Electroceramics
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Lecture - 24

So, again the start of the new lecture, we have come a long way from just understanding basic properties of dielectric materials, and then you know investigating polarizability, through simple mechanisms, getting around with the equations of polarizabilities for all three mechanisms, electronic ionic and dipolar. Then we looked at the frequency response of the electric, which is the real case of dielectrics because most of the dielectrics are used at certain frequency. And depending upon the frequency of operation dielectrics, dielectric materials exhibit typical behaviour, which is characteristic of this these materials, which is dependent upon the frequency at which they are used.

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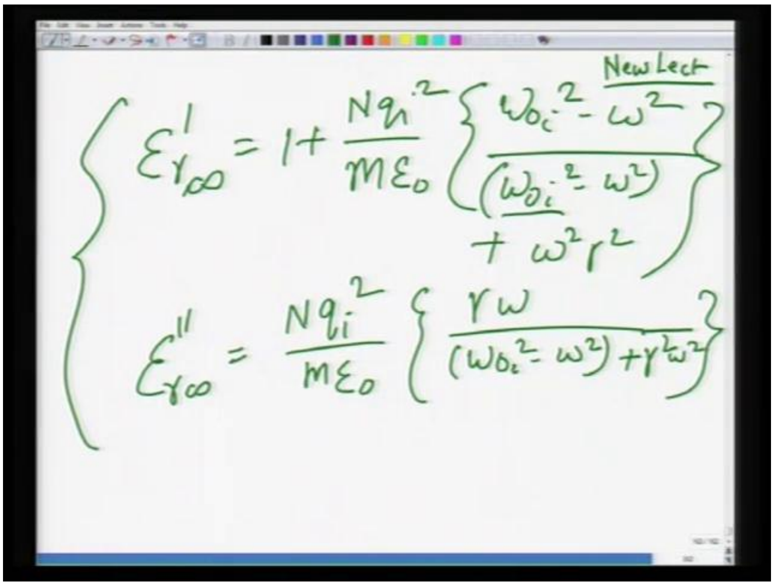

So, in this context, we looked at for instance the the dielectric constant, which was N q i square divided by M epsilon naught multiplied by omega naught i square minus omega square divided by omega naught i square minus omega square plus omega square gamma square. So, this was following the the consideration, that we were doing analysis for a charged dipole, assuming it to be a linearly, mechanically oscillating, linear oscillator. And and we worked around with the equation of motion to reach this expression, which is the frequency dependent expression for dielectric response specific to electronic and ionic mechanisms.

So, you have this frequency dependence of dielectric constants. Now, it could be taken both for, so omega o i would be characteristic for both electronic and ionic, depending upon the mechanism, the magnitude will change. So, when you plot this versus the frequency.

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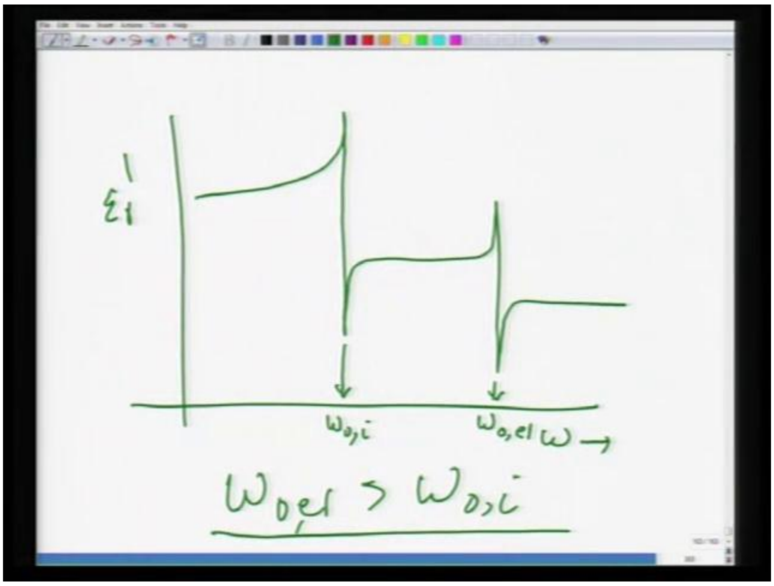

So, I am just going to plot the high frequency part. So, if you plot epsilon prime versus, let us say, let us not confuse, so let us just write omega, so it was something like, something like that, it is not the most precisely drawn. Let let me just draw it little bit more precisely. So, this was omega o electronic and this was omega o ionic. So, of course, omega o electronic is higher than omega o i, because the entities involved in terms of oscillation are lighter, we are talking of oscillation of electrons with respect to nuclei, in a in a in an atom itself.

Whereas we are here, in case of ionic mechanism, we are talking of oscillation of two different ions, with respect to each other. So, nevertheless what they undergo is, the phenomena called as resonance and this characteristic frequency is the resonant frequency where charges oscillate together with the applied field. So, they are they are in resonance with the applied field.

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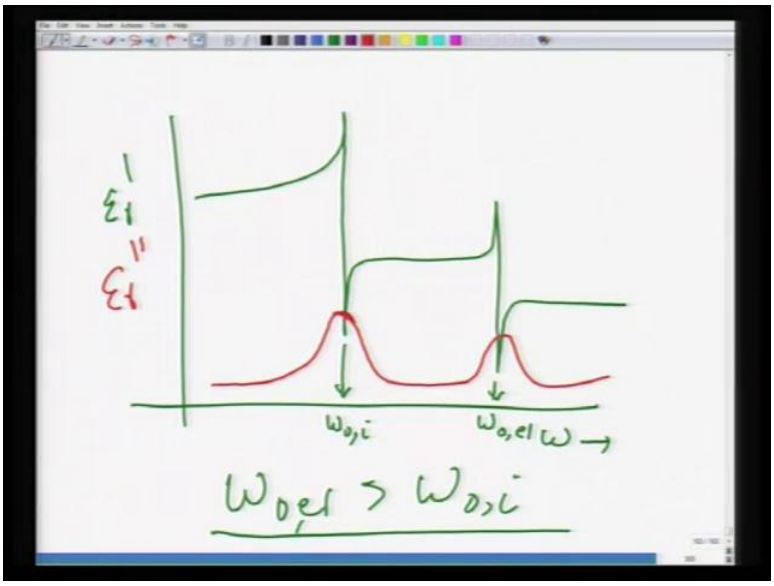

And if you if you plot epsilon r double prime, this shows loss at these frequencies. So, this undergoes a maxima in the loss, characteristic maxima. So, this is this is when they absorb maximum energy, as a result the loss is maximum. So, this is typical of these two mechanisms, where you can consider a charge dipole as a linear oscillator.

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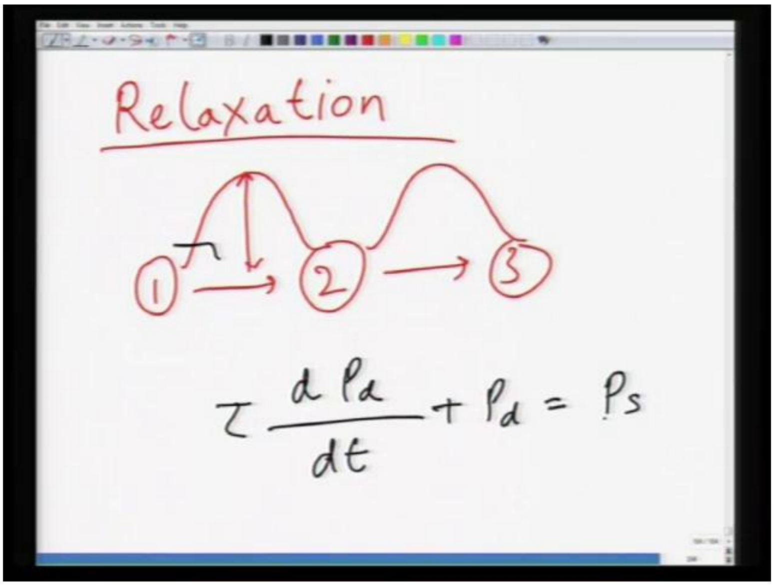

However, when you go to high frequencies, at high frequencies we encountered another term called as relaxation, because and that relaxation was nothing but when you have... now, this is this happens in polar materials and polar materials are typically molecules or big groups of atoms. Now, these group of atoms, when they go from one position to another, whether upon the application of electric field or when a field is released, they find, so they they they stay at position one, and from going to position one to position two to position three, which are all statistically equivalent position, they find they they encounter a barrier, for their migration. As a result this is a temperature dependent phenomena and they require time because it is a long range movement.

So, as a result or instead of calling it long range movement, let us say it is a energy assisted process. So, they do not tend to move, rather they tend to relax, in the a statistically equivalent position. So, this phenomena here, it is called as relaxation. So, and this relaxation we we looked at the relaxation equation and that relaxation equation was was given as... We looked for that, we considered, what is called as a, what is called as a dipole stable model, by stable model. That relaxation equation, we said was d P d by d t into tau plus P d that was equal to P s and this is based on this plot.

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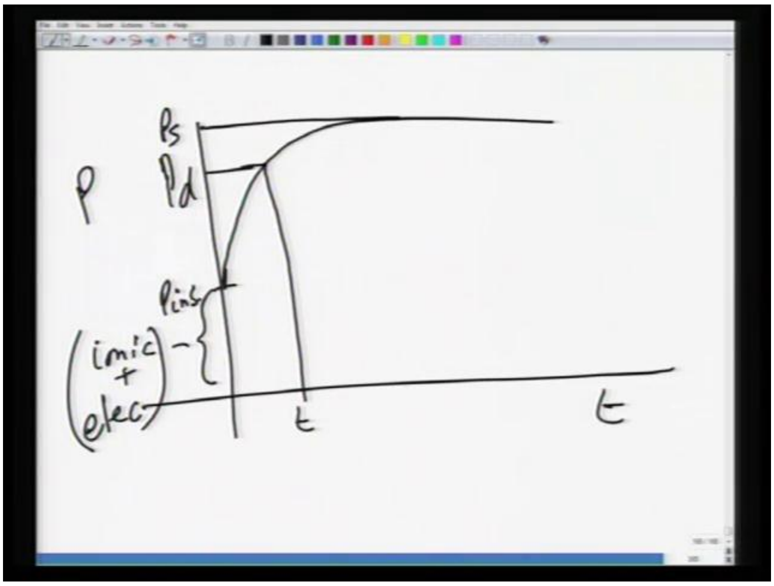

So, if you if you make a plot of polarization versus time, so you have a instantaneous polarization. So, this P instantaneous and this develops into P s, in a time dependent fashion. So, this is saturation polarization and polarization at any given point of time between these two stages, is time dependent polarization. This is because of need and so because of need of the molecules or the group of atoms to move from one position to other, in a time dependent fashion, because they are heavier groups.

