Nature and Properties of Materials
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Lecture 38
Electric Properties 2

In the last class, we have talked about some of the electrical properties of materials. We have talked about resistance, we have talked about resistivity, and we have talked about conductivity of metals, of polymers and of ceramics. Now we will talk about another very important electrical property of the material and that is the dielectric property of the material. It is just the reverse side of the conductivity that means if a material is not conductive, and then it is possible that it is a dielectric material or so to say very commonly says that it is an insulating material.

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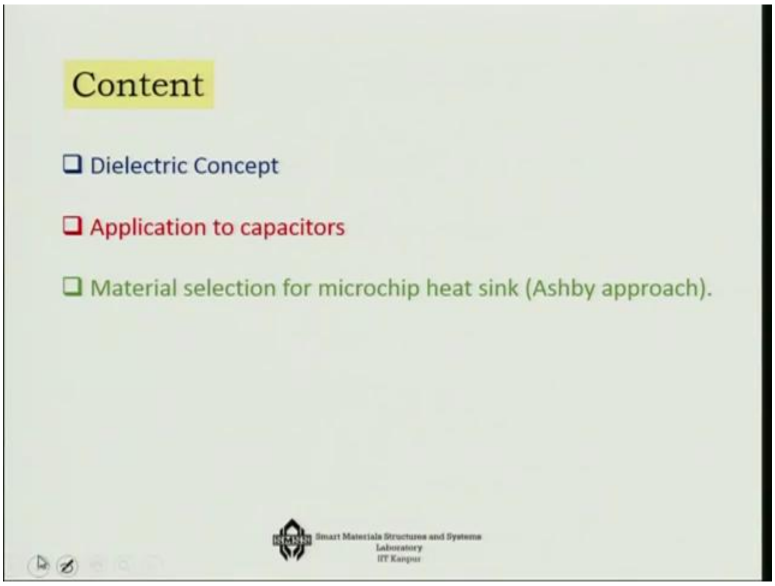

Content

❑ Dielectric Concept

❑ Application to capacitors

❑ Material selection for microchip heat sink (Ashby approach).

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But what is this concept of dielectricity that we will see and we will see that how it is applied to the capacitors. Finally, we will also do a small material selection again exercise for microchip heat sink using the Ashby approach. So these are the 3 things which is our learning goal in today's lecture.

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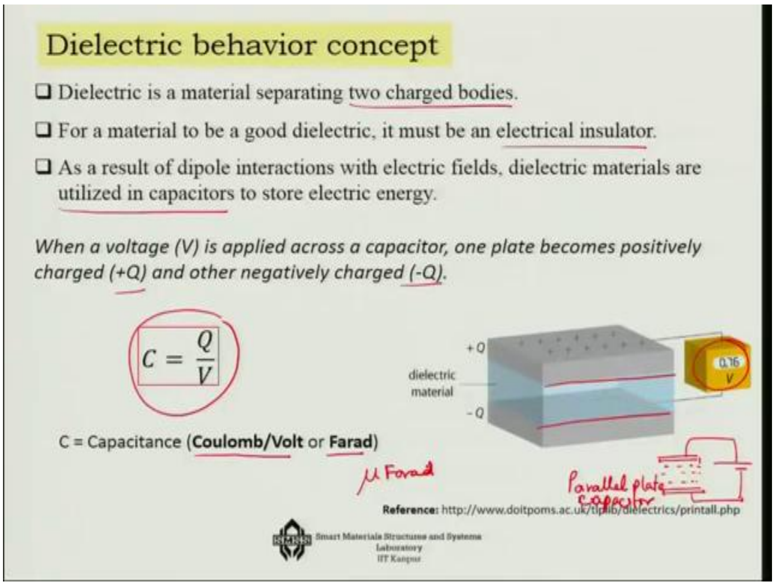

Dielectric behavior concept

- ❑ Dielectric is a material separating two charged bodies.
- ❑ For a material to be a good dielectric, it must be an electrical insulator.
- ❑ As a result of dipole interactions with electric fields, dielectric materials are utilized in capacitors to store electric energy.

