Electroceramics
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Lecture - 20

Today, we start a new lecture. Before we start the contents of this lecture, we will just review the previous lectures. So, this module is basically about dielectric materials in which we introduced essential concepts of dielectric materials like what is polarization? What is dipole moment? What is susceptibility? What is a relative dielectric constant? And then we looked into the origin of polarization. And we looked at various kinds of polarization mechanisms. And there are many essentially 4 different kinds of polarization mechanisms. You start with the most, the fastest one which happens at the smallest scale, tiniest scale at the atomic scale which is called as electronic and ionic polarization, electronic polarization or atomic polarization. And then we come to ionic polarization which happens in the solids which have cations and anions put together. And what how the polarization happens is basically when you apply electric field, these the centres of negative and positive charges displace with respect to each other.

So, in a naturally in an ionic solid, you will have electronic component as well because all the solids contain atoms. So, atomic or electronic polarization is fundamental to all of them, and then ionic solid on top of that that you will get ionic polarization contribution which is due to displacement of ions with respect to each other. And as a result you have net displacement in one direction as compared to another, so as a result you have dipole moment. The third mechanism is a dipolar or polarization, dipolar or orientational polarization which is because of rotation of dipoles typically in polar solids.

So, substances like water or barium titanate or any other substances which has permanent dipolar moment gives rise to dipolar polarization. So, molecules tend to rotate along the direction of applied field to align the dipole moment in the direction of applied field. And all these, and fourth mechanism was interface polarization which could be because of presence of various defects and electrodes.

Now, we took them sort of analytical treatment of electronic, ionic, and dipolar polarization. And there we calculated the polarizability of all these 3 mechanisms. And we find that the polarizability of electronic and ionic polarization mechanism is dependent upon parameters like, so electronic for instance electronic polarizability, alpha is function of size. So, and in the other case alpha ionic was function of y which is the elastic modulus.

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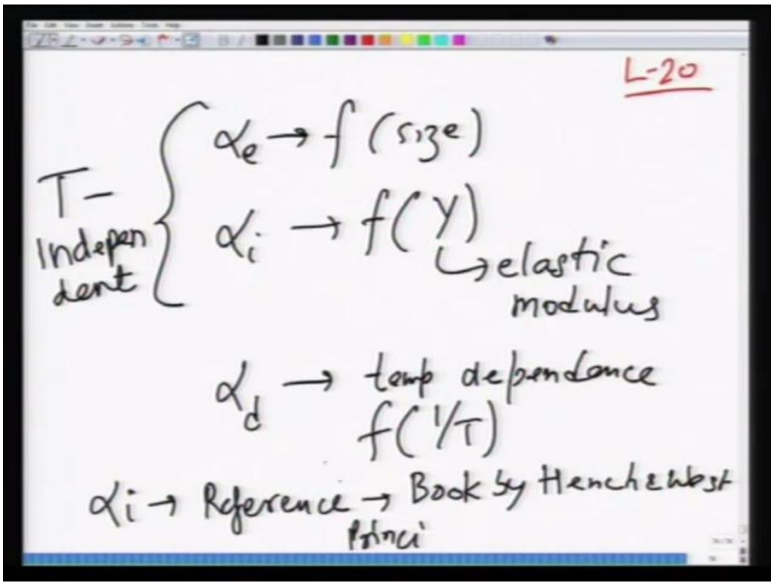

So, for instance alpha electronic which is the electronic polarizability is the function of size as it went as a there was a dependence on the radius of the atom. And typically larger atoms would give rise to larger polarization. So, as a result anions typically have higher polarizability as compared to cations and we looked at certain examples.

Then we looked at alpha i which was ionic interface, ionic polarization which dependent upon parameters like y which is the elastic modulus. And what it suggested was higher the elastic modulus, smaller the ionic polarization is that makes sense, because higher the elastic modulus which is because of higher bond strength. And so typically solids with higher modulus which is because of higher body strength will tend to have a smaller ionic polarizability, and that makes sense. And then finally, we looked at alpha d which is the dipolar and that was that had temperature dependence.

These two were temperature independent, and this was inversely proportional to temperature. And what they suggested was as the temperature increases the polarizability decreases or and vice versa. So, this also makes sense because as a temperature increases the tendency of dipoles to along align along the applied field will be will reduce because of higher thermal forces. And so either you increase the either increase the magnitude of field or you decrease the temperature in order to increase the tendency of alignment.

So, these were the 3 polarizabilities that we looked upon in terms of analytical treatment. We did not go into details of interface polarization that is the analysis of that is slightly out of scope of this course. However, if there, if you are interested in going into treatment of this I can suggest some references, you can look at. So, for alpha i, you can a reference would be the book by Hench and west which is principles of or i will just write in another slide.

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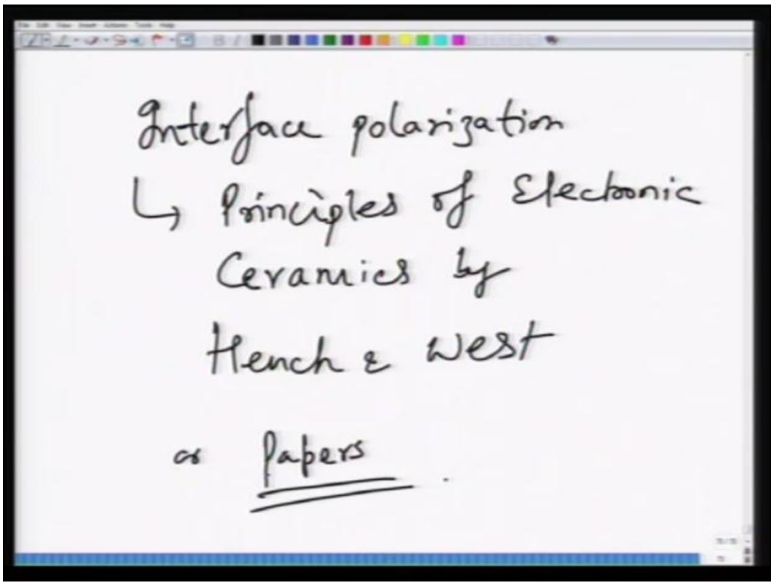

So, in this book you can find a reasonably analytical treatment or you can look at papers in various journals. So now, this establishes. So now, you understand the importance of polarizability, and how it is dependent upon physical parameters as well as temperature. Now, so far we have not considered any analytical treatment on the effect of frequency on the dielectric. So, what we will do now is, we will look at the behaviour of dielectric materials under the influence of alternating field that is the AC field.

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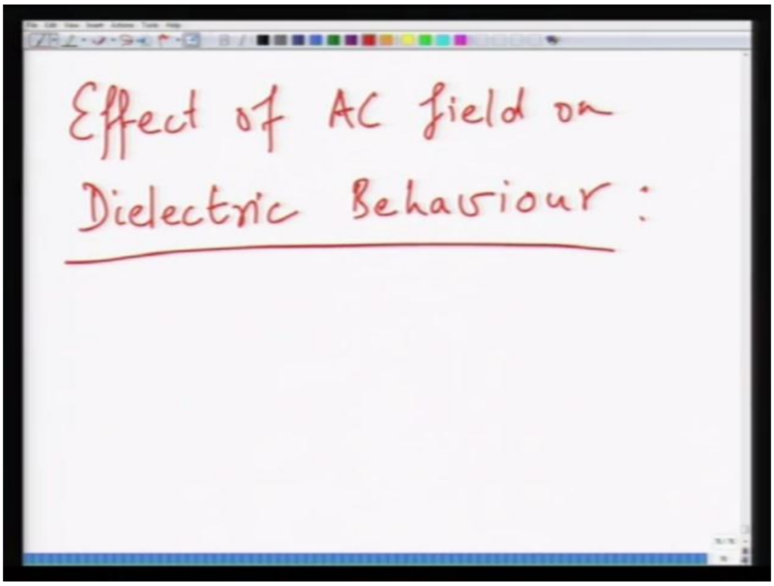

So, what we will do now is we look at effect of. This will be the theme of next this lecture as well as may be part of next lecture. So, in this context we will first look at that behaviour of ideal dielectric.