When you remove the field, they of course, the molecules relax back from P s to 0. And this P instantaneous is nothing but sum of ionic and plus electronic. These two are almost instantaneous because they take pressure very high frequencies. Now, the formalism and so we worked around this formalism and what we got here was, what we got here was which we defined as Debye equation.

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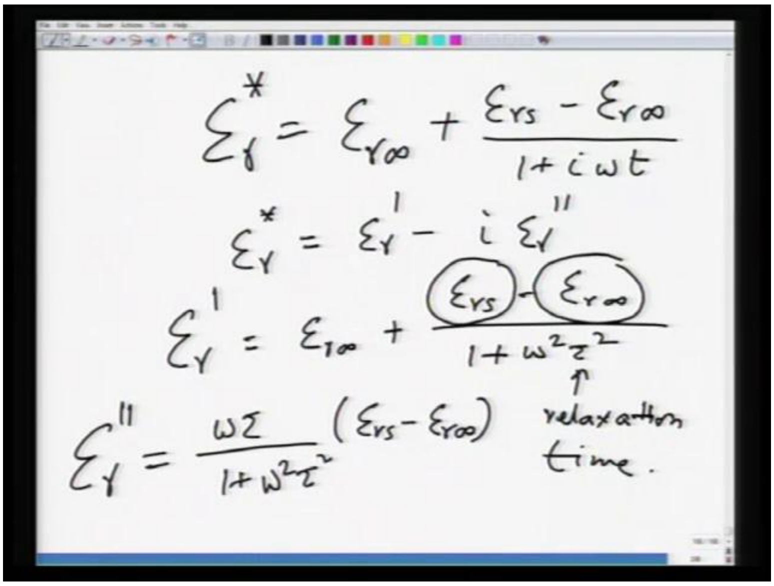

These Debye equation, let us to solution of above relaxation equation, equation leads us to what is called as epsilon r infinity plus epsilon r s minus epsilon r infinity divided by 1 plus i omega t. And and from this, you can also determined what is, epsilon r? Since, epsilon r star is equal to epsilon r prime minus i epsilon r double prime, you can break this up. What we determined from this is epsilon r prime to be equal to epsilon r infinity plus epsilon r s minus epsilon r infinity divided by 1 plus omega square tau square, where tau is the relaxation time.

Subsequently, you can also, 2 epsilon r double prime that was omega tau divided by 1 plus omega square tau square multiplied by epsilon r s minus epsilon r infinity, where epsilon r s is the static dielectric constant at low frequencies and epsilon r infinity is the static dielectric constant at high frequencies, which means r s is below the dipolar polarization frequencies and r infinity is above of the dipolar polarization frequencies. That is into the ionic and electronic polarization range. this gave us to, these are, these equations are called as to Debye equations and these are very fundamental to study of dielectric materials because they characterised the response of dielectric constant, for a ideal dielectric material, under the influence of frequency.

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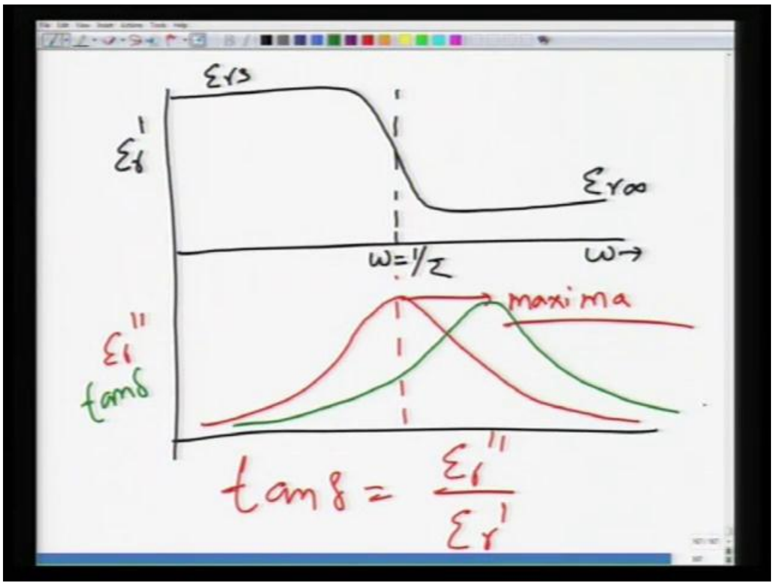

So, when you plot this, the electric constant, it goes. So, when you plot this as a function of frequency it under goes, inflexion. So, this is epsilon r s, this is epsilon r infinity, this is epsilon r prime and this frequency will be omega is equal to 1 over tau, if the axis was omega. And if you plot correspondingly epsilon r double prime, this shows a maxima at this frequency, and again so this is your maxima. You know from this tan delta is equal to epsilon r double prime by epsilon r prime, which can be again plotted, which would be shifted slightly towards. So, if you plot tan delta, it would be shifted slightly towards higher frequencies.

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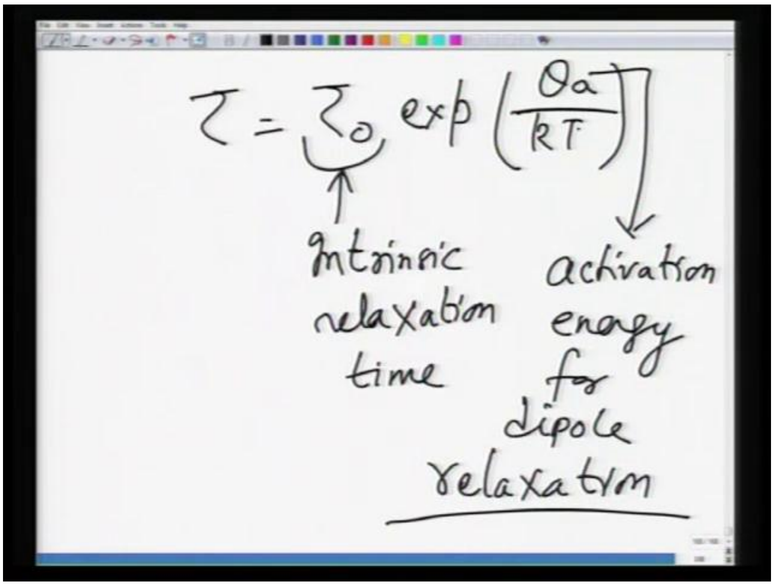

Then we also saw this, that that this tau or the relaxation time is also is also dependent upon the, what we call as temperature. And from this we we we saw that, this was equal to exponential of Q a by k t, where tau, now tau naught is the intrinsic relaxation time, and Q a is the activation energy, which is same as that we discussed earlier, e a for the dipole relaxation. So, you can terminology changes from Q a to e a, to whatever, but the meaning does not change. This activation, this relaxation time is, as you can see is temperature dependent. So, as the temperature increases, this relaxation time would decrease, which means the frequency will increase.

So, as we discussed last time for taking the example of glass ceramics, when you plot tan delta versus frequency, as as you increase the temperature, the the the maxima in the tan delta shifts towards higher frequency and that is explained by this activated behaviour of dielectric constant, relaxation time of the dielectric materials.

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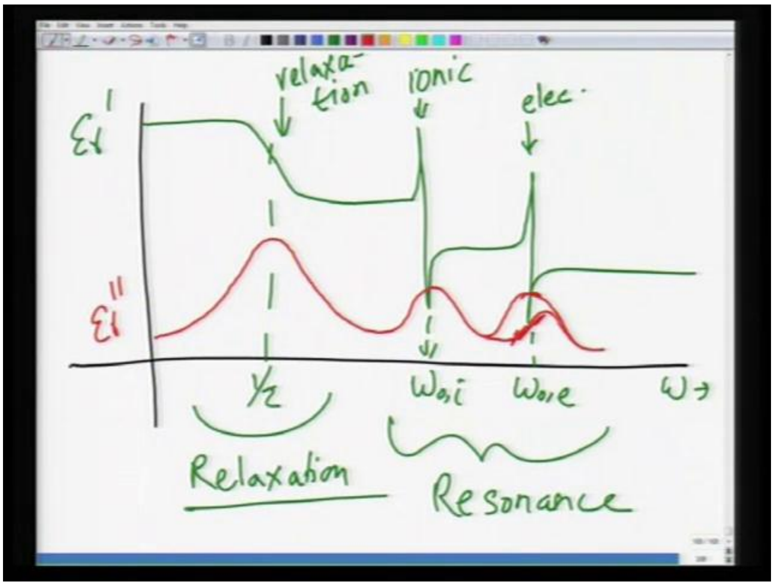

So, the overall picture is now pretty much clear. So, this is something like, so if you plot epsilon r prime, it looks like this. So, this is pertaining to electronic, this is pertaining to ionic and this is pertaining to relaxation. So, this is given as omega o i, this is given as omega o e or e l and this is nothing but 1 over tau. Again just to reiterate these are resonance resonance related phenomena, these two. This is relaxation, this is the crucial difference between dielectric behaviour at various frequencies. And corresponding loss goes through maxima at this point, maxima here, then and, then maxima here. So, this is your epsilon r double prime.

So, this sought of completes a discussion on the behaviour of dielectric materials, under the influence of alternating field. Now, the question is, we know the, what the what the behaviour theoretically is, but how do we measure, how do we characterise them practically? Now, this is something which, this is something which is not so easy, it is bit, it is a little bit tricky, because when you look at the dielectric material.

