Nano structured Materials-Synthesis, Properties, Self Assembly and Applications
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Module - 4
Lecture - 33
Dielectric Properties – II

Welcome back to this course on nanostructured materials, self assembly, properties and their applications. We are in the module 4 lecture number 5. And today, we are going to discuss the second lecture on dialectic properties of nanostructured materials. So, in the previous lecture, we had discussed about the basics of the dialectic properties a what are dialectic properties and what is capacitance, what is directed constant, what is dielectric loss? And how does that elected constant or loss behave as a function of frequency. The same things which we discussed general and where applicable to bulk materials which have particle size in microns can be extended to the nanostructured materials. And we will now in today's lecture specifically see what kind of variations occur in the dialectic properties of nanostructured materials.

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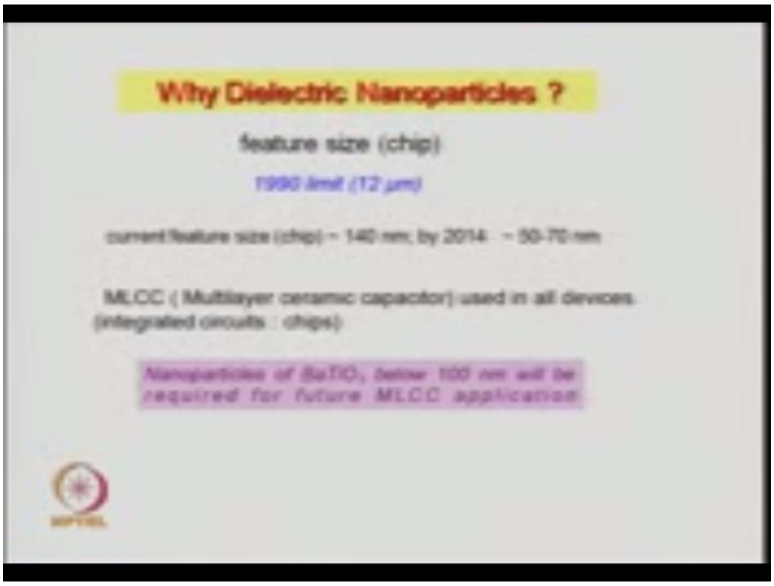

So, why one needs to discuss dielectric nanomaterials or why does one want to look at the applications of dialectic nanoparticles? The most important thing is that almost electronic devices all your devices like computers or image processing devices or digital cameras etcetera. Everything has integrated circuits or chips which have many many dielectrics involved. Now, these dielectrics in today's world are based on what is called M L C C's that is the multilayer ceramic capacitors and the main material which is used as a multilayer ceramic capacitor is barium titanate. So, they this barium titanate is acts as a capacitor and is involved in the fabrication of the chip or is applied in devices. Now, the size of this chip or the feature size as we say is about 12 micron in 1990 below 12 micron people could not make a ship in 1990.

Today the size of the chip has been reduced to around 140 among the best cases. And it is predicted that by 2014 the size of the chip can will be reduced to 50 to 70 nanometers the decrease in size of the has the advantage that you can put in the same area many many chips. So, your total amount or number of chips will add on to the memory of the device or whatever property it is being applied for. And hence you want as many number of i c chips on a particular in a packaged system in electronic devices. So, if you reduce the feature size as is expected we will be around 50 to 70 nanometers you will be able to putting lot more number of chips on a single device. And hence how to reduce the size of the chip is very important.

Now, since they are we are talking a multilayer ceramic capacitor being used in these chips the thickness of these layers have to be reduced. So, multilayer means several layers of these ceramic capacitor is involved. Now, if each layer is made up of the barium titanate material if you use nanoparticles instead of micron sized particles. Then you will be able to put many such layers in one chip. So, typical sizes below 100 nanometers will be required in the future for such M L C C or multi layer ceramic capacitor applications.

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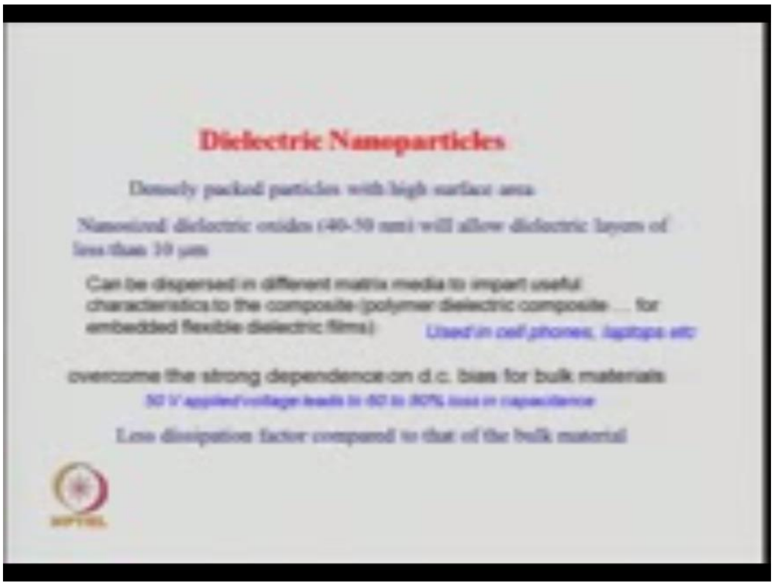

So, the dielectric nanoparticles are important because you can pack these nanoparticles in very dense manner. And they will still have high surface are, because the particle size is very small. Now, typically if you can reduce this dialectic oxide nanoparticles to the size of 40 to 50 nanometers. Then you can think of making dielectric layers of less than 10 microns. And that will be very very advantageous by in making the final size of the chip very small. The other property which is of importance of why we should go for nanoparticles of these dielectric materials is that these nanoparticles can be dispersed in a different matrix media.

So, you can have polymer or you can have a metal ceramic composite many many matrices you can use by use by starting with this dielectric nanoparticles they can be finally, dispersed in different media. So, that is one important and you can make a composite like polymer dielectric composite. And then because of the polymer it will have flexibility. And then you can make what are called flexible dialectic films or embedded flexible dialectic films where the dielectric nanoparticles are embedded within this polymer film. And such flexible films are of importance in flexible electronics especially in cell phones in laptops etcetera. And it is of great importance in the near future.

Now, another important of using nanoparticles is that in the dielectric measurements there is a strong dependence of the dc bias for bulk materials. So, you have to apply a high d c voltage whereas, if you reduce the size of the nanoparticles you can use say 50 volts applied voltage will lead to 60 to 80 percent loss in capacitance. So, this dependence on the dc wires can be deduced by using nanoparticles. The other factors which is of importance is the lower loss of nanoparticles of dielectrics lower loss means less dissipation factor is the same thing. So, a nanoparticle a dielectric nanoparticle will have a much lower loss or dissipation factor compared to micron sized dielectric materials.

So, all these properties make you make it important for one to understand and fabricate devices built up of dielectric nanoparticles rather than micron sized nanoparticles. So, the small size of nanoparticles will allow you to bring down the layers of these M L C C’s the multilayer capacitors. And hence will layer these thin dielectric layers will allow you to make smaller devices. The other thing is you can make flexible films by making composites of this dielectric nanoparticles with the plastics or with polymers.

