Electroceramics
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Lecture - 17

So, welcome to this new lecture. So, what we will do is that we will first review the last lecture, and then we will move on with new contents of this lecture. So, in the last lecture we started a new module, which is based on dielectric materials, and as some of you may already be, may be aware that dielectric materials are nothing but insulating materials, and they electrically insulating materials, and they are useful for variety of applications resulting from starting from capacitors to sensors to actuators etcetera. Now, so first what we were doing is that we were establishing some key concepts of dielectric materials and that is where we looked at first quantities like dipole moment, which is nothing but when you have separation of two charges, then as a result the system gets polarized and you have creation of a dipole moment; and this dipole moment is nothing but dot product of charge and separation distance.

Now, dipole moment gives rise to a quantity which is called as polarization of the material. Polarization as we established is nothing but surface charged density and this polarization is nothing but dipole moment per unit volume. Then we went on to establish some other some other fundamental concepts of dielectric materials. The one of the fundamental reasons why dielectric materials is interesting is, one key parameter that distinguishes is when you take a vacuum plate capacitor, and when you insert a dielectric material inside it the charged storage capacity of this capacitor goes up.

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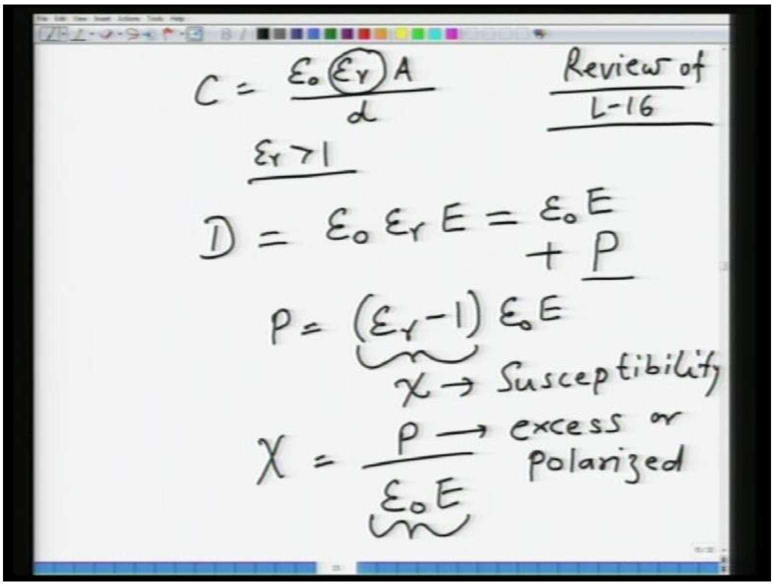

$$C = \frac{\varepsilon_0 \boxed{\varepsilon_r} A}{d}$$

Review of L-16

$\varepsilon_r > 1$

$$D = \varepsilon_0 \varepsilon_r E = \varepsilon_0 E + P$$

$$P = \underbrace{(\varepsilon_r - 1)}_{\chi \to \text{Susceptibility}} \varepsilon_0 E$$

$$\chi = \frac{P \xrightarrow{} \text{excess or polarized}}{\underbrace{\varepsilon_0 E}}$$

So, as a result we come across this expression, the capacitance gets modified as C is equal to epsilon naught epsilon r A by d and this epsilon r is the key parameter. So, I will just write this as a review of last lecture. So, this epsilon r is a quantity which is specific to a dielectric, and this is always greater than 1 for a dielectric material. Then we looked at quantities, then we looked at some other quantities, and we stumbled upon what is called as dielectric displacement D, which is nothing but when you insert a dielectric its epsilon r epsilon naught epsilon naught epsilon r E, which is equal to the dielectric displacement or equivalent to surface charge density in a vacuum plate capacitor plus that extra charge which is created extra surface charge which is created due to polarization of the dielectric. This polarization we equated as epsilon naught epsilon r excuse me, epsilon r minus 1 into epsilon naught E, and this quantity we defined as chi which is the susceptibility.

So, dielectric susceptibility is nothing but a response offer system when a dielectric material is inserted into a capacitor or in the system. So, chi can be represented as P divided by epsilon naught E. So, this P is the excess or polarized charge and this epsilon naught is the charge, when no dielectric is inserted in the vacuum plate capacitor. So, this is, these are things that we established in the last lecture. Now, in this lecture; so this is the new lecture. So, I will just put this is 17 lecture of this series of lectures. So, what we will do is that, we will establish now. What are the key reasons for polarization? Why does polarization occur? Are there any variables which affect the nature of this polarization? We look at these fundamental concepts again and build up on some more quantities as we move on.

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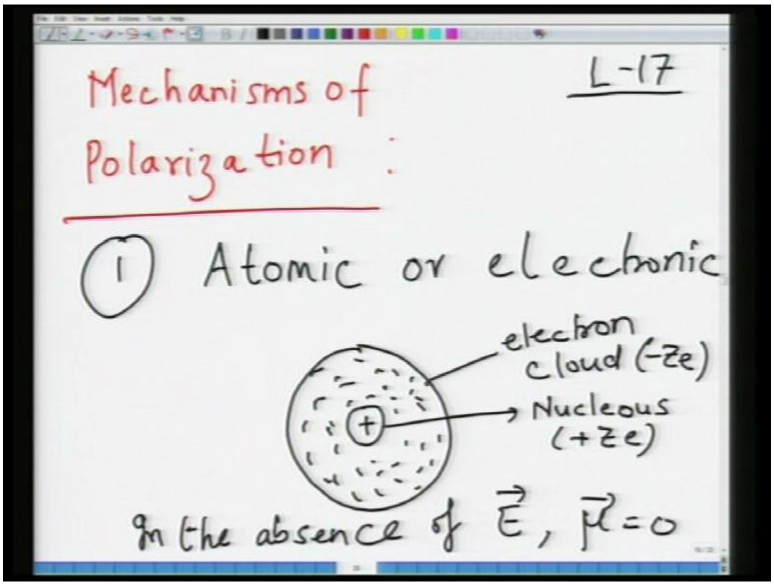

Mechanisms of Polarization :

L-17

① Atomic or electronic

In the absence of $\vec{E}$, $\vec{\mu} = 0$

So, the point that we take upon is we will do that is, we look at mechanisms of polarization. So, in this there are essentially there are, four mechanisms of polarization depending upon the scale at which we are looking. Polarization arises from separation of charges, positive negative charges and this separation of positive centre of positive charge with respect to centre of negative charge can happen at various scales. First of this scale is called as, it is referred as atomic or electronic. So, this is at really a small scale. Now, what happens at this is, when you have a an atom, let us say; in the absence of electric field the atom has a nucleus whose centre of charge is this. So, this is let us say, nucleus and this let us say, has a charge of plus Z e; and this is surrounded by what is called as a, what you may refer as a electron cloud which... So, this is your electron cloud and this has a charge of minus Z e.

Now, what happens in the absence of electric field is the centre of this cloud, coincides with the centre of this nuclei. So, what happens is that, since the centres coincidise coincide in the absence of electric field. In the absence of field mu is equal to 0 because there is no separation between the centre of the charges, but what happens is when you apply a field then what happens says.

