Optoelectronic Materials and Devices
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Module - 01
Lecture - 19
Linear Dielectric Behavior

Welcome to lecture number 19, today we are going to talk about Dielectric Material.

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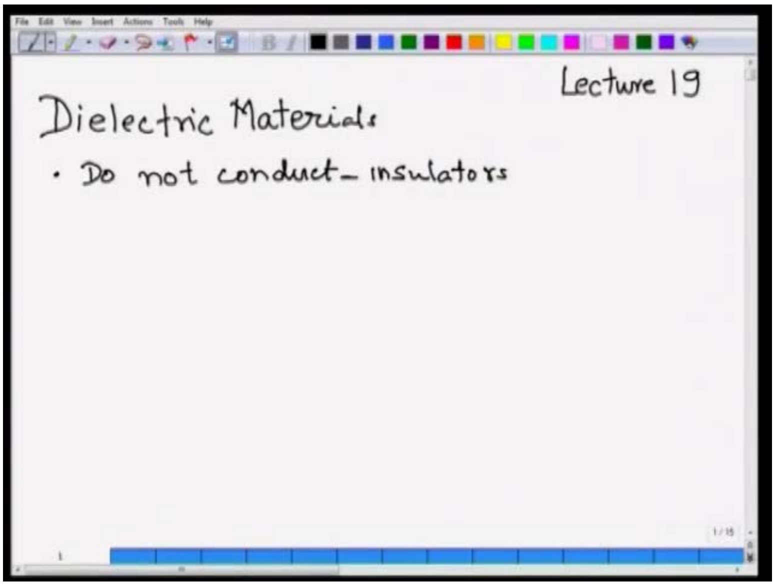

Let us connect to as to what we have been talking about, we started with the metals we started with the metals and which we started looking at conductivity of metals. Then we moved on and we talked about effect of periodic potential, in a lattice it eventually leads to a band gap, consequence of that band gap was that we got materials which were semiconductors. Why were the semiconductors, because there conductivity was lower than that of metals and why did this happen, notice that insulators will be very closely related materials to insulators.

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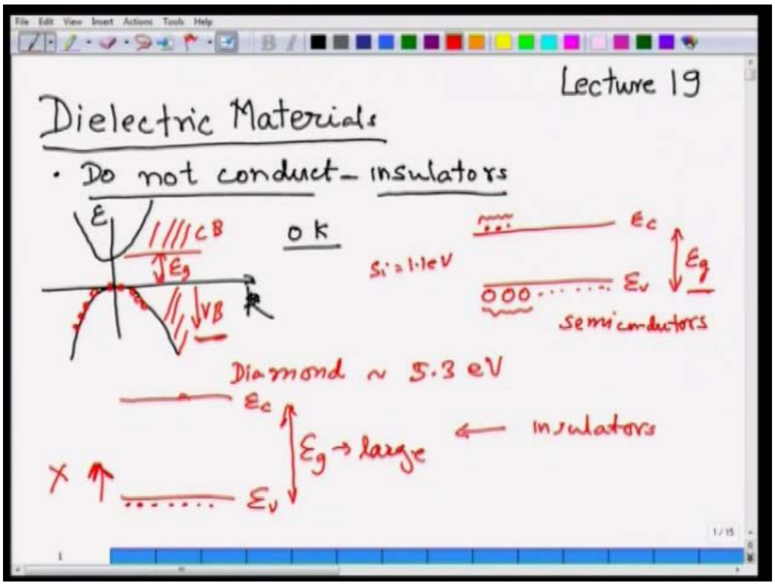

So, just before we start talking about today, we going to talk about dielectric. Since, we are going to talk about dielectric materials we going to talk about materials that do not conduct that they are insulators, but to connect it back to semiconductors what did happen was that recall e k diagram for a semiconductor, it look something like this. If this was k, there was a on this energy axis and this is of the k axis and in this axis we had a valance band, this was the valance band, if you look that 0 k, temperature which was 0 k, then we had that this elect this place was full of electrons.

The electrons everywhere valance band have a full of electrons. Whereas conduction band, which is this higher band up here, this is the conduction band, this is the conduction band and this is the valance band, this was all valance band and this was the band gap, this was E g. So, if I look at like this, on this side as something like E v and E c and a band gap here, E g then what happened was at 0 k this material, this semiconductor was also insulator, why was it insulator, because valance band was completely full of electrons all the to the top.

Whereas, conduction band right here, was completely empty and what that meant was that neither they could be since, were no electrons, no carriers in the conduction band they could not be any conduction due to conduction band. Similarly, in valance band it was completely full of electrons, though they were charges, but there was no space, no energy states for electrons to move around. And hence, even they could not conduct and this material there for, was an insulator at 0 k only at some slightly higher temperature electrons, began to jump when they have thermal energy was sufficient to overcome this band gap.

Some electrons from here, jumped up here, some electrons got jumped here, leaving behind holes and they left behind holes, where are they were still many electrons left here. Now, these holes in valance band conducted, these electrons in conduction band conducted, over all we got some conductivity out of these materials and these were semiconductors these were semiconductors. Now, what happens if this band gap was very large, remember in silicon this band gap is only 1.1 electron volt.

Whereas, if you go to diamond if you go to diamond then this band gap become something like 5.3 electron volts very, large very large band gap, what happens if this E g is very large, then in that case at nominal temperatures. So, let draw it like the this here, this is E c, this is E v and a large band gap E g, and a large band gap which is, this is large. Then remember, this electron which are here are not going to be able to jump up here, this jump will be very difficult.

And hence again, these materials will not conduct and these will be insulators, these will be insulators. See in other words there are materials, where we have charges, but they are bound charges they are not free. So, only free electrons which conduct once on a electron or holes, they are able to conduct only when they are free, but if charges are bound then they are not going to able to conduct.

Now, if you apply a electric field in a metal, the charges are able to move over long distances and you get conductions, but because, in insulators and dielectric materials charges are in there bound, state the consequence would be that they will not be able to travel and you will not get conduction. You may be inclined to neglect these charges completely because, there is no conduction, but that will be a mistake.

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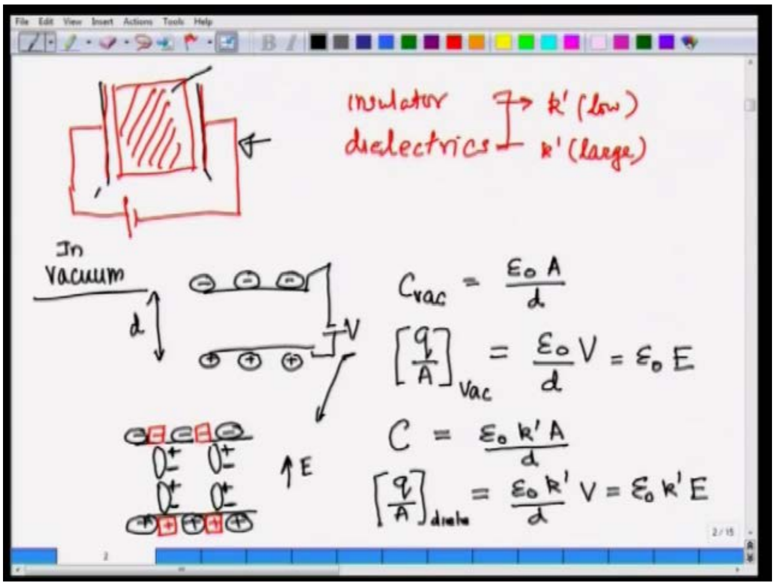

Because, what Faraday discovered was if you have two parallel plates something like this. on a On and if you are connected to a battery and you inserted these materials in here such materials in here, something happened that something which happened, you have learnt in your 12'th grade or earlier before also, which I am going to repeat again. But, before I do that, I am going to establish the importance of these materials, which is why we have shifted for semiconductor or dielectrics.

If you had, if you do not believe then capacity you have seen of course, all are all around, this capacitor capacitor materials, those are dielectric materials, they are suppose to not conduct, but provide some capacitates and that term you are familiar with and hence I am able to use it. But, if you look at for example, take your computer, take out a chip and cut it out look at SEM Scanning Electron Microscope, where you can see small siche sizes or even transmission electron microscope, you will see that devices of full of materials that are insulators insulators and what we call as dielectrics.

They are same material, same class of materials. Since, you are familiar with dielectric constants, then I am inclined to use those also though I will go through tho them in this lecture as well. But, when I said you will if you cut out a micro electron a micro electronic chip and you start looking HCM, you will find insulators, meaning there by these are low k materials, low dielectric constant materials, which are there for single purpose that, they do not they provide insulation from one device to another device, one layer to another layer.

