**Fundamentals and Applications of Dielectric Ceramics**
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**Module No # 04**
**Lecture No # 16**
**Dielectric Displacement and Polarization mechanics**

So welcome again to this new lecture of fundamentals and application of dielectric ceramics.

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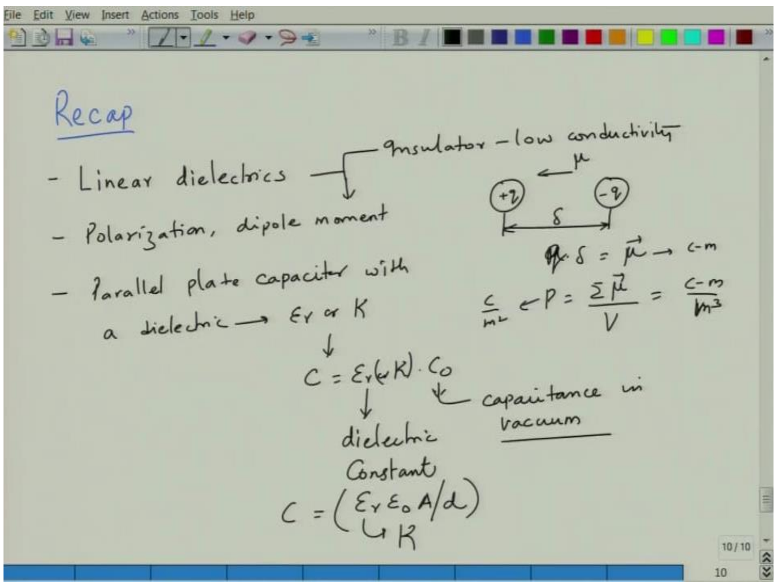


So, let us briefly recap the past lecture so in the previous lecture we initiated our discussion on linear electrics and we introduced terms like polarization, dipole moment so essentially the linear dielectric is a material which is first of all insulator. So, a dielectric is by definition an insulator ok so which means it has low conductivity what it basically means is that when you apply electric field it does not have long range motion of charges it has short range motion of charges.

And this short-range motion is one which gives rise to what we call a dipole moment so as a separation of charges +q and –q so this when you separate them by distance. Let us say d or δ then you develop a dipole moment that is μ and this $\mu \cdot \delta$ is the sorry $q \cdot \delta$ is the new vector that you get and this polarization is nothing but all that sum of all the dipole moments in a given material divided by the volume which is nothing but equivalent to surface charge density.

As long as polarization is perpendicular to the surface and the unit of this is in coulombs per meter square and this is in coulomb meter. So naturally when you have coulomb meter per unit volume and which is meter cube you will get coulomb per meter square. So, and then we looked at the case of parallel plate capacitor with a dielectric and there we found that if you have a dielectric material with strength $\kappa$ or $\varepsilon_r$ which is more than one.

When you insert it in a parallel plate capacitor it enhances the capacitance by amount $\varepsilon_r$ or $\kappa * C_0$. $C_0$ is the capacitance of parallel plate capacitor in vacuum and $\varepsilon_r$ is the dielectric permittivity or dielectric constant off. So, this is basically dielectric constant and $C_0$ is the capacitance of in vacuum a free space ok. So, this is something that we worked out and so $C$ is equal to basically you can say

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

that is what the and you can also write this as $\kappa$.

