Fundamentals and Applications of Dielectric Ceramics
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Lecture - 15
Introduction to Dielectrics

So welcome again to the new lecture of this course fundamentals and applications of dielectric ceramics. So, we will just briefly recap the past contents.

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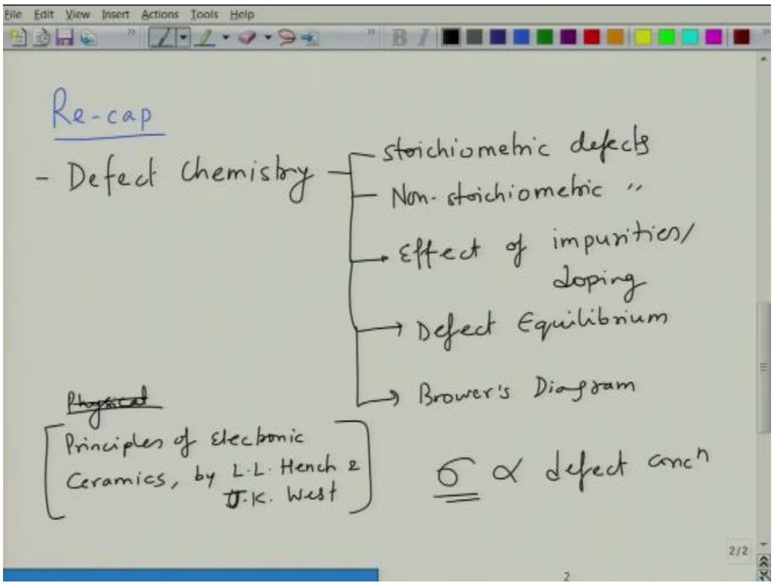

Re-cap

- Defect Chemistry
  - stoichiometric defects
  - Non-stoichiometric "
  - Effect of impurities/doping
  - Defect Equilibrium
  - Brower's Diagram

~~Physical~~
[Principles of electronic Ceramics, by L.L. Hench & J.K. West]

$\sigma \propto$ defect concn

So, in the previous few lectures, we learned about defect chemistry in ceramics, metal oxides mainly, and basically we saw concepts related to stoichiometric defects, the defects which do not disturb the stoichiometry of the oxide, and then we have non-stoichiometric, so which could be because of oxygen deficiency or oxygen excess or metal deficiency or metal excess and then we looked at the effect of impurities or you can say in some sense also doping, how you can alter the defect chemistry.

Then we looked at the defect equilibrium to calculate the defect concentration and the various condition and finally, we did an analysis of different concentrations under various conditions of partial pressure of oxygen and we created what we call as Brower's diagram. So, this whole exercise gave you a brief insight into what is the defect chemistry of oxides and how can you alter it under various conditions and this is very important especially from the perspective of dielectrics because conductivity of the dielectric materials are generally proportional to defect concentration.

So, in general for oxides higher the defect concentration is, higher the conductivity is, which is not a very good thing because more dielectrics are resistive material or insulators. So, any kind of electrical conductivity is going to be detrimental to their properties. So, we would like to minimize the conductivity of dielectrics, which means we would like to minimize the defect concentrations, appropriately you can choose the conditions of sintering, calculation, temperature as well as impurity concentration to minimize the defect concentration to ensure that they have lower electrical conductivity.

So, we have not gone into details of electrical conductivity, but in general, electrical conductivity in oxides are related to carrier concentration, carrier concentration is related to defect concentration and also their diffusivity, and more the defects are, higher the diffusivity is and more the conductivity is in general. So, if you are interested to read about it, I would recommend Principles of Electronic Ceramics by L. L. Hench and J. K. West. This is a book you can read, there is a chapter on electrical conduction in ceramics, which is very appropriate.