In addition, you would have dielectrics where k prime will be large and the goal of this dielectrics will be to provide large capacitance. That means, this circuit should be using capacitance themselves and hence, you would like to use k prime this is large. So, notice that though we are using the terms insulators and dielectrics, but at level of understanding a material, there is no difference accept, large k prime or a small k prime meaning dielectric constant.

And if I if we have if you understand what is the origin of this k prime, then it does not matter whether this insulators or dielectrics, we will deal them as one class. So, with that background, let us look at this experiment which we talked about, this experiment if you insert a dielectric here, between two paral two electrodes here, the two electrodes are and between them you are inserting a dielectric material, what happens let us look at that.

But, let us start with in vacuum first, let us start in with what happens in vacuum and what I am doing now, is something which your familiar with or sometime, you have done that in 12’th grade also and also, first year physics etcetera. And, so I am basically repeating it and to make the context. So, suppose I make this parallel plates, now horizontal. So, the same parallel pates which we are talking about here, these black lines here this. this electrodes I have drawn.

Now, you connect this two in this vacuum in between. in between there is vacuum you connect this to a battery, what do you have. Let us say, you connect this end to a positive terminal, you connect this end to a negative terminal, what you will get is positive charges here, you will get positive charges here like this, and you will get negative charges right here. Corresponding negative charges same amount of charge, cube you are going to put in in this case.

What do you know, we know that capacitates in vacuum is equal to permittivity of free space of vacuum that is, the area of this capacitor and the dis distances between, these plates d is the distant, between these plates and a is the a is the area of these plates. And suppose, it will be very large, if that is the case we also know what q is q is capacitance times, capacitance times voltage. So, I am going to take this A on here a down here.

And write this as in vacuum, in vacuum what happens the charge what is the total amount of charge, which accumulated on the plates will be q that will be given by c times v. But, I have writing q by A charge per unit area, what I am writing. So, you go I am going to write capacitance per unit area, which I am going to write there for as epsilon not d times multiplied by v, that is the quantity I am going to write this. But, v the voltage, v is the voltage between these two terminals, this is the voltage v that we have applied.

So, this v divided by d is the electric field that I am going to write as epsilon naught E. So, that is the electric field which you are going to get in vacuum, when you do that, now what happens if you take same parallel plate capacitor and you insert a dielectric between them. So, let us do that again now, you are going to insert dielectrics, actually that will be very clear, let me draw it consistently, let me draw this charges first what I had in vacuum I will add more two it.

Now, what I am going to do is, I am going to I will insert a material and there for I am going to write something here like this. Let us say, what hap happen I have bound charges when I applied a electric field like this; that means, I connected the battery in same way, as here can connected the battery here also the same way, which means I am going to get a electric field, in this direction. Why apply a electric field like this something happens, these bound charges though they cannot conduct and hence material remain insulator, but it does polarize.

Because, of this this field that we have applied, consequence is center of negative charge moves here, center of positive charge moves here, center of negative charges of these molecule moves here, center of positive charge moves here, negative charge here, positive charge here, negative charge here, positive charge here, that is what happens in the material, which you inserted in. Consequence of that is, you are going to get etcetera negative charge here, here is nega etcetera negative charge I am drawing or maybe I use different color now for this.

Here is a etcetera negative charge, which comes about as a consequence of these. And etcetera positive charge here, shown in a square box which appears here, as a consequence of this material which you have insert a insert it in. So, what happens now, if I write capacitance you very well know, the capacitance in this case is given by epsilon naught a dielectric constant, times area divided by d. And now, if I write want to write q by A in this case, if I want to write q by A in this case, then what will that quantity be is what we are wanting to write, this is dielectric.

What will that quantity be that quantity of course, would be equal to in same way would be epsilon naught k prime d multiplied by in this case, write the write v which we going to write as epsilon naught k prime e. Remember this equation, we will come back to this and now let see, what the total charges.

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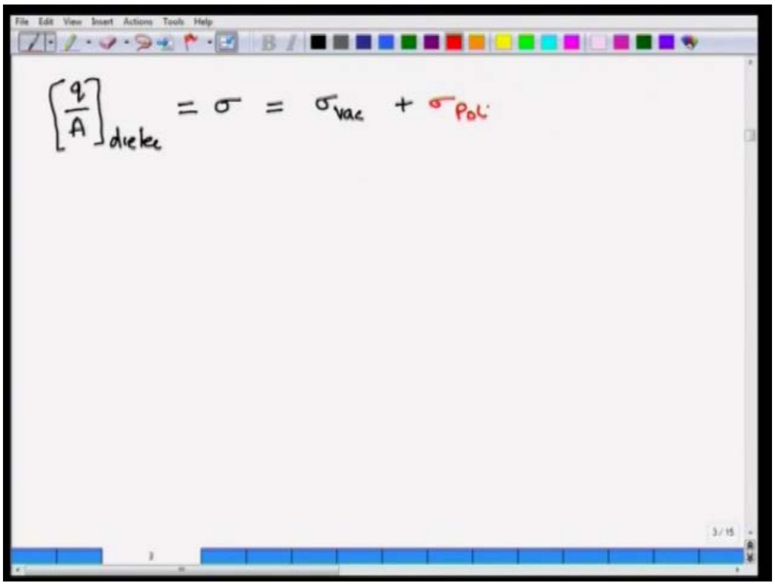

Now, in this case what we are going to write is that this q by A, dielectric you going to write this as surface charge that is the sorry that is the total charge on the surface or charge density, charge per unit area we going to indicate by sigma. That this sigma is going to split in two parts, one as sigma vacuum plus sigma polarization or I will use the color again differently, this was the red color charge. What do I mean by that what I mean by that is that this black charge which you are seeing here, this charge is corresponds to this this q by A, which is sigma vacuum, you are going to write this as sigma vacuum that is the sigma vacuum and this is sigma total sigma, what we are getting in total surface charge, when we getting when we insulate a dielectric. So, when this vacuum this is the charge, which we have inserted, which is the black colored circles the same black colored circles here, but when you insert a dielectric we got additional red color charge.

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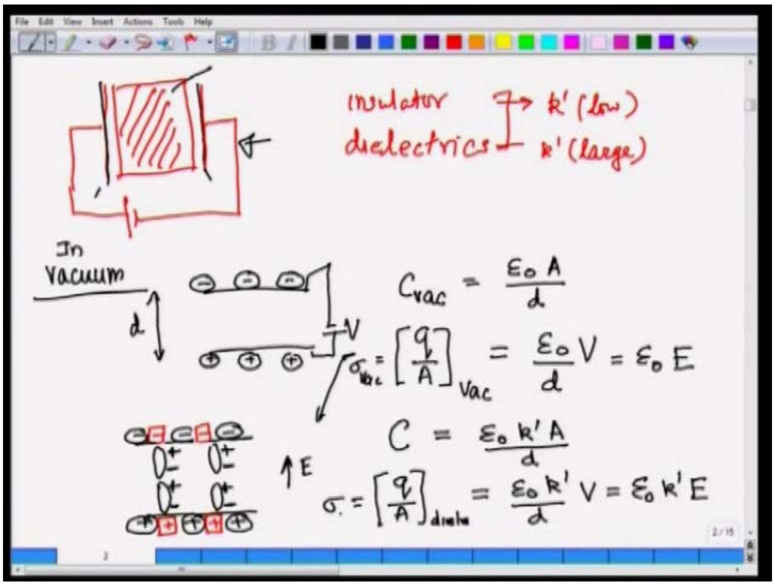

This red color charge. So, the total charge sigma, there for now we got ga get is what is due to vacuum plus something additional which we are calling as this polarization charges.

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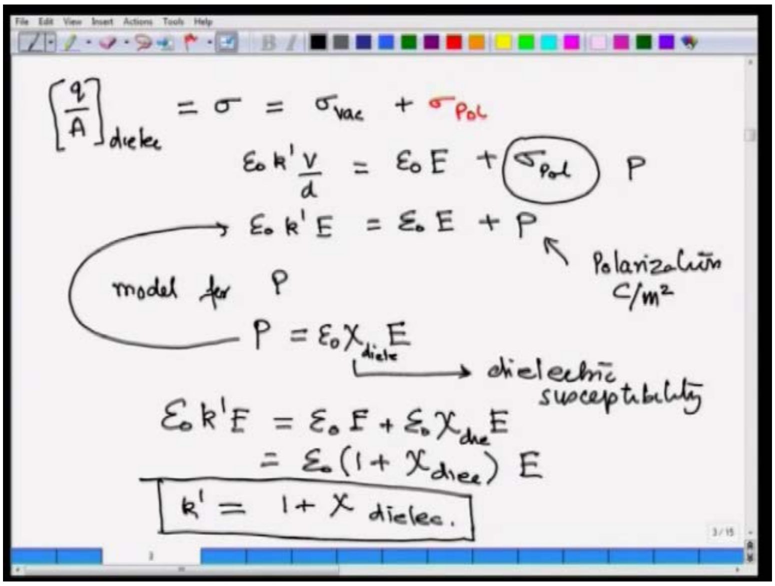

So, if that is the case then, we are going to write this as equal to this qua quantity as equal to epsilon naught k prime v by d as equal to epsilon naught E plus sigma polarize due to polarization, what is this quantity v by d of course, is a electric field. So, we going to write this as e 0 k prime E as equal to epsilon naught E plus this quantity, which we define as polarization and hence, I am going to write this P polarization.