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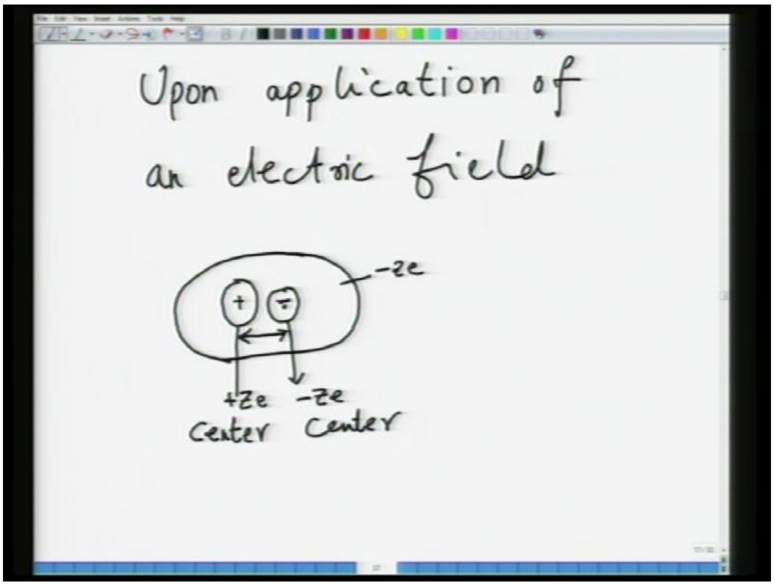

Upon application of an electric field

So, what upon application of an electric field, the situation gets modified. So, what you have now here is, you have situation like this. The electron cloud shifts with respect to the centre of the nuclei, so what you have is you have this positive charge sitting here, which is plus Z e and then the centre of this negative charge goes somewhere here. So, this is your minus Z e and this is the centre of negative charge.

So, this is minus Z e centre. So, now what you have is separation between these two. When you have separation between these two you have a dipole moment created and this mechanism of polarization is called as electronic or atomic polarization because it happens at atomic scale or at dielectronic scale. So, and as you can see that, since all the materials have atoms irrespective of their formula, their chemical behaviour all the materials show this kind of mechanism. As you can see, and what we will see that a little later this also has what is called as a frequency dependence. So, that we will see a little while later. So, this is the first mechanism of polarization which happens at atomic scale.

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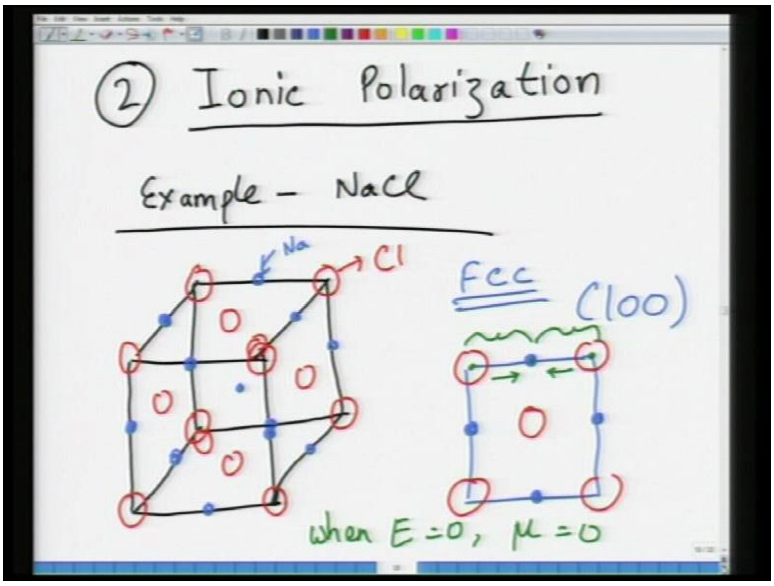

② Ionic Polarization

Example – NaCl

when $E = 0$, $\mu = 0$

Now, the second mechanism of polarization, is ionic polarization. This ionic polarization is a mechanism, which happens in solids. Which have, which are ionically bonded. Now, this ionically bonded materials for instance let us take the structure of sodium chloride. So, if you look at sodium chloride what it is it is a FCC structure? So, just take a example of sodium chloride. So, what you have here is now sodium chloride will have... So, sub lattices made by let us say, this is chlorine atom. So, this is your sodium chloride, chlorine sub lattice. Now, I want to make where does the sodium atom goes, sodium atom goes in all the FCC sides. So, all the FCC sides are located as edges at centres basically and one body centre. So, these are all your sodium atoms. So, let us say this is sodium and this would be chlorine.

Now, as we know this material is FCC, which means it is a symmetric structure. So, if I just draw the 1 0 0 plan view, 1 0 0 plan view looks like this. So, the chlorine atom would be here and sodium atom would be at these positions. So, this is your 1 0 0 1 0 0 plan view. Now, if you look at this plane on top of electronic polarization or atomic polarization which is, which would anyway happen in this material is, you can see that the centre of positive and negative charges are separated away from each other. So, this centre I will use a different ink here this centre and this centre will form a dipole. this centre and this centre will form a dipole Likewise all the positive and negative ions since, they are separated from each other they will form a dipole; however, the net dipole moment is equal to 0. Why is it equal to 0?

Since, the dipole moment vectors are opposite to each other for this. Let us say, this is a negative charge this is a positive charge it goes from this direction, this goes from this direction likewise all the dipole moments cancel each other in the absence of electric field. So, when E is equal to 0, mu is equal to 0 and this is simply because of symmetry of the structure, it does not show any dipole moment because of cancellation of all the dipole moments arising because of separation of positive negative ions. Which is any where there in the ionic lattice. So, how does this show polarization at all? This shows polarization when you have; however, when you apply electric field upon application of finite electric field.

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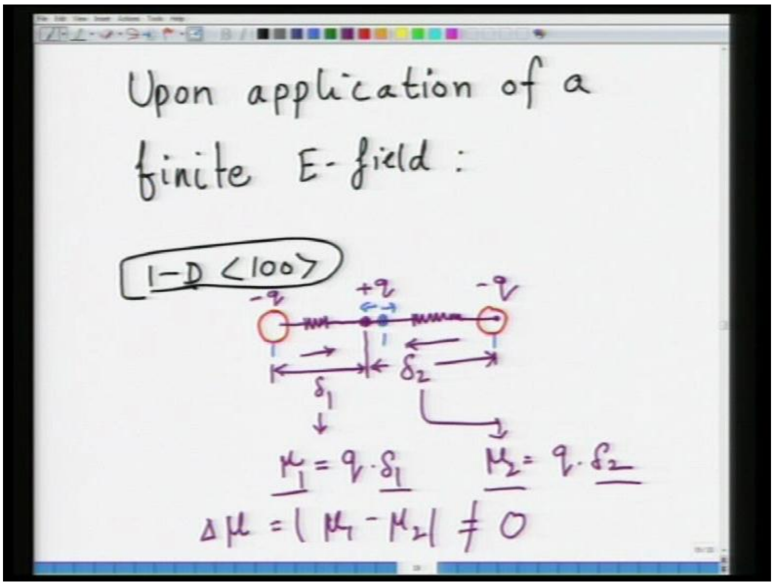

Upon application of a finite E-field :

$\underline{\mu_1} = q \cdot \underline{\delta_1}$ $\underline{\mu_2} = q \cdot \underline{\delta_2}$

$\Delta\mu = |\mu_1 - \mu_2| \neq 0$

What happens is that I just take the example of let us say, just a one dimension example. So, 1 D picture, so what will happen is, if I just draw. So, these are my chlorine atoms, I am just taking 1 D, let us say along 1 0 0 direction. So, since it is a FCC crystal it does not matter so 1 0 0 would be equivalent to 0 1 0 1 0 0 1. So, I have taken chlorine here and then I take sodium somewhere here. Now, this is the equilibrium position. The distance between these two and these two is equal, which means 0 dipole moment. When you apply electric field what will happen is, one of these bonds they change their lengths. So, what will happen is the, this sodium atom will move either this way or that way with respect to the centres of negative, negatively charged atom that is chlorine atoms. So, when you apply electric field what will happen is, the new position would be either this or this depending upon the direction of applied field.