When a voltage (V) is applied across a capacitor, one plate becomes positively charged (+Q) and other negatively charged (-Q).

$$\boxed{C = \frac{Q}{V}}$$

C = Capacitance (**Coulomb/Volt** or **Farad**)

μ Farad

Reference: http://www.doitpoms.ac.uk/tlplib/dielectrics/printall.php

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Now, about 1st the dielectric behavior concept, dielectric is generally is a material which is used to separate 2 charged bodies, so for a material to be a good dielectric; it must be an electrical insulator. Now, as a result of the dipole interactions with electric fields, dielectric materials are actually utilized in capacitors to store electric energy. You must have seen that very common example of a parallel plate capacitor, where we have 2 conducting plates and you have the dielectric material in between and what is it we call it when we apply high-voltage to the system, we call this to be a parallel plate capacitor, which is an example of this type of a parallel plate capacitor dielectric system.

So, when a voltage V is applied for example, that is what we have shown here across the capacitor, one plate becomes positively charged + Q and the other becomes negatively charged because electron is not able to freely conduct between the 2, so just the plates would become charged because in between you have the insulating medium okay, so that create the separation of charges and which remains stationary between the 2.

And the capacitance C is described by this very common equation, which is C = Q over V, where C is the capacitance which is coulomb per volt or Farad, is generally the unit for capacitance. Of course, the type of capacitors that you will usually see is 10 to the power - 3 farad or so to say microfarad that is the more common types of capacitance you will usually see. Now, while talking about these dielectrics, we have to also start our story from a little behind, we have to start our story from the polarisation.

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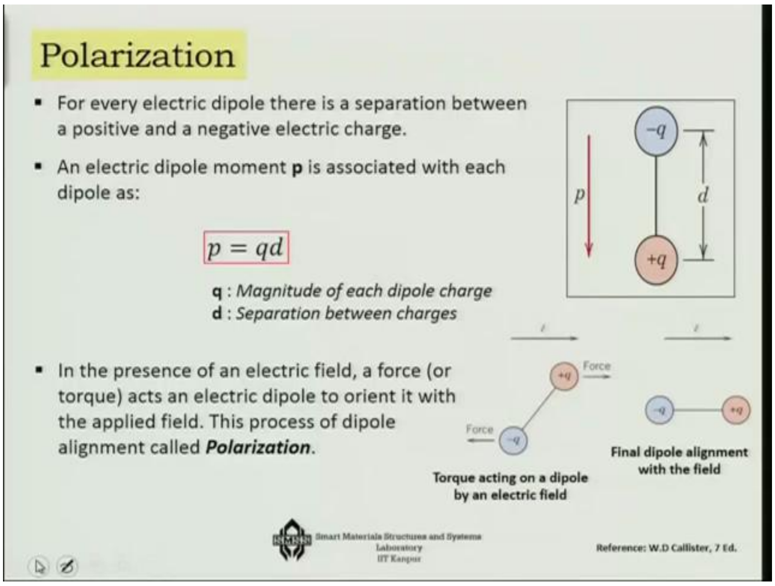

Polarization

- For every electric dipole there is a separation between a positive and a negative electric charge.
- An electric dipole moment **p** is associated with each dipole as:

$$\boxed{p = qd}$$

q : *Magnitude of each dipole charge*
d : *Separation between charges*

- In the presence of an electric field, a force (or torque) acts an electric dipole to orient it with the applied field. This process of dipole alignment called ***Polarization***.

Torque acting on a dipole by an electric field

Final dipole alignment with the field

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Reference: W.D Callister, 7 Ed.

For every electric dipole, there is dipole means whenever you have a negative charge and a positive charge like this okay, there is a separation distance between the positive and the negative electric charge, right. For any dipole 2 polar bipolar system with negative and positive charge, there is a separation distance d. And so that the force that works between these 2 is called the Coulomb force, right Coulomb force. And this also follows the inverse square law so it is actually proportional to the, force is proportional to the charge and then is inversely proportional to the square of the distance between the 2 poles.