And the 2 other important points are that using nanoparticles you can overcome the strong dependence on the bias voltage. And you can also lower the energy loss or the dissipation factor by using nanoparticles instead of micron sized particles. So, people work with barium titanate strontium titanate lead titanate or a p z t materials these are all dielectrics. And people have been using them in sizes of the order of half of a micron to 1 micron and above. Whereas, if you can make nanoparticles of these they have some advantageous over their micron sized particles.

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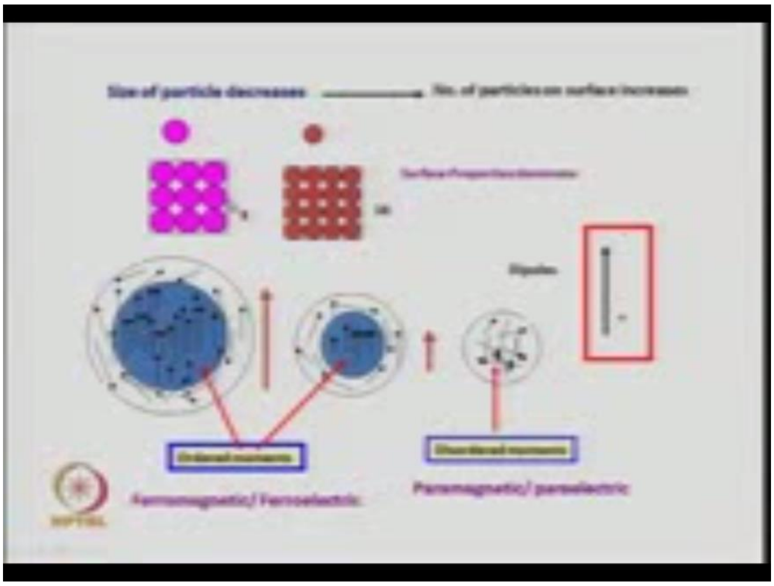

So, let us look at 2 important properties when you reduce the size. One is the surface area as you decrease the size of the particle for the same area you can put more number of particles if you have smaller particles. So, these particles as small so the length of this square. And the length of this square is the same here you can put less number of particles only 9. Because of the large size here you can put 16 because of the small size. So, that means more particles are on the surface when the particles are small. So, in the dielectric materials also the number of particles on the surface will increase as the size of the particle decreases. And hence the surface properties will dominate the other very important property especially any material with moments like dipole moment. Or magnetic moment is important in nanostructured materials.

Because imagine you have a particle of a large size then in a material with ordered moment like a ferroelectric material or a ferromagnetic material. The inner core is normally having the alignment which is due to the ferromagnetic component or the ferroelectric component as the the dipoles on the surface have higher energy. They are easily disordered, but the dipoles at the core remain ordered. Now, if you reduce the size of this particle as a whole if you reduce the size of the particle. The number of dipoles which are ordered become much less than when the particle was large. So, you will have less number of ordered dipoles in this case than in this case. And so the number of ordered a dipole started starts increasing in comparison to the number of ordered dipoles.

And if you make the particles still smaller you may not have any ordered dipoles. So, what is happening is from an ordered dipole type of arrangement. You are going to go to a disordered arrangement as you decrease the size of the particle. So, from ordered moments you go to disordered moments and from ferromagnetic you go to ferro paramagnetic. And from ferroelectric you go to paraelectric for this discussion of dielectric properties what is important is the ferroelectric and paraelectric transformation. So, you can say that in all systems where you have ferroelectricity as you decrease the size of the particle those materials will tend to lose their ferroelectricity.

Because the number of ordered dipoles will decrease as you decrease the size of the particles. And hence and when the particle size become smaller and smaller. You will end up with particles having only disordered dipoles and so it you go from a ferroelectric material to paraelectric material. This is one of the most important changes one can expect in a ferroelectric material when you decrease the size of the particle. So, after the basics that is the dielectric properties there is a dielectric constant their loss their dependence on frequency. And what happens when the size of the particle reduces to these properties?

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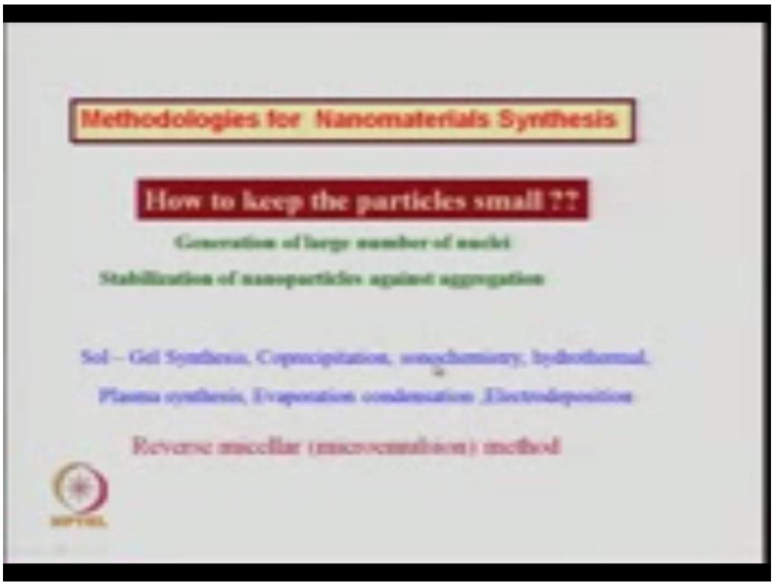

Let us look at how these dielectric materials can be prepared? So, we have earlier looked at methodologies for synthesis of nanomaterials. And we have discussed that we need to keep the particles small by generating large number of nuclei and stabilize these nanoparticles against aggregation. So, we have to keep apart now chemically there are several routes we have discussed in our previous lectures where we have discuss sol gel synthesis, coprecipitation, sonochemistry, hydrothermal methods.

All these methods are called chemical routes or the bottom up approach. And then you have the top down route or the physical approach which includes plasma synthesis or evaporation condenser a condensation. This evaporation can be due to lasers or electoral beam evaporation. And you can have an electrochemical process like the electrode position. We have also discussed the chemical process using my micro emulsions which is also called the reverse micellar method. So, all these techniques can be used for making dielectric nanoparticles and many other type of nanoparticles.

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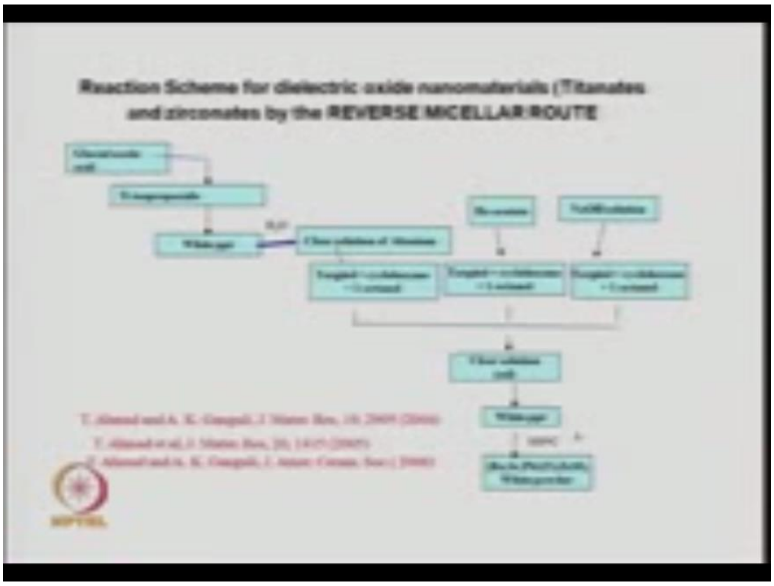

So, this is a typical example where the reverse micellar or the micro emulsion method where you use surfactants etcetera to control the size of particles has been shown here. This is a flow chart of how one can synthesize a dielectric nanoparticles. And typically we have discussed here for titanate zirconates. So, to make a titanate like say barium titanate B a T i o 3 or strontium titanate or lead zirconates this process can be used. And this has already been done very in very detail and has been published in the papers as the mentioned here. So, what you do is you take the titanium as an alkoxide and you use titanium isopropoxide and glacial acetic acid. You get a white precipitate and that you dissolved after adding some more water; you get a clear solution of with titanium in it. And you add barium acetate and sodium hydroxide to the microemulsion mixture.