So, what will now happen is let us, so let us assume that, the position is the left one. If that was true then this bond has become compressed and this bond has become longer. So, which means this distance is now delta 1 and this distance is now delta 2. So, this would give rise to mu 1 which is q let us say. So, this is minus q this is plus q this is minus q. So, this would give rise to q dot delta 1 and this would give rise to mu 2 would be q dot delta 2. So, but mu 1 and mu 2 are not equal because delta 1 and delta 2 are not equal, as a result and the vectors would be different, there direction would be different. In one case the direction would be that and in another case direction would be this. So, as a result you will have delta mu which is mu 1 minus mu 2.

I am just taking mod for the sake of simplicity this would not be equal to 0 and this would be the scenario which would give rise to what is called as ionic polarization. Now, this again, this happens in the solids where you have positively and negatively charged ions. Typically ionically, you are ionically covalently bonded solids and this again has dependence upon frequency which we will see a little later.

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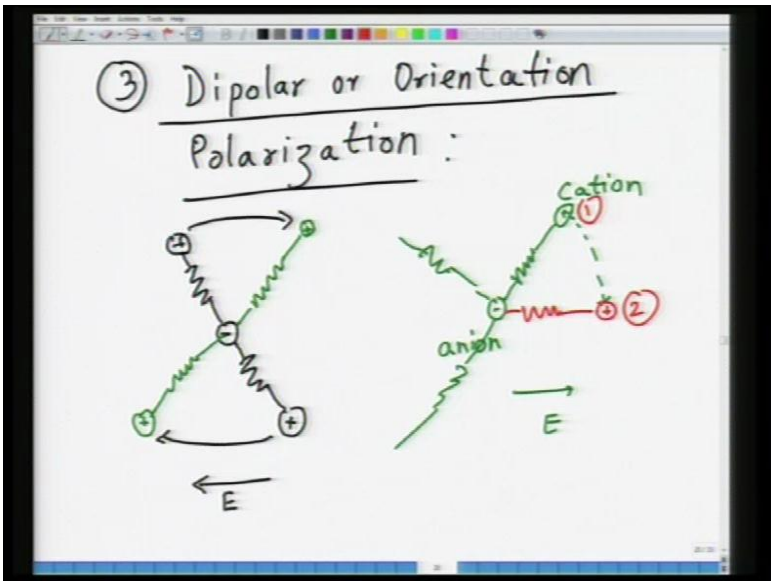

So, in the third mechanism of polarization in this category is, what is called as dipolar or orientational, orientation polarization. Now, in this category what we have is, this is now, this is unlike previous two cases. Again here also you have separation of positive negative, again you have formation of dipoles, but what happens here is here you have instead of when you apply electric field unlike previous two cases here what you have is, due to reorientation of molecular dipoles in the direction of applied field.

So, for instance you can have a scenario like this, let us say I have this as a negative charge and let us say this was bonded to positive charges like this. So, so when we now what I do is, that when I apply electric field let us say, in this direction and what happens is that, this particular guy wants to move to this side and this particular guy wants to move to this side, so as a result I have now new situation. So, this is so this is the new situation in which these two positive charges or vice versa, it could be positive at the centre and negative at the other side. These two guys have move to other positions and this is, this has become, this is called as a dipolar polarization mechanism.

Another scenario now, this typically is this is one mechanism dipolar polarization another could be coming from one state to another state. So, for instance if you have a picture like this, let us say. So, this is your let us say, negative charge this is your positive charge, so this is your cation, this is your anion and this is also bonded to other atom elsewhere. So, this guy when you apply field in this direction, this guy will move to position which would be something like this. So, going from one position to another which could be another equilibrium position. So, basically these two pictures what they illustrate is, rather than looking at the distinction between first two and this one is, here there is movement of molecules or molecular groups.

This involves a lot more energy as compared to previous two cases because that is there you are only looking at slight movement in x y direction or along the axis in one particular direction. Here you are looking at the rotation of molecule. Which is a far more difficult in energy consuming process and this again has implications in terms of the frequency at which they operate. Simply because here the whole of this molecule has to rotate. So, this is the third mechanism of polarization and the fourth one is interface polarization.

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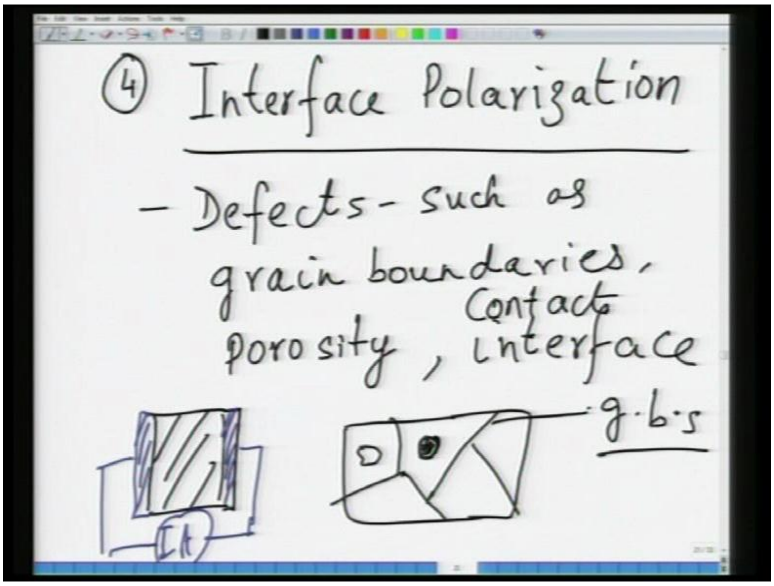

④ Interface Polarization

- Defects - such as grain boundaries, porosity, contact interface

Now, you might be wondering what is this? Now, this is because most of the materials in practice have a defects such as... So, you can you can name the defects, it could be grain boundaries, it could be porosities. So, we can have porosity inside the material and since all the materials need to be connected to any. So, if you want to for example, if you have a dielectric material and I want to measure at dielectric constant. How do you measure the dielectric constant? You need to put the contact on top. So, if you want to measure the dielectric constant, you need to put the contact on this side, you need to put the contact on this side and then connect it to something called as let us say, impedance analyser and this.

So, putting the contact gives rise to interface between the contact and the material. So, another reason is interface; however, contact interface any of these things whether it is a grain boundary, whether it is porosity, whether it is a contact interface all of these give rise to what is called as interface. In a polycrystaline material if you have grain structure like this, so these are nothing but grain boundaries and grain boundaries are nothing but interfaces. If you have let us say porosity like this porosity nothing, there is nothing inside and these walls of the pores are again for in interfaces in the sense because it breaks the continuity of the material. So, all these defects give rise to what is called as a interfaces and as a result you have alignment of charged dipoles under the applied field at these interfaces and this is the this is called as your interfacial polarization.