Now, the force that works like this that is separated by a distance d will actually create a dipole moment p and this moment can be actually expressed in terms of the magnitude of the dipole charge q times the separation between the charges d, so this is the dipole moment. And if there is a electric field a force or torque acts as an electric dipole to orient it with the applied field and this process of dipole alignment is called Polarisation.

For example, you have a charge q, - q and they are short of having the forces interacting and they are subjected to an external force. This external force will actually try to electric field type of force will actually reorient them, so this will rotate, reorient them with the direction of the external force and this activity is called Polarisation.

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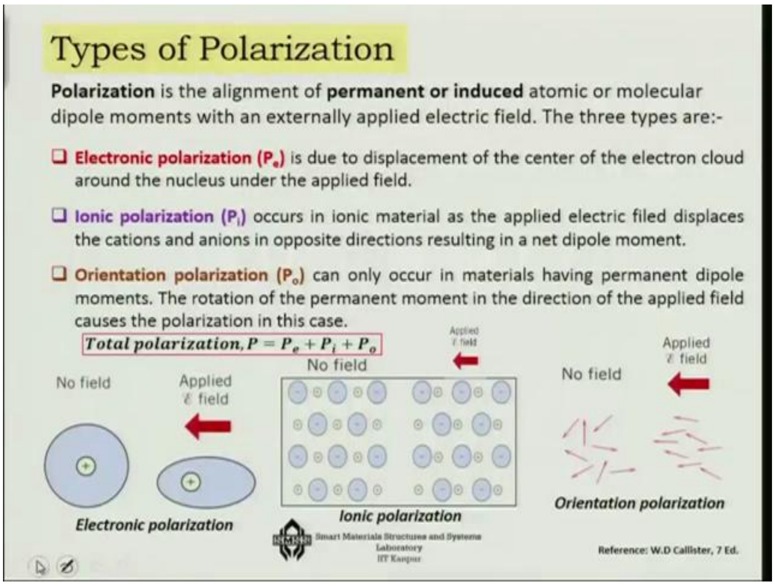

Types of Polarization

Polarization is the alignment of **permanent or induced** atomic or molecular dipole moments with an externally applied electric field. The three types are:-

- ☐ **Electronic polarization (P_e)** is due to displacement of the center of the electron cloud around the nucleus under the applied field.
- ☐ **Ionic polarization (P_i)** occurs in ionic material as the applied electric filed displaces the cations and anions in opposite directions resulting in a net dipole moment.
- ☐ **Orientation polarization (P_o)** can only occur in materials having permanent dipole moments. The rotation of the permanent moment in the direction of the applied field causes the polarization in this case.

$\boxed{Total\ polarization, P = P_e + P_i + P_o}$

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Reference: W.D Callister, 7 Ed.

Now there are several types of polarisation is like alignment of permanent or induced atomic or molecular dipole moments with an externally applied electric field. There are 3 types of polarisation which are very common are, one is Electronic polarisation, as the name suggests this is due to the displacement of the centre of the electron cloud around the nucleus under the applied field. And then there is Ionic polarisation P I, this occurs in ionic materials as the applied electric field displaces the cations and anions in opposite direction resulting in a net dipole moment, so that is the Ionic polarisation.

And then there is a 3rd type of polarisation which is known as Orientation polarisation, this I actually when I have talked about the smart materials I told you that this only happens in some materials, which are having permanent dipole moments okay, like this (())(7:01) crystals I told you that which has permanent dipole moments in it. The rotation of the permanent moment in the direction of the applied field causes the polarisation.

So once again the Electronic polarisation P e, which is due to the electron cloud displacement, Ionic polarisation occurs in ionic materials like all ceramics materials which are basically having Ionic bonds and then electric field displaces the cations and anions in opposite directions, so we will see this. And Orientation polarisation only in certain very specific group of you called Non-Centro symmetric crystals like this (())(7:48) type of system, where you are going to see the Orientation polarisation. Now the total polarisation P is then can be expressed as a submission of the Electronic polarisation, Ionic polarisation and Orientation polarisation.