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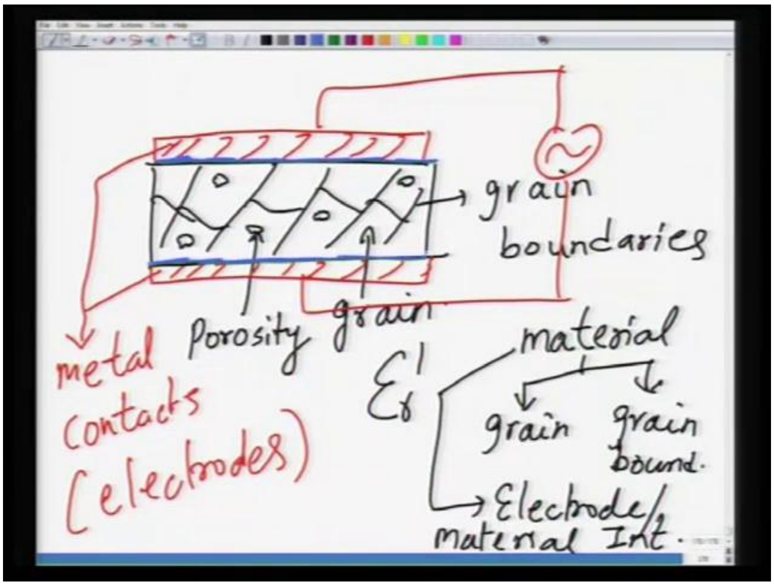

So, the dielectric material is used like this, you have a dielectric material. So, this is your material, this material it is not always single crystal, which means it can be polycrystalline. If it is the polycrystalline material, then it has thinks like grain boundaries, let us say these are grain boundaries. These are grains and depending upon the grain size and the nature of grain boundaries, these grain and grain boundaries act quite different in dielectric materials, which means the electrical response of charges under the application of electric field, in grain boundaries and in the grains is very different from each other.

Moreover, you can also have defects like porosity. So, this is let us say porosity, these are micro structural features on top of that. You cannot make a dielectric measurement without putting a contact on it, which means I need to put a contact. Let us say this is a metal contact, so these are nothing but your metal contact, which are often called as in technically they are called as electrodes. These two are connected to an electric circuit, where you apply the field. Now, not only you have polarization mechanisms, when you apply field, not only you have polarization mechanisms active in the dielectric material.

So, so you are looking at contributions to dielectric constant, from material and material will mean grain, it would mean grain boundary and it would also mean electrode material interface. Electrodes is a, suppose if electrode made is of a good metal electrode will not contribute any capacitance, but then but the but the contributes significant contribution comes from the space charge accumulation or the nature of this interface. So, this interface, nature of this interface is extremely important in, evaluation of real dielectric constant of the material.

So, when you have dielectric constant, which is being, which has contributions from the material itself, apart from that you have contribution from the electrode electrode material interface as well and host of other sources, such as the leads etcetera and the equipment, which you are measuring. That itself will have its own inbuilt impedance, which gives rise to capacitance. So, the question is how to separate these? So, the subsequent part of this lecture, is devoted towards building an understanding of how we are going to do that? What are the best possible method, what methods that are available to do this? So, the first thing, in in this regard is, what we discuss is, let us take the case of an ideal dielectric material.

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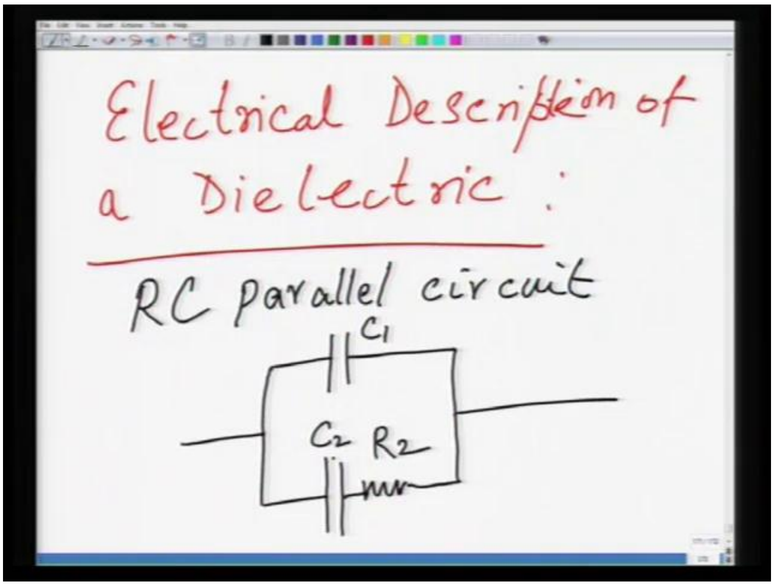

So, we start with the ideal, so what we can do is that, we can electrically describe this dielectric material. So, as a part of this electrical description on dielectric material, it has been shown that an ideal dielectric material can be represented by a equivalent R C parallel circuit. So, this is R C, so what you have here is, a equivalent, a perfect dielectric material looks as as as hypothesised by Debye. It looks something like this, it is made up of a capacitor and then R C element. So, R and C are in series, which are parallel to the another capacitor. So, let us say this is C 1 this is C 2 and this is R 2, so this is how an ideal dielectric material looks like.

Now, how do we know that, this looks like an ideal material? We need to analyze the admittance of this circuit, once we get a feeling of admittance, once we get an expression of admittance of these circuits, we relate it to the expression for ideal dielectric material, with the frequency term in there. Then compare both the equations, whether we arrived the Debye equations or not? So, we we will, as we will see that, we will arrive at the Debye equations, but how? Let us see that, so let us consider this circuit, that that just now we have drawn. So, you have a C 1 capacitor, which is in parallel with R R C element R 2 C 2, which are in series with each other. So, cone is the parallel to R 2 C 2.

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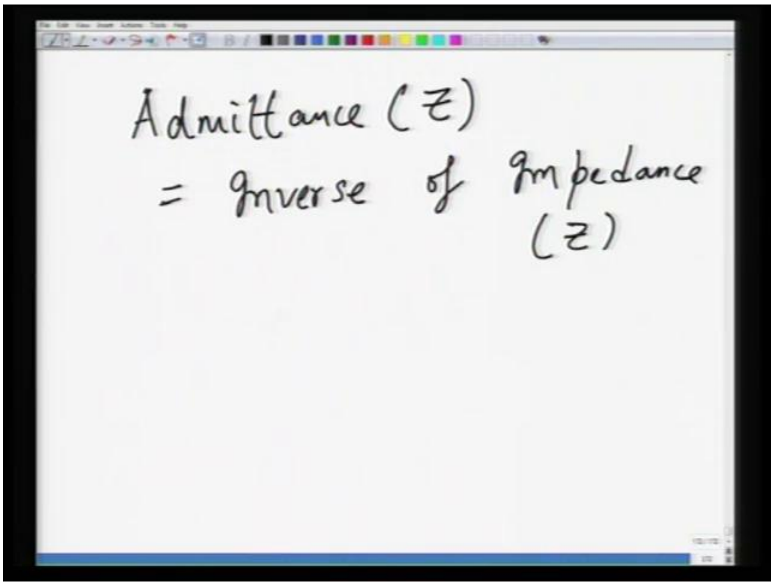

So, admittance, let us define as admittance Z, this is inverse of, let us say impedance. Impedance is nothing but as you can, as you can understand from these term itself. Impedance impedance means the overall resistance of the material, admittance is nothing but something which is related to you know admitting. So, admittance is nothing but really opposite to inverse of impedance.

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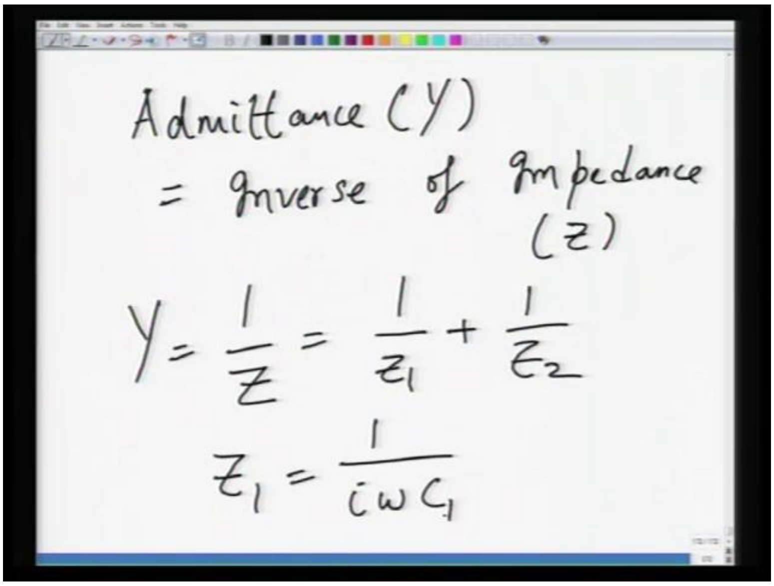

So, this Y this is sorry, I have written this Z wrong here, just make a correction. This should be Y, so Y is equal to 1 divided by Z overall impedance. What is this Z now? We are looking at two parallel elements, one is the C 1 another is the C 2, R 2 C 2. So, this would be nothing but 1 over 1 over Z 1 plus one over Z 2. So, what is Z 1? Z 1 is nothing but 1 over i omega C 1 part in into element C 1 and and Z 2 can be written as 1 over i omega C 2 plus R 2, okay?

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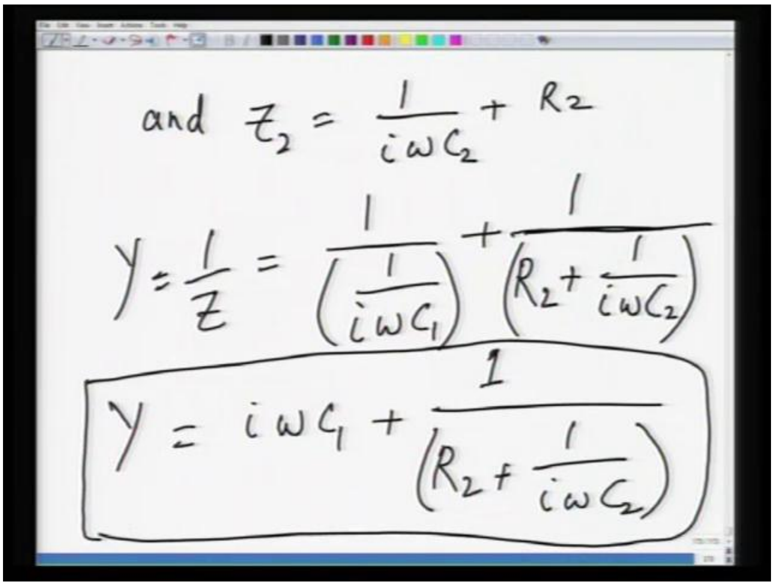

So, these are the two expression for Z 1 and Z 2. Now, admittance will be equal to, so admittance... So, 1 over Y is equal to 1 over Z 1, which means 1 over 1 divided by i omega C 1 plus 1 divided by R 2 plus i omega sorry, just this is y and that is equal to 1 by Z. This is, so R 2 plus i omega C 2, this can be written as i omega C 1 plus R 2 plus, let us not write that. Let us just leave it in this form, 1 divided by R 2 plus 1 over i omega C 2. So, this is the expression for admittance, that we get from just by putting the 2 impedances together.