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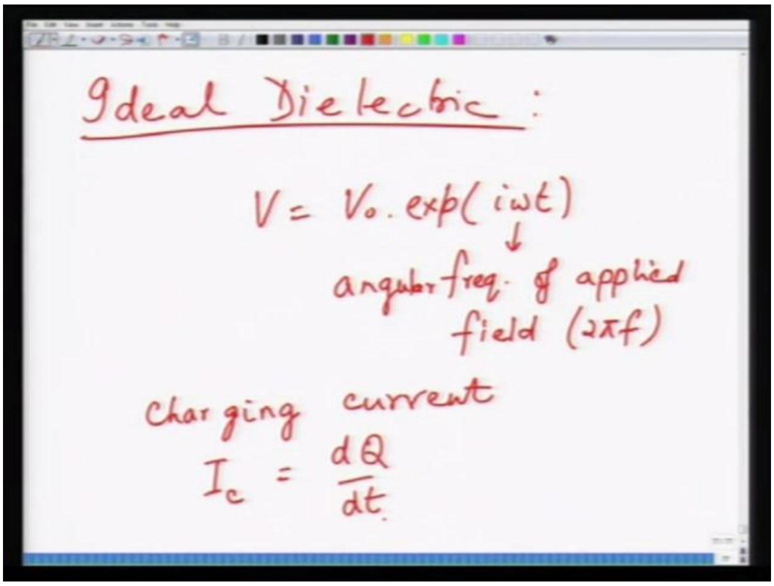

This is important because in most of the applications dielectric materials are used under the influence of AC field. As a result we need to understand how they behave what are various parameters which are influenced by application of AC field that is for instance AC frequency. And at what frequency we should be able to operate the material etcetera.

So, while most of the discussion that we did in past few lectures was basically on a DC or a static field. Here we will take up AC flied effect. So, let us say we apply a sinusoidal field. And this field is given as a voltage is given as V naught V is equal to V naught into exponential i omega t, where omega is the frequency of angular frequency of applied field basically 2 pi f, you can write angular frequency.

Now, the moment you apply this sinusoidally varying applied electric field that this V is equal to V naught the exponential i omega t. This gives rise to development of charging current. So this charging current I c. Now, why does this develop, this develops because as you as you apply a voltage to a dielectric there is a change in charge as a function of time. And this change in charge as a function of time gives rise to what is called a charging current and this I c is given as d q by d t. So rate of change of charge per unit with respect to time gives you charging current. Now, what is Q?

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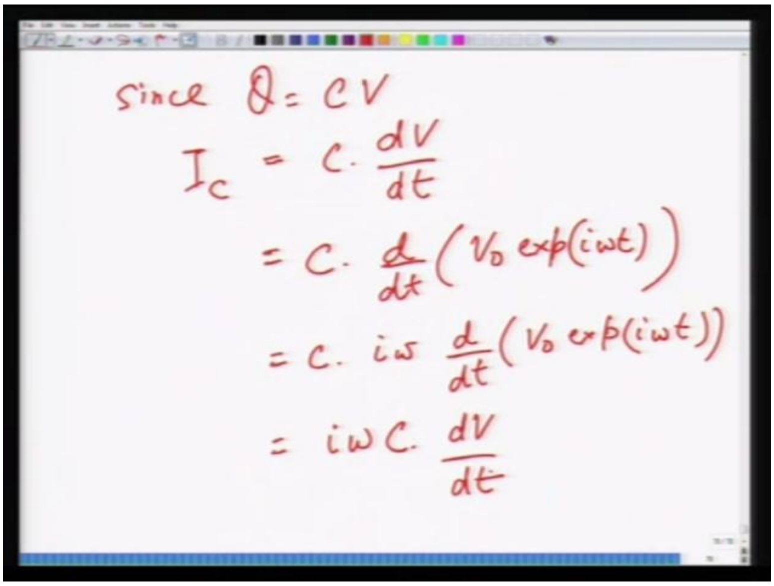

We know that q is equal to c v. So as since q is equal to c v I c can be written as c into d, v by d t and that makes sense, because c is a constant which is a capacitance of the material. And so this d by d t v naught exponential i omega t, and if you differentiate this will become c into i omega d of d t v naught exponential i omega t. So, this will become i omega c into d v by d t all right so because v naught exponential i omega t will make v.

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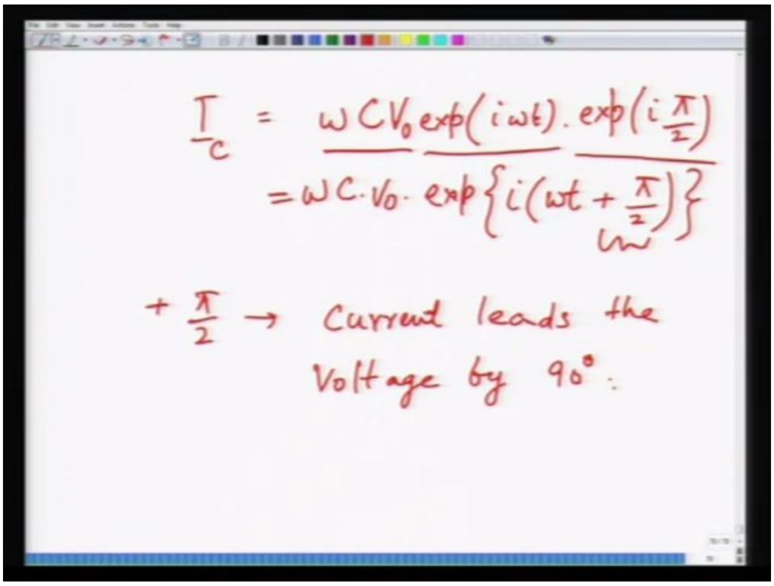

So, I c can further be written as. So I c will be equal to omega c into exponential of i omega t into exponential of i pi by 2. And this you can see from the previous expression omega c into v naught hang on there was some.

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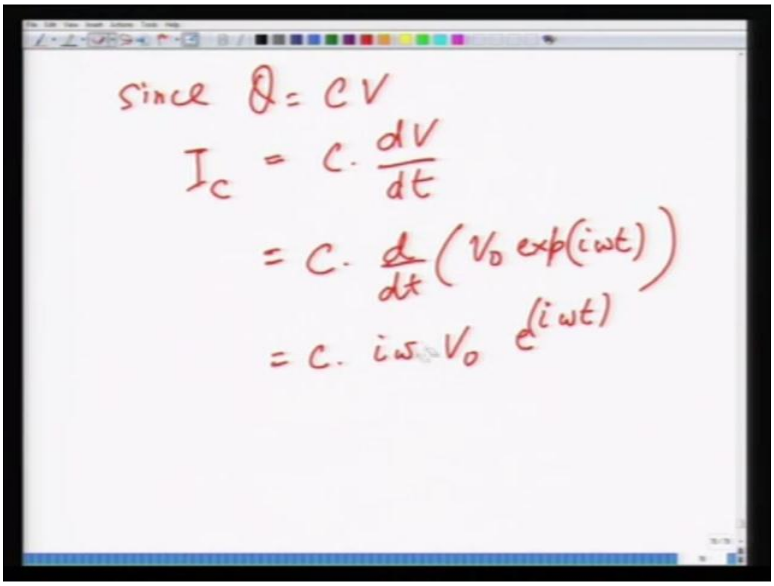

There was some mistake here. So, i omega comes out sorry this last line is. So, this i omega comes out and v naught comes out. So, what you have here is exponential i omega t, e to the power i omega t, v naught e to the power i omega t, we will just leave it as it is. So, i omega c into v naught exponential i omega t. So, i can write this as that particular equation as omega c, omega c v naught exponential i omega t, and I can multiply by another factor which is exponential i pi by 2 which is nothing but cos pi by 2 plus i sin pi by 2, and that is nothing but one . And this will be written as, and this can be further written as omega c into v naught into exponential.

So if I just rub this out into exponential i into omega t plus pi by 2. What this means? This means that the charging current which is developed due to rate of change of due to change of charge versus time, gives rise to is a leads by voltage, leads to voltage by angle pi by 2. So, the charging current so this plus pi by 2 term means that current leads the voltage by 90 degrees. So, how do you draw, and this is this we are considering in a perfect dielectric which means there are no losses in the dielectric. So, this you can draw this you can express in terms of phasor diagram.