And this is the key term polarization, which will have a dimension of coulombs per meter square, this polarization is due to which new something happens in something happens to our electric behavior in a device a when you insert a material in between the capacitor, it is this polarization which is responsible for something interesting. So, now let us look at what this polarization is, the simplest model for P is model for polarization is that we take polarization as proportional to electric field and this proportionality content constant let us write it as susceptibility.

So, this quantity is dielectric t, all these ideas we have studied before also. If we, take this module and we now insert, this into this equation then I am going to write epsilon naught k prime E as being equal to epsilon naught E plus epsilon naught psi dielectric E, which I am going to write as, epsilon naught 1 plus dielectric times E. And now, you can recognize this k prime is basically 1 plus susceptibility, so that is what this quantity is dielectric constant of a material alright. So, this is where, this is something you had known very well.

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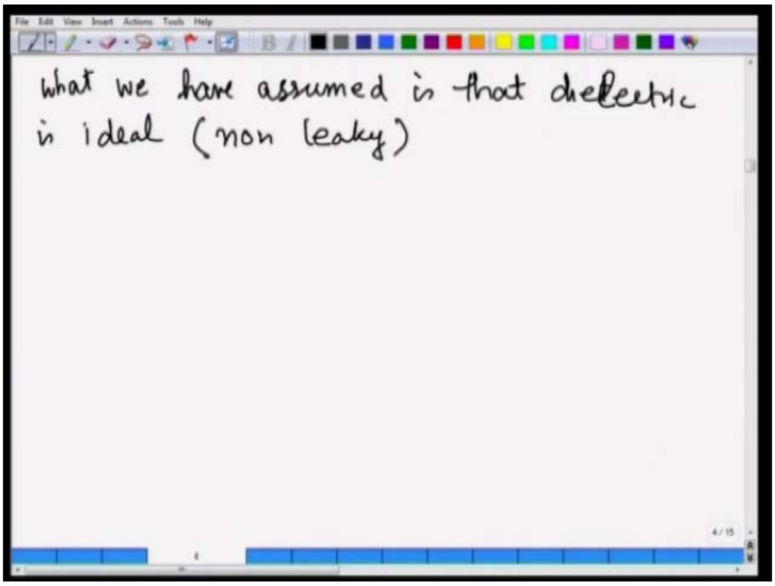

Now, what I am going to do is something else, what we have, so for assumed is that dielectric is ideal, non leaky. What do I mean, what I mean is, we are assumed that this dielectric material is perfectly is a perfect insulator.

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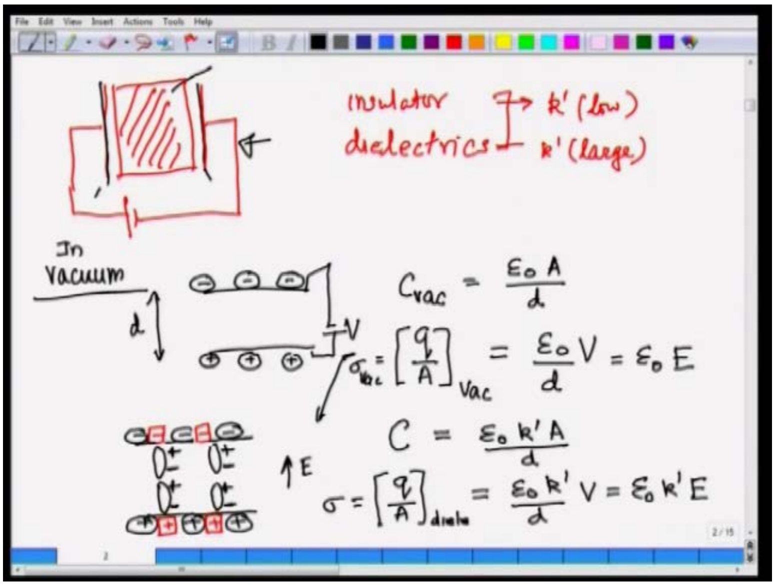

So, in this capacitor when you apply a voltage no current flows, in this capacitor since this dielectric material is not leaky, as vacuum there for when you apply a electric field there is no conduction what, so ever at all. And that is a die ideal dielectric, in that case we get some dielectric properties as measured by at microscope scopic le a va at microscopic level what is known as polarize polarizability, which I have not talked about, but by something called dielectric constant.

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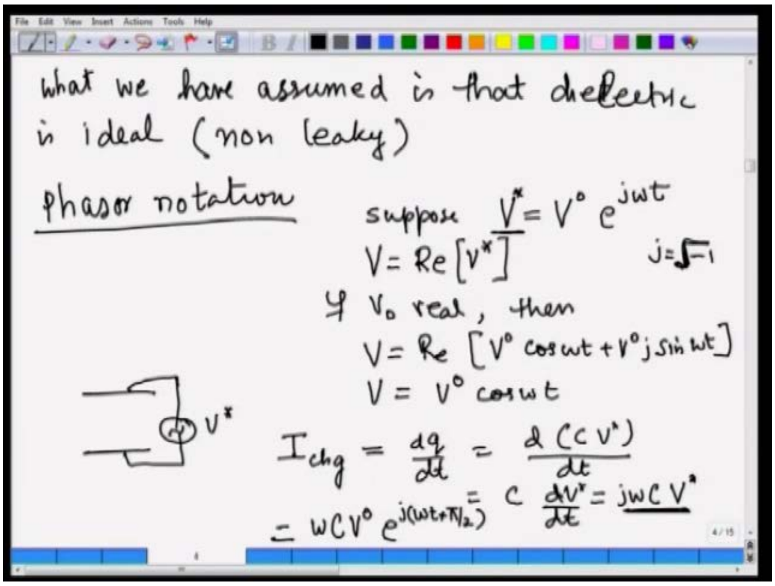

However, what happens if indeed this is material is mostly insulator, but it does give rise to some leakage current, what happens in that case that is what we want to establish now, a now want to establish, how do we deal with such situations. Now I will introduce you to what is known as phasor notation. And this something, which you would have done before also, suppose V is the voltage that we have applied and say a c field which we have applied. And this field is equal to V naught, which itself could be a quantity is a V naught, which could be a special independent quantity and let us use the e to power j omega t, that is the voltage we have applied.

What is j, j is equal to minus 1, root minus 1 some people refer to use i instead of j my preference is for j and, but do not confuse, if you see i in the same thing, you are, this will lead to a complex number. So, this itself could be a complex number this indeed is a complex number. So, what is the voltage that we have applied, the voltage that we have applied is actually V which can always be generated by getting real part of V star b complex that is the voltage we have applied.

For example, if V 0 is V l, if V 0 is V l then you can write V as equal to real part of V 0 and this I am going to write it as cos omega t this V 0 is V l then we can write, V this actual voltage, as the real part of and I am going to repeat this one more time in a in context of Maxwell equation. Real time, real part of V 0 cos omega t multiply plus V 0 j sign omega t and if you take there. So, this V there for will be simply V 0 cos omega t.

So, that is the voltage a c voltage we have applied. So, if this is the further notation for we have consider this as the V voltage that we have applied, then what happens to the capacitor that is the question. So, if I take a capacitor and you apply a c voltage and you apply a c voltage, if you apply a c voltage of V star then what happens I get a current, I get a charge charging current which will we given as d q by d t which would be given as d c v d t which will we given as c d v d t.

And that quantity then will be equal to that quantity in time it varies as remember omega t in time it varies as omega t this v changes y omega t. So, what would I get, I would get j omega C and I will get back since is a exponential, so I will get back V that is what I am going to get. So, charging current would be equal to this quantity, this current would be equal to this quantity which if I want to write, I can write as equal to I will continue here which I gone to write equal to j which i am go I am going to take this j inside and I am going to write is this as omega C.