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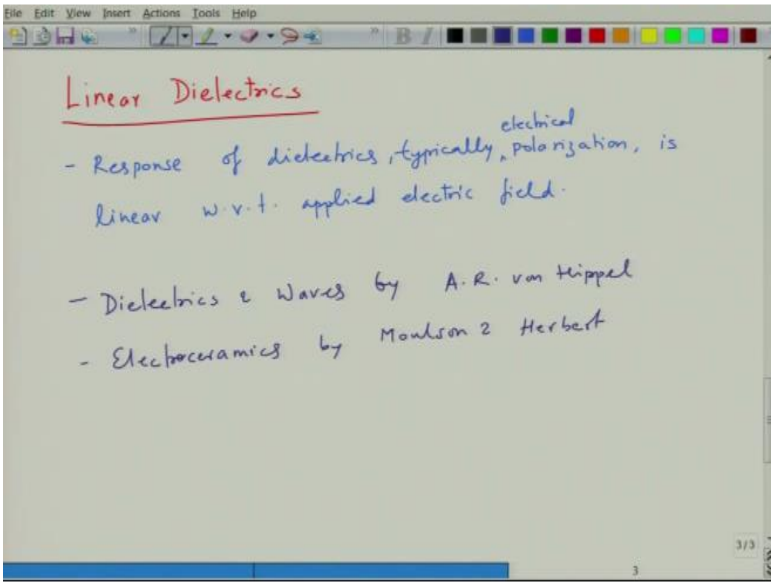

Linear Dielectrics

- Response of dielectrics, typically, electrical polarization, is linear w.r.t. applied electric field.

- Dielectrics & Waves by A. R. von Hippel
- Electroceramics by Moulson & Herbert

Now, let us move on to the next topic of a study, that is basically the linear dielectrics okay. Now, why we are calling linear dielectrics because dielectrics are generally of 2 types, one could be linear dielectrics, second could be nonlinear dielectrics. So basically, linear dielectrics are those electrics with the response of the electric material, which is in terms of a quantity called as electric displacement or even say polarization, it is linear with respect electric field.

Then there is other class of material in which the response could be nonlinear and that is why we segregate them because they have different physics as well as different applications. So, we first initiate our discussion on linear dielectric. So linear is basically the response of dielectrics, typically let us say polarization and we will define what the polarization is, it is electric polarization okay, it is electric, electrical polarization is linear with respect to applied electric field okay.

So, for this part of the module or series of lectures, I would recommend you in addition to the lectures so again the same book which I recommended earlier, the Principles of Electronic Ceramics, there is a chapter on linear dielectrics, which may be useful to pursue. In addition to Hench and West, you can also look at if you really want to go into details, Dielectrics and Waves by A. R. Von Hippel, Von Hippel is one of the pioneers in the area of dielectrics and this is a fantastic book if you want to get into details.

Then another book is Electroceramics by Moulson and Herbert. This is a reasonable book, but I would recommend Hench and West Principles of Electronic Ceramics and Dielectrics and Waves as 2 important books.

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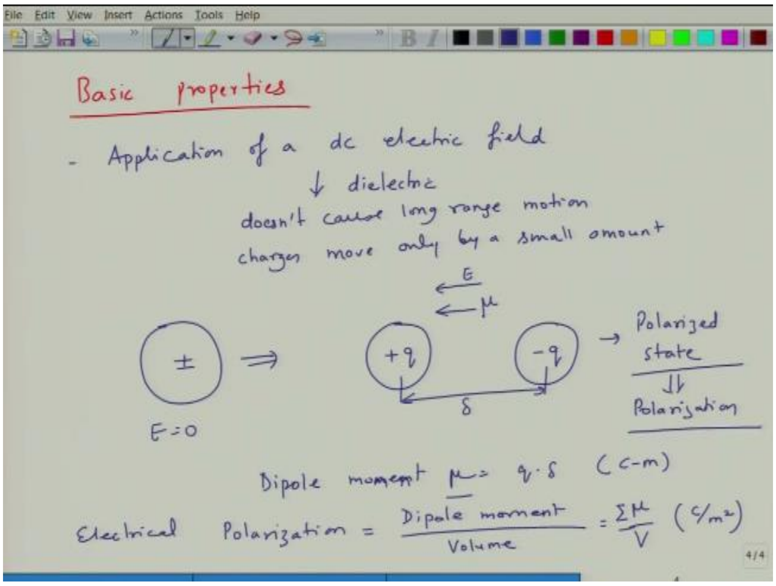