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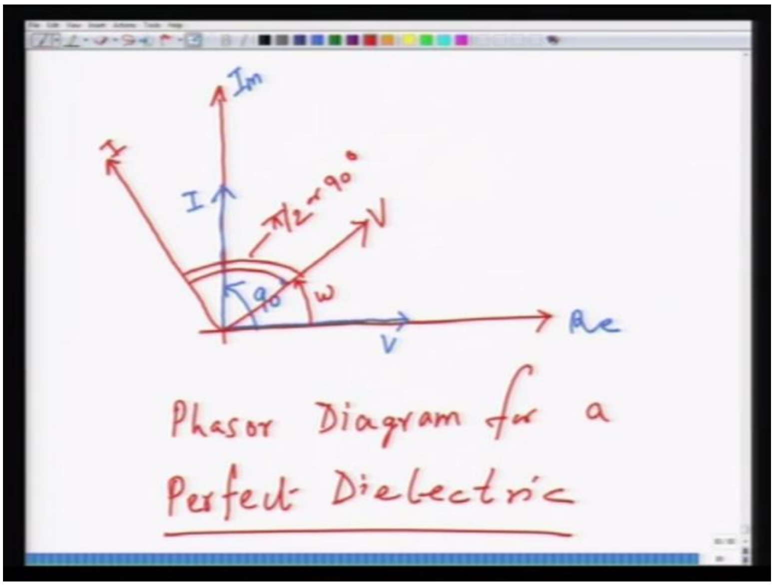

So, if you have, let us say these are. So, if this is your v then I will be led by 90 degrees in this direction. So, this will be I, and this will be v. So, on a real and imaginary plot if you draw I versus v that is how it would look like. So, this would be for instance R, R e real axis, this would be imaginary axis. So, no matter how you take it v will, the, I will always. So, if you take for instance if I change the angle of v, if v was like this and I would always be this would be. So, this is some angle omega, and this would be pi by 2 or 90 degrees. So, on a real and imaginary plot v and i relationship would appear something like that. So, this is the phasor diagram for a perfect dielectric.

Now, what we will do is that we look at the behaviour of real dielectrics. Now, real dielectrics hardly follow this 90 degree relationship what so. But before we do that we also would like to look at what is the power which is dissipated in a ideal dielectric. Now, what would be the power dissipated?

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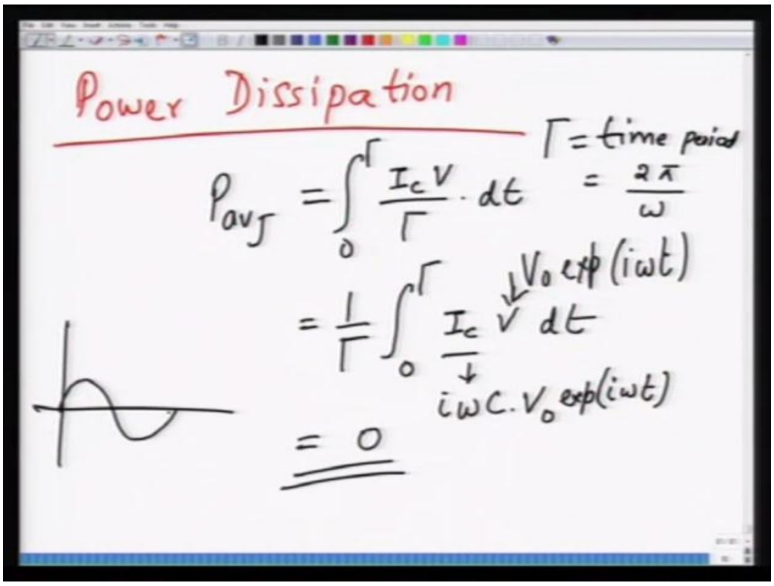

So, just now, looking at power dissipation just a small exercise before, we move to real dielectric. So, power dissipated, let us say the average power is p average. This p average can be written as over the time period tau. So, tau is equal to time period, and this can be written as 2 pi over omega. So, if we average the power that is dissipated over this time period, this can be written as 0 to tau, I c into V divided by tau d t. And so this can be written as 1 over tau since, tau is a constant 0 over tau I c V d t.

Now, since the voltage, since the current leads the voltage by 90 degrees in a ideal dielectric p average has to be equal to 0. So, you can put the expression for I c which is I c is equal to i omega c into V naught exponential i omega t. And v will be v naught exponential i omega t. And if you do the multiplication, and do the integral, you will find out that the net average the average power which is dissipated in an ideal dielectric is equal to 0. So, what it means is that, that when you apply during the cycle, let us say so during this cycle. So, A C field is applied like this. So, during this cycle the capacitor charges completely, and discharges completely without any dissipation of without any loss of charge. So, this is like a perfectly oscillating, perfectly oscillating oscillator under the for example, on a perfect spring under gravity. So, without so you have a spring, you attach a mass to it, and it perfectly oscillates without any dumping or losses.

So, in this case what the analogy is that when you apply this voltage v, oscillating field v is equal to v naught exponential i omega t to the dielectric in the first cycle. Let us say charges completely in the next cycle, it discharges completely, in the next half cycle it discharges completely. So, charging and discharging of this net charging, and discharging of dielectric does not lead to any dissipation of charge. As a result the net power dissipation is equal to 0. So, this is what, this is about perfect dielectric.

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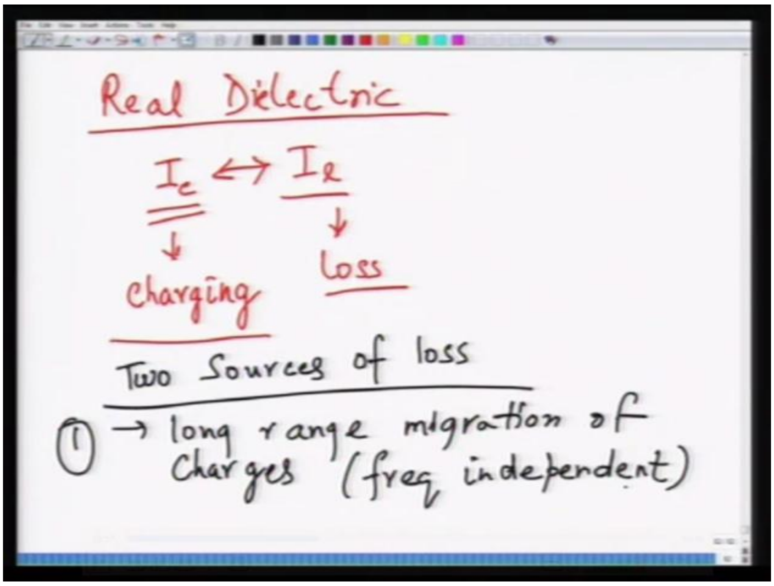

Now, the case is the case is slightly different in case of real dielectrics. Or rather quite different, in case of real dielectrics, what happens is that this charging current which is I c is also the, so for this charging current I c there is a accompanying current which is called as i l. So, this is your charging current, and then you have accompanying it is called as loss current. So, which means in real dielectric there are some finite losses of charge in the system, and which would happen because of variety of reasons. And whatever be the reasons are the current associated with them is called as loss current. And this is and there are typically two sources.

So, two sources of loss and this loss first it could be long range movement of migration of charges. So, this is number 1 which means just like a normal material when you apply voltage there is something like ohmic conduction that is taking place which means a long charges are able to move. So, in for a long distance, unlike in polarization where I told you that in normal dielectric charges are supposed to move only a tiny distance. So, that to so that they give rise to what is called as polarization. But when you have a real dielectric not only you have that polarization taking place, but also you have what is called as long range migration of charges or ohmic condition which gives rise to which gives rise to loss, and this is typically frequency independent. So, like a D C loss. So, this is typically frequency independent.