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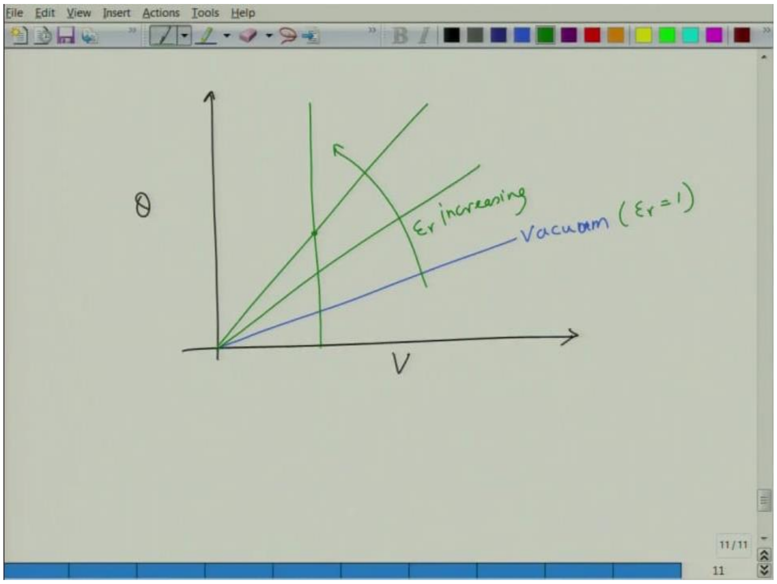


So, it is a choice that that we make sometimes so essentially when you now make a plot of let us say $Q$ *vs* $V$ for a material for a capacitor $Q$ *vs* $V$ so let us say $Q$ *vs* $V$ for a vacuum for vacuum is something like this. Let us say ok $Q=CV$ so you increase the voltage you increase the charge and when you have a dielectric material as you keep increasing that $\varepsilon_r$ increasing.

So, as you increase the $\varepsilon_r$ value so for this it would mean $\varepsilon_r = 1$. So, as you keep increasing the value of $\varepsilon_r$ more than 1 you keep basically for the same voltage you increase the charge storage capacity. So, you can say that for same capacitance you will reduce the voltage or for the same voltage you will increase the charge storage capacity by using a dielectric by the amount $\varepsilon_r$ or $\kappa$ ok.

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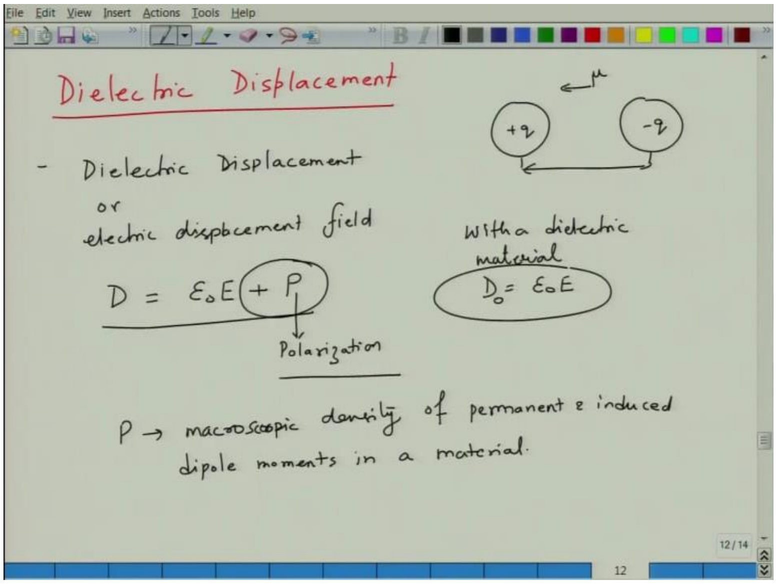


So, now let us see so we introduce some more things so now we introduce the concept of what we called as dielectric displacement. So dielectric displacement so when you have a dielectric material the presence of electric field causes the bound charges in the materials to slightly you know move away from each other to slightly separate. So, as we said that you have when you apply electric field the $+q$ and the $-q$ centers move away from each other by a distance tiny distance creating a dipole moment when you apply electric field.