Now, when you when you apply in alternating field to the capacitor, such a circuit, then capacitor goes cycles of depending upon the... So, wave form is something like this, if your wave form is like this.

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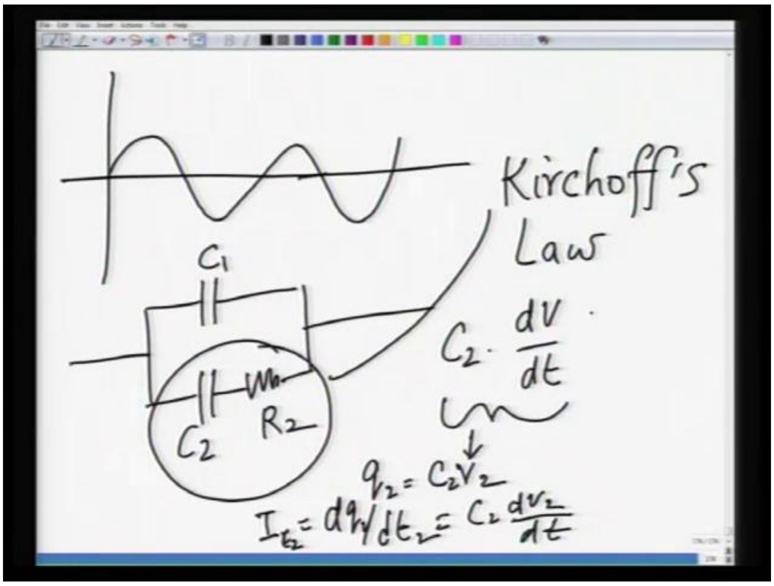

Then as a result of the nature of this this wave form your capacitor will charge and discharge and charge and discharge. Now, so based on that, if you, so if you apply this to the R 2 C 2 element, so you have C 2 C 1 C 2 R 2, so here what happens is, this capacitor C 2 charges through this resistor R 2. Now, what we need to do is that, suppose suppose we apply a field to this particular segment, we can apply, what we call as Kirchhoff's law to this segment. So, we apply Kirchhoff's law.

Now, Kirchhoff's law is a very basic law in physics, that you you know from your twelfth standard. So, if you apply Kirchhoff's law to this segment, then what it says is that, the sum of two currents, the currents due to current in capacitor, and the current in or current due to current in capacitor must be equal to current in the resistor, which means I I I need to, I, if I need to apply Kirchhoff's law then C 2 multiplied by d V by d t, which is the current term from capacitor. This is nothing but your... So, how how do you, how do you get to the this term because you know that q two is equal to C 2 V 2 and when you, so the current in capacitor would be d q 2 by d t 2. This is C 2 will be equal to C 2 d V 2 by d t.

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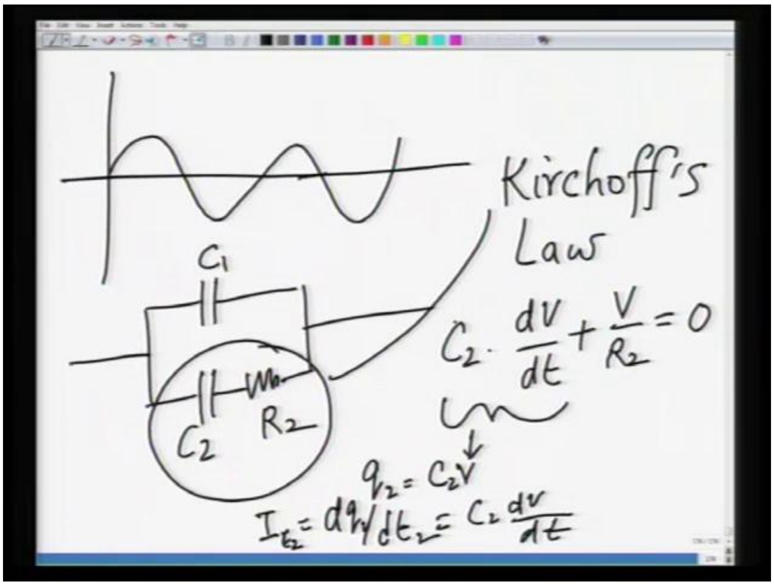

So, C 2, let just a, mistake. This is C 2 V, it is not write V 2, so C 2 d V by d t. The current in in the in the capacitor plus the current through the resistor, which is V divided by R 2, this is simple Ohm's law is equal to 0, this is your Kirchhoff's law. Now, this is simple differential equation. If you solve this equation, what you come across is V is equal to V is equal to v naught exponential of minus t divided by R 2 C 2, where V naught is the voltage at at t is equal to 0 naught exponential of minus t divided by R 2 C 2, where V naught is the voltage at at t is equal to 0.

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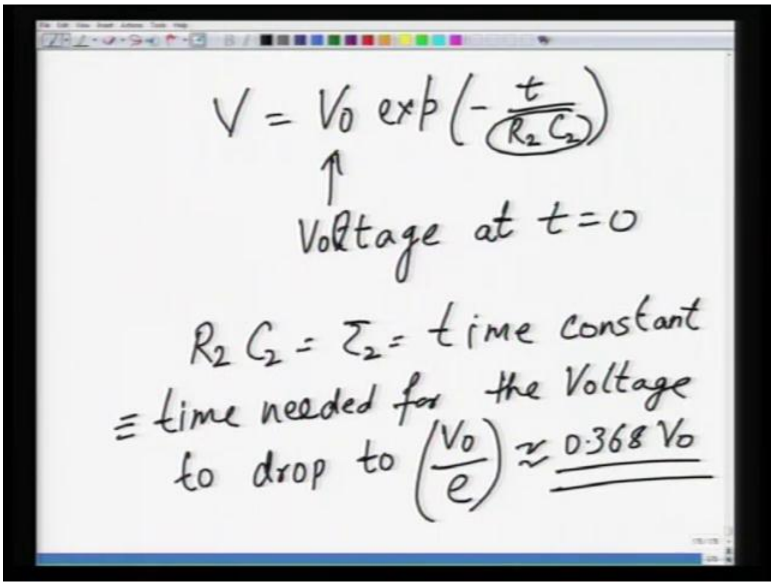

So, if V naught is the voltage at t is equal to 0, R 2 C 2, which is in the exponential term must have same units as of time. This R 2 C 2 is defined as tau 2, which is called as time constant. This time constant is basically the time, which is needed. So, this is nothing but equivalent to time needed for the voltage to drop to a value V naught by e, which is, which comes out to approximately 36.8 percent of V naught, so or 0.368 of V naught. So, tau 2 basically is the time.

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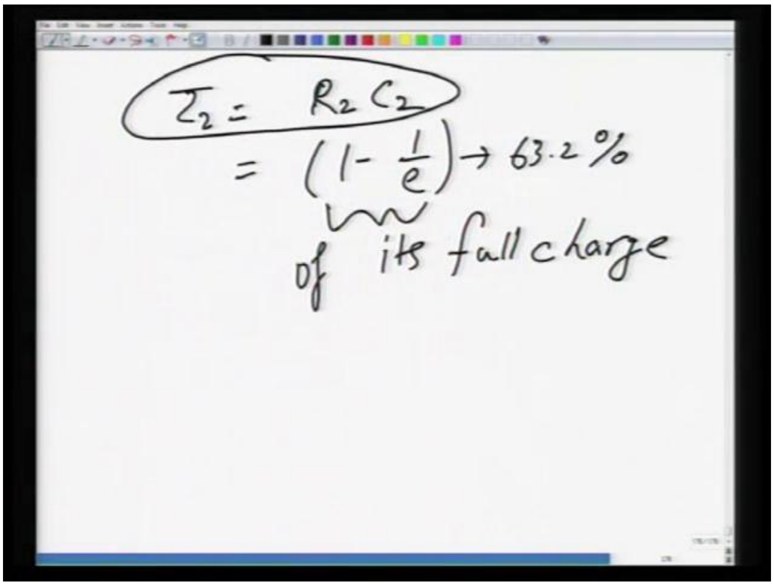

Tau 2, which is R 2 C 2, is the time, which is required to charge the capacitor, through the resistor, okay? So, you need to, you are charging the capacitor through the resistor, the time, which is required to charge the capacitor, through the resistor to a value 1 minus 1 by e that works out to 63.2 percent of its full charge. So, that is one definition, so time tau 2 is the time, which is needed to charge the capacitor C 2 through resistor R 2 to a value 63.2 percent of its full charge or the time, which is needed to bring the voltage down from V naught to V naught divided by e, which means to discharge the capacitor to 36.8 percent of its initial value.

So, both means, both are equivalents, either you charge it to 63.2 percent of full charge or you discharge it to 36.8 percent of the initial value. So, whether you, it is like holding same thing within two different ways. So, saying same thing, in two different ways. So, so this is tau 2, so tau 2 from this we have... So, this is now, what we do is that, we make use of this term and insert this in the impedance or admittance equation; that we earlier worked out.

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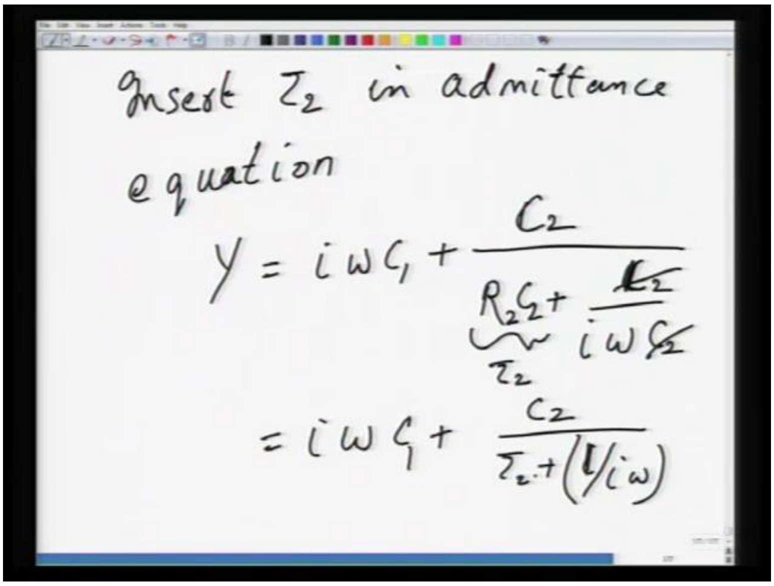

So, insert tau 2 in admittance equation, when you do that, what you get is y is equal to i omega C 1 plus what I had there was R 2 C 2, so I had was, let me write the original expression. So, what I had was R 2 plus 1 over i omega C 2. So, what I am going to do is that, I am going to multiply it by C 2 and multiply it by C 2 here. So, this becomes tau 2 and these cancel each other. So, what becomes, this is i omega C 1 plus C 2 divided by tau 2 plus 1 divided by i omega, okay? Now, you can further rework this equation.