Basic properties

- Application of a dc electric field

  $\downarrow$ dielectric

  doesn't cause long range motion

  charges move only by a small amount

Dipole moment $\underline{\mu} = q \cdot \delta$ (C-m)

Electrical Polarization $= \dfrac{\text{Dipole moment}}{\text{Volume}} = \dfrac{\Sigma \mu}{V}$ (C/m^2)

So, let us first define a few basic properties. So, the basic properties let us say, so when you apply electric field, so right now we are looking at application of a let us say dc electric field okay. So, when you apply a dc electric field in metals, when you apply field, there is a long range conduction of charges, as a result you have conductivity and then current flows in the metals. However, in dielectrics what happens is that there is movement of charges, this application of electric field to a dielectric does not cause long range motion.

The charges move only by a small amount, and this small amount is very small, it is not of the order of microns, it is not of the order of millimeters, it is of the order picometers or so. So, what happens is that when you have for example, two charges, let us say this is a positive charge and this positive charge coincides with the negative charge when electric field is zero okay. So, when you apply electric field to it, the positive charge and the negative charges, they get separated from each other and this is basically a state which is called as polarization of the material.

So, you have plus q, you have minus q, and when you separate them by applying electric field by magnitude δ, there is a quantity which is called as 'μ' which is developed which is called as dipole moment. So, dipole moment,

$$\mu = q \cdot \delta$$

This happens when you apply electric field, so electric field displaces the positive and negative charges. So, this would be the E vector okay. So, by definition, dipole moment is a vectorial quantity and it is a vector and correspondingly there is a quantity called as electrical polarization, which is basically dipole moment per unit volume.

So, this is basically you can say

$$Polarization = \frac{Dipole\ Moment}{Volume} = \frac{\sum \mu}{V}$$

So, naturally the unit of polarization is nothing but C/m^2, you can see the unit here is C.m. So, when you apply the electric field, when you separate the charges by a tiny distance δ, this state is called as polarized state. So, this state is called as polarized state of the material or material is in the state of polarization.

So, basically the electric field creates a charge dipole by separating the centers of positive charges with respect to negative charges and leaves the material in a polarized state and this net effect gives rise to what we call it as polarization in the material alright.

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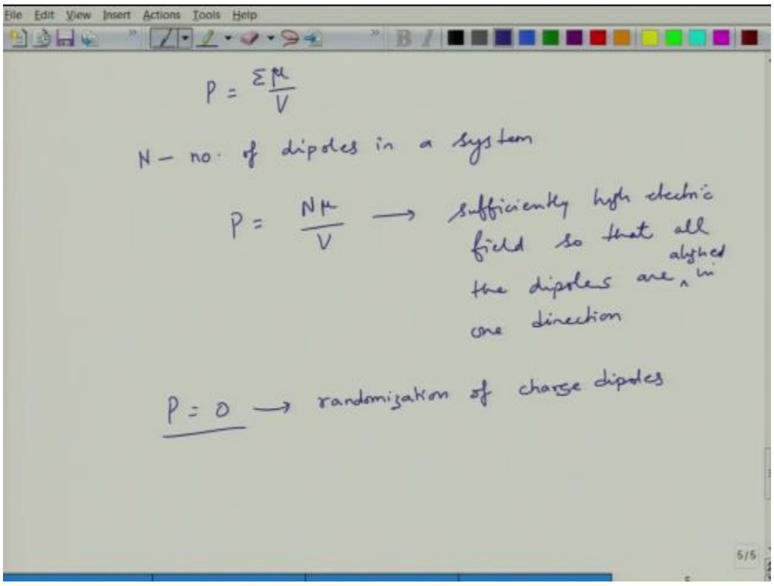