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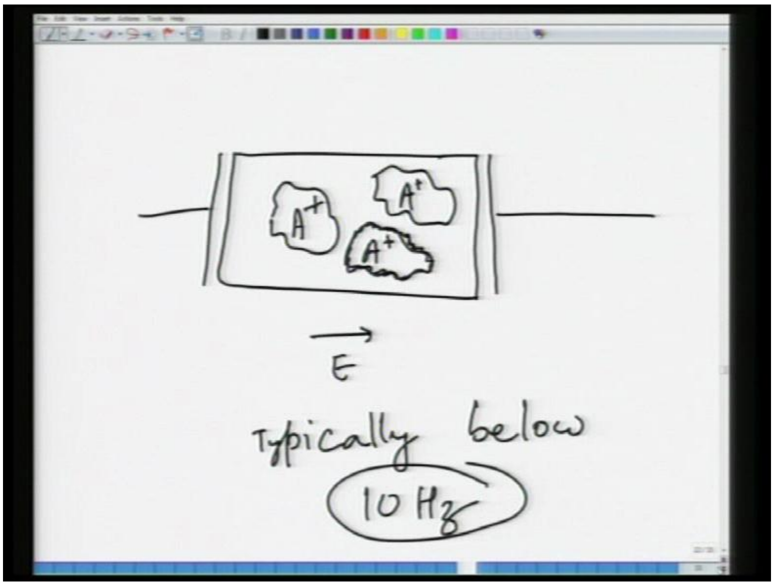

So, you might have a picture like this. You have a dielectric material for instance and let us say, you apply field to it electric field. So, what you might have is between these discontinuities you have separation of... Excuse me it is getting a little… So, let us say this is up discontinuity of pore, so between these you have segregation of these impurities or positive ions or cations. So, as a result you have segregation of one particular type of charge on one side another particular charge on another side. So, you have polarization at these interfaces because of this migration of charges under the application of electric field.

So, these are the four mechanisms which are commonly, which are observed in dielectric materials, which give rise to the polarization as we earlier talked about. Now, mathematical treatment what we will do is, that we will we will do the mathematical treatment of these mechanisms. First three mechanisms, for the first three mechanisms it is rather it is rather easier, but for the fourth mechanism it is rather cumbersome. So, we will we will leave that out. I would I would supply you some which is, it can be done, but it is beyond the level of this course. So, if you want to deal into it, I I will supply you certain references which you can go through and look at the interfacial polarization as well.

Now, what we will look at these mechanisms as we have talked about they have what is called as the frequency dependence and this frequency dependence is because of the reason they operate at different scales. Now, if we go back to previous slides, say if I go back to the first slide. Now, atomic polarization as we have seen, this happens at the atomic level, which means entities are very small and in terms of mass. We are looking at electrons and the nucleus. When we are looking at the electrons and nucleus this happens to, happen in the range of frequencies let us say, between 10 to power 14, 15 hertz these are. So, any frequency, at any frequency is smaller than 10 to the power 15 hertz this mechanism will operate simply because the mass of entities involved in this process is smaller, so these, this is because entities are lighter.

So, as a result any frequency is smaller than 10 to the power 14, 15 hertz this mechanism will operate. So, in most of the practical applications we when we... So, these are called as the optimal frequencies. So, in most of the practical applications practical applications typically we are talking about in the frequency range of 1 kilohertz to 1 megahertz or may be slightly higher gigahertz frequency range, but even at the gigahertz frequency range this mechanism is always going to be operative. So, this is a mechanism which is fundamentally present in most of the materials. Simply because these frequencies, frequency requirement for this mechanism not to operate its too high.

So, so these, next we move on to ionic polarization. Ionic polarization is a mechanism, now here the scale gets little bigger. In the previous case we were talking about electrons and nuclei here we are talking about displacement of ions with respect to each other. So, so it gets a little heavier as you can see in terms of mass because now we are talking of movement of migration of short range migration of ions with respect to each other. So, as a result this mechanism operates at the frequencies anywhere between 10 to power, 10 to power 9 to 10 to power 12 hertz. So, this mechanism will operate at frequencies below 10 to power 11, 12 hertz in any case.

So, depending upon mass of the ion of course, so anywhere between 10 to power 9 to 10 to power 12 this particular mechanism is likely to operate. Anything below this range will always have this mechanism taking place, provided the solid is solid is multi component, where you have cations and anions with the moving with respect to each. Of course, this is not going to happen in a material in a single elemental material because you would not have differently charged ions. So, and the third one as we looked at was dipolar or orientation polarization. Now, here we looked at two cases, both of these cases involve different kind of energies.

This is slightly, this particular cases are slightly lower energy consuming scenario as compared to what is shown on the right. So, as a result in case of dipolar or orientation polarization often one one encounters two regimes. One is the high frequency regime, second is the low frequency regime and both of these happen below 10 to power nine hertz. It is not necessary that you should see both the regions in many materials, you see only one region. So, it depends upon the type of material etcetera. So, but in any case this particular mechanism is going to be operative at frequencies below 10 to the power 9 hertz, simply because here the level of migration involved is much the or the mass of entities which need to be migrated or moved is much higher because here we are looking at the whole molecule itself, rotation of molecules which is rather more energy consuming affair as you can see as you can think.

The fourth one that we talked about is about interfaces and this operates at frequencies below typically below below 10 hertz. So, this happens at really below very small frequencies, interfacial polarization.

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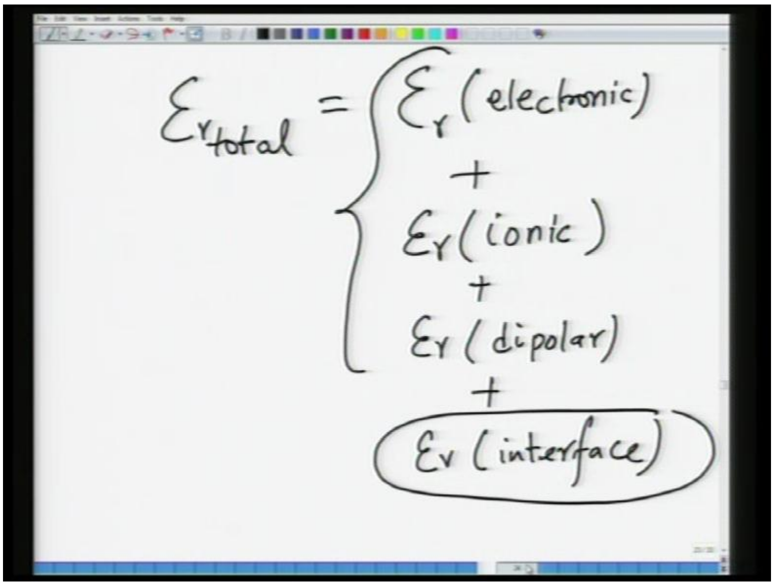

$$\varepsilon_{r_{total}} = \left\{ \begin{array}{c} \varepsilon_r(\text{electronic}) \\ + \\ \varepsilon_r(\text{ionic}) \\ + \\ \varepsilon_r(\text{dipolar}) \end{array} \right. \\ + \\ \boxed{\varepsilon_r(\text{interface})}$$

Now, so the first polarization which... So, the dielectric constant of a material is, so in general dielectric constant total epsilon r total, this can be written as sum of epsilon r electronic plus epsilon r ionic plus epsilon r dipolar plus epsilon r interface. Now, usually interfacial polarization is an extrinsic effect, that is why when we make calculations of dielectric constant. We take the first three things into account not the last thing last thing.