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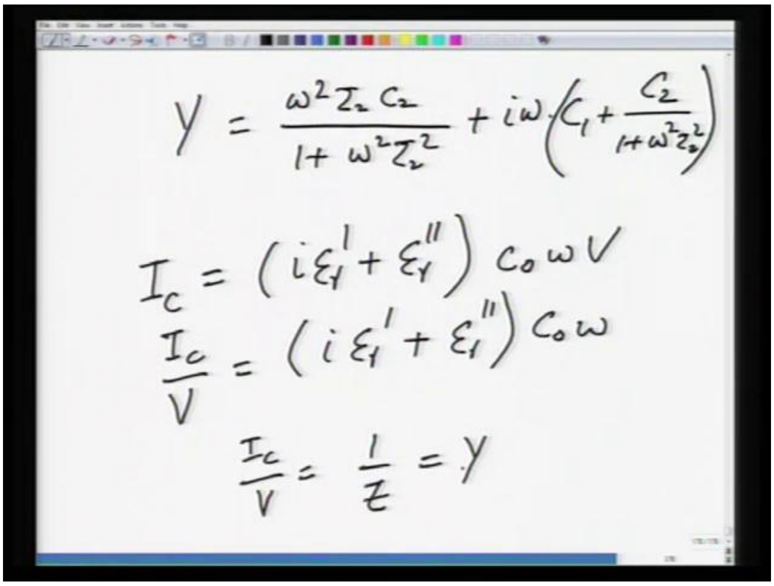

What we get in the modified form, is y is equal to omega square tau 2 C 2 divided by one plus omega square tau 2 square plus i omega multiplied by C 1 plus C 2 divided by 1 plus omega square tau 2 square. So, this is the expression for admittance. Now, from the previous expression, if you remember, in this module itself, when we worked out the, when we worked out the circuit for, or let us say the representation of dielectric material, using the under the influence of alternating field, we came across an expression charging current I c.

That was nothing but i epsilon r prime plus epsilon r double prime multiplied by C naught omega V. If you take this here, I c divided by V this becomes equal to i epsilon r prime plus epsilon r double prime multiplied by C omega. What is I c by V, which is nothing but 1 divided by, so I c by I c by V is is nothing but 1 divided by Z and this is nothing but admittance.

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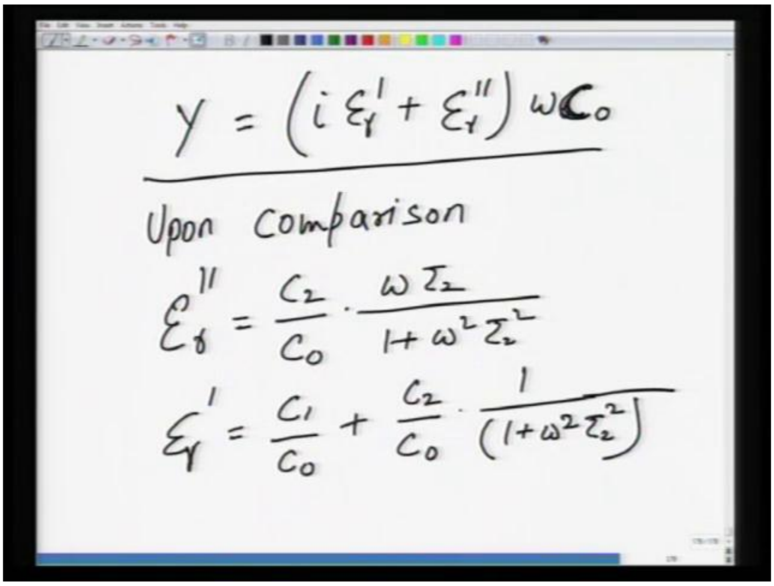

So, so Y is equal to i epsilon r prime plus epsilon r double prime multiplied by omega naught, sorry omega C naught. Now, you compare this equation with this equation, and what I am going to do is just, what we are going to do is that, all we are going do from that as you can see is to get expressions for epsilon r prime and epsilon r double prime. If you do that, then so upon comparison, what we get is epsilon r double prime to be equal to C 2 divided by C naught multiplied by omega tau 2 into 1 plus omega square tau 2 square. Epsilon r prime is equal to C 1 divided by C naught plus C 2 divided by C naught multiplied by 1 divided by 1 plus omega square tau 2 square.

Now, if you compare these with Debye equations, which is if you compare these with Debye equations, they are fairly similar. You you can write the Debye’s equation Debye’s equation parallelly and make a comparison.

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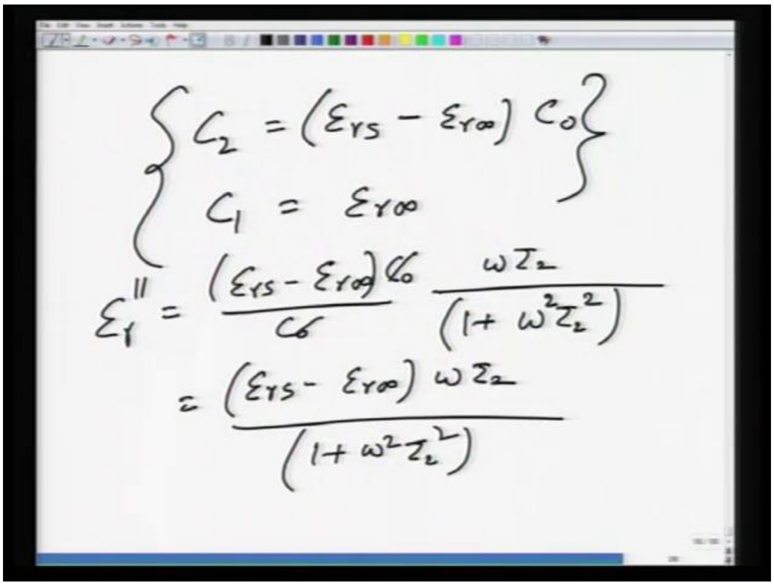

Upon comparison, what you will find, that these two equations are similar, very similar with C 2 happening to be equal to epsilon r s minus epsilon r infinity multiplied by C naught and C 1 happening to be epsilon r infinity. So, if this, upon this condition those two equations, which you have seen on the last slide are nothing but your Debye equations. So, this gives us a very nice way of modelling a dielectric material, as an electrical circuit.

So, basically if you rewrite these epsilon r double prime is equal to epsilon r s minus epsilon r infinity divided by multiplied by C naught divided by C naught into omega tau 2 divided by 1 plus omega tau 2 square and C naught C naught cancel each other. So, what you get is epsilon r s minus epsilon r infinity into omega tau 2 divided by 1 plus omega square tau 2 square.

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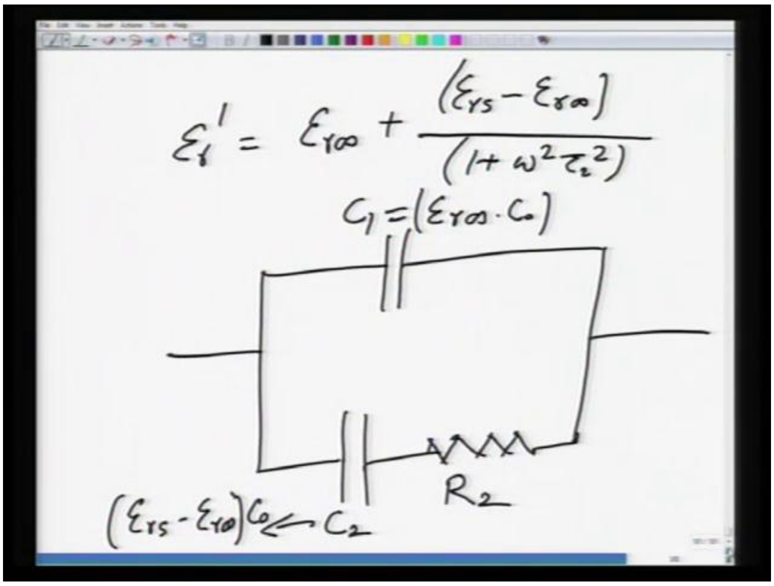

Similarly, for epsilon r prime C 1 divided by C naught, which is epsilon r s minus epsilon r infinity plus C 2 divided by c naught. Excuse me, it is other way around, it is C 1 divided by C naught. So, this is epsilon r infinity plus epsilon r s minus epsilon r infinity divided by 1 plus omega square tau 2 square. So, upon making the comparison, now the circuit looks like this. So, this is your R 2, this is your C 2, this is your C 1. So, this C 1 is nothing but epsilon r infinity, C 2 is nothing but epsilon r s minus epsilon r infinity multiplied by C naught.

So, now you can see, how does this dielectric material look like? It looks like an electrical circuits of this type, where C 1 and C 2 can be defined in terms of the differences, either the C 1 can, C 1 is nothing but your high frequency static dielectric constant. C 2 is nothing but the difference between low frequency and high frequency dielectric constant, in in series with a resistance R 2, which is the resistance of the material. So, this behaviour, this behaviour gives an opportunity to describe the behaviour of the electric material, in an electrical circuit, which can be modelled easily.

Based on that, based on this behaviour, there have been several attempts to characterise and understand the electrical and microstructural and relate it to microstructure and defect behaviour of the electric materials. In this regard in 1911, 19 sorry 1941 two brothers, two scientist K H Cole and R H Cole, Kenneth Cole and Richard Cole, they explained the behaviour of dielectric materials in the alternating fields, by plotting the real and imaginary parts of these two impedances, which are now a days being used in terms like impedance spectroscopy.