$P = \frac{\Sigma\mu}{V}$

N – no. of dipoles in a system

$P = \frac{N\mu}{V}$ → sufficiently high electric field so that all the dipoles are aligned in one direction

$\underline{P = 0}$ → randomization of charge dipoles

So, if you have N number of dipoles in a given system, so for one dipole you have a (μ/V), but if N is the number of dipoles in a system which are all aligned in one direction, then you can say

$$P = \frac{N\mu}{V}$$

So, this is when you apply sufficiently high electric field so that all that dipoles are aligned in one direction, that is a situation. You may have cases when P is equal to 0, when P is equal to 0 or close to 0, it does not necessarily mean that does not have charged dipoles.

It just means that dipoles are randomly oriented with respect to each other and the vector summation of all the dipoles is equal to zero. So, it does not necessarily mean that material does not have dipoles, it could be because of random and when you apply sufficiently large electric filed, and this randomization generally occurs because of let us say thermal energy. So, when you overcome thermal energy by applying sufficient amount of electric field, you may create large polarization in the materials. So, this we will come to a little later.

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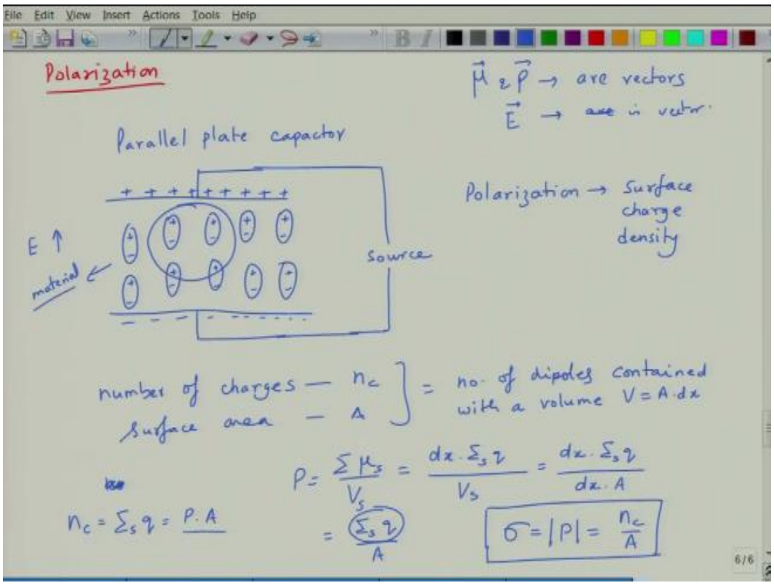

Polarization

$\vec{\mu}$ & $\vec{P}$ → are vectors

$\vec{E}$ → ~~are~~ in vector.

Polarization → Surface charge density

number of charges — n_c

Surface area — A

$\Big\}$ = no. of dipoles contained with a volume $V = A \cdot dx$

$$P = \frac{\sum \mu_s}{V_s} = \frac{dx \cdot \Sigma_s q}{V_s} = \frac{dx \cdot \Sigma_s q}{dx \cdot A}$$

$$= \frac{\Sigma_s q}{A}$$

$$n_c = \Sigma_s q = P \cdot A$$

$$\boxed{\sigma = |P| = \frac{n_c}{A}}$$

Polarization can be constituted as what we call as surface charge. So, you take basically a material, so let us say okay first thing both mu and *P* are vectors okay, so generally, you will write them as this okay. Electric field is also a vector okay. So, although in many circumstances, we denote them in scalar form and that is mainly because the materials are isotropic or polycrystalline material, but it does not mean that that is the right way to do it. The right way to do things is to write everything in that scalar form, but for the sake of convenience, we present these in scalar form, which makes things a little simpler.