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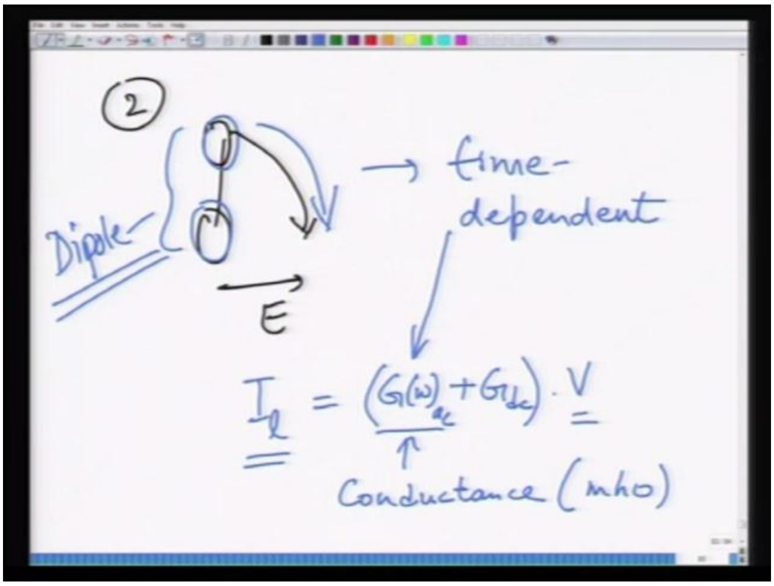

In the second term is now, when you have these dipoles which they have which have to rotate in the direction of light field. So, you have the dipoles like this, and if they have to rotate in the direction of applied field, let us say this is e so this is I will use different colours. So, this is the dipole, and when you applied field E, it has to rotate in this direction, and this rotation is resisted by what is called as inertia. And this inertia has to be there in a system if the entities involve some sort of mass. And the moment mass comes into picture you have a inertia, and this inertia opposes the rotation of these dipoles in the direction of applied field, and this is typically time dependent loss.

So, some sort of loss of energy which happens as a result of resistance to the movement of this dipole in the direction of applied field. And so there are two components one is the d c component which is at frequency independent you have another component which is frequency dependent or time dependent, and this is a c component. So, this i l can be expressed as so something multiplied by V. And this i when you so how can you we can we can calculate i something multiplied by V, and that something is called as G omega a c which is the, a c part, the time dependent part. And then you have G d c, and what is G? G is the inverse of resistance or conductance in the simplest terms, because we know from ohm's law v is equal to i r.

So, if you so if so i would be equal to 1 over r into v, and sought of one over r is called as conductance whose units are in mho. So, you have these two components of conductance one is the, a c component of conductance which is the time dependant part which is because of inertial a resistance to the movement of dipoles to the direction of applied field. And second is the d c component which is because of long range movement of charges.

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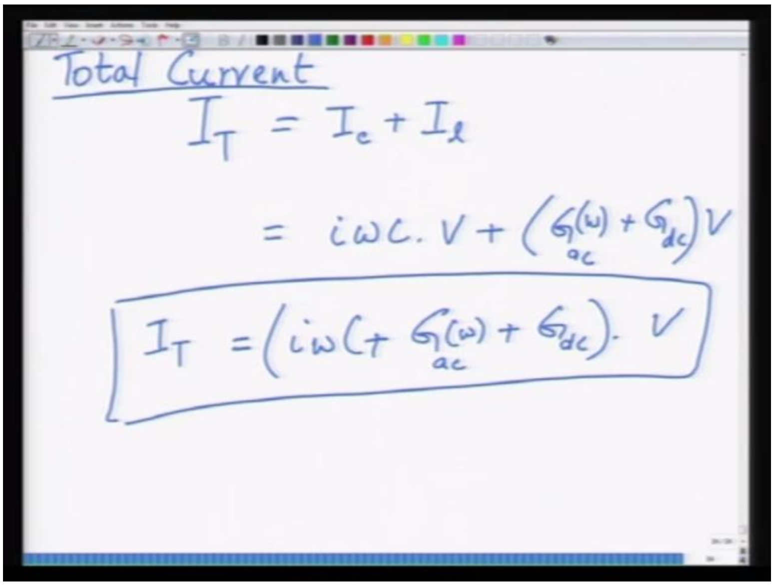

So, the total current I t total current, I t can be written as I c plus I l. I know I c is i omega c into V plus I know this is G, G omega a c plus G d c into v. So, this is i omega c plus G omega a c plus G d c into V. So, this is the expression for total current for a real dielectric. And what it means in terms of phasor diagram is.

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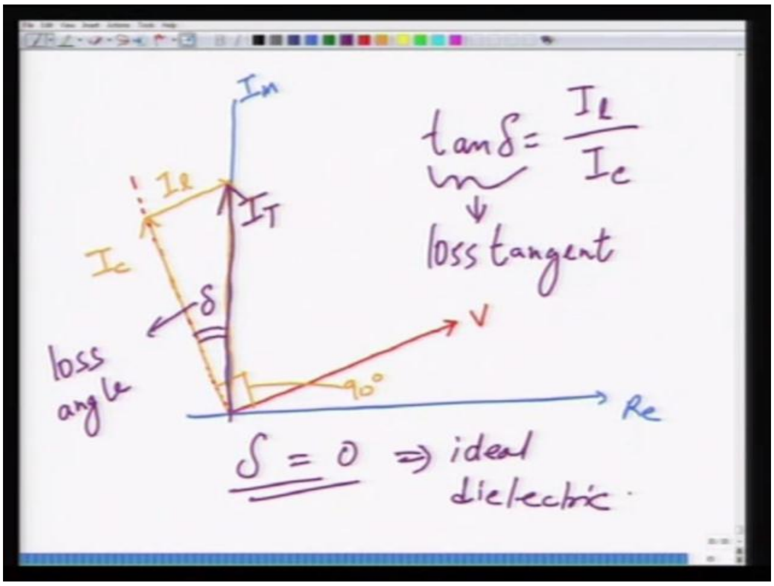

So, in it was a phasor diagram. So, if this was let us say V, for a perfect dielectric I would expect this I to be developed. So, perfect dielectric will have I. Now, since we are saying that we do not have a perfect dielectric, what is this component? This component will be I c which is a charging current. And you have so in the perfect dielectric this would be 90 degrees. But my overall current is not made up of I c it is smaller than I c. So, actually the charging current is not equal to I c in a real dielectric it is smaller, total current is made up of I c and another component which is called as I l. So, this I l is in phase with the applied field. So, this is your, I l and this would be your, I t.

So, this is your, I t for a real dielectric. And now, you can see you have the charging current which is at 90 degree to the applied voltage. And then you have I l which is in loss current which is in phase with the applied field or applied voltage. And this angle made between I t and I c is called as delta and this is called as loss angle. So, you can see that delta. So, you can represent delta as tan delta which is called as loss tangent, this is equal to I l divided by I c. So, what it shows basically is larger the loss current is larger your tan delta would be which means, total current would move to closer and closer to the voltage. So, this is the deviation which happens in a real dielectric as compared to the ideal dielectric.

The total current in the real dielectric is I c only so as a result the angle is 90 degrees whereas, in total current in a ideal dielectric, I am total current in the ideal dielectric is I c which is which leads the voltage by 90 degrees whereas, total current in the real dielectric is I t which is made up of I c which anyway leads to the voltage by 90 degrees. But also I l which is parallel to v, and as a result this gives rise to a, and this is defined by a quantity which is called as delta or loss angle.

So, the total current makes an angle delta to the, I c in the direction of omega. And in the direction of V, sorry voltage and this delta is called as loss angle. And tan of this delta is nothing but I l by I c as you can see from this. So, higher the, I l is higher tan delta would be which means worse which means more the losses would be in a dielectric. So, higher tan delta means more loss in the dielectric is. So, basically delta is equal to 0 would mean an ideal dielectric, and higher the delta is more loss in the dielectric is. So, when field is a static.