We want to actually subtract because it could be because of electrodes that are put on the material. So, it is not a intrinsic effect in, if you are able to control the quality of your material provided you do not have too many grain boundaries as well as too many porosities inside the material.

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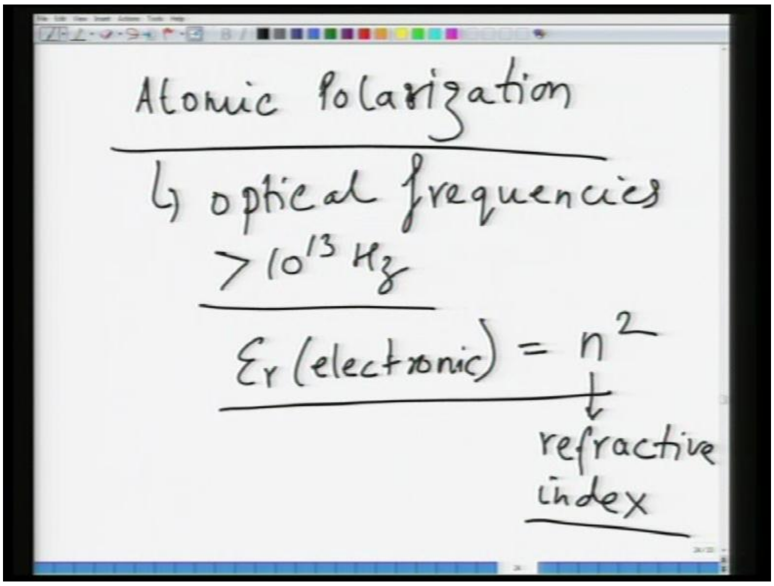

Atomic Polarization

↳ optical frequencies

$> 10^{13}$ Hz

$\varepsilon_r (\text{electronic}) = n^2$

↓

refractive index

Now, another thing that I wanted to point out was based since, this atomic polarization it happens at optical frequencies, frequencies which is frequencies above 10 to the power 13 14 hertz at around 10 to the power 13, 14, 15 hertz. According to Maxwell’s theory electromagnetic theory for a non magnetic dielectric material, this epsilon r electronic can be related to what is called as n square, which is the refractive index. The treatment of this exercise can be found in any book on physics, solid state physics. So, if you want to if you want to know how this is derived you can you can look at any book on physics, solid state physics such as Ashcroft and Mermin or Kittel, all these books will have that treatment on this, so this is the basic relation. So, anything which is observed any single elemental material, which does not have cations and anions and where you observe this electronic polarization, this electronic polarization will be equal to n square.

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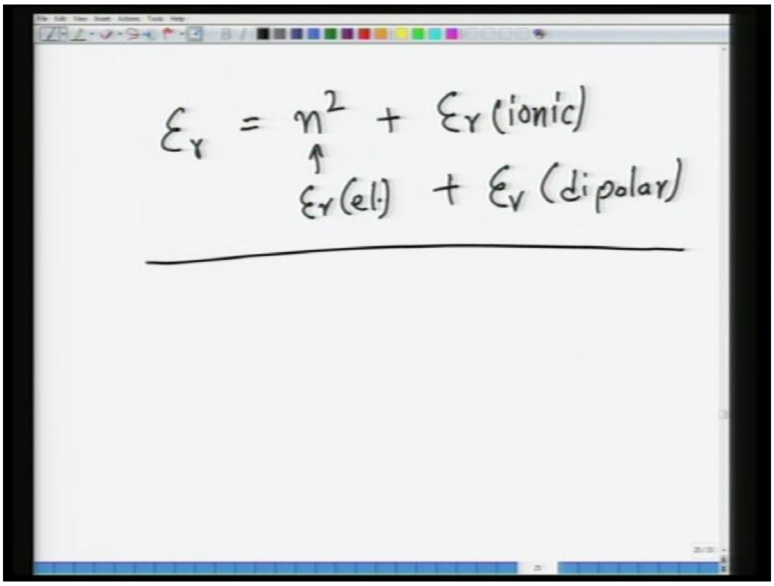

$$\varepsilon_r = \underset{\substack{\uparrow \\ \varepsilon_r(\text{el.})}}{n^2} + \varepsilon_r(\text{ionic}) + \varepsilon_r(\text{dipolar})$$

So, what this equation will be? So, epsilon r will now be equal to n square which is nothing but epsilon r electronic plus epsilon r ionic plus epsilon r dipolar. So, far I have mentioned that there is a frequency dependence, which you can think and this frequency dependence arises because of because of differences in the masses of entities, which need to be moved or rotated at. So, there are various scales of masses as a result there are various differences in the energies involved or the time scales involved in which things are going to happen as a result you have frequency dependence.

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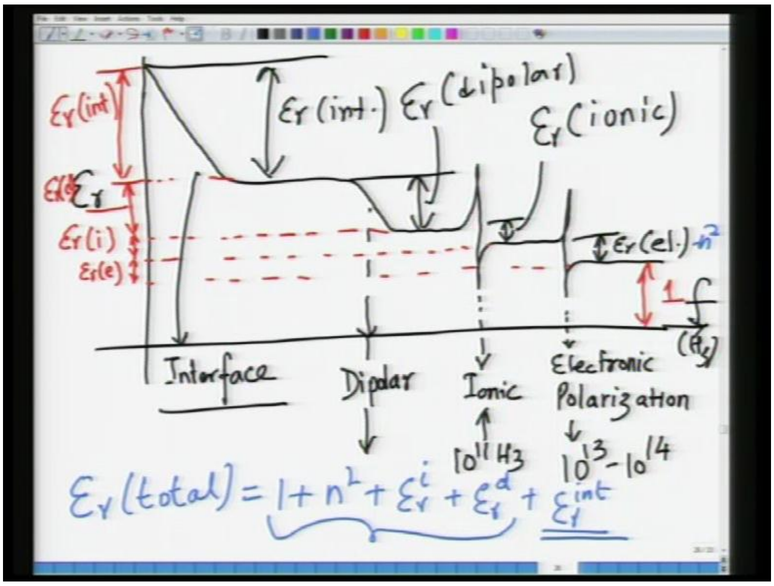

$$\varepsilon_r(\text{total}) = \underbrace{1 + n^2 + \varepsilon_r^i + \varepsilon_r^d} + \underline{\underline{\varepsilon_r^{int}}}$$

So, when you plot this dielectric constant as a function of frequency. So, you now plot this epsilon r as a function of frequency. So, this looks something like this, right? This is how it looks like. This particular point is refers to electronic polarization, this particular point refers to ionic polarization and this is where your dipolar mechanisms come into being and this is where your interface things come into. So, as a result what you have here is epsilon r electronic here, you have epsilon r ionic here you have epsilon r dipolar and here you have what is called as epsilon r interface f in hertz. So, this is going to happen at about 10 to the power 13 hertz, this will happen roughly at about 10 to power 11 hertz, this will happen approximately any frequency below 10 to power basically 9 hertz.