And this gives rise to what we call as local electric dipole moment so correspondingly you have a quantity called as dielectric displacement or it is also called as electric displacement field. This quantity is called as D ok D is a vector and this D is defined as

$$D = \varepsilon_0 E + P$$

So, essentially when you do not have dielectric material so without a dielectric material,

$$D = D_0 = \varepsilon_0 E$$

And when you insert a dielectric material you induce a surface charge which is due to the presence of the material a term called as polarization which modifies the directly displacement by amount

$P$. So this $P$ is that added quantity so you can say $P$ is the macroscopic so $\varepsilon_0$ is the permittivity of free space is the field that you have applied and $P$ is the it is a macroscopic density of you can say permanent and induced dipole moments in material ok. And this is also called it can also be defined as polarization density often it is called as polarization density.

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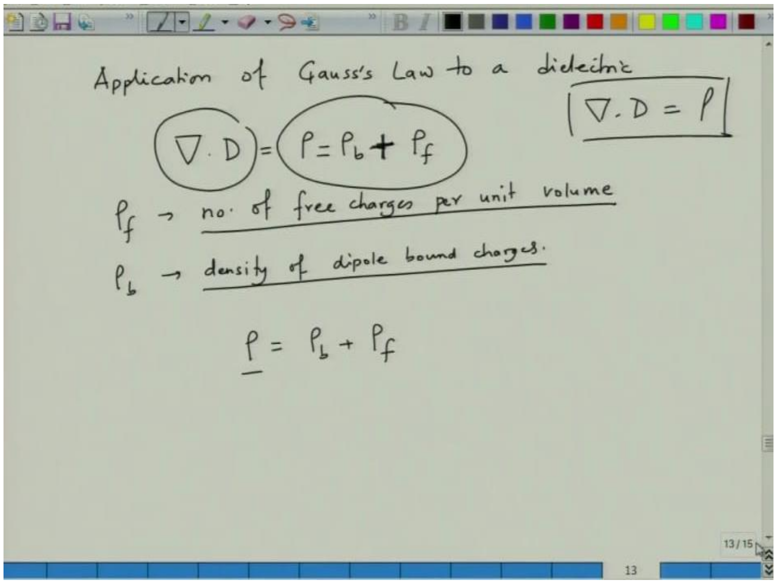


So, this displacement vector D is also defined by Gauss's law so if you apply when you apply Gauss's law to an electric. So dielectric displacement has to satisfy that Gauss's law what it means is that

$$\nabla \cdot D = \rho - \rho_b$$

which is equal to $\rho_f$ what are these $\rho$'s, $\rho_f$ is basically you can say number of free charges per unit volume so basically charge density ok.

$\rho_b$ is essentially you can say density of you can say dipole bound charges ok and so basically you can say from this $\rho = \rho_b + \rho_f$. So, the net charge density $\rho$ = the number of free charges per unit volume + number of bound charges per unit volume and it is the difference between the total charge density and the bound charge density which is nothing but the free charges present on the surface.

And that is what is Gauss's law which is this which basically Gauss's law says that and it basically relates the distribution of electric charges as a from the applied electric field ok. So, you can see that this is dielectric displacement is related to electric field as we saw earlier and this is related to the surface charge density. So, this surface charge density for example you can take in a spherical cases the bound surface you can take or there are variety of cases you can take.

But it could be basically a enclosed spherical surface in this case so now let us say let us do a little bit of proof of the previous equations so we said that $D = \varepsilon_0 E + P$ ok. So, this $P$ is the polarization term which adds on to the dielectric displacement if you did not have a dielectric material then $D$ will be equal to $\varepsilon_0 E$ ok and when you insert a electric material then $D$ becomes $\varepsilon_0 E + P$.