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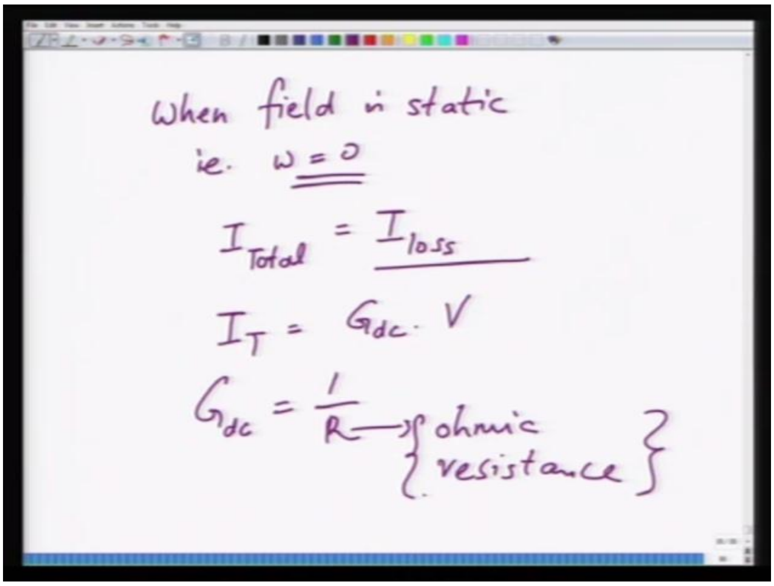

Let us say static field would mean that omega is equal to 0. And when omega is equal to 0, I total will be equal to I loss multiplied by V. And this you can see because if you go to previous expression I t was equal to I omega c, a c component d c component into V so a c and d c components of conductances. So, if you make omega is equal to 0 both of these o c, a c components disappear as a result I becomes equal to I total becomes equal to I loss multiplied by V. And this so I t is equal to G d c into, sorry what did I. So, as a result I I total will be equal to I loss only, and I which means I t will be equal to G d c multiplied by and V.

So, G d c will be equal to nothing but 1 by R and this is your ohmic resistance. So, another way to express these real dielectrics is to use to depict this charging in loss current is by using permittivity as a complex quantity. So, we can also express.

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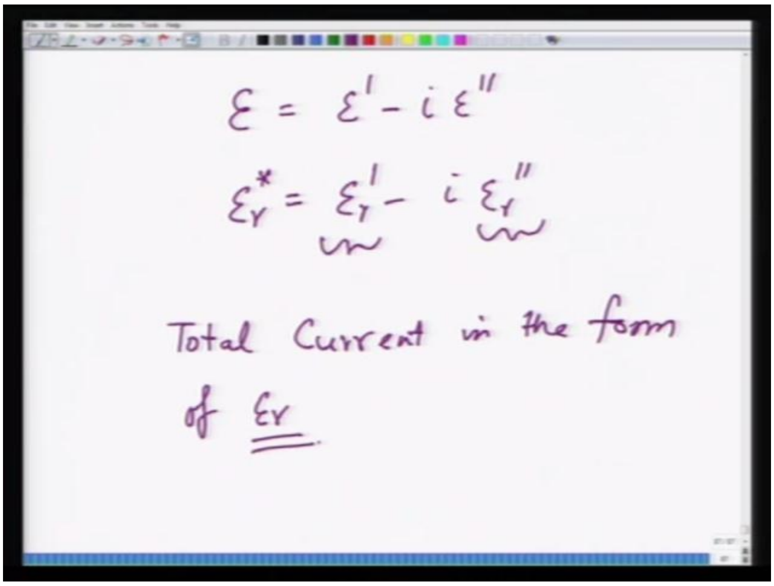

So, this epsilon which is a permittivity that can be expressed as epsilon prime minus of i into epsilon double prime. So, what it means is that basically given the fact that you have now two components of current, one is the charging current; one is the loss current or discharging current as a result. So, basically the current has both d c part frequency dependent part as well as frequency independent part, given the fact that that happens the permittivity of the material has to be, has to have a real part as well as the imaginary part So, this can be written as r epsilon star is equal to epsilon r prime minus i epsilon r double prime.

So, this will be called as your real part of dielectric constant, and this will be called as imaginary part of dielectric constant. And this represents the charging as well as loss currents accurately. So, idea behind doing this is so that we can we can express the total current in a dielectric in terms of a single parameters, and that is in the form of epsilon r So, one single term takes care of the overall current in the dielectric material. So, we can write now.

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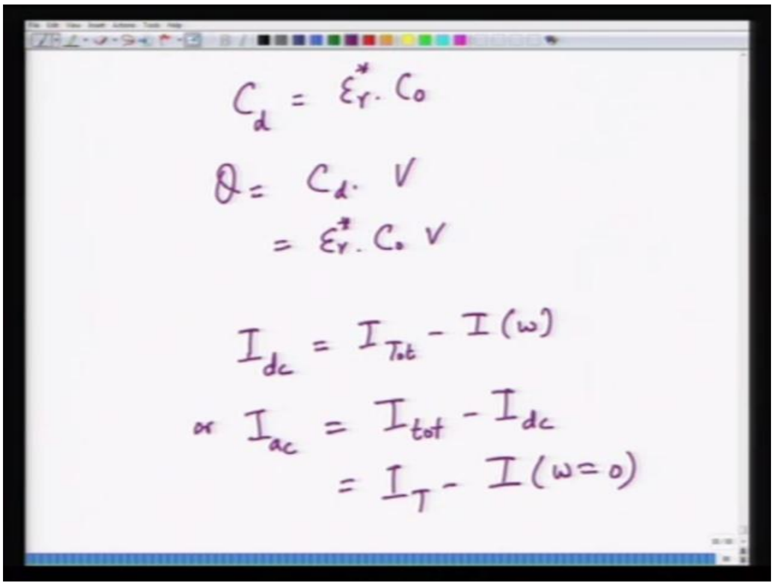

The capacitance C dielectric would be equal to epsilon r into c naught which is the capacitance of the vacuum capacitance. And we can write Q as we know is equal to c d multiplied by v. So, this will be epsilon r. So, this epsilon r will be epsilon r star since, we have charging in loss current. And assuming that we are taking that dielectric constant is a complex quantity having a real and imaginary part. So, we can write Q in this manner which will be equal to epsilon r c naught into v.

Now, we can express now, we again get back to the current equation. And total current we can write as or I let say the d c current, I d c will be equal to I total minus of I of frequency dependent part. So, what about the frequency dependent part of current is since, we have so. What we have done is instead of taking charging and discharging current separately, we have taken d c and a c component. And this will be equal to or alternatively, you can write I a c is equal to I total minus I d c. And what would I d c mean so I t minus I omega is equal to 0, this would be the current.

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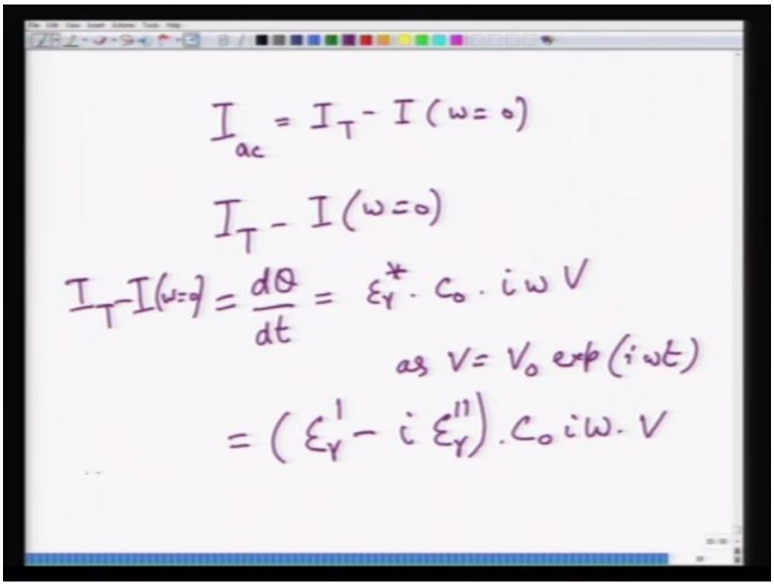

So, I a c is i t minus I of omega is equal to 0, and this is nothing but your. So, this, we take this equation as it is at the moment. And we write this I t minus I omega is equal to 0 as what can this be? This could be written as d q by d t. And this is so from the previous expression, we know that Q is equal to epsilon r star into c naught into v. So, if we plug this definition of Q in this equation. So, this I t minus I omega is equal to 0 is d q by d t, and this becomes epsilon r star into c naught into i omega v because v, as v is equal to v naught exponential I omega t. So, that is stays the same as we took earlier. Now, what you can do is that you can write this epsilon r star as epsilon r prime minus i epsilon r double prime multiplied by c naught i omega into v. So I total will become.