So here in the figure we have explained the same thing to you that under no field this is the system, but as you apply the electric field, then the electron cloud shifts itself and that is the Electronic polarisation. In the Ionic polarisation, you can see that this happens with the Ionic system itself that they reorient themselves as you can see it here. And for the Orientation polarisation, where you have randomly dipoles aligned dipole, the moment you apply the field, all of them approximately aligned themselves towards this direction of the applied field that is the orientation polarisation.

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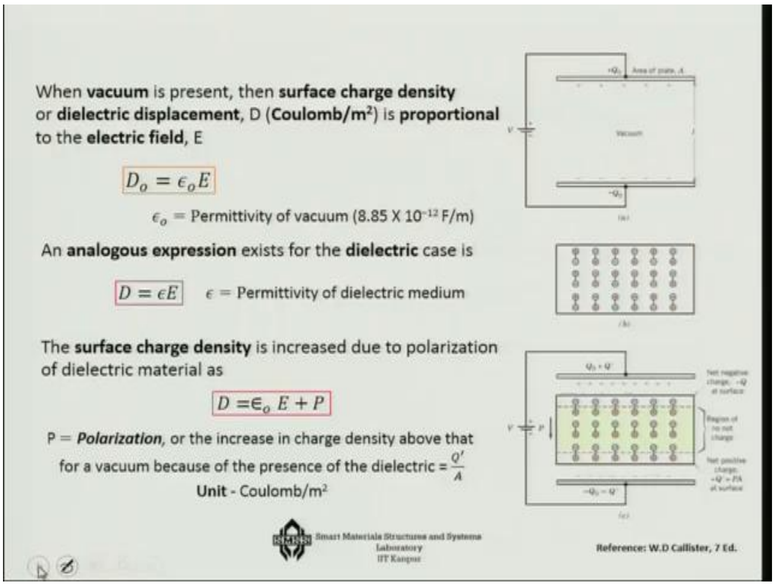

When **vacuum** is present, then **surface charge density** or **dielectric displacement**, D (**Coulomb/m^2**) is **proportional** to the **electric field**, E

$$\boxed{D_o = \epsilon_o E}$$

ϵ_o = Permittivity of vacuum (8.85 X 10^{-12} F/m)

An **analogous expression** exists for the **dielectric** case is

$\boxed{D = \epsilon E}$ ϵ = Permittivity of dielectric medium

The **surface charge density** is increased due to polarization of dielectric material as

$$\boxed{D = \epsilon_o E + P}$$

P = ***Polarization***, or the increase in charge density above that for a vacuum because of the presence of the dielectric = $\frac{Q'}{A}$

Unit - Coulomb/m^2

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Reference: W.D Callister, 7 Ed.

When vacuum is present, so now we are talking about quantification of the dielectric field. When vacuum is present, then surface charge density or dielectric displacement we will call it D is actually proportional to the electric field okay, D if there is a vacuum here, then D is Epsilon 0 times E, where Epsilon 0 is the permittivity of the vacuum which is in terms of farad it is of course as I told you that is even smaller than microfarad, very-very small something close to Pico farad, it is 8.85 into 10 to the power - 12 farad per meter.

Any other material and analogous expression exists for dielectric case, which is D = Epsilon E, where Epsilon is the permittivity of dielectric medium. So the surface charge density is possible due to 2 things, one is due to the applied electric field and another is due to the polarisation, so hence D is Epsilon 0 E + polarisation, so P is here the polarisation or the increase in charge density above that for a vacuum because of the presence of the dielectric medium that is there.

And as you can see that this is what is also explained in this particular figure that the moment you apply this voltage, there is net negative charge at the surface, there is a net positive charge at the other surface and accordingly the dielectric medium orients and there is a region of no net charge which will be there. Actually as you increase the voltage, this starts to penetrate actually and as it penetrates more and more, there could be a dielectric breakdown a dielectric sharp break down that means its capacity of holding the charge will suddenly break and that will be a collapse of the insulator.