I am going to write this v v naught co e to power j omega t plus pi by 2 this pi by 2 appears because, I have taken this written this as exponential now, I have written this quantity as exponential pi by 2, j pi by 2 that is why this quantity is appearing here like this. What is it mean, it means that the charging current is pi by 2 of in face from the voltage that we have applied. So, if I draw this and this I am assuming as a ideal continue to use in ideal capacitor right now, so what happens.

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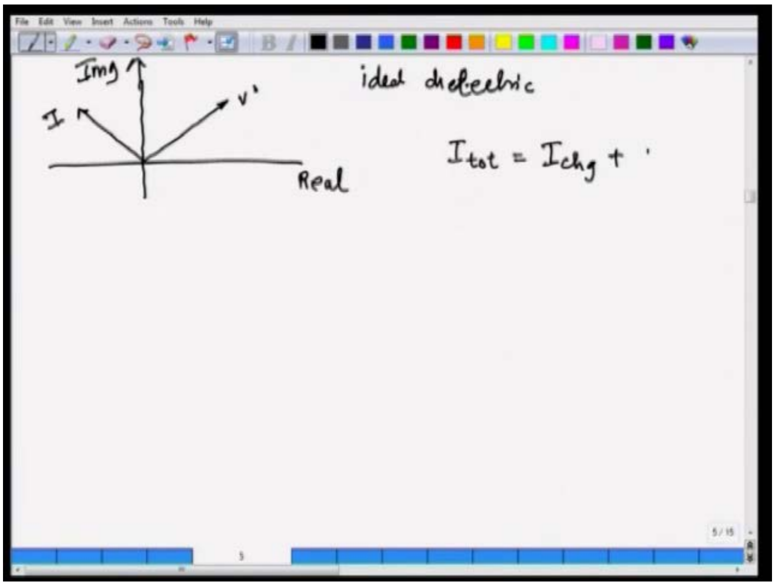

So, this is the cap if I draw this the way I will draw it is like this, if I plot the real part and imaginary part, then this voltage which voltage this V star voltage which we are plotting, would have a real part and a imaginary part. So, if I draw that then I am drawing this voltage V as v s this is the voltage V star. And the charging current that I get charging current that I get would be pi by 2 of from this, this will be pi by 2 or fro this V 0 face.

And hence, I will write this as current I am going to write draw it as perpendicular to it pi by 2 this is I meaning there on this same plot, I am plotting both current and voltage. So, this is the current, this is for ideal dielectric, but remember we started saying, what if it is leaky also, if it is leaky then in that case we going to write this I total in that case, we will write as this ideal I charging current plus some I loss we going to write some I loss.

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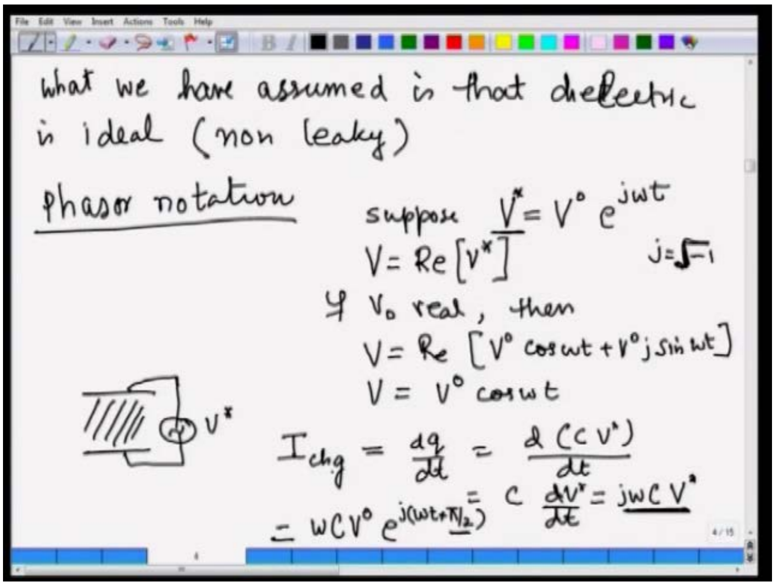

What do I mean, what we saying is if if this capacitor, this dielectric which was here was leaky. In that case if it is not leaky then we getting get a face difference of pi by 2. If it is leaky, then we will not get a face difference of pi by 2, but something else. So, what we are going to do is, we are going to write in that case the charging current which is d q by d t as we total current, we will write it as a charging current which is the current for for a ideal die capacitor plus some loss.

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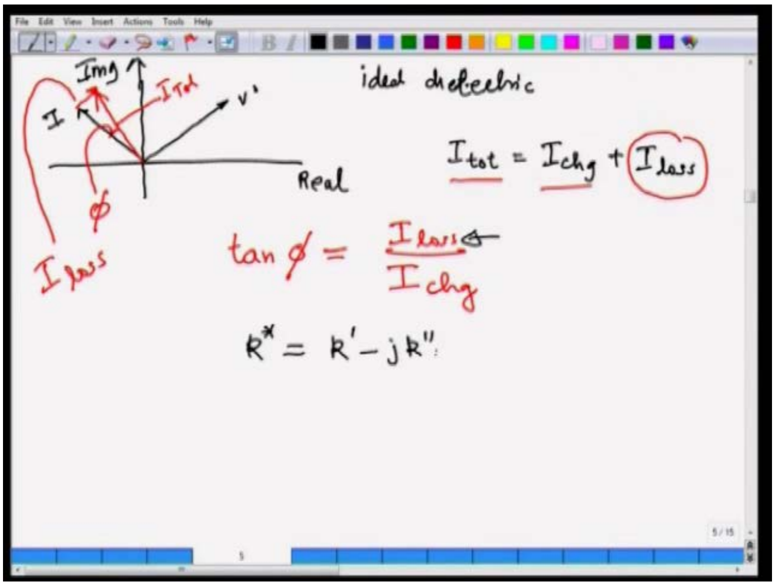

So, in that case this red portion has to be shown I charging is this current, if I show lost current as something like this, I lost current then this total current is this current. And this is I loss, this is the loss current and in that case, we get a is angle let us define this angle as angle pie and this tan pie or the lost tangent would be I lost divided by I charging, charging current.

Now, what I am going to show you is that this behavior can be represented by, if you consider die the dielectric constant itself as a complex quantity consisting of that same k prime, which was the dielectric constant, the real dielectric constant of a perfect dielectric minus j times some k double prime which is connected to this loss which is connected to this quantity loss.

So, that is what this k prime is a sorry k double prime is and this charging current, which for the ideal dielectric was connected to what those what is this k prime. If you use this k prime and we still be able to work out an a what I explained through a charging current in a capacitor, let us do it in a more generic fashion, as to what this loss term is that, is why interest is. That if the capacitor is perfectly ideal, then we know what what they says, but where does this come from and that is what we trying to understand and let me do it more it more general for fashion by writing Maxwell's equations.

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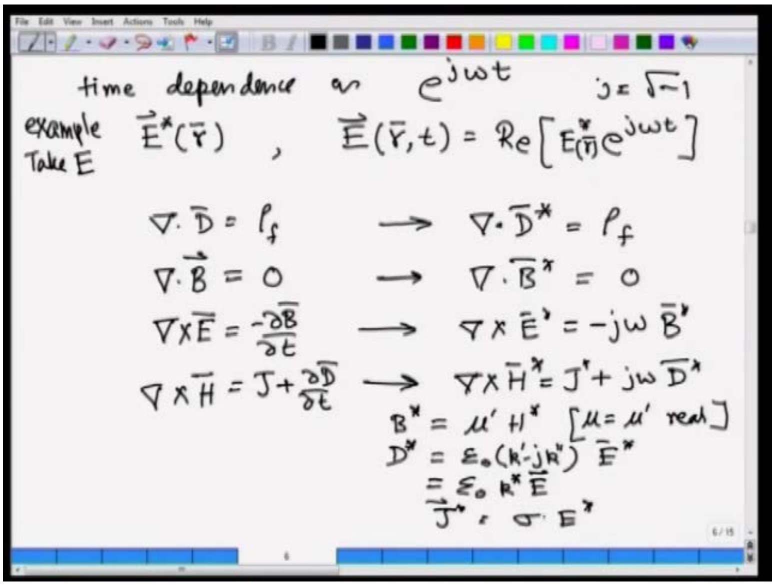

The way we have write the Maxwell's equation and this something you might have seen before also, that assuming time dependence again time dependence as e to power j omega t as we had done j again I repeat is minus 1. In that case, to be very well specific now about this Frazer quantities. Now, you are going to write this E, let us say electric field, let us say any quantity a le I am is an example as an example take electric field E. Similarly, you can do it for magnetic field or other quantities as well.