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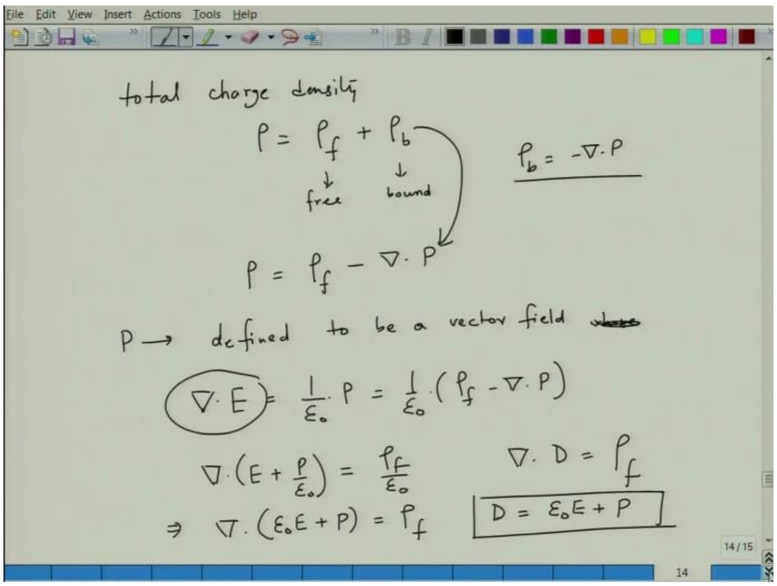


So, let us see what is the can we prove it so we said that total charge density

$$\rho = \rho_b + \rho_f$$

So, we said $\rho_f + \rho_b$ this is free and this is bound free is the free charge that is present on the surface of the parallel pate right and b is the charge that is bound because of presence of dipole in the material. So, as we saw that you had initially 8 charges, out of 8, 6 get bound and 2 remain free.

So basically total = $\rho_f + \rho_b$ alright so now if we write this as a function of polarization so Rho can also be written as

$$\rho = \rho_f - \nabla \cdot P$$

and this $\rho_b$ is nothing but $\nabla \cdot P$. Rho so this is basically you can say the polarization is basically so $P$ is basically defined to be a vector field whose if you take whose if you take the divergence of this vector field you will get that density of bound charges.

So, P is related to the bound charges and but by definition this $\rho_b = \nabla \cdot P$ so divergence of $P$ = nothing but $-\rho_b$. So, if you take now $\nabla \cdot E$ so,

$$\nabla \cdot E = \frac{1}{\varepsilon_0} \cdot \rho$$

where did this come from this is the divergence of electric field should be equal to charge density basically. This is what is the law this is called as this is from Gauss's law right or you can say Poison's law as well it is also defined as Poison's law.

So, this is nothing but now

$$\nabla \cdot E = \frac{1}{\varepsilon_0} \cdot \left(\rho_f - \nabla \cdot P\right)$$

ok and as a result you can say

$$\nabla \cdot (E + \frac{P}{\varepsilon_0}) = \frac{\rho_f}{\varepsilon_0}$$

Alternatively, you can say

$$\nabla \cdot (\varepsilon_0 E + P) = \rho_f$$

and this is what is the original definition is we said that $\nabla \cdot D = \rho_f$. So basically, what it means that

$$D = \varepsilon_0 E + P$$

this is what we wanted to prove.

That the dielectric displacement is equal to the $\varepsilon_0 E + P$ which is because of bound charges in the material. So, this is the additional effect that you create by inserting a dielectric in the parallel plate capacitor.