So, the microemulsion is made of this surfactant which is tergitol it is a non ionic surfactants. And we know surfactants are molecules which have a long chain which is a hydrophobic and a head group which is a polar head group here it can be and an ionic. Or ionic in this case we are taking a non ionic surfactant which is tergitol. And we have to add some water and some non aqueous solvent to make the microemulsion. So, you use the same microemulsion with all the 3 components; one is the titanium source; one is the barium source and one is the precipitation source. So, you make a titanium source in the microemulsion, you use barium acetate for the barium source in the microemulsion.

And then you take the precipitating solution which is sodium hydroxide in the same microemulsion. So, you get 3 microemulsions and you mix them to get a clear solution and then you start it for a while till you get a white precipitate. And that precipitate you heat at 800 degrees celsius approximately to get depending on whether you have taken barium strontium or lead you can get barium titanium oxide or lead titanium oxide. Or if you have taken instead of titanium isopropoxide if you have taken zirconium alkoxide then you will end up with a zirconates. So, you can end up with barium zirconium oxide all of them you see the formula is kind of A b O 3 which we have discussed.

But they can be of other formal also for example, by changing the ratio of barium to titanium we can make B a 2 T i O 4 instead of B a T i O 3, so you can modify the conditions and the stoichiometry to generate different kinds of titanates and zirconates etcetera by this method. So, this is one method; one chemical route by which nanoparticles of barium titanium oxide which is another most famous a dielectric materials. And is also a ferroelectric has been synthesized by a similar method strontium titanate oxide which is another important dielectric material can be synthesized in nanometer size dimensions. Similarly, lead titanate, lead zirconate and many other compounds which have important dielectric properties can be obtained and they can be obtained in the nano size range.

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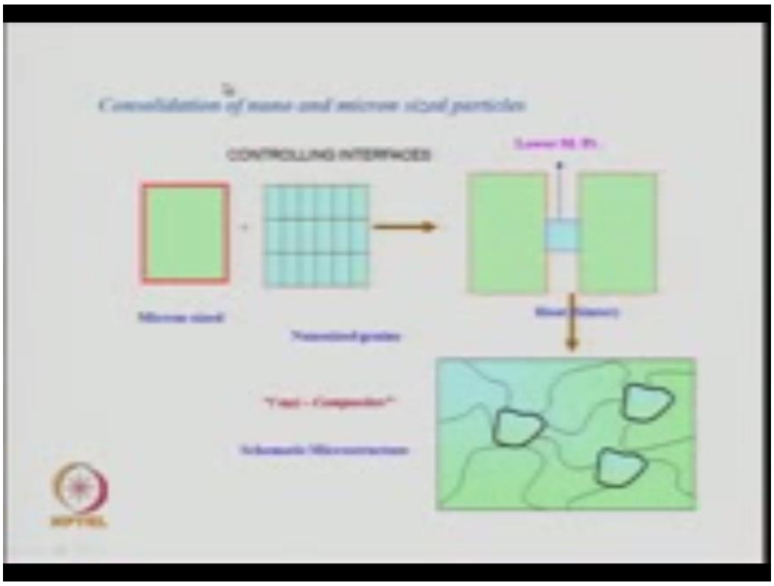

Now, if you look at a mixture of micro sized and nano sized particles you can make composites of nano and micron size particles. And you can see that when you’re adding micron and nano sized particles of the same material. For example, barium titanium oxide you take micron sized particles and nano sized particles. And you mix this a schematic diagram which shows that what this small particles will do this small particles can join the large particles. Because the smaller particle has a lower melting point it melts first and so it will help bonding these larger particles. So, when you heat this, this part melts first and it sinters. So, you get a schematic schematically it is shown here you will get this kind of grains of nano and micron sized particles which are highly compacted. Because and will give rise to high density of these ceramics and this we can call them as n mu composite. This is the schematic microstructure of nano particles and micron sized particles which have been sintered together.

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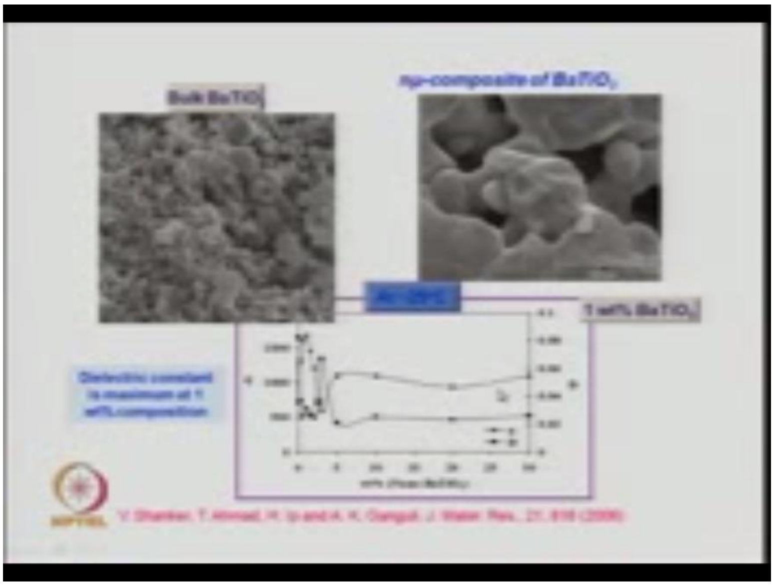

So, this is an example of barium titanium oxide, the micron sized particles are shown here this is a scanning electron micrograph of barium titanium oxide. And when you mix nanoparticles of barium titanium oxide to this bulk or micron sized particles. You get this kind of a very compact that grains which shows signs of melting which is due to the N mu composite. That means you have both nano and micron particles sintered together and the dielectric property. This is only 1 percent 1 weight percent of the nano barium titanate has been added. So, 99 percent is the micron sized particles and 1 weight percent is the nano sized particles when you make a composite of that how does its dielectric properties vary. So, epsilon here is the dielectric constant and you plot as a function of variation of the weight percent of nanoparticles.

So, you can add 1 percent, 2 percent, 5 percent like that data is shown here for 30 percent. And you see that for small region where then edition of the nanoparticles is around 1 or 2 or 3 weight percent the dielectric constant epsilon as shows a an increase. And the dielectric loss which is shown as the squares which is d the dielectric loss d is plotted on the this scale and that shows also an increase. So, there are some changes occurring when you add nanoparticles to the dielectric micron sized particles. And this is a kind of reflected in the measurements that you do for the dielectric constant and dielectric loss.