So, let us say you have a parallel plate capacitor with, so this is let us say, we just wanted to get over a concept of polarization a little bit. So, you have a parallel plate capacitor and then you apply electric field let us say in this direction in this capacitor okay. This is connected to let us say source okay. When you apply electric field in this direction, you are going to create, so you may have something inside it or you may not have anything inside it, but eventually what happens is that there are charges which are present on the surface of this parallel plate okay.

So, polarization is basically nothing but, let us say you had a material present inside okay. So, let us say we had a material present inside, so when you apply electric field, material will be polarized right? Okay. If you look at any given volume, the net charge density will be equal to zero in any given volume right, but it does not mean if you just consider the surface of the plate, because these charges at the end of dipoles have to be compensated by the charges on the plates of the surface.

So, as a result, if assuming that all the dipoles are aligned in one direction, polarization can be constituted as basically surface charge density on the plates of a parallel plate capacitor, which could be with or without the material, you may have parallel plate capacitor in vacuum which means you have nothing inside between the plates and you may have a parallel plate capacitor with a material inserted inside it, that could be a normal dielectric capacitor. So basically, when we say, so essentially you can say the number of charges, let us say number of charges be defined as n_c, surface area is let us say A.

So, number of charges on the surface area A is equal to the number of dipole, so this is equal to number of dipoles contained within a volume V and this $V = A \cdot dx$, where dx is the separation, A is the area. So, I can write basically number of dipoles contained within a volume V times the charge of that dipole, so we can say this

$$P = \frac{\sum \mu_S}{V_S} = \frac{dx \cdot \sum_S q}{V_S} = \frac{dx \cdot \sum q}{dx \cdot A}$$

and what a $\sum \mu$, $\sum \mu$ is nothing but if you just let us say 'S' is the surface okay, we denote this as the surface, then,

$$P = \frac{dx \cdot \sum_S q}{V_S}$$

all the surface charges added together divided by V_s and what is V_s, this is $dx \cdot A$

$$P = \frac{\sum_S q}{A}$$

and what is $\sum_S q$, $\sum_S q$ is basically the total surface charge summed over together. So, this is basically total charged present on the surface per unit area, which is nothing but dipole moment per unit volume. So, generally, you would assume that surface, this n_c you can say, number of charges n_c, this can be taken as this is nothing but $P*A$.

So, n_c, the total number of charges okay $n_c = \sum_S q = P \cdot A$, that is the total charge that you have present on the surface. So, the surface charge density you can say sigma, you can write this as

$$\sigma = |P| = \frac{n_c}{A}$$

So, you are just writing the same term in different fashion. So, basically polarization is nothing but surface charge density okay, polarization charges per unit area.

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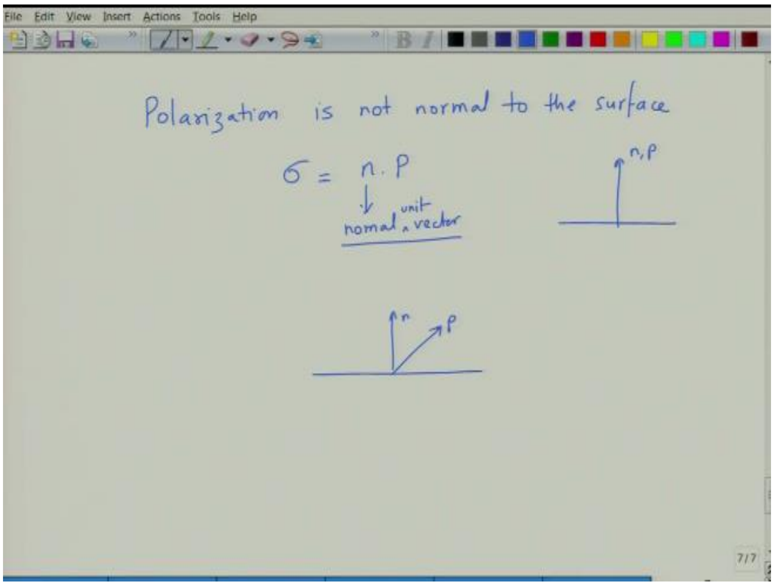