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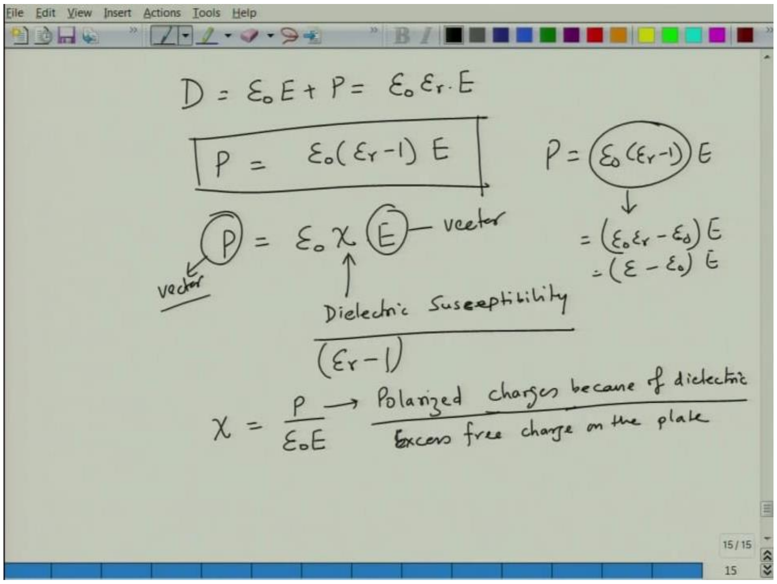


So, we say that,

$$D = \varepsilon_0 E + P$$

and after the after inserting the dielectric what is the dielectric displacement this is nothing but

$$D = \varepsilon_0 \varepsilon_r E$$

So, from this we can say that

$$P = \varepsilon_0(\varepsilon_r - 1)E$$

or we can say this will become so this is what is the essentially polarization and this is and we define this as $P$ is defined as

$$P = \varepsilon_0 \chi E$$

where chi($\chi$) is the dielectric susceptibility.

Essentially what you need to know to begin with if you know concept such as what is Gauss's law and what is Poison's law then you will be able to appreciate this. The Gauss's law says that the divergence of $D$ must be equal to the surface charge free surface free charge density and so that is and then we from this we moved on to we said that this is $\nabla \cdot D = \rho_f$ and then we know that total charge density is equal to surface charge density plus bound charge density.

And hence and this bound charge density can be written in terms of polarization as $-\nabla \cdot P$, divergence of polarization is nothing but the bound charge density you have to add a minus there to account for the signs to get the correct math sign so $\rho_b$ becomes $-\nabla \cdot P$, and then we substitute we get $\nabla \cdot E$ and we know that $\rho_f$ is equal to basically $\nabla \cdot E$. So, this is nothing but so $\nabla \cdot E$ for a dielectric is so we have taken now we have a dielectric inside right.

So, we have dielectric inside so the field inside the parallel plate capacitor the dielectric will be $\nabla \cdot E$ this $\nabla \cdot E = \frac{\rho}{\varepsilon_0}$, and this is $\frac{1}{\varepsilon_0} \cdot (\rho_f - \nabla \cdot P)$ and accordingly we make this. We make the terms move right and left side and we get expression $D = \varepsilon_0 E + P$ ok. So, this is what basically the so del dot basically you can say that $\nabla \cdot D = \rho$ this is what the general relation is.

So here we have taken sorry we have taken one something nothing but this is equal to $\rho$ and this is equal to $\rho_b + \rho_f$ that is how it should be ok. Because you are taking divergence you are taking with respect to the all the charges that are present so that was a little alright so now let us so we have defined a quantity called as dielectric susceptibility which is nothing but $\varepsilon_r - 1$.

So, more the dielectric constant is more the susceptibility is and basically this is what is the response of the material. So, you can say that polarization is nothing but you can say

$$\chi = \frac{P}{\varepsilon_0 E}$$

this is also one definition of phi (ϕ). So basically, it is a ratio of polarized charge so this is the polarized charge because of bound charges right to the excess charge that is present on the surface of a vacuum plate capacitor.

So, this is the polarize charges because of dielectric to the bound excess charge excess free charge on the plate ok. So higher the $\varepsilon_r$ is more the polarize charges will be more the response of the system will be and by the way these systems will be and by the way these quantities are vector in nature. So, we know that $P$ is vector in electric field is vector ok polarization is a vector as a result that electric constant becomes second rank tensor ok.