So, there is a change in the properties so there is a role of the nanoparticles on the properties of the major phase which is the bulk sized particles which is micron sized particles which is 99 percent or 98 percent. And only small amount of nanoparticles you have added But that small amount of nanoparticles has modified the properties of the composite. Now, same thing can be seen in strontium titanate so it is not only in barium titanate. The previous one what we discussed was composites of barium titanate where you have added small amounts of nano additives in these micron sized particles.

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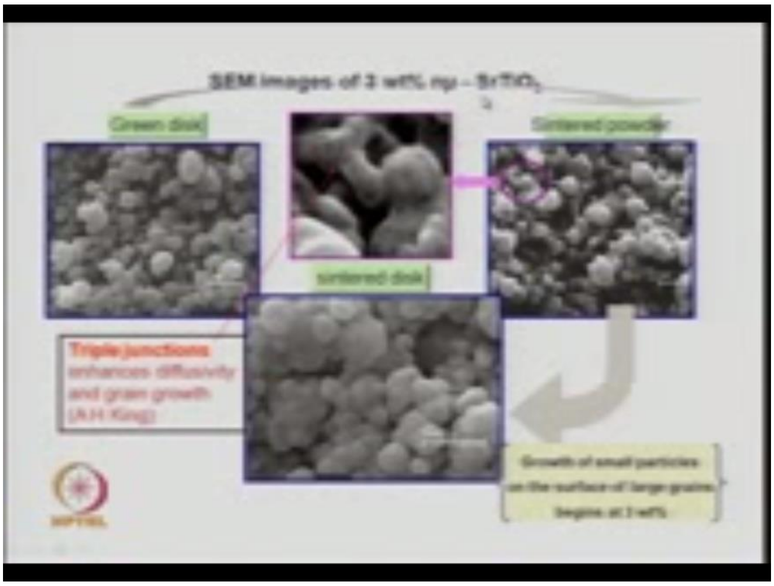

Now, here this is the same kind of experiment that you have done with another material which is strontium titanate S r T i O 3, S r T i o 3 is not a ferroelectric. But it has got many applications which are different from barium titanate which is used mainly as an M L C C or multilayer ceramic capacitor. It is a ferroelectric, but S r T i O 3 is not a ferroelectric, but it has many other applications in electronic devices. So, S r T i O 3 same similar studies based on small amount of dopants of nano sized strontium titanate added to micron sized particles of strontium titanate. And sintered powder is shown here this is before sintering you make a compacted disk. And that is called the green disc and when you sinter it those particles it is the sintered powder. And if you see the powder in much more closely you will see some kind of junctions, these are called triple junctions. And in literature it is known that when you have such kind of triple junctions it enhances diffusivity and green growth.

So, one thing is what we saw you were in barium titanate there is increasing grain growth due to at edition of nanoparticles. Here also you see an enhancement in diffusivity and grain growth which can be corresponding to the presence of these triple junctions and the theory has been worked out by Alan king. And there are several references and books in which this kind of the enhancement of diffusivity where triple junctions are obtained are known. Now, in this particular case you can look at this pictures much more closely and if you look at these pictures closely you will see that there is large grain and on the surface of the large grain there are smaller particles. So, there is a growth of small particles on the surface of large grains at particular a specific compositions an in strontium titanate. That is very much seeing at 3 weight percent of dopant of the nanoparticles.

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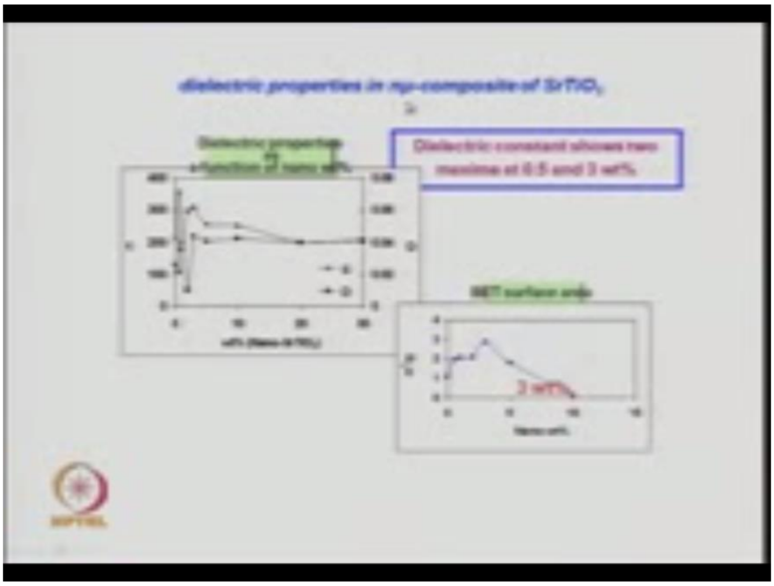

Now, if you look at the dielectric properties in these nano micron composites of the strontium titanate. Then you can see that here on the y axis is epsilon which is the dielectric constant and is plotted with weight percent of the dopant which is nano strontium titanium. So, when you add small amounts of nano strontium titanate there is initially an enhancement. And then it goes down and becomes nearly flat and this property that is there is some enhancement around 0.5 and 3 weight percent you can see a reflection in the behavior of the surface area. So, the b e t method is a particular method by which you calculate the surface area using nitrogen adsorption methodology. So, you do nitrogen adsorption studies and from that you can see that here the surface areas is plotted in meter per gram and versus nano weight percent of strontium titanate. And that also shows some kind of maximum around the numbers or the weight percent doped of strontium titanate.

And typically at 3 weight percent of strontium titanate there is a maximum in the surface area. There is also a maximum in the dielectric constant epsilon there is also the variation of the dielectric loss as a function of the nano dopant. So, what is clear from these 2 cases both the case a barium titanate and or of strontium titanate that there is a roll of the nano dopant or the nanoparticles on the overall property of these composites of these nanocomposites. And that is reflected in its surface area that is reflected in it dielectric constant and its dielectric loss. And it appears that the maximum dielectric constant which is an important number is a highest when the amount of dopant is close to 1 to 2 or 3 percent. So, very small amount of addition of the nanoparticles enhances the dielectric constant.

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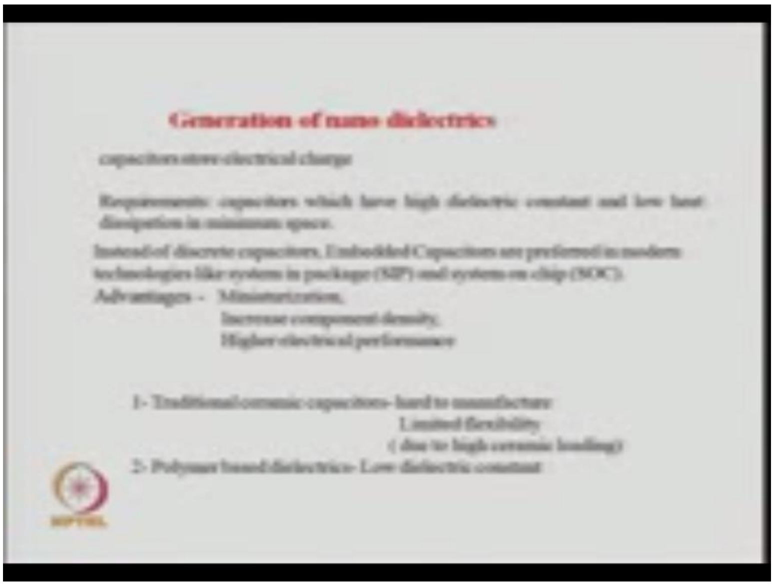

Now, the generation nano dielectrics we have now known. Actually in the previous lecture we discussed about capacitance and what is the role of the dielectric material which is an insulator is to store electrical charges. So, if it has to store electrical charges you need materials with high dielectric constant and which should not lose energy that is it should not dissipate energy and dissipation of energy is heat. And so it should have low heat dissipation and also this material should be able to be pack in minimum space so capacitors which have high dielectric constant. And low dissipation, low heat dissipation and can be accommodated in a minimum space would be the materials of choice.