So, of I take this electric field E, then we know that this we going to write this as a function of space that is position, then E actual real E, physically E as a function of position and time can be obtained by taking real part of this E star quantity multiplied by e j omega t. Is a same thing which we did earlier also now, I am doing it in a more generic fashion and this of course is a function of position only. This is what a definition of a Frazer is, in that case the Maxwell equation the first Maxwell equation, which is given as row f translate into in Frazer notation translates into diversions of d vector in Frazer notation.

I am drawing this s tends to indicate Frazer notation, as rho f and the second Maxwell equation, translates as 0 and all interesting once, the curl of E which is minus del B del t not a time dependence is coming hence, it is interesting it translates into curl of this quantity E star. And remember, what is the time dependence, what is the derivative of derivate how we take the derivative, remember time appears only as g omega t. So, the time derivative, we can write and we will write as my as j omega.

So, same quantity since there in exponential it will recover the same quantity, I am going to write there for j omega wherever, the time derivative del del t appears a j omega will appear because, time derivative is taken in this form in this form of B star. And similarly, curl of H is equal to J plus del D by del t which translates into curl of H star and now, J plus j omega D star. Remember, this j omega comes as del del t and since, always time dependence is like this, so j omega shows up here.

In addition to that, let us assume B star not assume this is a constellation ship, is mu prime times H star. Means, permity permeability this is a magnetic properties, there is no magnetic loss otherwise you would have written this quantity also is complex. So, mu; that means, we are taking mu as equal to mu prime; that means, real we will taking as real. Whereas D we are going to write as epsilon naught times now, we going to take complex dielectric constant k prime minus j k double prime times E star.

And this we are going to write as, epsilon naught k star E and of course J is equal to sigma times E star and this is the conductivity.

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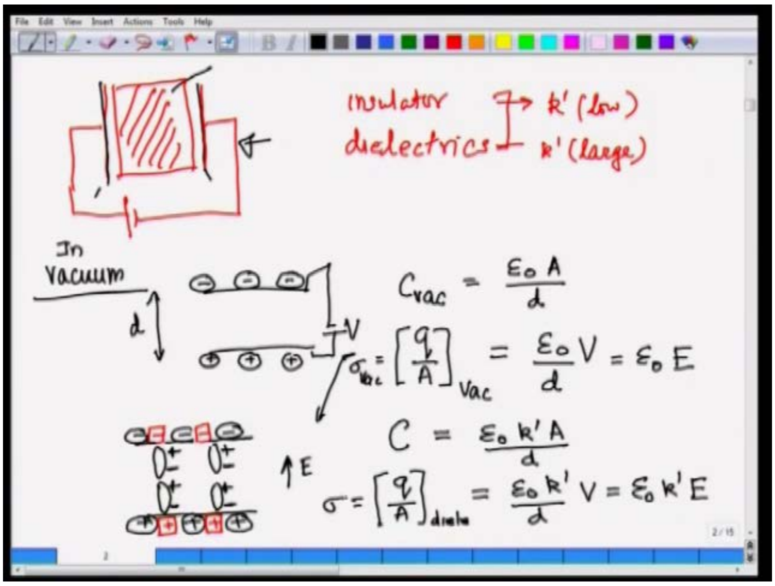

I had used this sigma for also in this first slide here, I had used sigma as sigma for charge per unit area. So, I am reusing the same symbol I am going back here.

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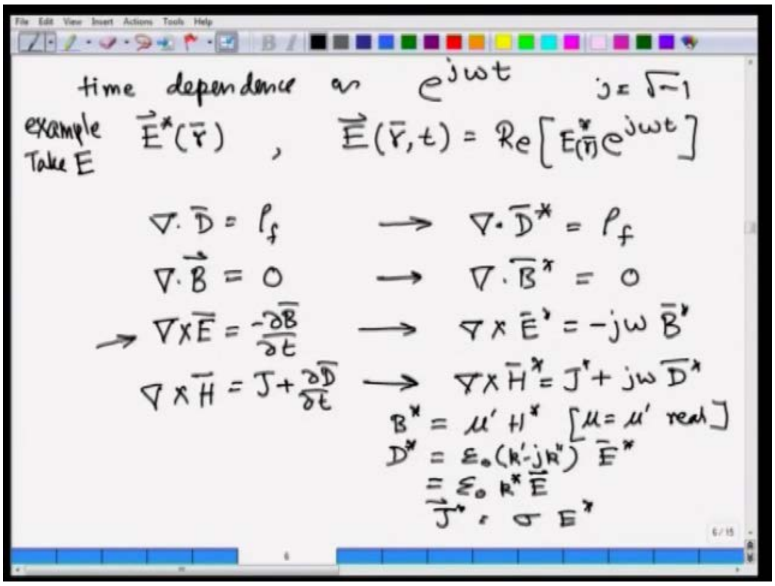

This sigma as remember ohms law, where sigma represents conductivity. So, here is the sigma representing conductivity and I will not be anymore using sigma as charge per unit area, that is was only in context of capacitor. So, now we are going to stick to this sigma as conductivity, itself if that is the case we are going to take this equation and it takes it is curl. Let us take this equation and let us take it is curl what happens then, let us write down.

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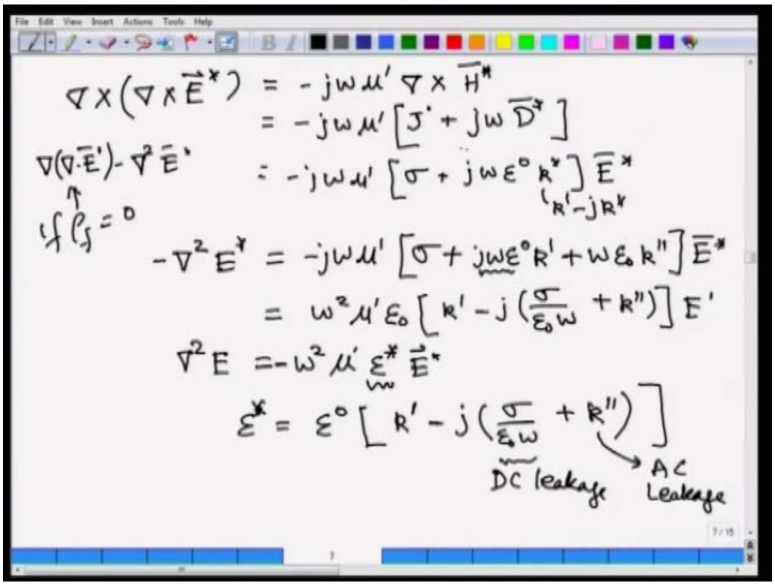

That there for curl of this equation actually I am taking curl of this equation, in Frazer I am working Frazer rotations, I am taking curl of this particular equation. So, curl of star is equal to minus j omega mu prime and I am going to write take curl of H, what I have done is a first for b I have substituted this quantity mu prime H and I am assuming mu is not space space dependent is a homogeneous medium. So, it is not a specially dependent, so I am taking this out of the curl and hence am writing this as j omega mu mu prime curl of h.

But, we know what curl of h is, so they can write this also minus j omega mu prime I am going to write curl of H from here, as j j plus j omega D, D star let us write as, let us write one to more steps and then do it this is this quantity. Now, we going to further expand this, this is equal to minus j omega mu prime, we going to write this as sigma times conductivity times E and we are going to write this as plus j omega epsilon naught k star times E write this as follows.

Let us look at the left side also, in fact, we can write this as, in free space if then this quantity is 0, in that case if I derive the wave equation, then this is minus is equal to I am going to write this as minus j omega mu prime sigma plus j omega epsilon naught k prime plus omega epsilon naught k double prime these all vectors. So, if I miss please a keep that in mind these are all vectors, so I am remember I have taken k, I am writing k as this quantity as k prime minus j k double prime because, is the minus j and multiplied with j that gives me a plus here.

Similarly, I am going to write this further, so I am going to write this as omega square mu prime and take epsilon naught also co common. So, I am going to take epsilon naught common and another omega here, so I am going to write this as and I am if I take this omega no omega one omega out, omega not out I have taken this out. So, I am going to write this as I am going to write this as a k prime and I am going to take one j out also, if I take one j out j I am taking this quantity out, if I take this quantity out then I am going to get omega square epsilon naught and j multiplied by j will be the minus 1.