Polarization is not normal to the surface

$\sigma = n.P$

normal unit vector

Now, if polarization is not normal to the surface, in that you can take this. So, this is alright as long as polarization is normal to the surface, but what happens when polarization is not normal to the surface. In that case, we can write $\sigma = n \cdot P$, where n is the outward pointing vector which is normal to the surface of the polarized material okay. So, this is you can say normal vector. So, you have to take the dot product of normal vector, which is the unit vector basically, normal unit vector pointing outwards on the surface.

You might have a situation like this where this is n and the P could be something like that right, then the surface identity is $n \cdot P$ if this is a situation. In most cases, you will see n and P being collinear, in that case it is simple, sigma is equal to P, but if n and P surface normal is not collinear with P, then surface charged density will be $n \cdot P$. So, now let us look at the case of dielectric little bit.

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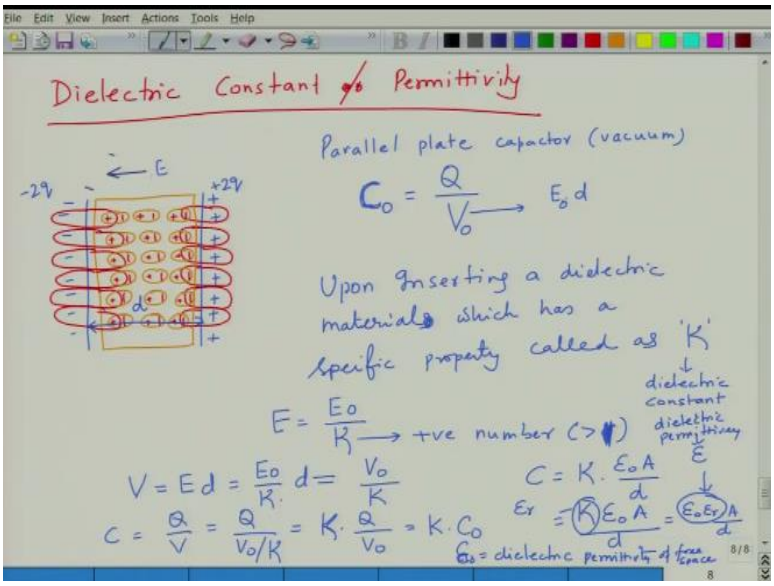

Dielectric Constant ~~%~~ Permittivity

Parallel plate capacitor (vacuum)

$$C_0 = \frac{Q}{V_0} \qquad V_0 \rightarrow E_0 d$$

Upon inserting a dielectric materials which has a specific property called as 'K' ↓ dielectric constant

$$E = \frac{E_0}{K} \qquad K \rightarrow \text{+ve number } (>[illegible])$$

dielectric permittivity ↓ ε

$$V = Ed = \frac{E_0}{K} d = \frac{V_0}{K}$$

$$C = \frac{Q}{V} = \frac{Q}{V_0/K} = K \cdot \frac{Q}{V_0} = K \cdot C_0$$

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

ε_0 = dielectric permittivity of free space

So, we first look at the concept of dielectric constant/permittivity okay. They are different things but. So, let us say we have a case of dielectric, so we have a parallel plate capacitor. We apply electric field. When you apply electric field, the electric field creates a surface charge density. So, we have a distance which is nothing but some distance 'd' ok. Now, first situation is parallel plate capacitor in vacuum okay, there is nothing that is present on the surface.

So, in such a case, the capacitance of the system is nothing but let us say C_0.

$$C_0 = \frac{Q}{V_0}$$

,Q that is charges present on the surface of the capacitor and V, the voltage that you applied, and this voltage is nothing but $E \cdot d$, whatever the electric field that will be present okay. So, let us say this is V_0 to begin with and this is E_0 alright. Now, let us say, so this is a simple parallel plate capacitor when you have 2 plates separated by a tiny distance δ or d, when you apply electric field you create surface charge density and accordingly you have certain capacitance.