So, you want to make or generate nano dielectrics which have such properties. Then instead of using discrete capacitors what is more important today is to use embedded capacitors. An embedded capacitors are used in what we call system in package in these electronic packaging systems and it is also called a system on a chip. And in this kind of embedded capacitors which are used in all modern technology the advantage is if you can miniaturization them. Then you increase the component density the number of components increase per square range and that increase its performance. So, overall you want to miniaturize you want to increase component density. And so you want to get the highest performance of the device.

Now, traditional ceramic capacitors are hard to manufacture and they do not have much flexibility. Because the ceramic content is very high it is not so flexible. Whereas, if you use polymers or polymer based dielectrics you can get the flexibility, but the dielectric constant become slow. So, these are 2 factors which are kind of counterproductive, if you want flexibility you use polymers, if you want high dielectric constant then you use ceramics. So, if you want to combine both the properties that is you want to retain the high dielectric constant of the ceramic part an increase flexibility by adding a polymer to make a polymer composite.

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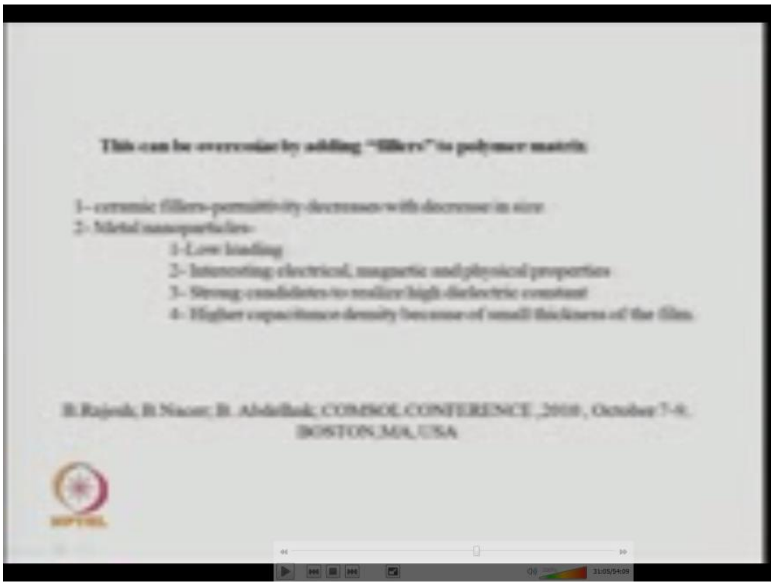

Then you can make such a composite by adding fillers to the polymer matrix so both the properties will be retained. The ceramic fillers will give you the dielectric constant that you required and the however the permittivity will decrease. Because you are decreasing the size and metal nanoparticles can be used with low loading. They can have interesting electrical magnetic physical properties and they are strong candidates to realize high dielectric constant. They will also have higher capacitance density, because of small thickness of the film. So, both these are applicable you can use ceramic fillers you can use metal nanoparticles in a polymer matrix.

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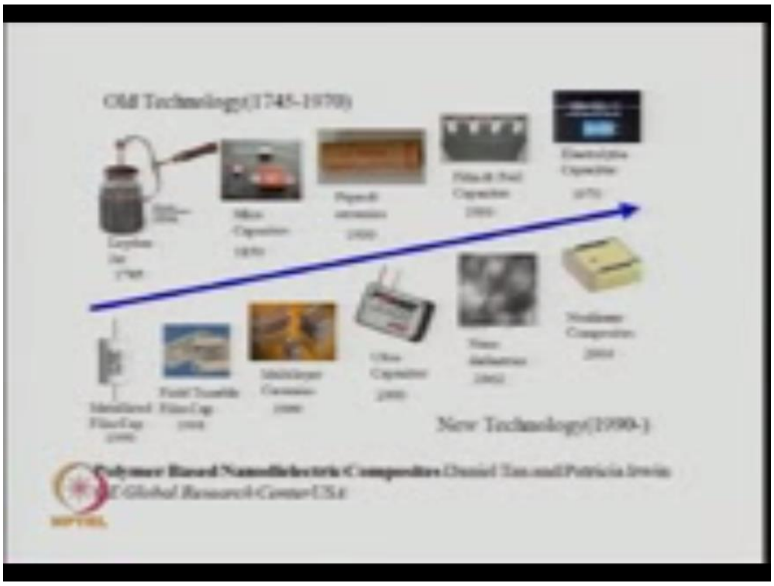

Now, over the years you can see that there has been a great change in the technology being used for capacitors. So, from this is kind of historical plot where the Leyden jar first dielectric which was a kind of use then to the microporous capacitor which was very popular till the 1900s. And then you had this paper based and ceramic based capacitors shown here and then the film and file based capacitor in the 1960s. And then the electrolytic capacitor in the 1970s further developments have taken place and you have metalized film cap based capacitors in the 1990s. And then you have field tunable film caps in 1998 and then what we discussed earlier the multilayer ceramics became very popular after 1999. And more recently we have come to the generation of ultra capacitor and nano dielectrics which we are discussing today.

And the nano dielectrics which are basically ceramics, but the particle size is very small when you combine with polymers etcetera you get flexible dielectrics. And many of them you can make like non-linear composites which have a discovered in 2004. So, a lot of a change has occurred and polymer based nano dielectric composites have become very, very important in these days, because they combine the properties of high dielectric constant of the ceramic and the flexibility of the polymer. So, together the polymer nano dielectric composites are a very important and futuristic materials for applications in electronic devices.

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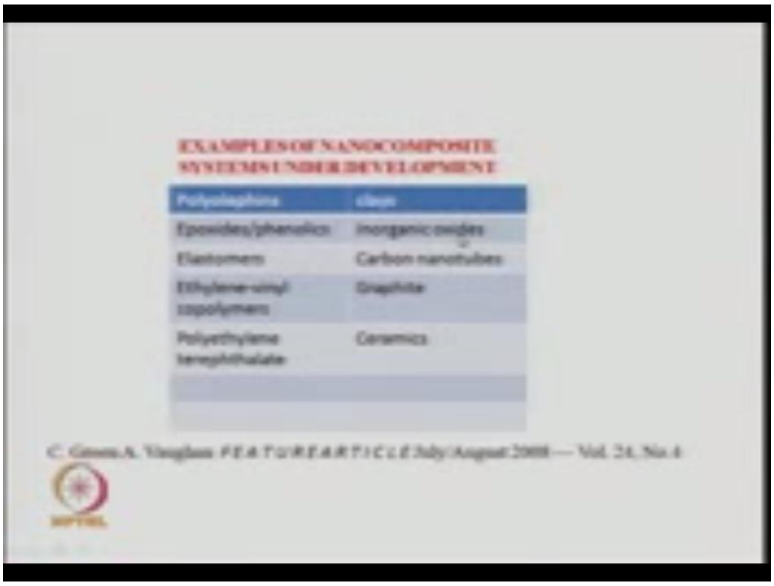

Now, some of the examples of nano composite systems which people have been working in the recent past are where the ceramic clay has been used like many inorganic oxides that is the ceramics. And the polymer or like polyolephins which are epoxides phenolics then carbon nanotubes have been used with the elastomers graphite has been used with it. Ethylene vinyl copolymers and other ceramics materials with polyethylene terephthalate, so this type of combinations of a polymeric material and the ceramic material have been done in the recent past to develop the nanocomposites for dielectric properties.