So, and this will happen at very low low frequencies. So, this is how dielectric dielectric constant versus frequency plot is going to look like. So, if we just elaborate this point further, you can draw lines which illustrate this point clearly. So, this would be epsilon r electronic, this would be epsilon r ionic, this would be epsilon r dipolar and this would be epsilon r interface. Do not worry about the relative magnitudes of these with respect to each other because this is just a schematic diagram. Now, the point is, what is this would... So, this is nothing but as if there is no dielectric present, so this would be nothing but one.

So, now when you look at epsilon r total. So, epsilon r total this becomes 1 plus and this is nothing but n square n square plus epsilon r ionic plus epsilon r dipolar plus epsilon r interface. Now, whether or not you add interface it is a different issue depending upon type of contributions, but this is how this dielectric constant is going to look like. This is the picture of polarization mechanisms, which are going to be operative and which contribute to different which contribute to different segments of the dielectric constant as a function when we look at it, as a function of frequency. At the moment what we have looked at is the qualitative picture. We will do the quantification in the further in the next few lectures, when we look at some more quantities, which quantify this whole affair little bit better.

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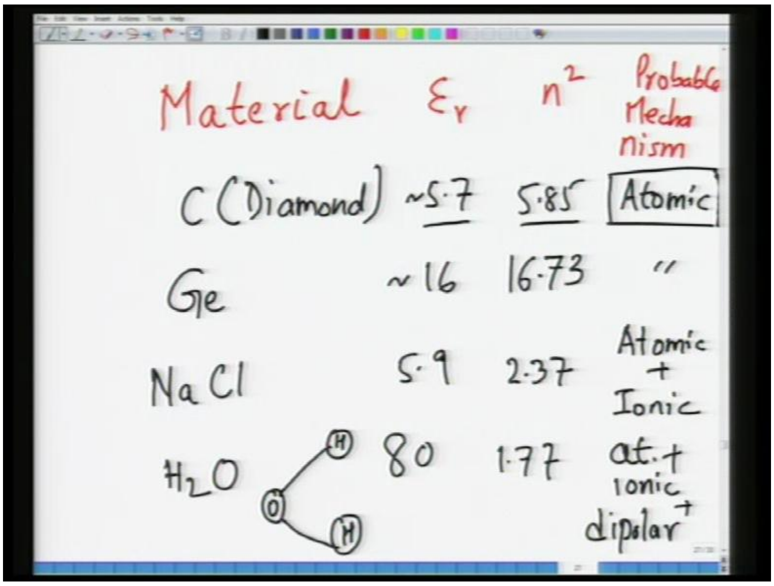

Material	ε_r	n^2	Probable Mechanism
C (Diamond)	~5.7	5.85	Atomic
Ge	~16	16.73	"
Na Cl	5.9	2.37	Atomic + Ionic
H_2O	80	1.77	at. + ionic + dipolar

Now, I will give you some examples. So, for instance I will just put material and value of epsilon r and value of n square and then probable probable or likely mechanism. So, so let us say, the case of first diamond which is nothing but carbon. Now, diamond has a value of refractive index according to which n square is 5.85, the measured value of dielectric constant is 5.7. So, close to 5.7 and since you can see these 2 values are close to each other, the probable mechanism is going to be atomic mechanism. This makes sense because diamond is a single elemental material and it is a FCC diamond cubic structure, it does not have it does not have rotation of it does not have molecular structurem as a result you do not have ionic or dipolar mechanisms present. So, all you have is the atomic polarization, which is present in the material. Then you have what is called as germanium. Germanium is a semiconductor.

So, according to this n square is 16.73 and epsilon r epsilon r is always measured. So, if you look at the previous expression, you always remove this 1 from here because 1 is any way as if it is here. So, because you always, what I have shown you schematically, but you always measure it from 0. So, and this epsilon r will always include that. So, so this germanium will have, germanium again is a single single elemental material. It is a semiconductor the value of n square is 16.7, the measured value is 16 again germanium is going to have atomic polarization mechanism; which is going to, do going to be dominant. Now, if you look at the case of sodium chloride. Sodium chloride as we just looked it has a FCC structure, it will have atomic polarization mechanism and intuitively it should have it should have ionic polarization mechanism dominant as well.

So, let us see what is the difference between the n square and epsilon r. n square for this is 2.37, so if it had only atomic polarization, epsilon r should be approximately equal to this, but the measured epsilon r is 5.9, which is more than 2 times of this value. So, as a result this will have atomic plus ionic. Then you have example of water and this water measured value is 1.77 n square. Value is 1.77 and the measured value is 80 and this is because water not only has atomic also ionic because you have hydrogen oxygen ions, but also dipolar simply because molecular structure of water is something like this. So, this is oxygen, this is hydrogen this is hydrogen.

So, as a result it has a finite dipole moment and this can be rotated by application of electric field. So, I forgot to mention one thing, that most of the dipolar polarization materials they also tend to show what is called as a finite dipole moment. They have a structure which allows them to have a finite dipole moment in the absence of electric field, that is the important aspect of dipolar material, the materials. So, this will have atomic plus ionic plus dipolar. So, this is this is how... So, I have just given you this table just for a qualitative illustration. You can have a you can have a look at variety of various materials, go to journal papers, literature find out what is the value of n square find out what is the value of epsilon r. Which you measured and just try to correlate this with the structure of the material or type of the material and you can get a better feel of what kind of polarization mechanisms are likely to operate in a particular kind of material.

So, what now we will do is, that we will take a microscopic approach and we will look at some other quantities which are relevant to dielectric materials. So, and this approach is called as a microscopic approach because...

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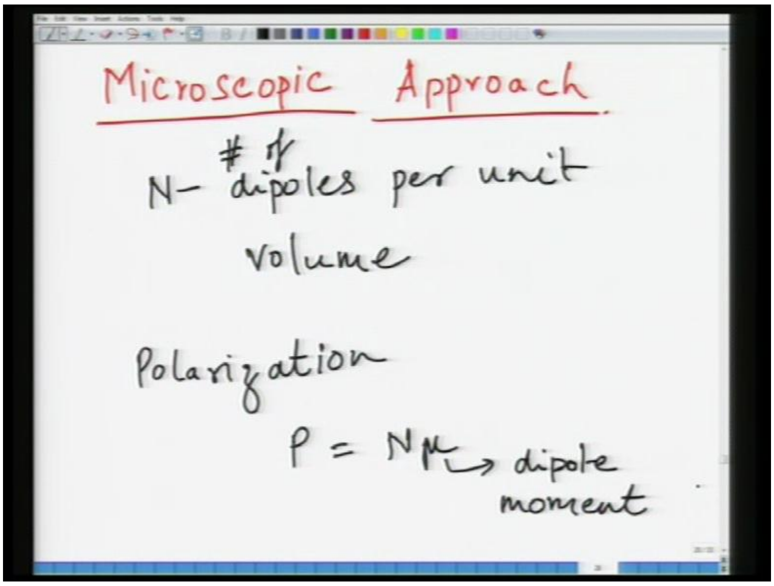

Microscopic Approach

N – # of dipoles per unit volume

Polarization

$P = N\mu$ → dipole moment

So, far what we have been talking about are the quantities which are macroscopic. Which can be seen to the outside world rather easily by measurements etcetera but there are some quantities which are more microscopic which you cannot measure, but you can derive them through certain means. So, this is, so what we will do is that we will take a microscopic approach. So, earlier we saw, we encountered a system and we defined polarization as dipole moment per unit volume. Let us say, a if there are N dipoles in that particular volume and if all of these dipoles are aligned in one particular direction, it is not a isotropic case where all the dipoles are randomly distributed for such a scenario. So, we say that N dipoles per unit volume. So, number of dipoles per unit volume, then polarization P can be written as N mu, where mu is the dipole moment of each dipole.