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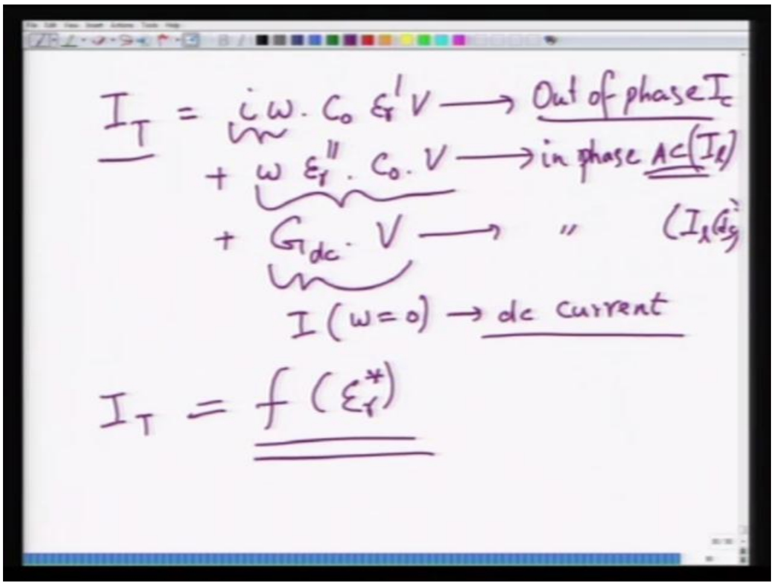

So, I total will become now, i omega into c naught into epsilon r prime v plus omega into epsilon r double prime into c naught into v plus I have taken the d c component on right side that will be G d c into v. So, this is your, I omega is equal to 0 basically the d c current. Now, what we have done is we have represented this total current as a function of epsilon r star. So, a single quantity gives rise to the total expression for current. And this single quantity can also be measured experimentally. So, the first term so which is the in phase current, and which is the outer phase current. The first term is out of phase charging current term. So, this is out of phase charging current, because this is you know imaginary part is there i omega is there. And then this would be the in phase a c loss current I l, and this would be in phase I l d c. So, these are different components of current that you can write in terms of dielectric constant.

So, by invoking this relation, that the dielectric constant of a real dielectric material also has a real and imaginary part. And if you so this helps you to write the total current expression in terms of that quantity. So, if you compare some of these equations earlier specifically the total current expression. If you compare the total current expression so we have two expressions.

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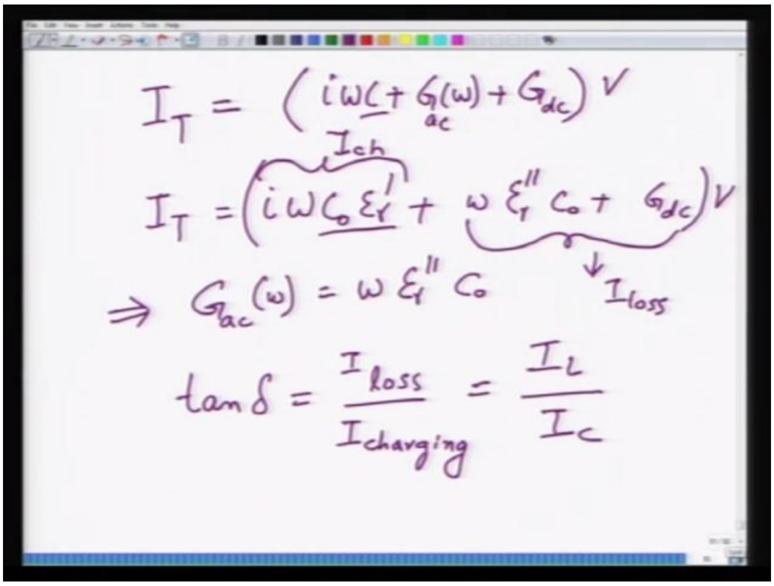

The first one is, first one, we developed as I t was equal to, if you go if you go back earlier, we wrote it as I t is equal to just a second, i omega c plus G omega a c plus G d c into v. This is first expression we had. And the second expression now, we have is I t is equal to i omega c naught epsilon r prime v. So, if i just take v out plus omega epsilon r double prime c naught plus G d c into v.

So, here I get G omega a c as equal to omega epsilon r double prime c naught. And this by definition gives you c is equals to c naught epsilon r prime which is true. And G d c is nothing but G d c so. And from this you can also calculate what is tan delta, tan delta as we know is equal to I loss divided by I charging which is I l divided by I c. So, what is this written as so tan delta, you can now mention as so what is I loss from the previous expression? This would be your, I loss, and this would be I c h.

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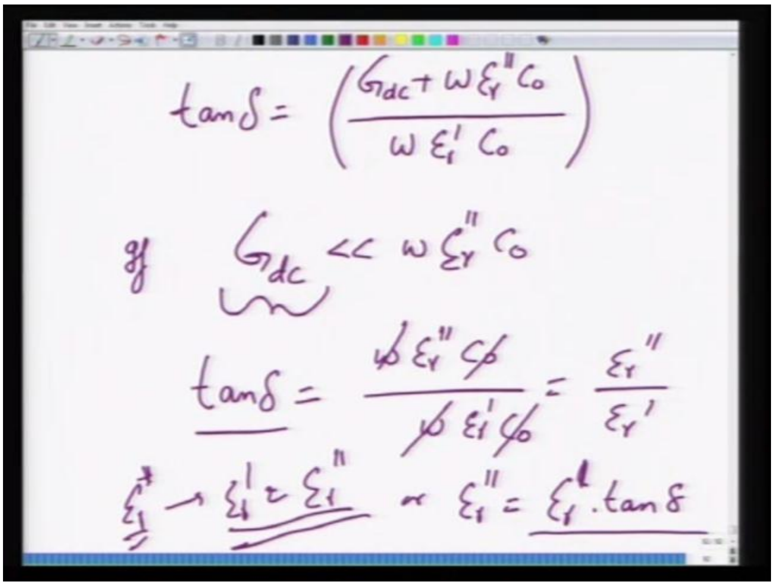

So, this would be G d c plus omega, if you go back here omega epsilon r, epsilon r double prime c naught divided by i omega, epsilon r prime into. So, tan delta is G d c plus omega r double prime c naught divided by i omega epsilon r prime divided into c naught.

So, now, this looks like a much more complicated expression than what we wrote earlier, simply I loss divided by I c. However, if we assume that G, G d c is much more smaller as compared to omega epsilon r double prime c naught which is not a unreasonable expression assumption, because G d c for most of the dielectric materials which are reasonably insulating can be very small. So, if that is true. And this is nothing but a conductance. So, they are not really conducting, they are insulating materials. So, if r is reasonably high, that means G d c is reasonably is sufficiently low. And we can assume that G G, G c is much smaller than omega r double prime c naught then you can ignore G d c in the above expression. So, this tan delta is equal to omega epsilon r double prime c naught divided by i omega epsilon r prime, sorry here you do not need to keep i, because current term will not include, i represents the loss current.

So, epsilon r prime c naught. So, we replace c naught c naught, we cut c naught c naught cancel each other; this will become epsilon r double prime divided by epsilon r prime. So, this is a very nice expression, because earlier we started with definition of tan delta as you know loss current divided by charging current. And this now, you can represent by a single quantity which is epsilon r star.

So, if you know epsilon r star, you would know epsilon r prime and epsilon r double prime. And this would give rise to this fundamental quantity which is tan delta. So, higher tan delta would mean higher the imaginary constant, imaginary component of dielectric constant or higher the real part of dielectric constant, smaller tan delta would be. So, r alternatively you can write epsilon r double prime to be equal to epsilon r prime into tan delta. So, basically for dielectric materials higher the loss angle is higher epsilon r double prime is, and even higher epsilon r prime gives rise to often higher epsilon r double prime. So, and this epsilon r double prime is called as dielectric loss factor.