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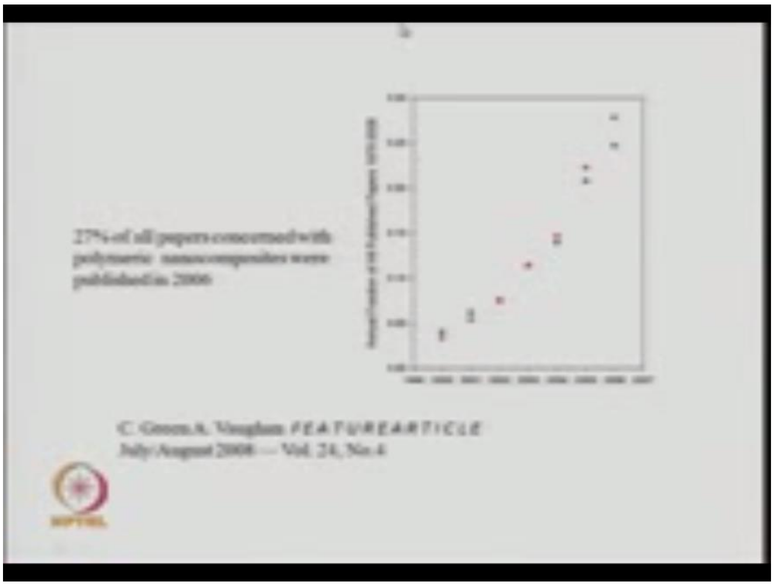

And you can see in the literature there is a tremendous jump a in the number of publications in the area of nanocomposites and a very large peak exist in around 2006. So, lot of work has been done in the last 7, 8 years in dielectric based on polymer and ceramics nanocomposites.

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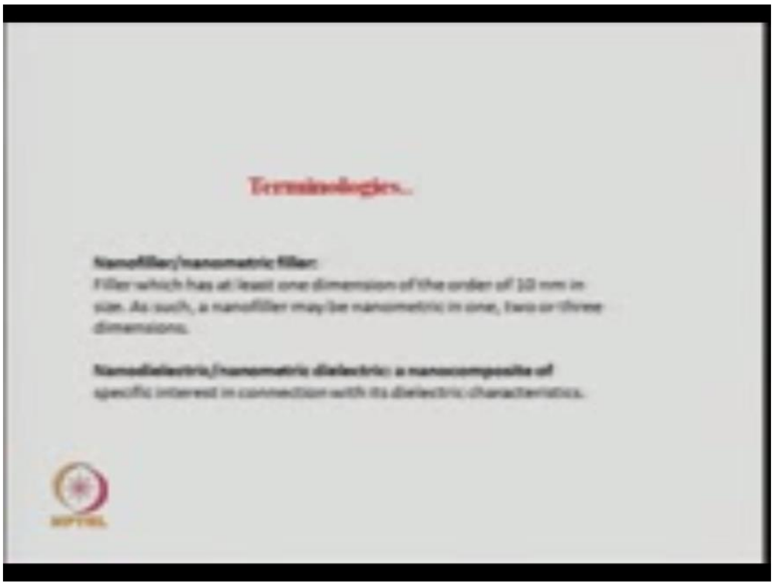

Now, this terminology is one can clarify that what is a nanofiller or what is a nanometric filler. So, filler should have if it is a nanofiller it should have at least one dimension of the order of few nanometers. So, you can have a material a say is not shaped, but one of the dimension is 10 nanometers or 20 nanometers in size and such a nanofiller can be nano sized in 1 2 or 3 dimensions. So, if it is a nanosphere that can also be a nanofiller you can have a nanorod or a nanoplate all them can be used as nanofiller.

So, is the terminology and what do you mean by nano dielectric or nanometric dielectric is a nanocomposite of specific interest with dielectric properties. So, if you have a material which is a nanocomposite that means you have a nanoparticle with a polymer or nanoparticle with micron sized particles of a ceramic. That is also a nanocomposite and if that nanocomposite has interesting dielectric properties. Then it is a nano dielectric or nanometric dielectric this is what is the terminology which is being used very often in the literature are nanofillers and nano dielectrics.

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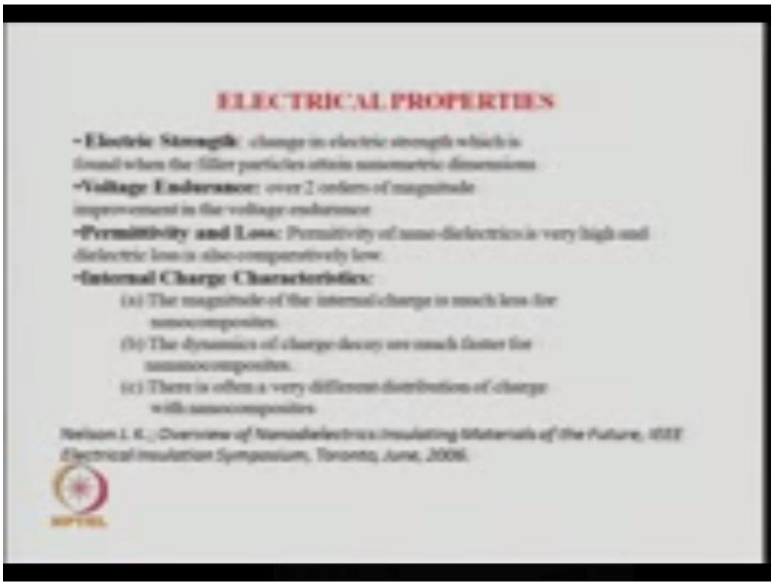

Now, the properties of these dielectric materials which is of importance when one wants to apply them for many of these devices especially as MLCC the it you have to look at the electric strength of the material. So, this nanocomposite or this material with the nanometric dimensions, what is the change in the electrics strength when the filler particles are in the nano dimensions? So, one has measured the electric strength of these device with nanometric fillers. The other thing is the voltage endurance how long you can apply the voltage. So, over 2 orders of magnitude improvement is there when you go from micron sized particles to nano sized particles. So, this is a large change in the endurance of a material that means this material can withstand a voltages over much larger values over much larger time. And this the other thing is about the dielectric constant which is also called the permittivity.

So, permittivity is the dielectric constant related to the dielectric constant and loss here means the dielectric loss are the dissipation related to the dissipation factor. And the permittivity of the nano electric dielectrics is high and the dielectric loss is comparatively low. So, these are both very advantageous points if you can have a high dielectric constant or a high permittivity and low dielectric loss. So, both are advantageous and that seems to be the case in many of the nano dielectrics. Then internal charge characteristics of these nano dielectrics is that the internal charge is much less in these cases of nanocomposites. Then the charge decay dynamics is much faster for non nano much faster for nanocomposites.