So, this a vector is a rank 1 tensor so polarization electric field at rank 1 tensors as a result due to since $P$ is equal to $\varepsilon_0(\varepsilon_r - 1)E$. This term basically becomes the so here you can take you can say this will be $(\varepsilon_0\varepsilon_r - \varepsilon_0)E$. This will be

$$P = (\varepsilon - \varepsilon_0)E$$

,so permittivity will be a second rank tensor for a dielectric material ok. So now the question is what is the microscopic reason of this polarization in the material?

So right now, we have seen that it is because of separation of charges but in a given material the separation of material separation of charges can happen at various scales ok. So that is what we will look at now and we will also since most dielectrics are used not in DC applications but in AC applications under the effect of alternating electric field. As a result, we also need to look at response of this polarization or dielectric constant as a function of frequency of electric field.

And this is because the microscopic mechanisms of charge the dipole creation of polarization creates creation is also there could be multiple scenarios in which that charges which are involved, they may have different weights different masses. As a result, they will have different responses to frequencies of light field so that is what this is look at now.

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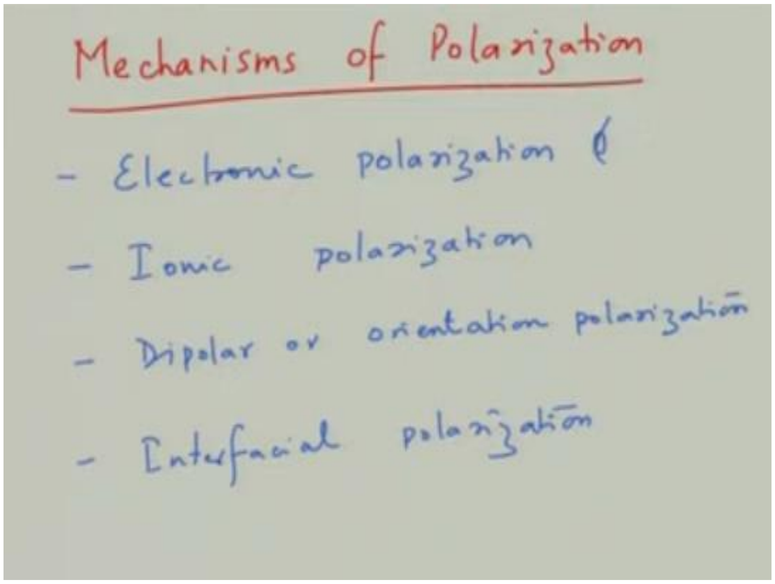


So now we are going to look at what is called as mechanism of polarization. So essentially microscopically speaking there are four mechanisms the first one is called as electronic polarization second one is called as ionic polarization third one is called as dipolar polarization dipolar or we can say orientation polarization and the fourth one is called as interfacial polarization ok. So, what is electronic polarization? Electronic polarization happens at the level of so this polarization mechanism.

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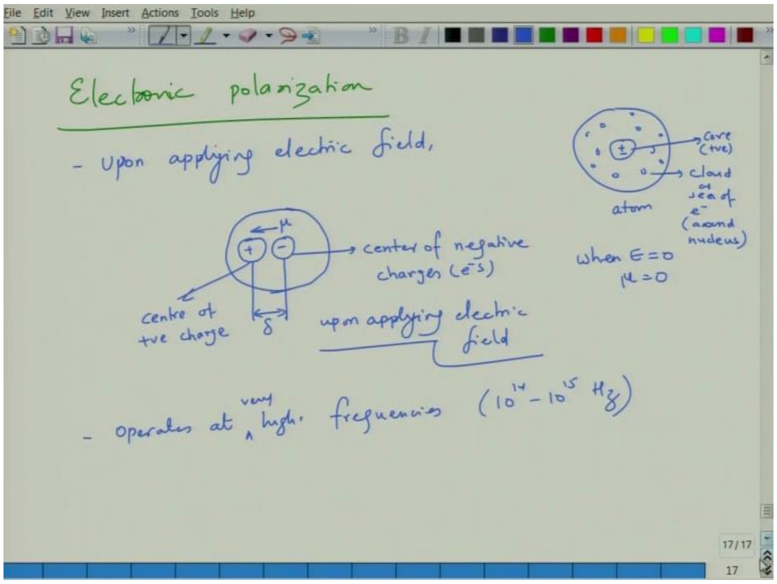