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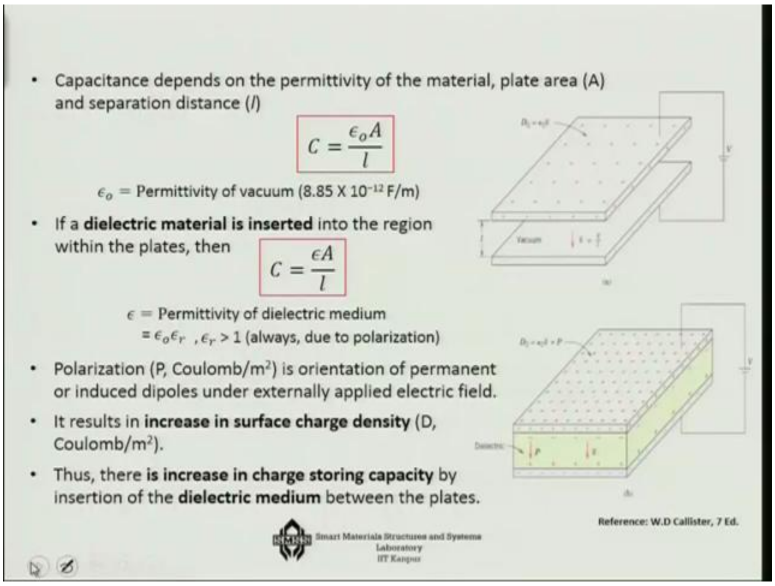

- Capacitance depends on the permittivity of the material, plate area (A) and separation distance (*l*)

$$\boxed{C = \frac{\epsilon_o A}{l}}$$

ϵ_o = Permittivity of vacuum (8.85 X 10^{-12} F/m)

- If a **dielectric material is inserted** into the region within the plates, then

$$\boxed{C = \frac{\epsilon A}{l}}$$

ϵ = Permittivity of dielectric medium
$= \epsilon_o \epsilon_r$, $\epsilon_r > 1$ (always, due to polarization)

- Polarization (P, Coulomb/m^2) is orientation of permanent or induced dipoles under externally applied electric field.
- It results in **increase in surface charge density** (D, Coulomb/m^2).
- Thus, there **is increase in charge storing capacity** by insertion of the **dielectric medium** between the plates.

Reference: W.D Callister, 7 Ed.

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Now the capacitance depends on the permittivity of the material that means it that it depends on the plate area, area of the plate. Of course, when you will calculate the area of the plate, you have to find out what is the common area of the plate. Suppose this plate is slightly bigger, in that case still the overlapping area will be this much with the plate in the bottom, so that is the common area. And then Epsilon 0 that is permittivity of vacuum divided by the separation distance L between the 2 which is the separation distance between the 2.

The same thing is also true for the any other dielectric medium, where C is Epsilon A over L, where Epsilon is the permittivity of dielectric medium and that is Epsilon 0 times Epsilon r that is Epsilon 0 is the vacuum permittivity and Epsilon r is the relative permittivity, Epsilon r is always greater than 1. Then polarisation is the orientation of permanent or induced dipole under externally applied electric field I already told you.

And it results in increased in the surface charge density D, which is measured in Coulomb per meter square, so thus there is increase in charge storing capacity by insertion of the dielectric medium okay because in comparison to the vacuum it has Epsilon r which is greater than unity, so there will be more charges that you will be able to store if you insert a dielectric medium in the system.