So, I am making plus 1 here, I am going write this as k prime there for what else, minus I am going to write this as j minus j sigma by epsilon naught omega plus k double prime E star. So, what do I see, I see this as some complex dielectric constant, some complex dielectric constant times E and often this wave equation minus sign here. And from wave equation, we can recognize this quantity as being the permittivity equivalent to permittivity in free space.

And that we are writing as, we are writing this quantity as equal to now you can see, this is the real part, if it is on leaky minus a complex part arising out of this is because, of d c leakage, this is DC, this is DC leakage and this is DC leakage frequency dependent leakage, this is frequency dependent leakage. So, this is the lost part, so this represents the lost part the DC and the AC lost and this is represents the store stored energy in a capacitor.

And if there is no lost is perfectly non leaky capacitor, then of course this quantity will be 0, this quantity here would be 0 and you would have only stored energy, part in there and nothing else. So, that is the general idea that you can write a dielectric constant in form of a what permittivity in form of a complex quantity, in which you have permittivity is is a k prime k prime minus j k double prime and this k double prime represents the AC losses.

And of course, on top of that because, of this quantity j you can also add remember this is the displacement current, this is displacement current arises only because, of this is arises only because, of time dependence time changing electric field. And that is what this k prime is leading to, is this current which is flowing which is going to call heat, heat the dielectric lost of energy that is due to k prime, where is j which is sigma times e is DC conductivity and thus the DC part here of the loss.

If both these quantities are 0, then they will keep will be perfectly non leaky, will be perfectly non leaky alright. Now, with this definition we have got, now what I am going to do is talk about dielectrics and the mechanism which leads to polarization.

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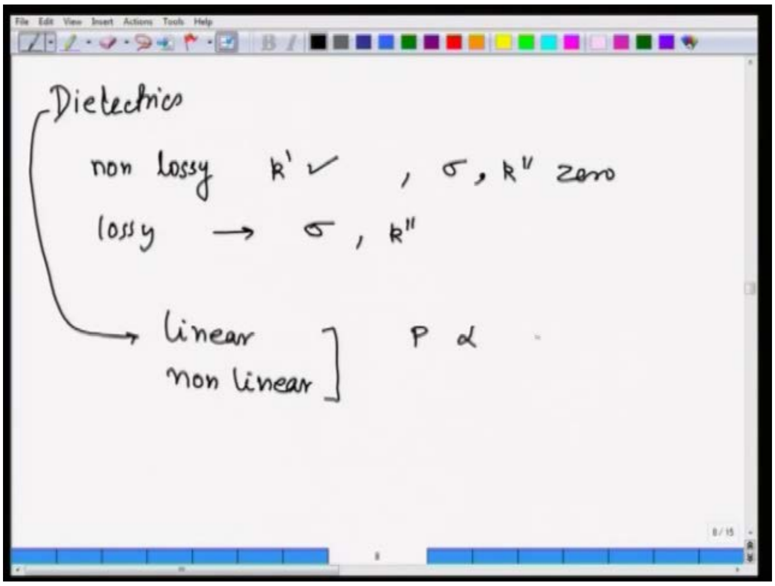

So, this dielectrics which may be lossy or may be non lossy, if it is non lossy. Then if it is non lossy, then they will be some k prime, but sigma will be 0 sigma and k double prime, this sigma represent conductivity would be 0. And if it is lossy, then we will have either due to some DC conductivity or because, of some AC conductivity or the the the lost part of a dielectric would leave to some energy loss, if that is the case then let us look at either way the dielectrics I am going to divide into two parts, one is linear and other non linear.

This definition comes from, this relationship that what is P as, if what is the proportionality between P and E.

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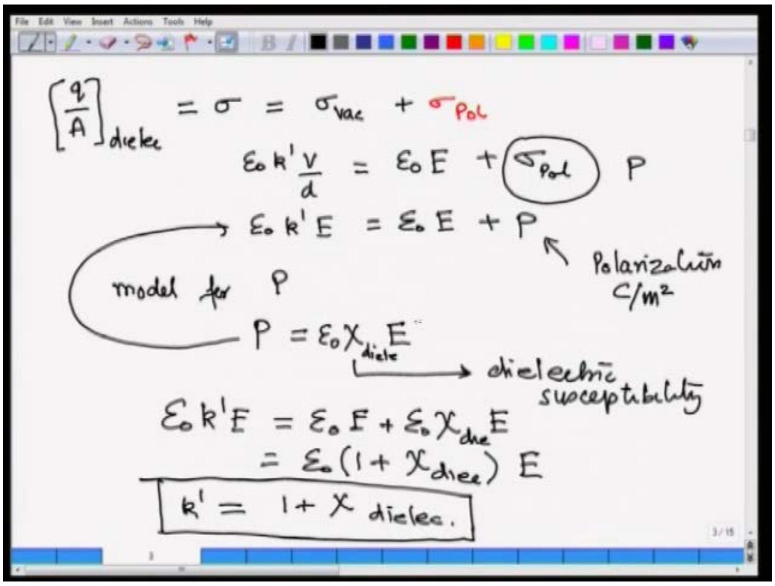

Remember if you go back since some slides back, we had said the proportionality of P and E even is given by this dielectric susceptibility. The question is, the whether his dielectric susceptibility is also function of E or it is not or is it constant.

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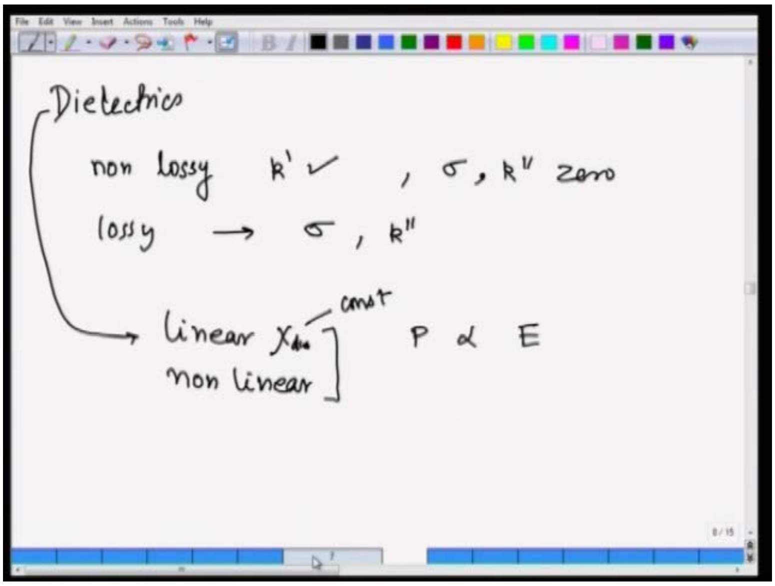

Now, this what that is the question we are addressing, Now, if it is, if i is constant then there is linear dielectric and if it is not it depends on E itself, then it is non linear non linear dielectric. What I am going to cover now today is, linear dielectric and in the next lecture I will talk about non linear dielectrics. So, this is the this let us start looking at the mechanisms for polarization.

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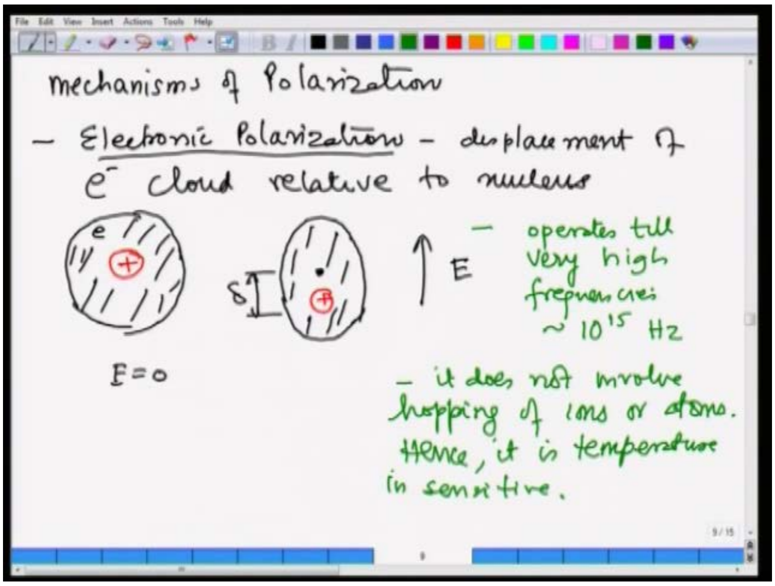

The first mechanism we going look at is the electronic polarization. What is electronic polarization, it is a displacement of electron to work out, meaning there by let us look at like like this, something like this. Here, is the center of positive charge and let us say this is the electron cloud, this here spherical form of electron cloud, this is electron charges or these are the electron cloud and electric field is 0. What happens if you apply a electric field, let say you apply a electric field in this direction.