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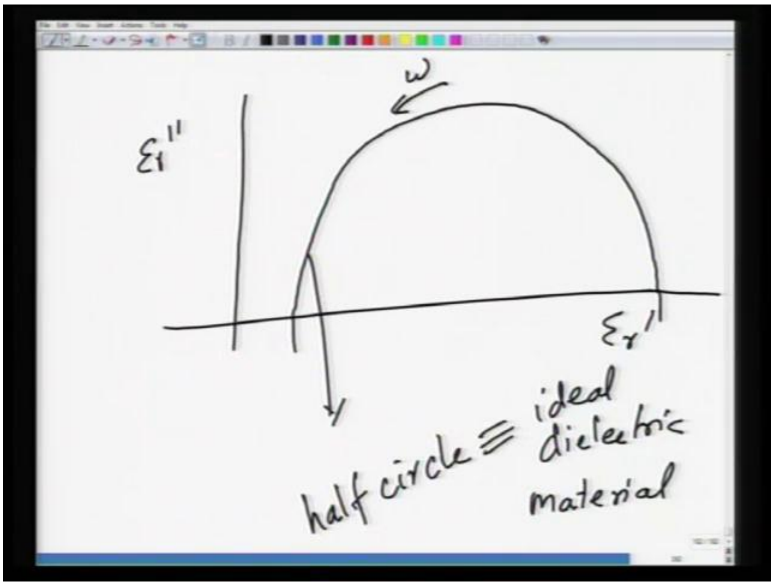

So, what they got was if these two materials exhibit like a perfect material. Then for a perfect material the dielectric response, if you plot the imaginary part versus the real part, then they should represent a perfect semi circle. It does not look like perfect here, so let me just try to draw as perfect as possible, okay? This is with increasing frequency, so the, so this should like an ideal half circle and this would mean an ideal. So, basically I want to say, half circle would a perfect half circle, would represent the response of a ideal dielectric material. Here as you can see, these two intercepts on the x axis would mean the values of dielectric constants.

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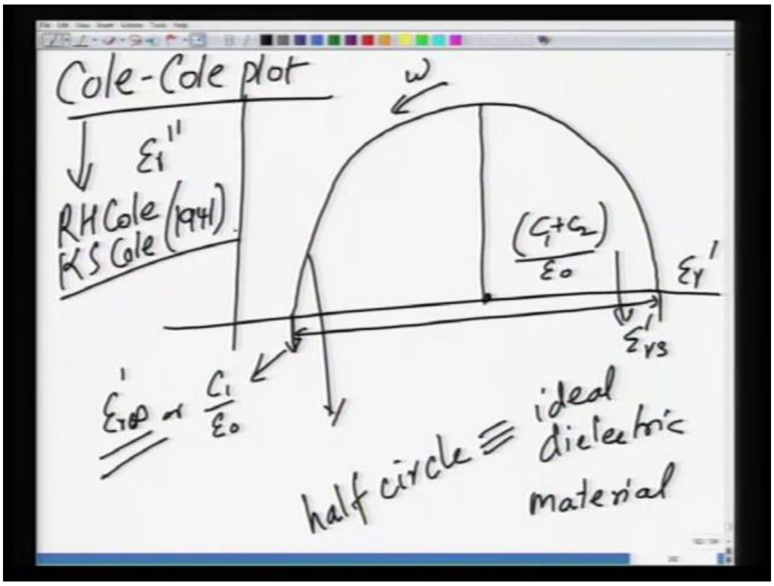

If you just, if I just write it slightly away, so that it does not get confusing epsilon r prime. So, this value becomes epsilon prime r s, which is the because in we are increasing the frequency in this direction, a static dielectric constant and this becomes your... So, or alternatively, in terms of electrical circuit, this becomes equal to C 1 plus C 2 divided by epsilon naught and this becomes or C naught depending upon, how you say?

And this intercept becomes C 1 divided by epsilon naught or you can write it epsilon r s epsilon r infinity. So, this is the high frequency part, this is the low frequency part and that difference between these two, is the epsilon r s minus epsilon r s, epsilon r s minus epsilon r s infinity.

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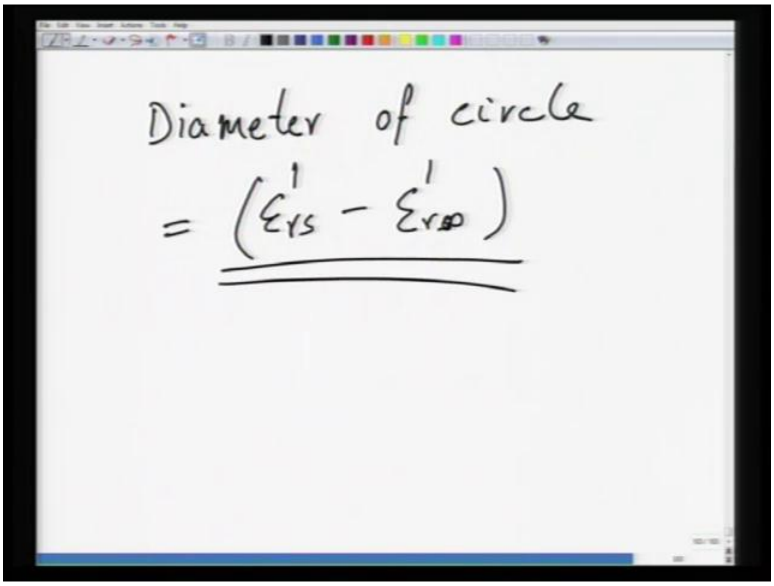

And the circle of, and this circle, so the diameter of this circle would be, diameter is this circle would be as you can see from here, would be epsilon r s minus epsilon r infinity, this will be a diameter of this circle. So, a perfect electric material at Kenneth and Richard Cole proposed would look like a perfect half circle, when you plot epsilon r epsilon double prime, with respect to epsilon prime as a function of frequency. So, however this is true only for materials, which exhibit ideal behaviour.

In case of non ideal behaviour, this Debye equation get modified according as Kenneth and Richard Cole showed and that we will, so that we will just try to eliminate. So, any now, this as we said that, if you have a perfect semi circle, this means, this represents the behaviour of perfect dielectric material. Now, any deviation from this perfect semi circle is going to lead to deviation from ideal behaviour, which can be related to various atomic and microstructural features of the material.

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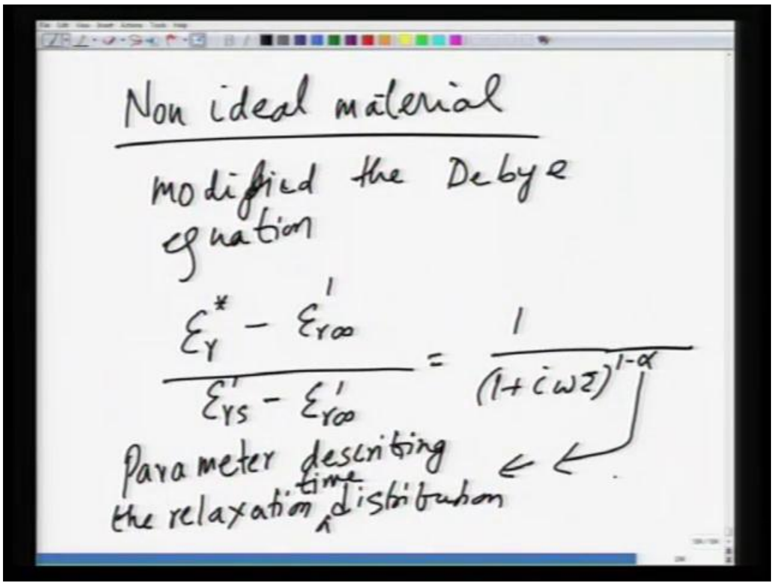

So, for a modified for a non ideal material Cole, both Cole brothers, Cole and Cole they modified the Debye equation, so... By the way, let us just go to previous page and this is called as Cole-Cole plot and this goes after R H Cole and K S Cole 1941 there are papers online, which you can go through them. So, modified this equation, so this becomes now epsilon r star minus epsilon r infinity divided by epsilon r s minus epsilon r infinity. This becomes equal to 1 plus i omega tau to the power 1 minus alpha.

So, this is the modified Debye equation, where alpha is a parameter, which takes care of nonideality. And that, since that and this nonideality is effectively represented in terms of variety of relaxation time. So, you do not have a single relaxation time. What rather you have many mechanism, many relaxation mechanisms, which have their own relaxation times. So, this alpha describes parameter describing the relaxation distribution or relaxation time distribution in the material.

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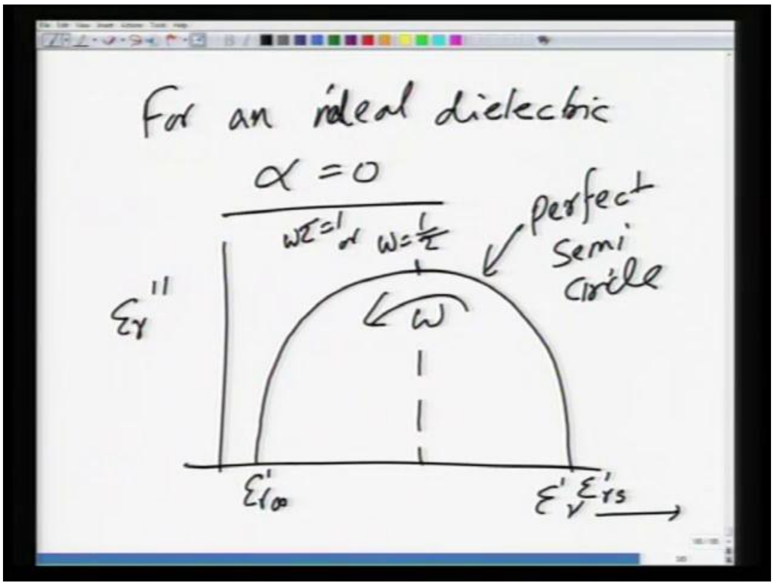

So, for a naturally, as you can see for an ideal material, this alpha would be equal to 0 and system would be characterized perfectly by the Debye equations, which we just now saw. If you plot epsilon r epsilon r prime versus epsilon r double prime as a function of frequency, you should get perfect semi circle. So, perfect semi circle and maxima naturally will occur. So, this corresponds to maxima in epsilon r double prime and you know this happens at omega is equal to 1 by tau or where omega tau is equal to 1. So, this is the way, frequency is changing, so this is your epsilon r s and this is your epsilon r infinity, okay?

This way of characterizing the dielectric materials is called as impedance spectroscopy. And and you can do this by using techniques like impedance analyzers, which work very well to characterize these materials. So, all you do is that, you measure the real and imaginary part of the impedance related to the dielectric constant, from the equations that we have seen earlier. Then make a plot to see, whether you have an ideal behaviour or not?