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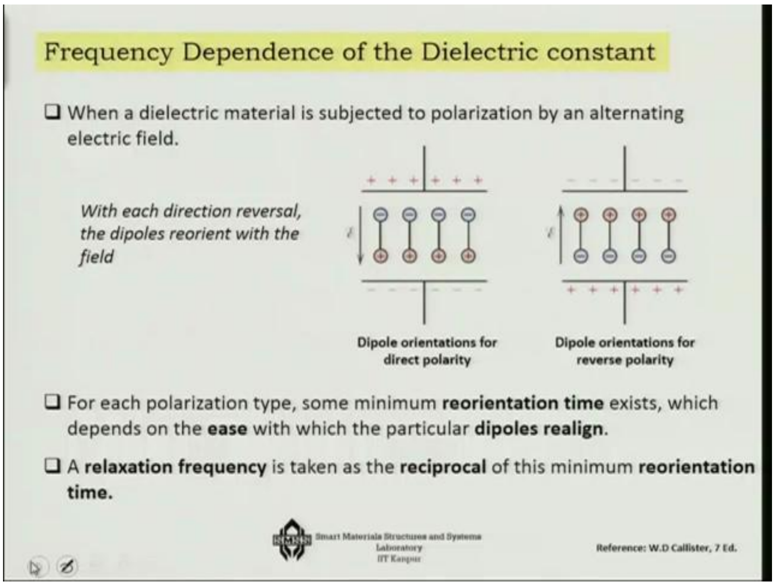

Frequency Dependence of the Dielectric constant

❑ When a dielectric material is subjected to polarization by an alternating electric field.

With each direction reversal, the dipoles reorient with the field

Dipole orientations for direct polarity

Dipole orientations for reverse polarity

❑ For each polarization type, some minimum **reorientation time** exists, which depends on the **ease** with which the particular **dipoles realign**.

❑ A **relaxation frequency** is taken as the **reciprocal** of this minimum **reorientation time.**

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Reference: W.D Callister, 7 Ed.

This dielectric constant, it has a frequency dependence for example, when it is subjected to polarisation by an alternating electric field, then with each direction reversal, the dipoles will reorient itself with the field, so this is the case where dipole orientation for direct polarity and then as you change, then this negative will become positive, this positive will become negative so a dipole reversal is happening.

For each polarisation type, some minimum reorientation time high over exists, it cannot happen very-very fast okay. So it all depends on the ease with which the particular dipoles will realign and this is actually how fast it can do is governed by its relaxation frequency, which is taken as the reciprocal of this minimum reorientation time of the dipole. So what happens then if I apply a electric field which exceeds its relaxation frequency?

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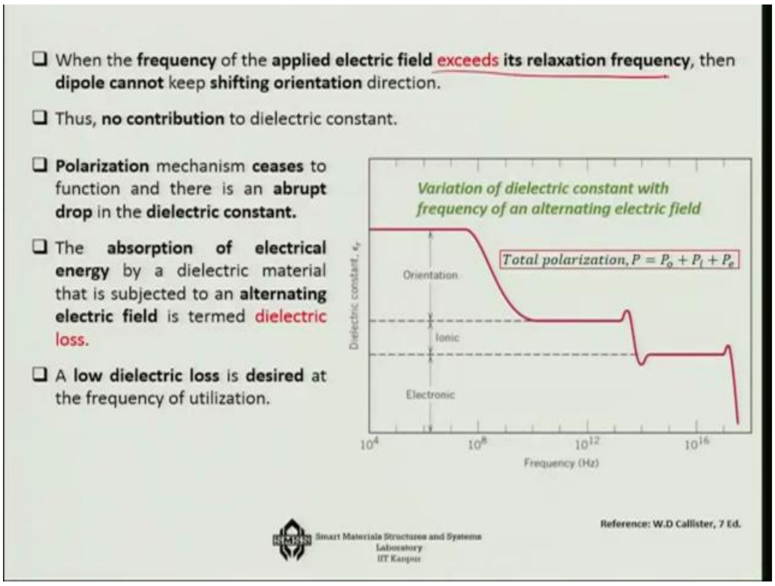

- ☐ When the **frequency** of the **applied electric field** exceeds **its relaxation frequency**, then **dipole cannot** keep **shifting orientation** direction.
- ☐ Thus, **no contribution** to dielectric constant.
- ☐ **Polarization** mechanism **ceases** to function and there is an **abrupt drop** in the **dielectric constant.**
- ☐ The **absorption of electrical energy** by a dielectric material that is subjected to an **alternating electric field** is termed dielectric loss.
- ☐ A **low dielectric loss** is **desired** at the frequency of utilization.