What will happen, if that is the case then your positive center of positive charge, would move this way and electron cloud may shift something like this, with it is center somewhere here of electron cloud. In this case the center of electron cloud and center of negative charges that is and the per center of positive charge were coinciding. And there for, there was no net dipole moment and since there is no dipole moment, there for they will be they will be no dipole since there is no dipole moment, there for there is no polarization refer refer back this was the dipole moment.

When you applied electric field, what happens was center of positive charges positive shifted one way and negative charges other way, these are bound charges which moved related to each other and correspondingly they did have give rise to dipole moment. And now, you are looking at is that is situation E field is 0 of course, there is no polarization, but once you apply electric field in this direction, then this two centers shift by quantity, let say delta and this leads to a dipole moment.

And hence, a is a a it leads to polarization. So, this is the mechanism of electronic polarization, this is the electronic polar polarization displacement of electron cloud relative to the nucleus. This is very important mechanism, why why is it is it operates till very high frequencies, on order of 10 to power 15 hertz. So, it can operate till and then it drops of and then it after that it drops of, so if all the way from low frequencies to high frequencies, this quantity this a mechanism is able to operate.

Second point is that, it does not involve hopping of ions or atoms. Hence, it is not diffusion like process hence, it is temperature insensitive, in this course I will not do the mathematics of this, I will simply tell you what the mean different mechanisms are, so this this is the base this qu a this is quick overview about electronic polarization.

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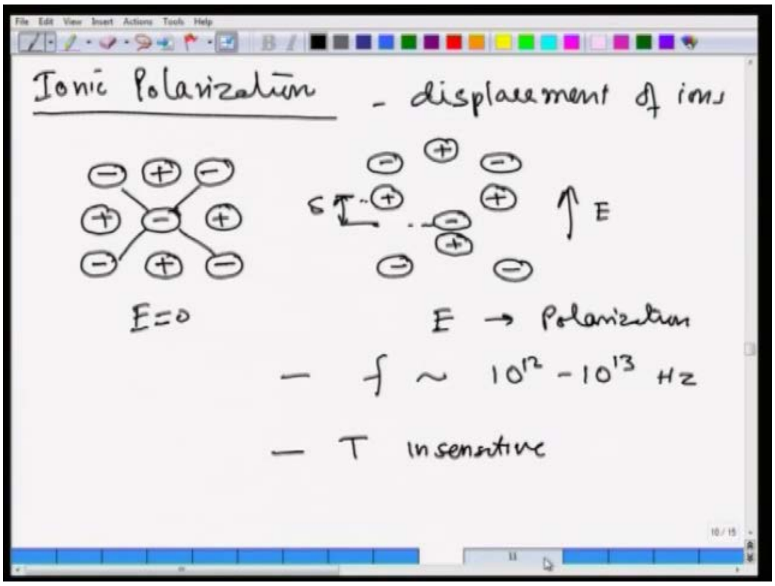

Let us move on to next mechanism, which is ionic polarization. And now, as the name suggests, it is displacement of ions when you apply electric field and this picture will give you idea what I mean, let say this is negative charge ion, positive ion, negative ion. Let us draw a few more is a ionic crystal and now, we apply a some electric field let say we apply electric field in this direction, what happens in this case. So, if we apply a electric field in this direction, so positive charges are going to move and negative charges are going to move.

So, I am going to write something like this then if I draw this, these are positive charge which has displays slightly. And negative charge which has come here and positive charge which is moved away and a positive charge moved here away and negative charge just here. So, the whole negative charge this sort of has moved down and the whole positive charge has moved up slight, as negative charge is moved down and positive charge positive charges have moved down and sorry I am missing up the negative charges have moved down and the positive charges have move slightly up.

And the consequence, now you are going to get a net as a conseq as as a result of it you going to get a net. If you look at the center of positive charges and the center of negative charges which is right here, this is center of negative charge, this is the center of positive charge. And there is a displacement between them and this leads to this is equal to 0 and this some E field leads to polarization, E leads to polarization. This mechanism operates in a frequency range of 10 to power 12 to 10 to power 13 all the way up to 10 to power 12 to 13 hertz.

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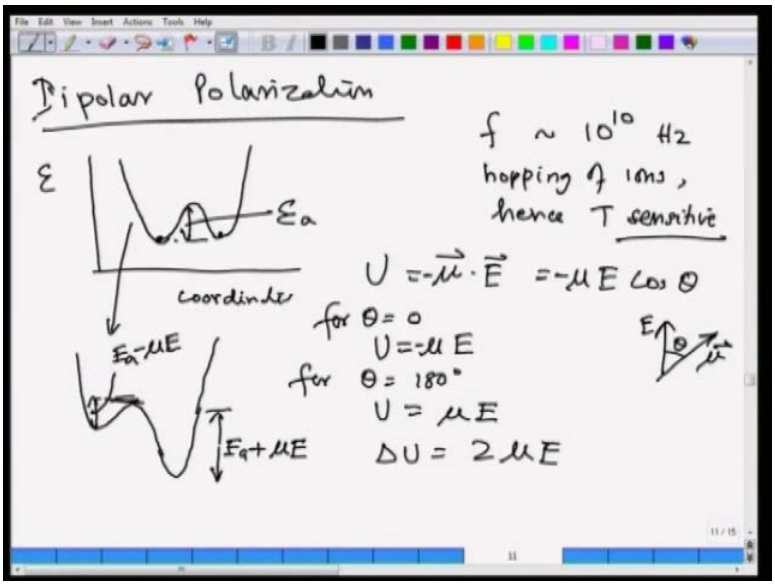

It can move up operate up to that remember, electronic polarization could operate up to 10 to power 15 this mechanism operates up to frequency about 10 to power 12, 10 to power 13 and then drops off. So, if you go to for frequency 10 to 15, you will only see electronic polarization, if you are operating up to frequency of 10 to 12 to 13 you will see both, ionic polarization and you will see electronic polarization both these mechanisms will be applicable. Second point this is also temperature insensitive because, again there is no hopping of there is no hopping of cha cha ions or atoms.

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Now, let us move to next one, dipolar polarization and this I am talking about more because, tomorrows lecture or next lecture 19 the 20’th lecture, would we will talk about non linear dielectrics. And this mechanism play a major role there, just to say a frequency of operation is up to about 10 to power 10 hertz, this is the frequency up to which it is able to operate and this hopping of charges hopping of charges of sorry hopping of ions hence temperature sensitive.

This is at very temperature sensitive mechanism, which we will see will lead to which will we see in some non-linear dielectrics will see this mechanism playing a important role. So, the way one can explain is that suppose, you had two put different polarization side, let me plot like this let say some coordinate system, some position coordinates of at ions and here I am plotting a energy. Suppose, they are two equivalent energy is possible; that means, if this energy curve is something like this.

So, this two minimums possible here, then you can have equally pre equal preference for sitting on this side or sitting on this side. And this is the activation barrier between them let us say, this is the e a activation barrier, question we ask is what happens if we apply if there is a dipole moment. One let us say corresponds to dipole rotating in the direction of electric field and one totally away for one an away from it and totally with the electric in the direction of electron electric field.

Then what happens you apply a electric field. You know that that if you apply a electric field if there is dipole moment is mu is a di dipole moment and we apply a electric field then dot product of dipole moment and a electric field, gives us the energy or minus the minus sign here, which is equal to mu magnitude e cos of theta, where if this is the electric field and this is the dipole moment direction, then then this is the theta between them if that is the case.

So, if for theta equal to 0 we get U as equal to minus mu E whereas for theta equal to 180 degrees, we get U as E for for theta, we get, I am missing a minus sign here and this will be mu of E then between these two two positions delta U could be equal to 2 mu E. This I can show, if I apply a electric field then you could have this picture changing, over to one side becoming more preferred, than the other side. That is, this barrier reduces by amount E a minus mu E, whereas this barrier whereas this barrier same this barrier increases by amount mu by amount E a plus mu E mu, but plus mu E.

Now, if you look at this picture when you had applied no electric field, between two polarization directions, there is equal property of ions hopping from here to here or hoping from here to here. The rate at which ion hoped from here to here, would be same as rate at which ions hope from here to here and then there will be no net polarization. But, now with dipole directions different between this side and this side, if there will be greater preference for ions to jump from this side to this side then from this side to this side. And hence, I am going to get net dipole moment.

And because, of this dipolar mechanism we get there for a dipole moment and because, net dipole moment when you apply a electric field. And hence a polarization and hence a dielectric behavior changes.