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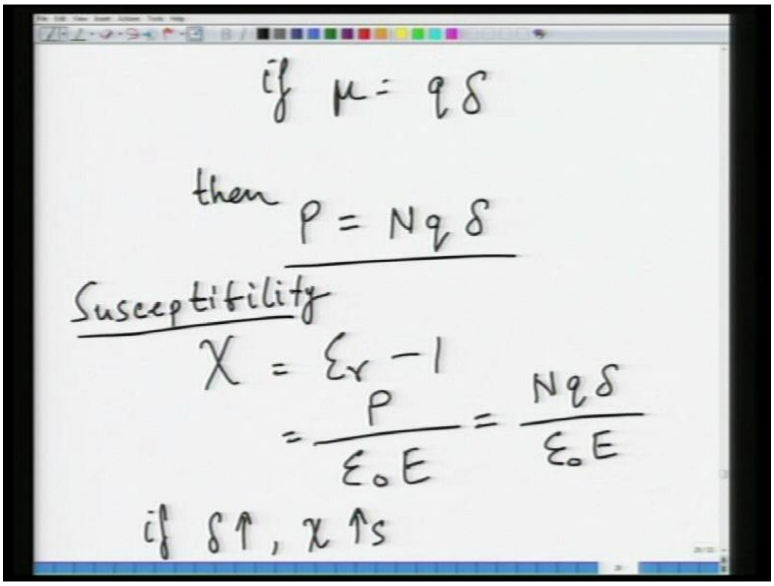

if $\mu = q\delta$

then $\underline{P = Nq\delta}$

<u>Susceptifility</u>

$$\chi = \varepsilon_r - 1$$

$$= \frac{P}{\varepsilon_0 E} = \frac{Nq\delta}{\varepsilon_0 E}$$

if $\delta \uparrow$, $\chi \uparrow$s

If each and if if mu was equal to q delta, then P becomes equal to N q delta; this is the this is the simple equation that we get when we put in the when we again use the previous knowledge. Now, so chi is nothing but epsilon r minus 1 chi is the susceptibility. This is given as P divided by epsilon naught E and if we replace the magnitude of P, this becomes N q delta divided by epsilon naught E. So, this is the magnitude of chi. So, here you can see if delta is larger, then chi is larger; so, if delta increases, chi also increases, which means as the separation between charges become bigger, the material becomes more and more polarisable. Material is said to be to be more polarisable, and as a result it will have higher dielectric constant, because chi is epsilon r minus 1.

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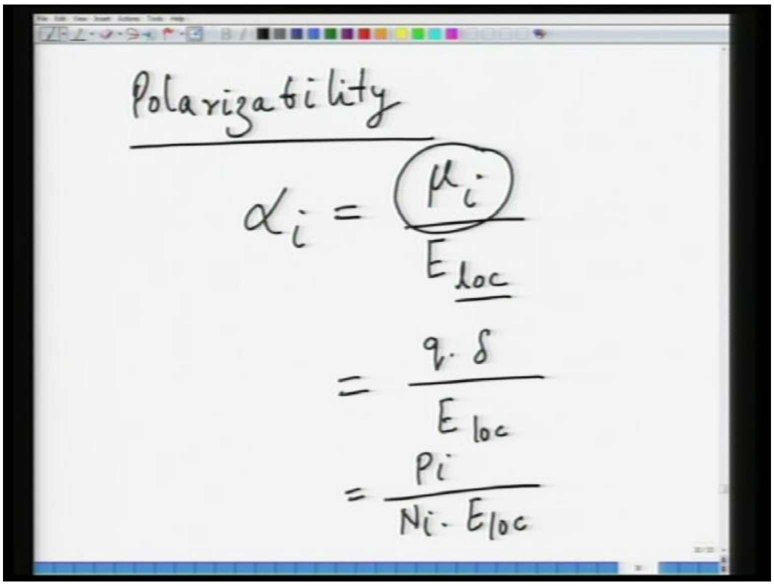

Polarizability

$$\alpha_i = \frac{\boxed{\mu_i}}{E_{loc}} = \frac{q \cdot \delta}{E_{loc}} = \frac{P_i}{N_i \cdot E_{loc}}$$

Further now, we define another quantity; so which is called as polarizability; polarizability of a material of an atom or ion in a particular dipole is defined as, so let us say, we call it alpha i of i eth atom or ion or; so this will be called as mu i dipole moment of in that particular dipole. So, alpha i is the polarizability of an atom or ion in the dipole i, mu i is the dipole moment of that dipole i divided by what is called as E local. Now, here we have written E local, because the local applied field which is felt by that particular entity may be slightly different as compared to applied field. So, we look at the magnitude of local field a little later, but basically what it means is that what we have defined is alpha i is equal to mu i divided by E local. So, now, what we do is that we replace this P.

So, this E local become mu i is your q divided q into delta divided by E local and this can be written as P i divided by N i E local as well, because I know that mu i is equal to P i divided by N i. So, there are variety of ways of writing this. So, this is another way of writing. So, what we will do is that in the subsequent lectures, we will work out what is the magnitude of E local.

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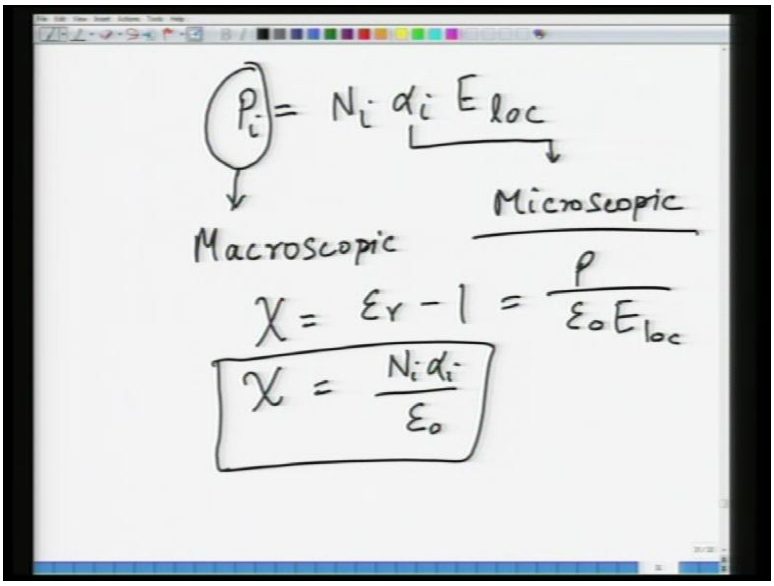

$$P_i = N_i \alpha_i E_{loc}$$

$$\chi = \varepsilon_r - 1 = \frac{P}{\varepsilon_0 E_{loc}}$$

$$\boxed{\chi = \frac{N_i \alpha_i}{\varepsilon_0}}$$

So, now we can express P as N i alpha i E local from the previous expression. So, what it does is it P i. So, what this equation does is, what this equation does is to relate a macroscopic quantity which is P. P is the macroscopic quantity simply because we can measure it and alpha i is a quantity which is microscopic, which pertains to atoms and ions. So, what this equation does is, to relate a macroscopic quantity with the microscopic quantity and as a result in general, we get an expression for susceptibility which is epsilon r minus 1 is equal to N alpha divided by epsilon naught. So, this is a general sort of expression for susceptibility as a result which we get because this is equal to P divided by epsilon naught E and what is. So, now, alpha is also again sum of all sorts of polarizabilities.