Variation of dielectric constant with frequency of an alternating electric field

Total polarization, $P = P_o + P_i + P_e$

Reference: W.D Callister, 7 Ed.

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Of course, dipole will not be able to keep shifting orientation of the direction thus there will be no contribution to the dielectric constant. And polarisation mechanism ceases to function; there is an abrupt drop in the dielectric constant of the material. So you can see here that the dielectric constant with respect to frequency as you can see here that I am increasing the frequency gradually from like kilo hertz to megahertz, gigahertz levels onwards. And the dielectric constant initially is stable, but then it actually fails so it is coming down okay.

And then it is remaining stable and then it further comes down. Finally, so the point is first what is going to fail is the Orientation polarisation, 2nd is the Ionic polarisation, and finally if it is very-very fast electric field, then it is Electronic polarisation which is going to fail and it will not be able to follow and there will be a sharp breakdown of the dielectric constant, so this you will see a dielectric loss in the system. Now of course a low dielectric loss is what is desired at the frequency of utilization.

So for example, when we actually transfer power a high-voltage power from position A to position B. This property is very-very important that whatever is the line frequency, with respect to that line frequency the relaxation frequency should be such that the particularly the orientation losses what you expect and that should not happen okay, so that is how you have to choose the material.

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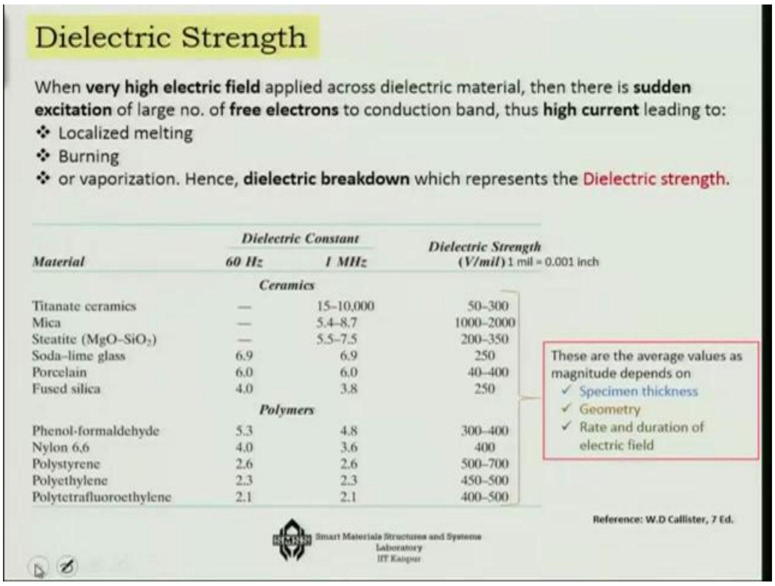

Dielectric Strength

When **very high electric field** applied across dielectric material, then there is **sudden excitation** of large no. of **free electrons** to conduction band, thus **high current** leading to:

- ❖ Localized melting
- ❖ Burning
- ❖ or vaporization. Hence, **dielectric breakdown** which represents the Dielectric strength.

Material	*Dielectric Constant* *60 Hz*	*Dielectric Constant* *1 MHz*	*Dielectric Strength (V/mil)* 1 mil = 0.001 inch
		Ceramics	
Titanate ceramics	—	15–10,000	50–300
Mica	—	5.4–8.7	1000–2000
Steatite ($MgO–SiO_2$)	—	5.5–7.5	200–350
Soda–lime glass	6.9	6.9	250
Porcelain	6.0	6.0	40–400
Fused silica	4.0	3.8	250
		Polymers	
Phenol-formaldehyde	5.3	4.8	300–400
Nylon 6,6	4.0	3.6	400
Polystyrene	2.6	2.6	500–700
Polyethylene	2.3	2.3	450–500
Polytetrafluoroethylene	2.1	2.1	400–500

These are the average values as magnitude depends on
- ✓ Specimen thickness
- ✓ Geometry
- ✓ Rate and duration of electric field

Reference: W.D Callister, 7 Ed.