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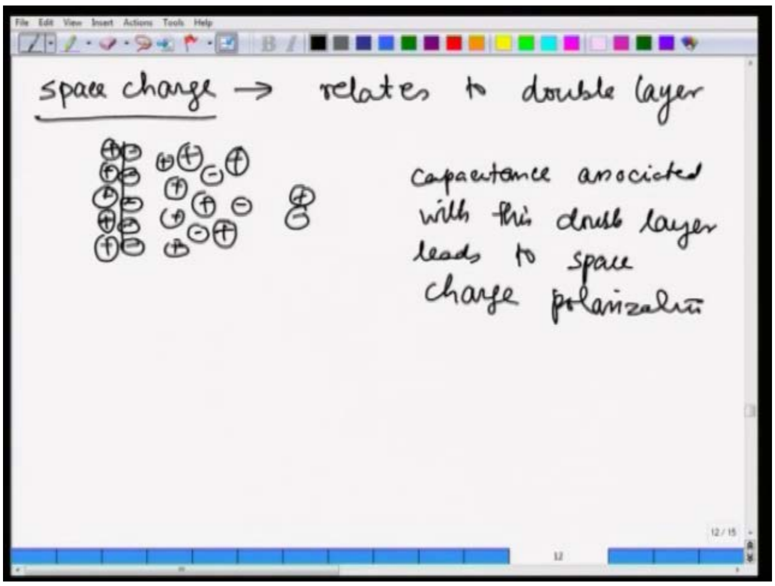

Last one or also a space charge polarization. And when you see if I green the frequency domain in which this operates, I have written 10 to power 10. So, space charge this can operate at very low frequencies and really, related more to electrochemistry and double layers, relates to two double layers and is not of that great value in solids. It is more interesting in case of solid surfaces and liquids, where you may be familiar with the surface getting charged let say it is positive charge and surface.

Then what happens, is then if you add liquid on this side, then they form all the negative charges form a stationary layer here. So, this liquid then acquires a net positive charge, then requires a ne net positive charge something like this then, but this is a net positive charge, ultimately far away the number of negative and positive charges become same. So, what you get is a net charge here, a charge region and capacitance of this double layer, this a capacitance associated associated with this double layer, layer leads to or is related to leads to space charge polarization.

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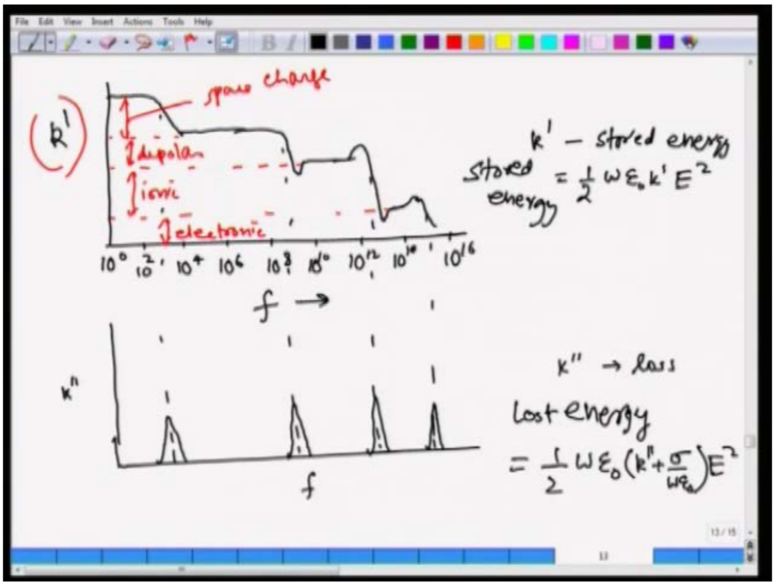

So, these are the difference mechanisms which operate finally, let me show you, how this there for if I plot k prime k prime this is the dielectric constant. What is this frequency then what we have said is let say this is 10 to power 0, 10 to power 2, 10 to power 4, 10 to power 6, 10 to power 8, 10 to power 10 this is long scale 10 to power 12, 10 to power 14, 10 to power 16 this the frequency. Then what we said is up to 10 to power 15. This mechanism, electronic mechanism operates somewhere here up to here the electronic mechanism operates. And this is what we are showing you here, this is the electronic mechanism.

So, if I look at this somewhere here, like this, this is electronic due to electronic reasons we are having this k prime due to electronic reasons. Then, if you go to lower frequencies, slightly lower frequencies the up to about 10 to power 9 I am going to draw something like this and I am going to smoothly join this, something like this and something like this. Then this region up to here, this is the next which is ionic polarization.

So, if you up to this frequency then both electronic and ionic polarizations contribute to k prime, then if I go further somewhere here, then dipolar somewhere up to here, operates dipolar. This is now dipolar and then finally, the space charge polarization which is something like this, this is the space charge this is the space charge polarization. And correspondingly, if I plot k double prime, then wherever there is change is occur somewhere here, we are going to get p this I am not talked about, the relationship which we based on which, you can calculate this, but I am not going in that much detail you will get k prime.

Remember, what k prime is k prime is about loss and k prime, k double prime is about stored energy. That means, stored energy would be equal to if I if we since do the half c v square integrate over times period and you behave should be able to show, that this will be equal to epsilon naught k prime E square would be the stored energy and the stored energy ener. And a lost energy would be equal to half omega epsilon naught, I going to write this as k prime double prime plus sigma this is a DC part, this is a AC, part this is a DC part E square will be a lost energy.

And just for your if you are wonder, why does microwave ovens work it is this. When you apply a AC frequency water molecules are made to rotate and this polarization is not able to keep keep up with the rate at which the electric field is switching directions. If they were able to switch, the polarization was able to switch at the same rate as electric field, then we would have add only this k prime and we would have all stored energy.

Because, because, but because, it is not able to follow it and hence, the face difference a emerges and you start getting a loss. And this quantity is the quantity which is the lost energy, which appears is heat and water starts boiling, you can cook your food etcetera, it is because, of this energy which is why this is happening.

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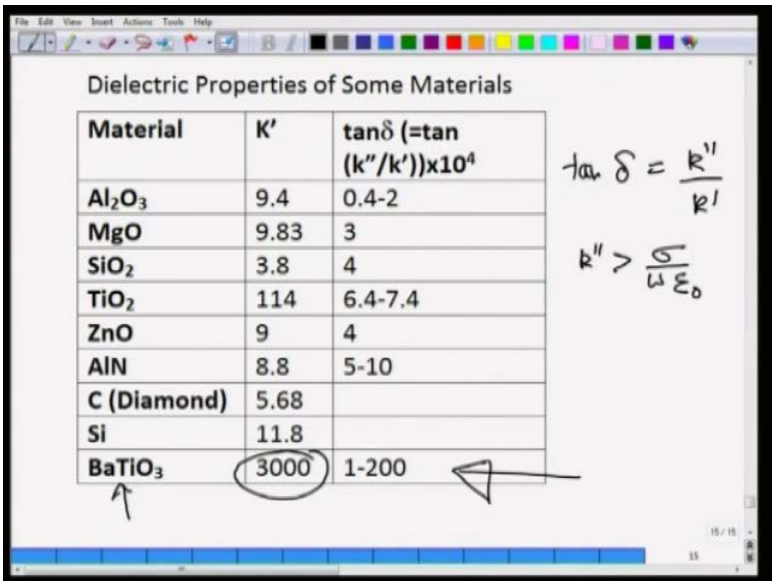

Material	K'	tanδ (=tan (k''/k'))x10[4]
Al_2O_3	9.4	0.4-2
MgO	9.83	3
SiO_2	3.8	4
TiO_2	114	6.4-7.4
ZnO	9	4
AlN	8.8	5-10
C (Diamond)	5.68	
Si	11.8	
$BaTiO_3$	3000	1-200

And last slide which I will show you some I will leave you with some values, this tan delta is the lost tangent is basically k prime by k prime assuming k double prime is much larger than sigma by omega epsilon naught epsilon naught. In that case, we define this as lost tangent and some materials, important materials alumina (( )) dielectric constant of 9.4 and this is lost tangent.

So, you can heat this a little bit M g O, silicon oxide a very common material in a electronics T i O 2, zinc oxide, aluminum nitride, diamond a silicon are the very high dielectric constant. And this material is going to start focusing on and the next lecture, which is a non dialect non linear material and has huge dielectric constant and it has a it is a also a pizo electric material. And these are the material, we will start looking as non linear dielectric, to explain what non non linear dielectric is that we will do in the next lecture, but I hope this gives you a quick overview of what dielectric materials are.

Thank you.