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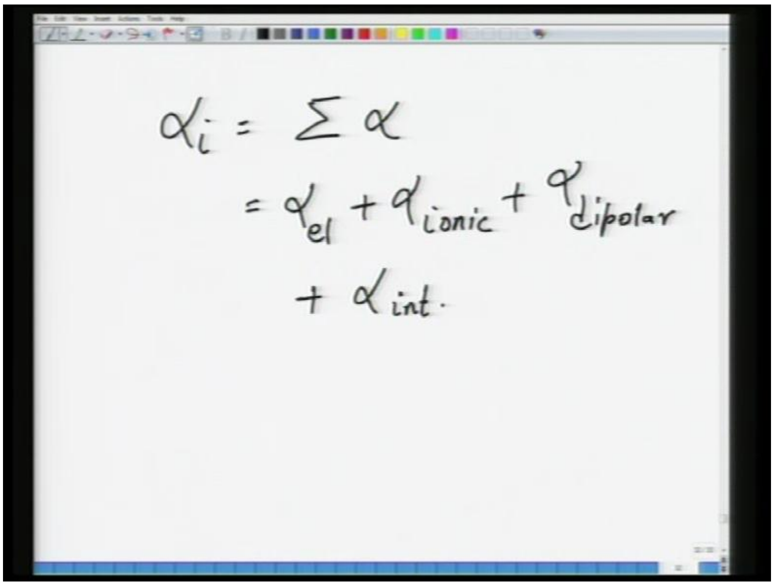

$$\alpha_i = \Sigma \alpha$$

$$= \alpha_{el} + \alpha_{ionic} + \alpha_{dipolar}$$

$$+ \alpha_{int}.$$

So, when we look at alpha i, so you can say sigma alpha. So, this would be alpha electronic plus alpha ionic plus alpha dipolar plus alpha interface. So, alpha is just like dielectric constant, alpha being a microscopic quantity does not mean that it is just one quantity, it is also sum of all the polarizabilities which arise from all the mechanisms of polarizations. So, this we will quantify here little later. So, what we are now left to do is, that here we have introduced a thing which is called as E local.

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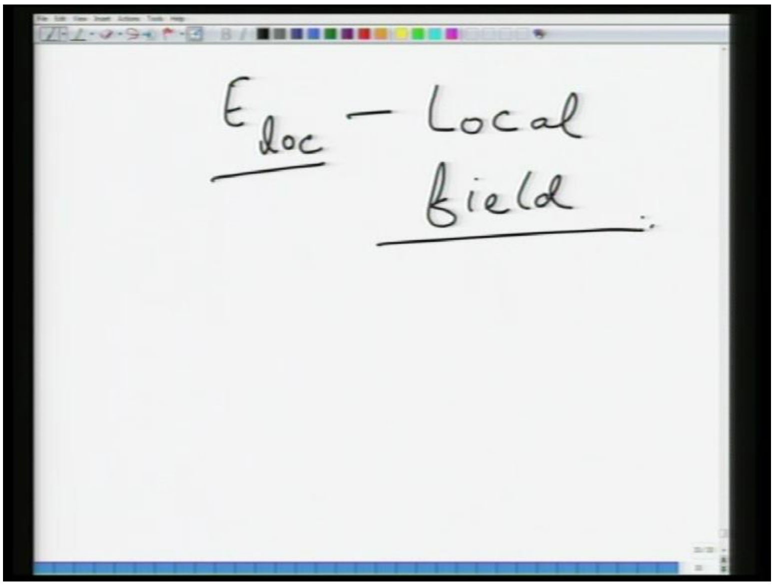

$\underline{E_{loc}}$ – Local $\underline{\text{field}}$.

E local and E local field is a field, which we, which we are saying that is because of effect of surroundings on the on the dielectric at a particular point in the dielectric. So, the, so any entity inside the dielectric fields, field which is slightly different as compared to the applied field, and we will see how this local field is determined in the next class. So, at the moment in the, in this lecture, we do not have sufficient time to go through it, but we will do that in the next class. So, what I will do now is, I will just summarize this lecture. So, what we did in did in this lecture was we had a look at what is called as polarization mechanism. Understanding of this polarization mechanism is important because in order to understand polarization at various scales of frequency because most of the measurements that we make on dielectric materials, they are all a c measurement.

They are made in fields of various frequency and as a result of the frequency at which you operate you get various contributions to polarization and you must know it. So, there are four mechanisms of polarization, which are which we talked about first is the atomic polarization. Atomic polarization is the polarization where charges separate at the smallest possible scale and that particular that scale is the atomic scale. So, what happens here is, when you apply electric field the centres of positive charge which is the electron, which is the nucleus separates with respect to what is called as centre of negative charge which is the electron cloud.

So, as a result you have formation of a dipole moment and this gives rise to what is, what we called as electronic polarization. This happens at very high frequencies in the optical range of frequencies which is 10 to the power 13 to 15 hertz. Then when you have, now this is first mechanism is always likely in the case of single elemental material. The moment you move to a bi-elemental or multi elemental material, where you have cations and anions, then you come across what is called as ionic polarization. So, here in addition to the first mechanism the second mechanism gets operative. So, here when you apply field, the centres of positive negative charges move with respect to each other as a result you have again creation of additional dipole moment and this gives rise to ionic polarization.

Then and since it must be added that since, this since it involves movement of slightly higher entities which is the atoms with respect to each other or ions with respect to each other this happens at slightly lower frequencies, which means it requires more time. And the third mechanism was dipolar mechanism, dipolar mechanism happens in solids which have permanent dipole moment which have molecular which have molecular structure.

So, as a now what happens is here you have rotation of dipoles. So, rotation of dipoles would require movement almost rotation of four molecule from one position to another, which would imply that it requires more energy. As a result this happens at much further, much lower frequencies. Then finally, you have what is called as interface, interfacial polarization which is due to presence of variety of interfaces as we discussed and this could be an extrinsic or intrinsic effect. So, we need to be careful in taking this particular contribution into account when we make measurements and this happens at frequency is typically very low frequencies, of the less than 1 hertz or so around 1 hertz.

So, these are the four mechanism of polarization which we discussed and we also introduced the concept of what is called as polarizability. Which is a microscopic polarizability and this polarizability has various contributions depending upon the type of polarization mechanism. So, what we will do in the next class, we will do estimation of local field and once we do that, after doing that we will, we will stumble upon what is called as a Clausius Mossotti relation, which very nicely relates the microscopic and macroscopic parts of the dielectric properties and then we will move into quantification of these variety of these polarization mechanism that we just had a look.

Thank you.