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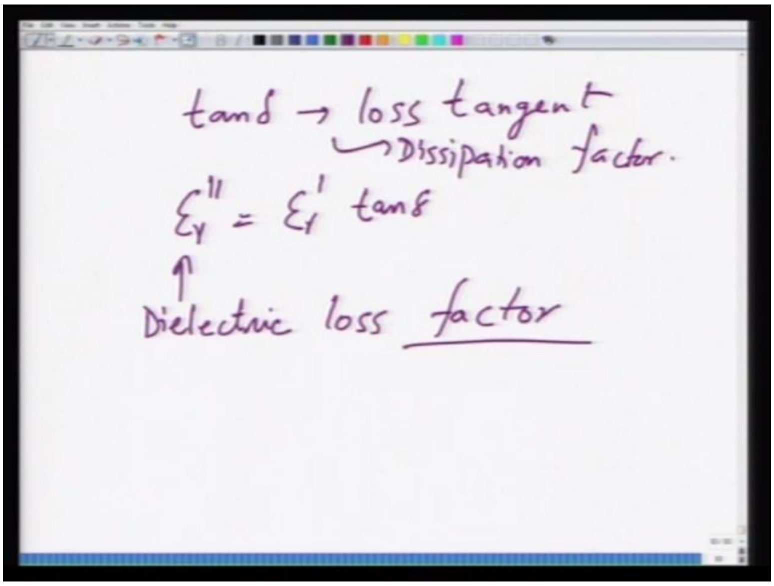

So, tan delta is called as loss tangent, and epsilon r double prime is equal to epsilon r prime tan delta, and this called as dielectric loss factor. So, tan delta is often called often also called as not only loss tangent, but also dissipation factor. There are various definitions various terms which are used for tan delta. So, I am just giving you some of those terms for these materials. Now, which are used in typically used in material science? So I will give you various some values for dielectric constant and tan delta for some materials. So, for instance;

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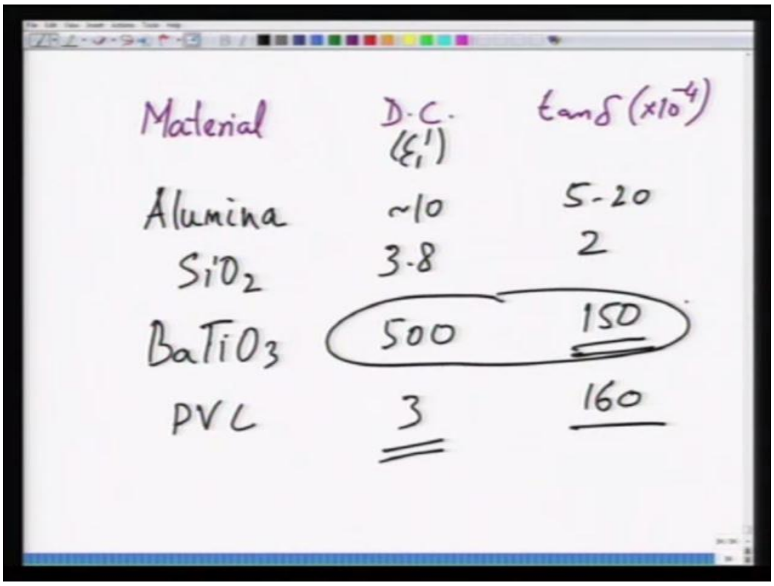

So, let us say this is you know material and then dielectric constant and then tan delta into ten to power minus 4. So, for instance alumina, alumina has, and this is the real part epsilon r prime. So, this would be approximately 10, and the dielectric constant, dielectric loss is tan delta is 5 to 20, in to divided, 10 to the power minus 4. A material like silicon oxide, silicon oxide is a very well known dielectric material used in transistor devices, 3.8 is the dielectric constant, and it can have dielectric losses which are pretty low. Similarly, you have barium titranate; this is a very famous material used for variety of ferroelectric and piezoelectric applications, this has high dielectric constant.

So, as you can see it also has a slightly higher tan delta as compared to silicon oxide and alumina. If you look at polymers like P V C, some of the polymers also polymers are insulating materials as a result they are also classified into category of dielectric materials. And so polymers have lower dielectric constant they can have high tan delta. And these two together for instance for barium titrate would result in higher epsilon r double prime as well. So, these are some of those correlations that you need to understand.

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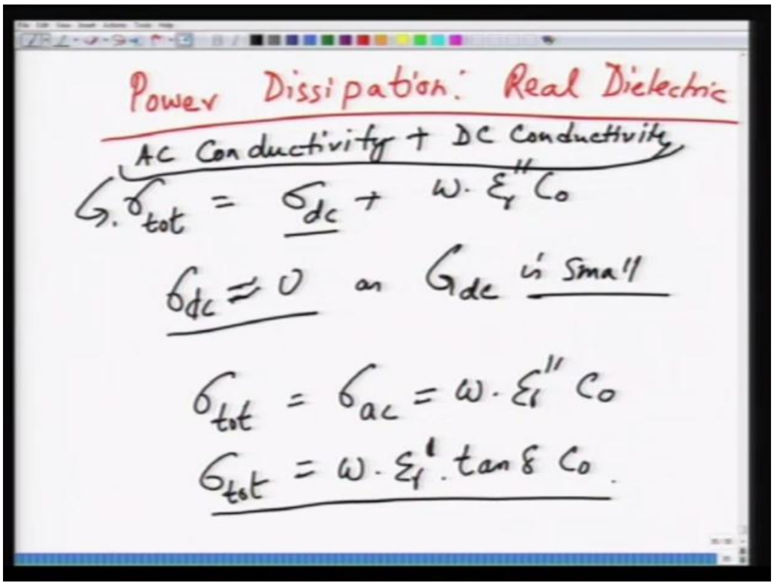

Now, what would be the power dissipation in, power dissipation in a real dielectric? So, by definition, we had the term p is p average is equal to 1 over tau, and integrated over the whole I c and v as a function of time. Now, first here we need to write what is a c conductivity? So, sigma a c which is the c conductivity, sigma a c is nothing but sum of sigma d c plus. So, sigma d c plus omega into, so the conductivity term will include the d c term as well as the loss current which is a c.

So, this is epsilon r double prime into c naught. So, rather I should say this is sigma total a c plus d c conductivity will give rise to this total. So, and as I said, as we said that is if sigma d c is very small. This sigma d c can be ignored, and sigma d c is almost equal to 0 as we are saying that G d c is small. So, if that is true then sigma total will come equal to sigma a c. And that will come equal to omega into epsilon r double prime into naught. And this will come equal to omega into epsilon, into epsilon r prime into tan delta into c naught. So, this is how you can determine the conductivity of a dielectric material?

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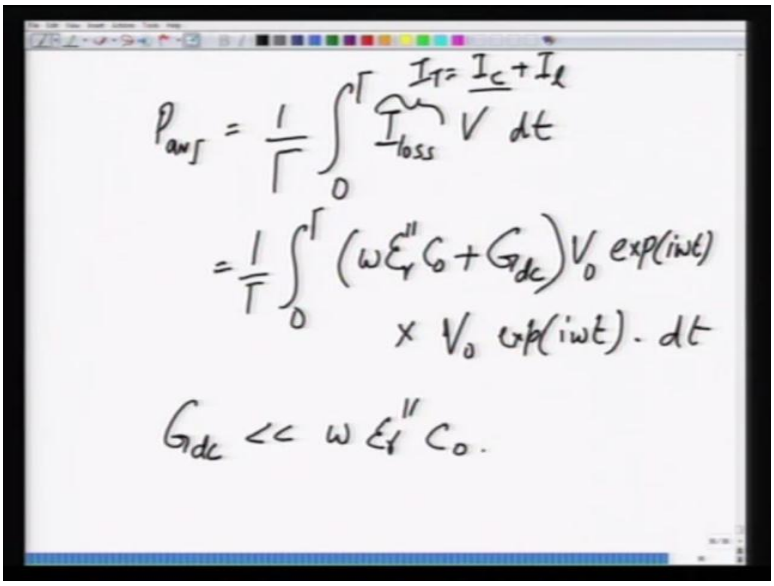

So, the time average power loss p average will be equal to 1 over tau, tau you know what it is 2 pi over omega into I loss into V d t and because if you take for charging current, it would anyway be equal to 0. So, we only need to consider so basically this would be I t is equal to I c plus I l. So, if you take only for I c this would be equal to 0. So, we need to consider only I l in our, in order to work out what is the total power loss.

So, this would be 1 over tau 0 to tau into omega epsilon, epsilon r double prime plus G d c plus. Now, since, this will have a v v term. So, we can multiply both the v terms. So, this is the conductance multiplied by v. So, or I can just do it later on, exponential of I omega t multiplied by v naught exponential of i omega t into d t. So, and we have already assumed that G d c is equal to omega epsilon r double prime c naught. So, this takes us to. So, if you assume that.