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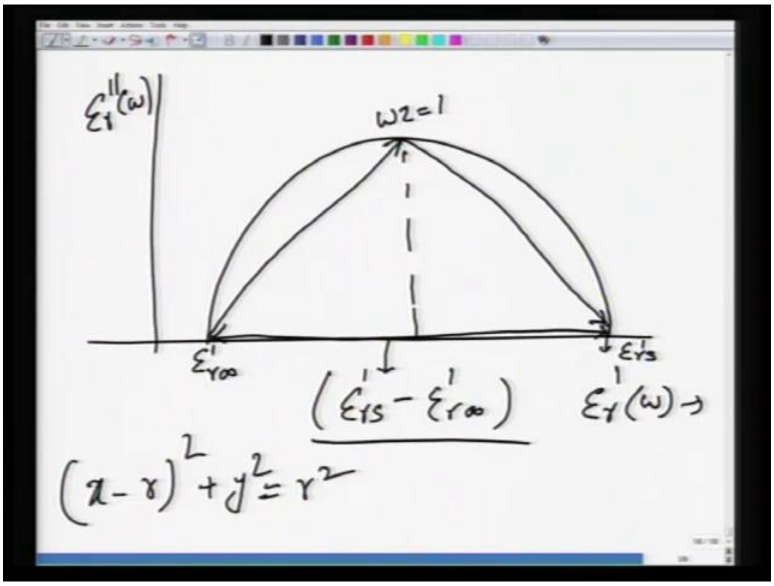

So, if you have an ideal behaviour, again I will, I am going to plot, epsilon r omega versus epsilon r prime omega, so imaginary versus real part and if you have ideal circle, so this should be your epsilon r s, epsilon r infinity. This happens at omega tau is equal to 1 and as you know, the diameter of this circle, you can see, it is nothing but the difference of these two, dielectric constants. So, this semi circle is represented by, so you know what is a semi circle equation is, semi circle equation is nothing but x minus r square plus y square is equal to r square. So, you know that r here is nothing but epsilon r s prime minus epsilon r infinity prime divided by 2, diameter divided by 2, and x and y you can plot from...

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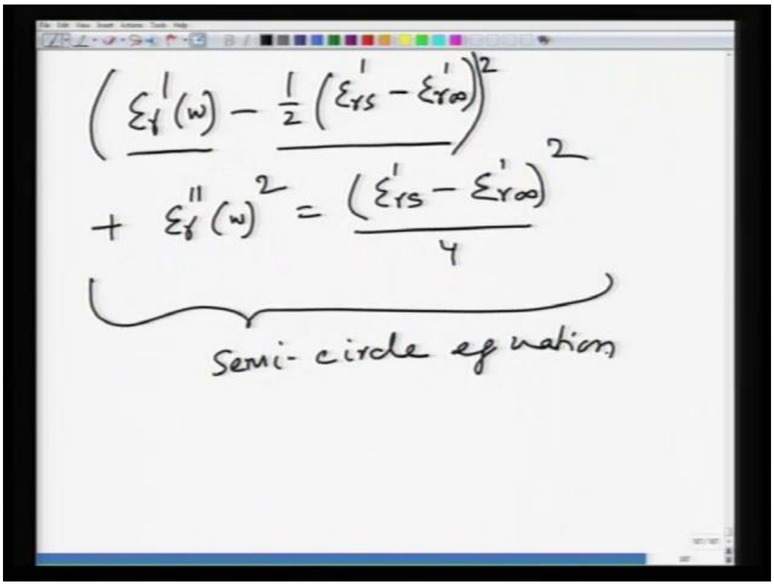

So, this is x and this would be y and so this can be represented by the semi circle equation, which is epsilon r minus half of epsilon r s prime minus epsilon r infinity prime to the whole square. So, x minus r square plus y square epsilon r omega square and that is equal to r square, which is epsilon r s minus epsilon r infinity square divided by 4. So, this is your semi circle equation.

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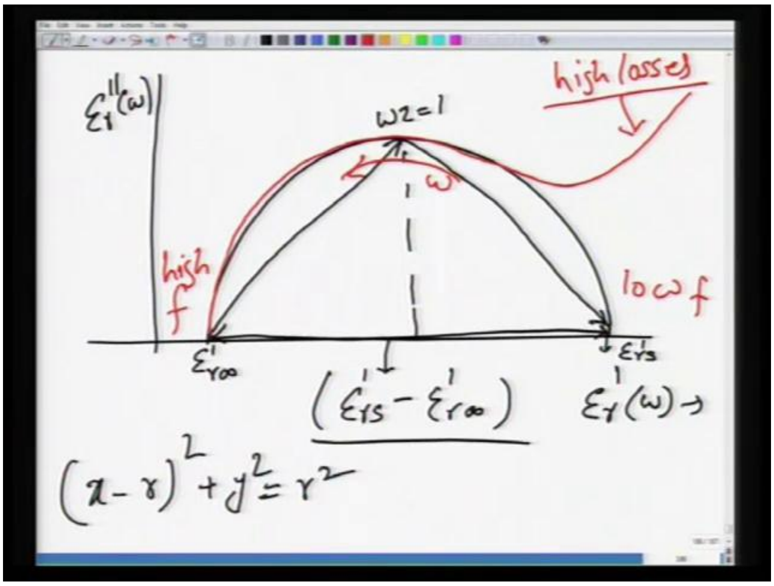

Often what you see in in reality, that you do not get a semi circle and you you get a semi circle like this, with the tail. This tail often presents high losses in the material or distribution in the... So, if you have this dash line, on the low frequency side, so this is low, so frequency goes like this. So, this is low frequency, this is high frequency and if you have a tail, this tail indicates high losses. So, basically what it means is that, at the low frequency your epsilon r double prime is very high, which means material is very lossy. Another thing is that, you see often is, you do not have one semi circle.

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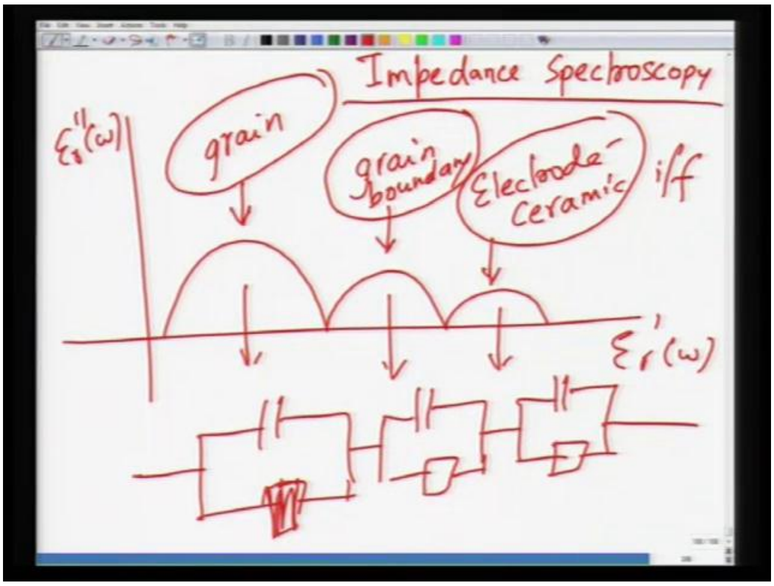

What you have is, you have a range of semi circle. You have semi circle like this, like that, when you have such kind of phenomena present, then what happens is material has contributions coming from more than one mechanism. So, what may happen is in in such a scenario, the material the material exhibits contributions from grain, from the grain boundary and from the electrode ceramic interface. So, this is typically your electrode ceramic interface, this would be your grain boundary and this would be your grain.

As you, as you see since, we are, so this is epsilon r prime and this is epsilon r double prime. So, you need to make a circuit for this, you need to make a circuit for this and you need to make a circuit for this. So, basically what it means is that, you have three parallel, three circuits running parallelly, see in series. So, so one would be one would be corresponding to grain, another would correspond to grain boundary, another would correspond to electrode ceramic. And as you can see from the frequency, this should occur at the lowest frequency, this should occur at the middle frequency and grain should show the bulk effect at the high frequency.

So, if you have these multiple mechanism presents, present in the materials, then you would encounter more than one semi circle. Very rarely you will encounter a perfect semi circle, often these semi circles also over lapping with each other, so you need to model them properly, in order to analyze the effect of each and every contribution, which is a complete different subject altogether and this subject is also known as impedance spectroscopy. So, basically it is a tool to characterize the dielectric materials, nicely and to understand the behaviour of this dielectric material, under the alternating field and to extract the contributions to the dielectric constants, from various segments individually.

So, this is the technique, which is a very powerful technique. It is a very detailed technique, we cannot unfortunately go in this course but what all I wanted to say is, that if you if you plot real and imaginary part of dielectric constant or nothing but which is nothing but extracted from the impudent data. Then you can you can get these semi circles, which can be effectively used the characterize the the dielectric material. So, these, this takes us to the end of this module, which is finally... Now, so we have discussed what dielectric materials are? What various polarization mechanisms are? We have looked at the polarizability through simple formalisms, analytical treatment and then effect of frequency to look at the resonance and relaxation phenomena.

And then finally, and then how do we characterize or how is the dielectric behaviour characterized really? That we see that by presence of semi circle or ideal or non ideal, you can distinguish between various contributions, that make to the dielectric constant in a dielectric material. Finally, and the final content of this module is, how the dielectric... So, dielectric materials work long, but they do fail. As you can see in the poles, electricity poles that you see often a sparking takes place and the capacitor, which is put around the pole, that suddenly gets busted or there is a fire. So, you see that capacitors fail.

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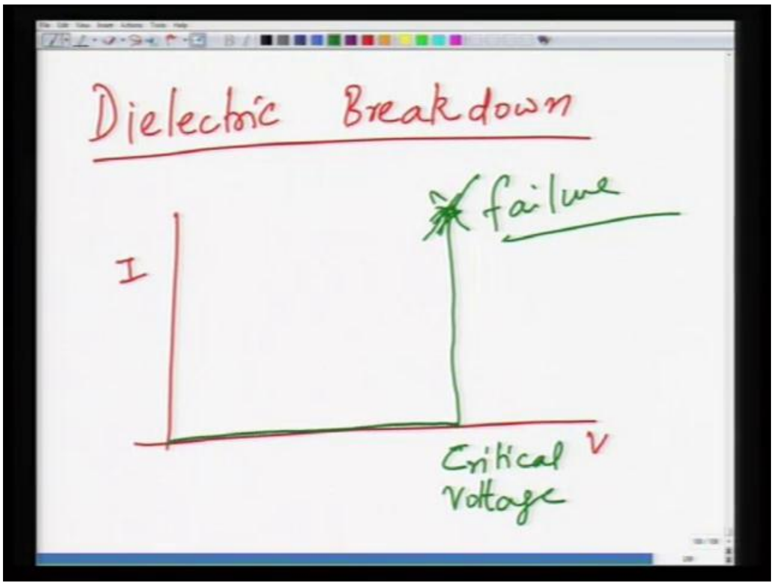

So, these, this failure of capacitor capacitor failure is called as dielectric break down. This is nothing but so when you plot this I versus V or I versus E, there is a very small amount of current that flows, up to a critical field and when you reach a critical field a sudden jump in the current and this is nothing but your failure or break down. So, this is called as critical voltage or field. So, beyond, so there is a critical voltage for these materials, which if crossed these materials fail. There are variety of mechanisms, which are proposed to explain, proposed to explain these failures.