And there is very different distribution of charge with nanocomposite as compared to normal dielectric materials. So, all this a great deal of work and analysis of the properties and measurements after adding nanofillers or nanoparticles to micron sized particles to make nano dielectric composites has been studied. And especially people have looked at the electric strength the voltage endurance the permittivity which is the dielectric constant related to the dielectric constant and loss which is related to the dissipation factor. These all these properties have been found to be beneficial when you are having nanocomposites as compared to when you have materials which have particles only in the micron size range. And this is an interesting article on the overview of nano dielectrics and insulating materials of the future and published in 2006. So, it talks a lot about the nano dielectric problems and what nano dielectrics and how it is beneficial to the field of electronics in general?

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Now, you can have self assembled nano dielectrics. So, there is a word self assembly which we were discussing earlier in terms of particles coming together under certain forces which may be electrostatic forces or van der Waals forces. And then the particles arranging themselves in a minimum energy configuration and that kind of self assembly is known. Now, this is self assemble nano dielectrics where the main aim is to use these dielectrics in circuits where they do the role of what is called the gate. The gate allows the charge carriers to flow and then it is like a gate if you open something can go in a null If you close the gate then it does not allow the flow of charge carries.

So, that is why many of the a many of the dielectrics can be used at such gates to control a moment of charge carriers. And the dielectrics are good materials for this gate properties due to their robust insulating properties there are they are highly insulating. So, that means the conductivity is very low for these dielectrics which is important. And then you can tune the thickness of these dielectric materials at the nanometer size. So, you can have thickness of these materials of say 10 nanometer 20 nanometers etcetera. So, you can make very thin dielectric layers so the gate which is quoted on top of another material basically has to be of a certain thickness and if you can control the thickness of the material that is very good and you the lower the thickness. You can control the better it is for designing a electronic devices.

And since it is possible if you have particles in a nanometer scale then it is much easier to tune the thickness at the nanometer scale. So, in these self assembled nano dielectric a this property of a the controlling the thickness at the nanometer level is very important apart from the insulating properties in edition. These can be made optically transparent in the visible that means they do not any energy in the visible range. So, they are optically transparent in the visible range of the electromagnetic spectrum. So, that is another important property. And finally, how do you make them easily and in large quantities since many of these can be made by solution processes. So, you have and efficient solution process ability and hence you can make a large amount of these gate dielectrics as a result of easy processing. So, such self assemble nano dielectrics or which are called sand in general a are important and have gain significant attention due to the about properties which we discussed about these materials. This is an example of what we just said that the endurance of the material with the nanoparticles is much higher.

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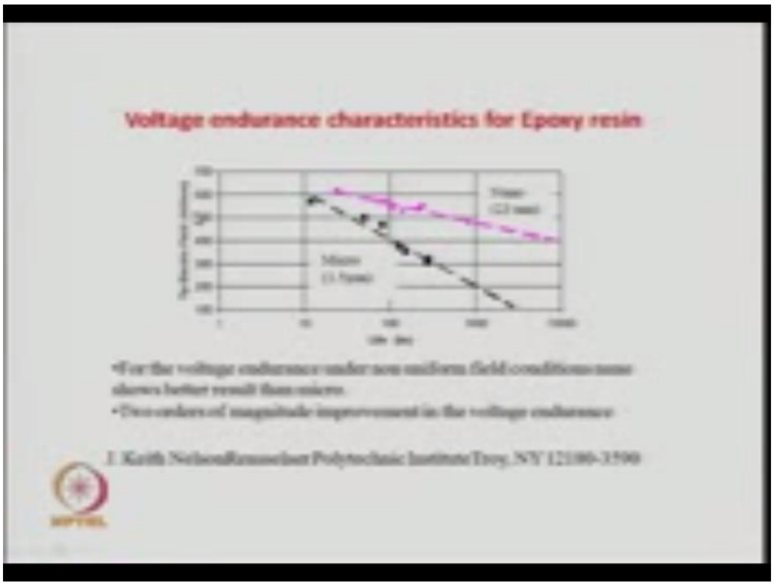

And you can see in this plot that the electric field which is few 100 kilo volts per millimeter plotted on the y-axis this is much higher for the nanoparticle. So, when you have nanoparticles in a polymer this is an epoxy resin these nanoparticles of 23 nanometers are embedded in this epoxy resin. It has a much higher electric field as seen here the electric field decreases with time. So, this is life or time so this black line shows the decrease in these electric field strength for the epoxy resin when you have micron sized particles embedded in this polymer.

So, then you have micron sized particles embedded in this epoxy resin and the micron sized particles are of the size of 1.5 micron then you have this strength. Whereas, if you small particles very small say twenty 3 nanometers. So, these nano sized particles when they are embedded in the same epoxy resin the strength electric field. Strength is always higher much higher than the a values when micron sized molecules are present and also the decrease as a function of time is much slow. So, this slope is much higher this decreases much more slowly and. So, there is 2 orders of magnitude in improvement in the voltage endurance where when use nanoparticles embedded in the epoxy resin compared to micron sized particles. So, this is this is of tremendous use a or benefit industry.

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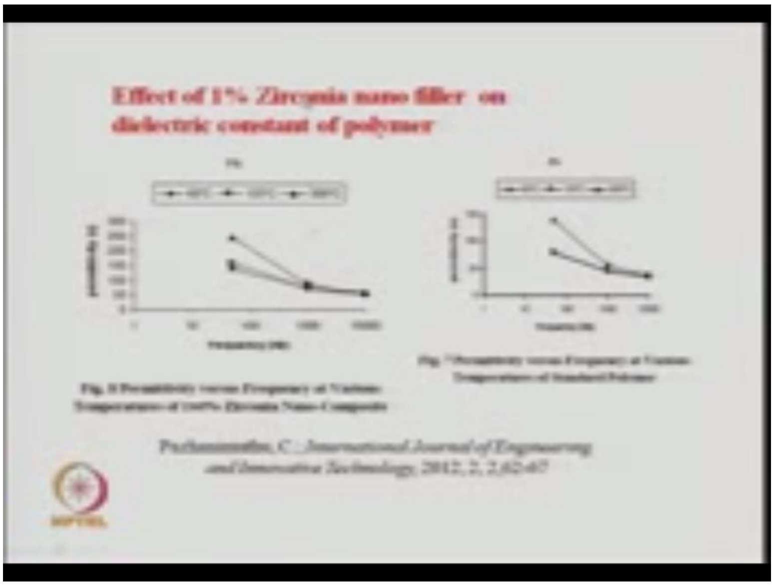

Here we look at variation of a nanofiller of zirconia which is Z r O 2 zirconium dioxide is zirconia and when you are using these zirconia nanoparticles as filler in polymer. So, what is the effect are the dialectic characteristics? When you say dielectric characteristics you can be dielectric constant dielectric loss or dielectric strength. So, here we are looking at dielectric constant which is related to permittivity and the permittivity as a function of frequency. And you see the permittivity is for one weight percent of nanofiller added to the polymer and this is the drop in permittivity as a function of frequency in this case you have there is no zirconia additive.