Now, what happens when I insert a dielectric material inside it? Let us say I insert a dielectric material inside it now. Now, dielectric material inside, dielectric materials generally oxide kind of thing, it could be oxide, it could be polymer, basically it is a symbol of positive and negative ions, it has certain atoms inside it. When it has certain atoms inside it when you apply electric field, which means you are going to polarize the atoms themselves. So, the molecules inside the dielectric materials, they will also get polarized okay.

So, you will create, so this is a simple picture let us say. So, let us just do the counting of charges. So, you have 1, 2, 3, 4, 5, 6, 7, 8. Let us just remove one of them. So, let us say we had 8 charges to begin with okay. What we have done is now we have created this, we have put in a dielectric material inside it now, and when we put the dielectric material inside it, we polarize the material under the electric field. So, let us say in this case you will have, okay. So, now you can see that this positive charge is bound by this negative charge, this positive charge is bound by this negative charge, so on and so forth.

So, you can see out of 8, my 6 charges are now bound charges. Similarly, on this side, so which means that now I do not have to polarize, in fact, although you are applying a voltage to polarize the similar amount of surface charges, but these 6 charges on the surface are taken care by 6 opposing charges on the dielectric material. So, which means, in effect, the free charges which are left on the surface of dielectric material is 2 on this side, so let us say *2q* on this side, so *+2q* on this side and *-2q* on this side essentially, right.

So, essentially what I am saying is that let us say upon inserting a dielectric material, which has a specific property called as Kappa 'κ', which is dielectric constant okay, κ is dielectric constant. So, when we have this, so essentially, what I am saying is that now the electric field requirement to displace the charges has reduced because I have only 2 free charges on the surface what is the magnitude of that? The magnitude of that is

$$E = \frac{E_0}{\kappa}$$

because other 6 charges are bound charges.

So, the only free charges on the surface after insertion of a dielectric are let us say 2 charges. So, essentially, that 6 and 2 will be determined by what is the strength of dielectric and the strength of dielectric is determined by κ and κ is a positive number. So basically, it is a positive number, so κ is always greater than 0. So, when you insert inside it, the field that you require to now polarize the dielectric reduces by this amount κ.

So basically, we can say the potential now V is nothing but $E \cdot d$, this is equal to

$$V = \frac{E_0}{\kappa} d = \frac{V_0}{\kappa}$$

So, what is C,

$$C = \frac{Q}{V} = \frac{Q}{\frac{V_0}{\kappa}} = \kappa \cdot \frac{Q}{V_0} = \kappa \cdot C_0$$

So now, the capacitance, what we have done basically is we have increased the capacitance of the dielectric, the parallel plate capacitor by κ times.

So, higher the κ is, more the capacitance on the system is going to be. So, when you write now, the capacitance C, this is equal to Kappa and what was C_0, C_0 was equal to,

$$C = \kappa \cdot \frac{\epsilon_0 A}{d}$$

, this is the definition of C_0. So, κ is also written as

$$C = \varepsilon_r \cdot \frac{\epsilon_0 A}{d}$$

and this is called as often ε, which is called as dielectric permittivity where ϵ_0 is basically dielectric permittivity of free space okay.

So, basically when you insert a dielectric material inside it, it is the drop in the electric field which is caused by inserting the dielectric material provided that κ is greater than 1 okay. So, it should be greater than 1 and which is more than 1 for most dielectric material, it results in increase in the capacitance of the parallel plate capacitor okay. So, this is the first very basic thing that we encounter when we insert a dielectric material in a parallel plate capacitor.

Relative quantity that we are interested in is the κ or ε_r which is the dielectric constant or dielectric permittivity of the material okay, and it is always more than 1. So, we will stop here, we will further discuss more details of dielectric materials in next lecture. Thank you.