So, let us go one by one electronic polarization happens at the level of electrons basically as by definition so what it means is that you have here when you apply upon applying electric field the so at the level of atoms that every atom has. So, if you consider atom right so atom has a nucleus this is the positive core and around it you have electrons in various shell sitting here ok.

But the center of these electrons will be coinciding with the center of these positive charges so when you do not apply so this is an atom ok. So, this is the core which is positively charged and this is the cloud of electrons cloud of sea of electrons around nucleus right. So, when $E = 0$, $\mu$ is also is equal to 0 ok so when you apply electric field what will happen is that this core which is positively charged will shift with respect to this electron cloud in such a fashion.

So that they will be a so this is the center of negative charges that is electrons and this is the center of positive charge and this is happening at the scale of atom. So, this is just an atom in which the sea of electron cloud sea of electrons shifts marginally with respect to so when you apply electric field you create a distance delta and you have a dipole moment upon applying electric field.

Now this is a mechanism which happens at the level of atoms the entities which are involved here are light in nature because an atom has very low mass and in correspondingly you have you have to only shift a sea of electrons with respect to the atomic core as a result this mechanism operates at high frequencies or you can say very high frequencies typically frequencies of the order of you can say $10^{15}$ Hz, so roughly $10^{14}$, $10^{15}$ Hz.

The second mechanism which can happen so this is present in all the materials right every material has atoms as result this mechanism will be present in every material the electronic polarization.

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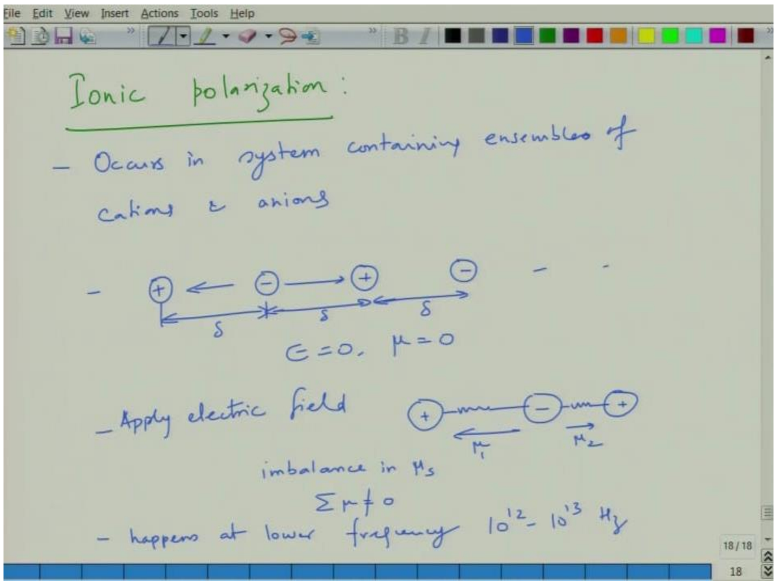


The second mechanism that we call is called as ionic polarization is it generally it now this happens in systems where you have positive and negative ions. So basically, it occurs in containing ensemble of cations and anions so imagine for example sodium chloride or any oxide that will be so this is something that will be present in every oxide for instance so as a result most dielectric materials will have this mechanism.

So, essentially you consider you have a positive ion you have a negative ion and again a positive ion again a negative again. So, this positive this is negative this is positive this is negative and so on and so forth when you do not apply electric field the distance is delta. So that this displacement vector this dipole moment is in this direction both of them cancel each other. So, when $E = 0$ $\mu = 0$ when you apply electric field what will happen when you apply electric field so one will become shorter and another will become longer.