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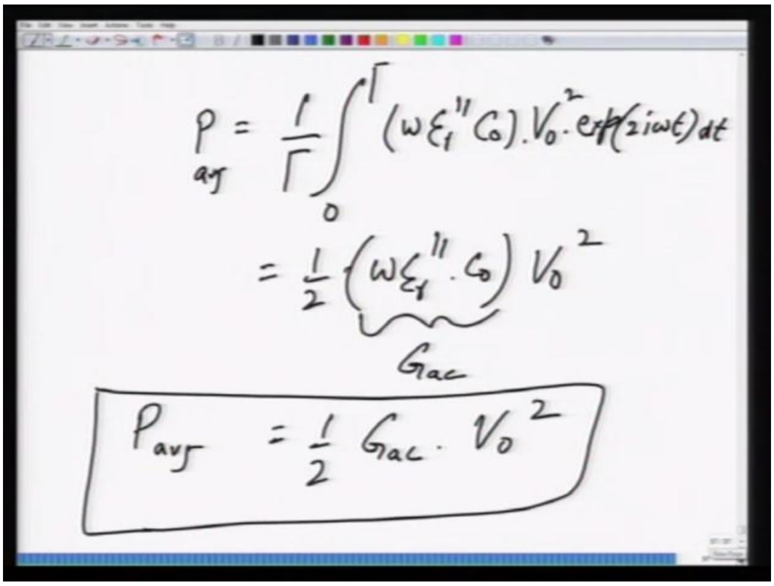

Then, this will take us to 1 over p average is equal to 1 over tau. And this would be omega epsilon r double prime c naught into v naught square into exponential of 2 i omega t d t. And if that was the case, if you solve it, what you will get here is half of omega epsilon r double prime into c naught into v naught square. And what is this? This is G a c. So, this is half of G a c into v naught square. This is an important term.

So, the average power which is dissipated in the real dielectric is proportional to the a c conductance, and which is dependent on the epsilon r double prom, double prime as well as the frequency value.

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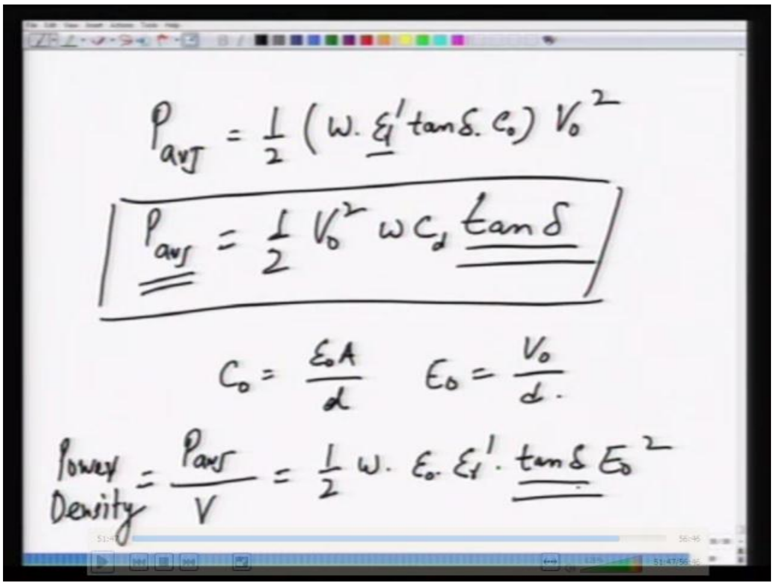

So, P average now can be written as half of, if you further make substitutions. This would be half of omega epsilon r prime tan delta into c naught into v naught square or half of v naught square omega c tan delta. So, this would be the expression for pure power loss in a real dielectric.

So, naturally if I multiply omega epsilon r prime by c naught, and this will be c, you can say c d, c dielectric. So, naturally higher tan delta is higher your P average would be. Now, if we take c naught is equal to epsilon naught A over d, and E naught is equal to v naught divided by d. Then p average divided by volume will give rise to average power dissipate power density. And this would be half of omega into epsilon naught epsilon naught prime into tan delta into E naught square. So, this is power density.

So, this is quite a nice expression, because average power basically it drives from the same. So, what it tells you is that higher the tan delta value is or higher the angle between the total current, and the charging current more the power loss will be. That make sense, because your I loss component will go bigger and in this expression if you.

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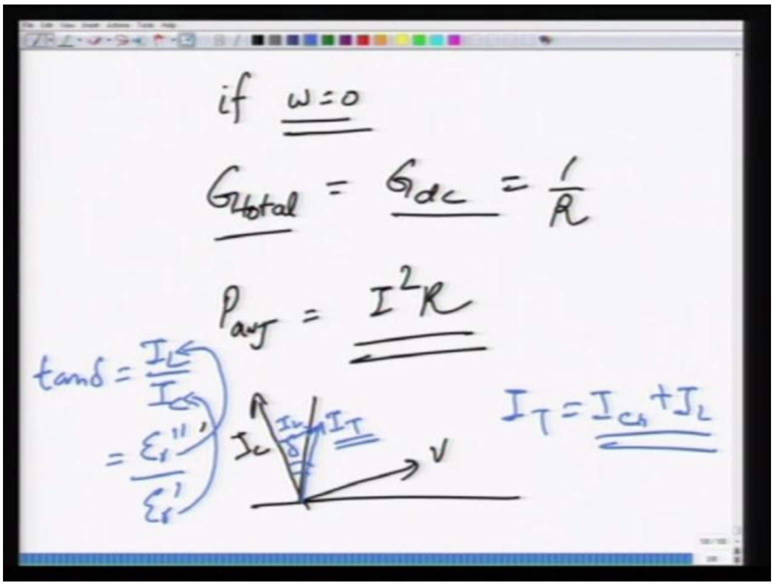

Now, just to take it back juts to prove that we are right if omega was equal to 0 then if omega was equal to 0. In that case, if you go back to this expression; this a c component will become equal to 0. So, in this case, G total will be equal to G d c that was the case and which is nothing but 1 by r. If this was the case then p average would be equal to nothing but I square R ohmic power loss.

So, we will finish this lecture here, but what we have before we do before we end, what we have done here is we have summarised the behaviour of dielectric materials under a c field. So, for normal for a real dielectric, for an ideal dielectric, for an ideal dielectric the current as we looked leads the voltage by angle 90 degrees. And that is the case for, and this current is called as charging current. And that is the case for most of the, for all the ideal dielectrics which means no loss current. So, perfect phasor diagram where i is perpendicular to v whereas, in the case of real dielectric, this total I is never perpendicular to v. What it does is it makes an angle delta with respect to the charging current which would otherwise be at 90 degrees.

So, this angle between total current, and the charging current delta which is towards the v side. So, I so basically, what you have is, if you have v in that, and this is so this is v; this is I c the, I would be somewhere in this direction. So, this would be delta. So, this total current now will include not only I c, but also a component which is in the direction of v applied field which is called as I l. So, I t will be equal to I c c h plus I l. So, this delta larger the delta is as you can see from the phasor diagram higher I loss will be. And the higher will be the loss power dissipated in the dielectric, and that we have also verified from various equations. And this equation I t is equal to I c plus I l can be very well represented by taking real and imaginary parts of the dielectric constant, because the given the fact that you have a real part of current and imaginary part of current. You would have real imaginary part of dielectric constant as well. And this total current expression can be expressed very well by real and dielectric parts of dielectric constant.

So, as a result tan delta which was equal to I l divided by I c becomes epsilon r double prime divided by. So, basically in the in the nutshell epsilon r double prime represents I l, and epsilon r prime represents I c. So, higher I loss is higher epsilon r double prime will be, because higher tan delta would be. So, this is the summary of this lecture which basically shows that dielectric materials in real dielectric materials are lossy. They contain some losses, but those losses can be quantified by various quantities which are measurable. And these epsilon r and tan delta, and epsilon r can be measured by a technique called as by a by an equipment called as impedance analyser or something called as l c r meter, where you measure the capacitance and tan delta values. And from that you can determine various real and imaginary parts.

So, these are all. So, tan delta as well as the capacitance can be measured, and from that you can determine various properties of the dielectric material. So, we will finish here. In the next class, what we will do is that, we will we will look at some more quantitative analysis of the frequency dependence of dielectric materials.

Thank you.