So, there is no nanoparticles 0 percent and then you see how the permittivity varies with the function of frequency. So, certainly there is a difference when you see then when it is 0 percent the value of the dielectric constant are the permittivity here is less than 150. Whereas, in this case the values are nearly close to 250 in some case and around 150 in another case here the values range from say 80 240 145. So, you get much larger values of the permittivity or dielectric constant by just adding one percent of the zirconia nanofiller in the polymer. So, this is an enhancement of the dielectric constant of the nanocomposite compared to the bulk material or the bulk polymer.

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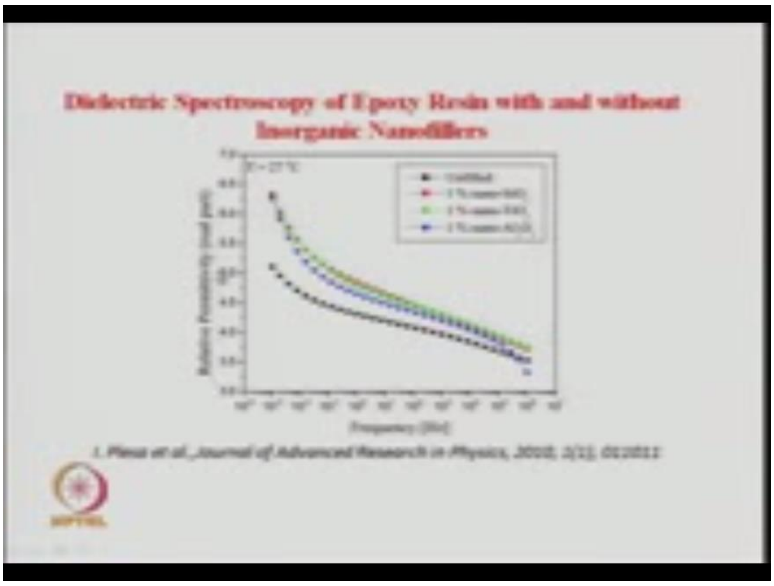

This is a again a plot of the relative permittivity and this the real part. So, epsilon actually the permittivity is a sum of the real part of the permittivity which is epsilon prime plus term which is dependent on the dielectric loss. That is the imaginary part of the permittivity and of course, there is there is a coefficient which is i which is root of minus 1 as you write a complex number epsilon plus i epsilon prime plus i epsilon double prime. So, here epsilon prime is the a real part of the permittivity and epsilon double prime is the imaginary part of the complex permittivity. And in this case on the y axis you are plotting the relative permittivity the real part that is epsilon prime we may call and that is related to the dielectric constant.

And as a function of frequency you can see the dielectric constant comes down and that is, because of the how we the mechanism which contributes to the dielectric constant of the permittivity. It depends on several factors and you can see that in the resin which is unfilled that means no nanoparticles are added to that resin. That is the black squares and that has got the lowest values when you add some nanoparticles say you add silica nanoparticles 1 percent of silicon nanoparticles those are the red dots. And the red dots are some where here and these red dots actually tell you that the value of the dielectric constant is always much higher than what you have when there is no nano silica.

So, the red ones are for nano silica the green ones are for nano titania and the blue ones are for nano alumina. Whatever be the material just 1 percent of the nano sized material of any of these 3 increases the relative permittivity that means means increases the dielectric constant by some value. You see the numbers go from 5 to 6.5 here and here the numbers go from say 3.75 to somewhere 4.25 or something 4.1. So, adding nanofillers inorganic nanofillers which means metal oxide nanofillers are upside like silica, titania, alumina is shown here If you add them even by a small amount then the permittivity of the polymer enhances.

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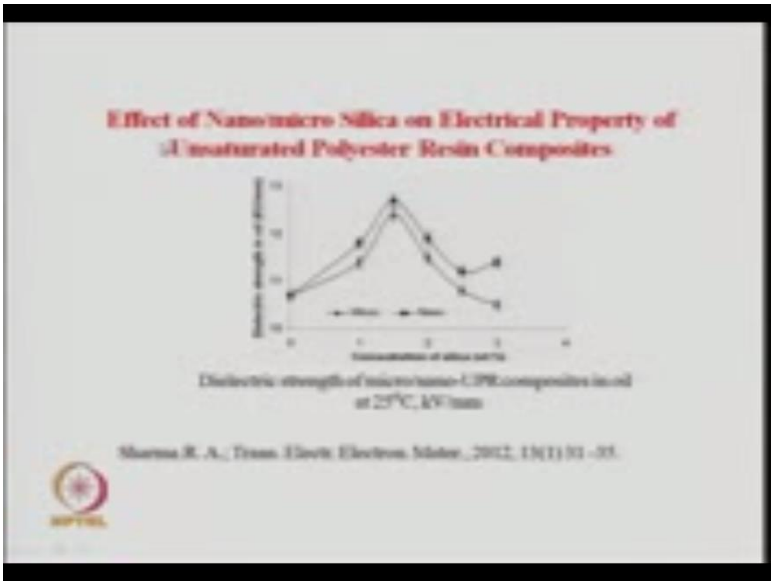

This is another example, where you see that a on adding small amount of silica. So, this is between 1 and 1.5 percent the dielectric strength increases and goes to a maximum. And this is kind of similar to what we have seen earlier in barium titanate where dielectric constant increases at by the addition of nano dopants. So, this is addition of silica in an unsaturated polyester resin nanocomposite dielectric strength enhances you have nano silica the nano silica shows always higher values. And the micron size silica always show lower values when you have increase the concentration of silica in weight percent in the polymer resin.

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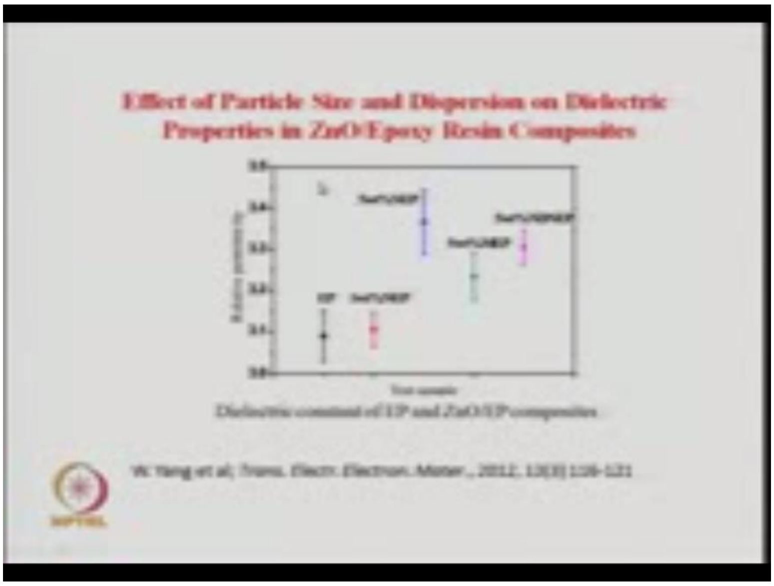

This is another example of a polymer raisin with zinc oxide and the dielectric constant, you can see to different a materials with different epoxy you have added zinc oxide. And you can see that with simple epoxy is here and when you add 1 percent or 5 weight percent you have much larger permittivity compared to the epoxy as such. So, with this we will come to close to our lecture today. And so we have finished 2 lectures on the dielectrics and this is the fifth lecture of the module 4. And we will continue our lectures of module 4 and we will now look at magnetic nanoparticles and properties of magnetic nanoparticles in the next lecture.

Thank you.