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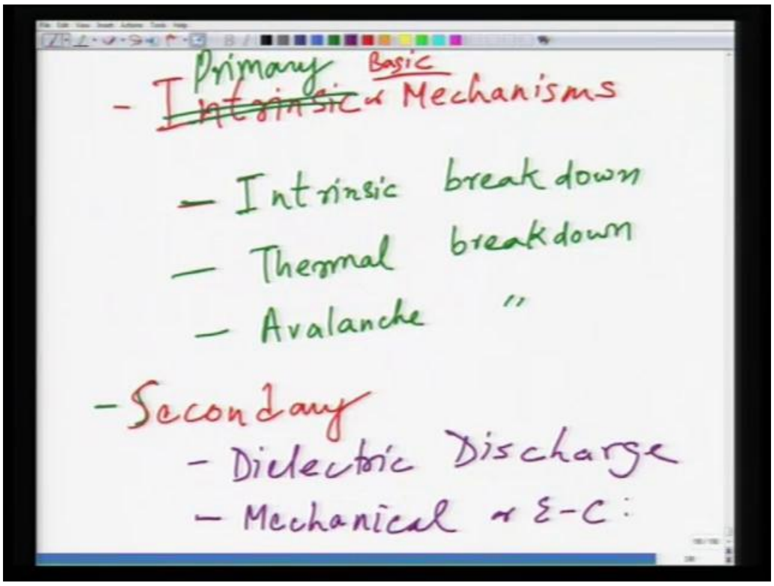

So, these these failures are often you you you divide them in two categories. One is the intrinsic mechanisms and these intrinsic mechanisms are nothing but your defined as, or or rather intrinsic or basic mechanisms. So, one is called as intrinsic break down, then you have thermal break down. Instead of intrinsic, let us call it primary, primary mechanisms, because these two intrinsic clash with each other. Then you have avalanche break down, and then and you have, what is called as secondary.

And in case of secondary mechanisms, you have dielectric discharge. Say or or you can say mechanical break down or electro chemical break down, electro chemical break down. So, we will we will not go into details of these break down mechanisms, we will just go through very casually, what this means is?

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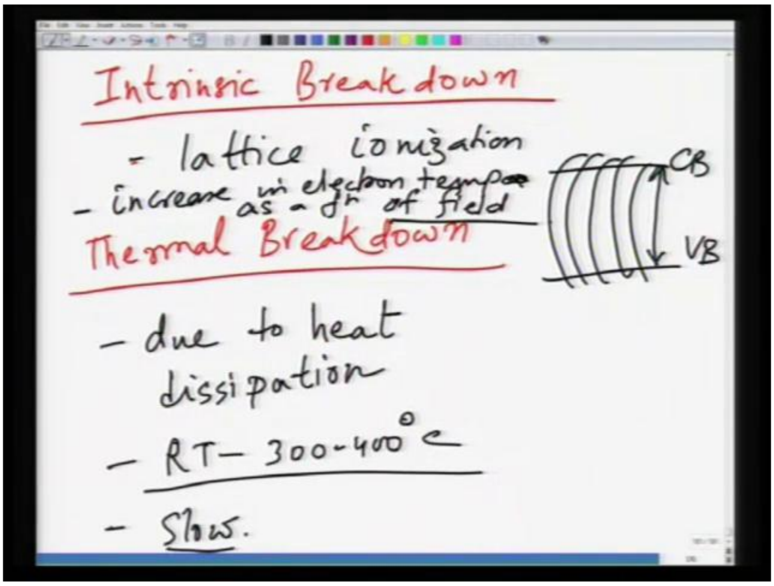

So, in case of intrinsic break down, what it simply means is, that this mechanism is based on lattice ionization. So, and what this means is that, basically as as you keep applying the field, the lattice gets ionised. These subsequently increase the electron temperature and this electron temperature, once it reaches the critical field value, corresponds to the critical field value the failure occurs. This is this is characterized by large increase in the current in the material. Now, this process, the the process break time is very short and this as a result, this process is very quick and this process is also electronic in nature.

So, basically what it means is that, you have conduction band,you have valence band. So, basically you make enough electrons to go into conduction band. So, that the material become conducting, so and that critical field will correspond to what is called as the band gap of the material. Then second mechanism is thermal break down, so here you can also add increase in electron temperature as a function of field. As you field increase, the field the electron temperature increases.

In case of thermal break down, what happens is that, this occurs due to heat dissipation and this is basically due to current flow, that is happening in the defective parts of the sample, which in turn increase and those defects could be ionic defects, lattice defects etcetera. As a result some material has a resistance, which leads to or material have some conduction and this long range conduction leads to heat dissipation, and this is a very common process in the bulk materials.

It observe at temperatures between room temperature to 300 degree 400 degree centigrade and typically here, the rate at which you apply the field is a very important factor. This process can be slow, since it takes sign to build up, for the heat to build up and this, the the time range varies from milliseconds to few minutes. It also depends upon sample geometry because sample geometry will determine, how the heat is dissipated out of the sample. So, essentially it is basically because of increase in the temperature of the sample, which is thermal not the electron temperature, but the real temperature.

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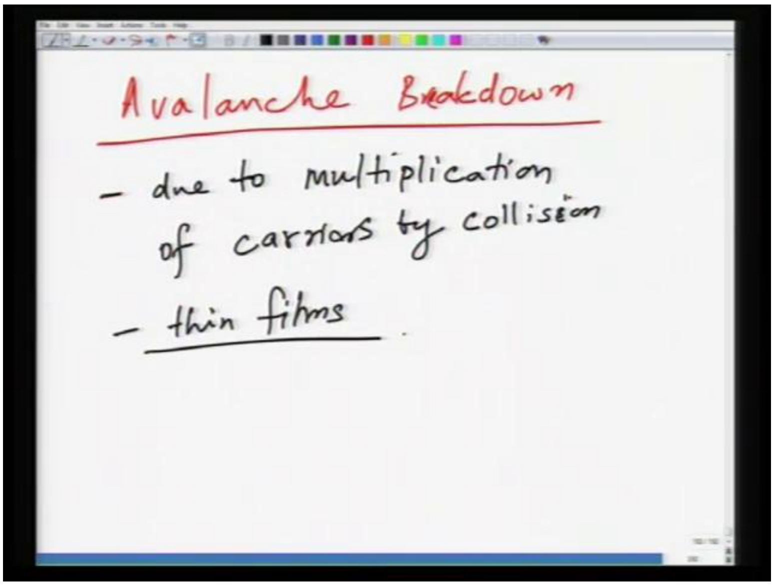

And the third is called as avalanche break down and avalanche as a name suggest itself a few electron, get sufficient energy by application of high fields. These high energy electrons knock off many other electrons in the lattice, thereby increasing the conductivity of the material. So, basically due to multiplication of carriers by collision, so high energy electrons knock off many more electrons, from the conduction from the from the lattice. These, this multiplication in the electron numbers leads to increase in the conductivity, which which is, which leads to eventually the failure and this happens in typically thin films. This the process, which can, which occurs at lower temperature and it is very fast process very short time process.

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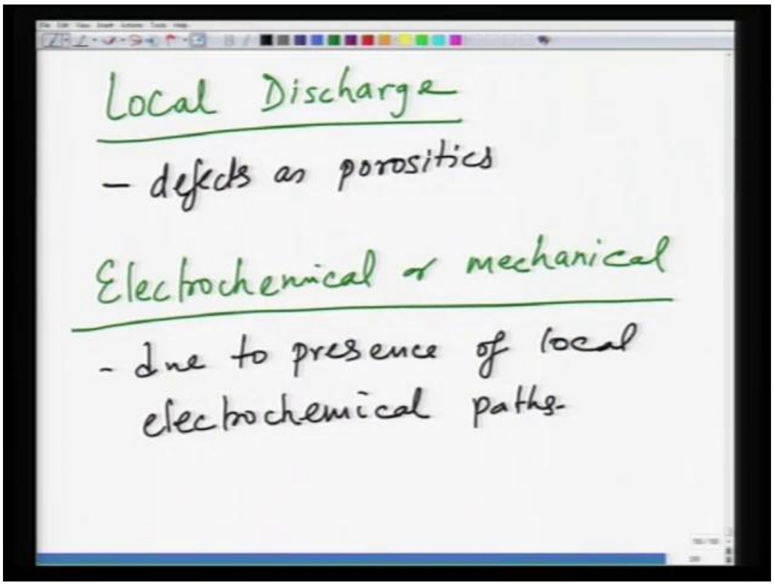

And then finally, secondary mechanisms are your local discharge or dielectric discharge. This is due to presence of defects, such as porosities or entrapped gasses. So, when you have this porosity and entrapped gasses, these gasses gets ionised inside this. So, inside these force and defects. Due to ionization of the these defects, they suddenly explode inside the inside the dielectric material, leading to local discharge. As you can see this suddenly, this is characterized by some sort of a sparking in the material as well. So, this is typically due to microscopic force. Then finally, we have what we called as, electro chemical break down.

Electro chemical or mechanical breakdown and this is essentially due to transport of conducting material because of local electrochemical current paths that may be created inside the material or in the interior of electric. Basically due to presence of local electro chemical paths and these are effected by atmospheric conditions, such as humidity and pH. So, so we we finished this module here. In summary, what we have looked at is the behaviour of dielectric materials, started with fundamental properties. Looked at the polarization mechanisms and then polarization mechanism is characterized by what is called as polarizability, which is you know a microscopic property.

We try to get analysis of this microscopic property, just by looking at simple dielectric treatment, without using the frequency. And then we looked at the behaviour of these dielectric materials, in the presence of frequency to get a real picture. Finally, we looked at how the behaviour, of these materials can be modelled and how they can be studied by using techniques like impedance spectroscopy? Thanks to the efforts of Cole-Cole scientists, who developed a nice method, to study these materials.

And then finally, we looked at some of the break down mechanism, to dielectric materials. So, this finishes this module here. In the next module, we will look at special dielectric materials, which are, which which are different from what we have studied so far and we will take them further in next class.

Thank you.