So, this is let us say positive this negative this is positive so this will be μ and this will be $\mu_1$, $\mu_2$. So, there will be imbalance in μ's as a result $\sum \mu \neq 0$ so this is what is called as ionic polarization.

So, in this case what is happening is the whole ion is moving with respect to another ion and let us say it is connected by a spring sort of situation. So, we can model it as if ions are connected to each other by spring we will do that in a little while probably in the next class.

So, this will give rise to when you apply electric field the net dipole moment will not be equal to 0 so this called ionic polarization. But this happens since here the ions are moving with respect to each other the masses involved are higher as a result this happens at lower frequency. Generally, this will happen at frequencies with the order of approximately $10^{12}$-$10^{13}$ Hz approximately ok depends upon the type of ion and so on and hence so forth.

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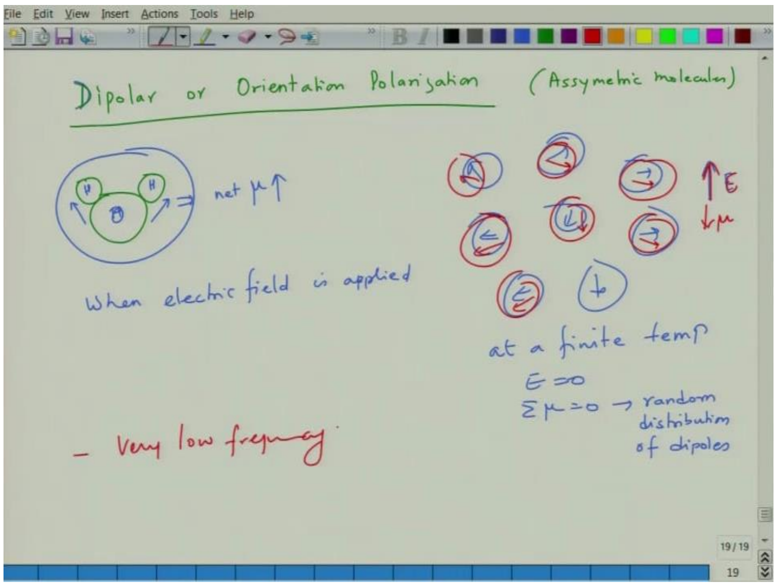


Third one is called as dipolar or orientation polarization ok so this generally happens with let us say you have water molecule ok. So, this will happen in system where each of the molecule itself has a dipole moment so for example if you look at water ok. So, water is asymmetric molecule so generally it happens in systems with asymmetric molecules so let us say this is O this is H this is H ok.

So, you have a dipole moment vector here and you can resolve the positive negative component so as a result it will have a net μ pointing in this direction ok. Now this is dipole moment of one molecule now let us say you have these water molecules if I contain this molecule as a sphere. So, you have multiple molecules in space so one has vector in this direction or another has vector in this direction.

So, when they are thermally randomized so at a finite temperature the dipoles are random even though each molecule has dipole moment. They are all randomly distributed there is no electric field so when E = 0, $\sum \mu = 0$ because of randomization because of random distribution of dipoles. What happens when you are applying electric field so when electric field is applied these then may so let us say if electric field is in this direction then you might have little change in orientation.

So, we are for the sake of simplicity we are depicting in the same direction but they will be in different directions so what will happen is that if you apply electric field in this direction there will be some change in the so this will be. For example, in this direction so this will be in this direction this may shift to this direction this may shift little bit in this direction. This may go around this direction so this may go to this direction so basically you are going to then.

So, when you apply electric field you may have net dipole moment to generate it and as you keep increasing the strength of electric field you will increase more and more electric. So, this is called as orientation polarization it happens at very low frequencies ok. Because of higher mass of the molecules then we have interfacial polarization we have run out of time we will discuss that in the next class and will further look at the frequency dependence ok thank you.