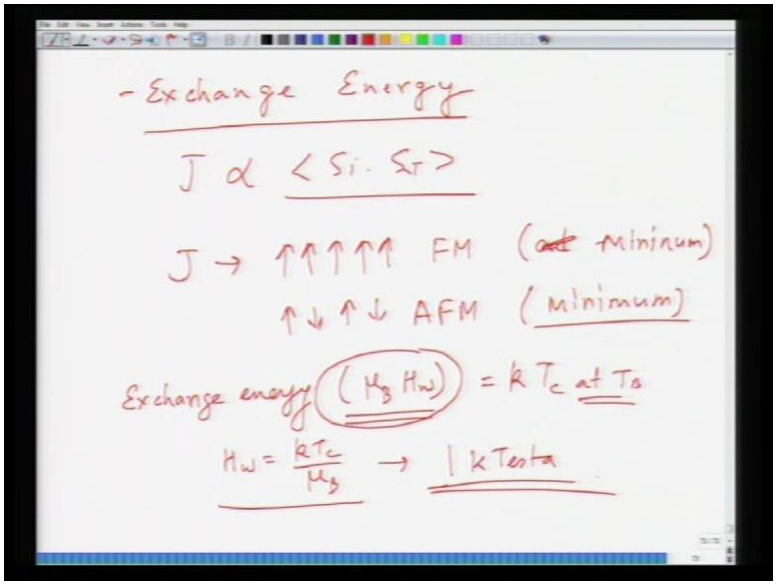

So, again it follows the same curie Weiss behavior with the introduction of this molecular constant. But the real picture was slightly different the real picture was there's no as such internal field. But rather what you have is what is called as exchange energy and this exchange energy is a very funny quantum mechanical concept. And what basically it is it is a exchange integral essentially J which is proportional to product of S I S J which is a spin magnetic moment of all the atoms. And you sum them together and this J happens to in a ferromagnetic material. This J happens to adopt a minimum for a parallel configuration.

But if you, but for a anti ferromagnetic materials as we will say later this J happens to adopt in the anti parallel configuration. So, this J integral which is the exchange which represents the exchange energy at the which plays a important role in the alignment on these spins in one direction. It is not something which is I mean you can still call it a internal field. But it is not internal field as such it is just exchange energy which is because of alignment of spins which is because of which is because of product of these spin magnetic moments. And so, this is essentially it is essentially because of coupling of you know the balance between various energies in the system which gives rise to this kind of effect; so in the in the in another another difference of exchange energy with respect to this. So, called molecular field is that where as molecular field is a large area concept the exchange energy is a short range concept.

So, this is one of the differences that was later produced later explained by quantum physicist. And another thing is this magnitude of internal field. If you can if you work out just by taking the magnetization which is shown for instance this exchange energy which is based on this internal field it is given as mu b H w. If you just relate it to thermal energy k T at T c. So, this H w will work out approximately k T c at divided by mu b because at thermal at T c, this exchange energy or the internal energy will be overcome by thermal energy. So, that is where they become equal and if you work out this H w this is very high this is one kilo tesla or so. And these kind of magnetic fields cannot even be produced on best of the machines in the world.

So, this concept of internal field is slightly wrong in that sense rather exchange energy which later was explained by quantum physicist which is based on the spin alignments and minimization of energy is a far more accepted phenomena. But we will not go into discussion of that because it is beyond the scope of this course. But if you are interested you can read on variety of books on ferromagnetism. I will give you some titles in the next class where you can read about it.

And so, essentially you have in this class what we have discussed is we have another class of materials which are called as ferromagnetic materials. And the difference between these and paramagnetic materials is they have large positive susceptibility which means large magnetization. And it happens in materials with permanent magnetic moments, but these moments are aligned with respect to each other thanks to the exchange energy minimization. And this exchange energy is a is a is a quantum mechanical concept again. So, we will we will not take this into discussion in this in this course. But essentially it gets minimized in ferromagnetic materials when you have parallel configuration in one direction and the these materials also show similar hysteresis group just like in ferroelectric materials when they are switched.

So, you have a M H curve width of this curve governs whether you have a soft magnet and hard magnet. And again you have this concept of domains and are nothing, but regions of uniform magnetization. And these domains form as a result of balance between various kind of energies. Most importantly the domain wall energy and the magneto static energy and this governs the minimum size of the domain that you must have. And the materials also follow what is called as a curie Weiss behavior which

means you have a drop of magnetization to paramagnetic state at a at a temperature which is called as a T c or transition temperature.

So, we will finish this lecture here with this summary. In the next class we will take up the remaining causes of magnetism with a more strong focus on magnetic ceramics which is ferrites which fall in the category of ferry magnetism. And this is a under broader umbrella of anti ferromagnetism.

Thank you.