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So when very high electric field, so the other point is I told you that if you apply the voltage a very high voltage, then there is a sudden excitation of large number of free electrons to conduction band and thus high current will lead to either localised melting or burning or vaporization and that is called the dielectric breakdown, which represents the Dielectric strength. So you have to think of 2 things, one is the frequency and another is the dielectric strength.

So for many materials like common insulating materials like suppose titanate ceramics, its dielectric constant is 15 to 10,000 at 1 megahertz level and dielectric strength is about 50 to 300 voltage per mil, where one mil is 0.001 inch, it is still the kind of a PS unit which is important here, which is used here. For mica, which is also used as very good dielectric material, it is 5.4 to 8.7 and that is the dielectric constant, strength is 1000 to 2000. Then there are some natural materials steatite, soda, et cetera and porcelain which is very commonly used is about 6, dielectric strength is about 40 to 400. Fused silica, it is about 3.8, it is about 250 volt per mil is the dielectric strength.

How about the polymers? Well, some polymers show excellent dielectric strength like Phenol Formaldehyde 4.8, but the strength is 300 to 400 quite comparable to porcelain, nylon is about 400 okay. So what is low for them is generally the dielectric constant is low for them, but they have a good valley of the PTFE for example, Polytetrafluoroethylene, they have good value of dielectric strength. Now these are the average values of magnitude, but it also depends on the specimen thickness, the geometry, rate and duration of electric field, all these things comes into picture, but this is like the average value that you will find in these materials.

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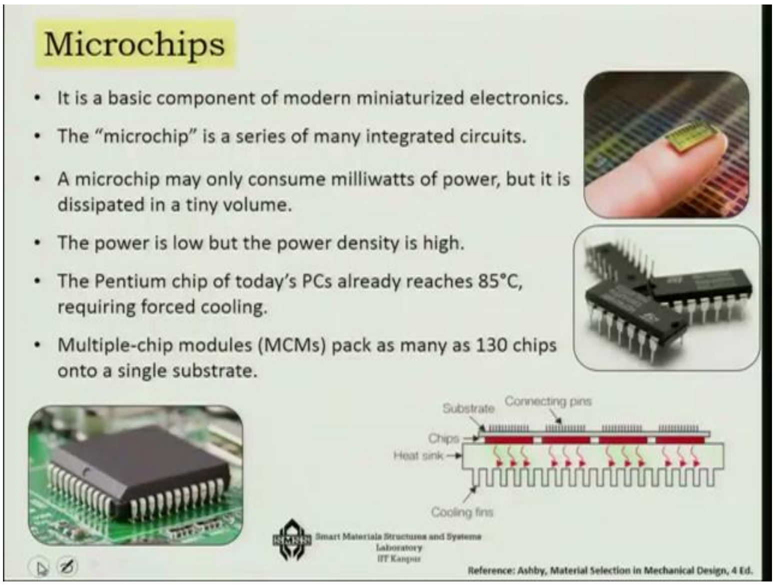

Microchips

- It is a basic component of modern miniaturized electronics.
- The “microchip” is a series of many integrated circuits.
- A microchip may only consume milliwatts of power, but it is dissipated in a tiny volume.
- The power is low but the power density is high.
- The Pentium chip of today’s PCs already reaches 85°C, requiring forced cooling.
- Multiple-chip modules (MCMs) pack as many as 130 chips onto a single substrate.

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Reference: Ashby, Material Selection in Mechanical Design, 4 Ed.

I am going to talk about one exercise that we have said that this will be related to the material selection for the Micro chips heat sink okay, so let us see that how we can do it and this is an exercise towards another application of Ashby chart for a non-mechanical property set. This is a very interesting one, you must have seen the microchips right, any computer system any miniaturized electronics is full of such microchips. Now this microchip is a series of many integrated circuits, which are there and they consume milliwatts of power, but it is dissipated in a very-very tiny volume.

As a result the power is low, but the power density is high. The Pentium chip of today for example, that reaches the temperature of 85 degree centigrade, so which means you have to cool it constantly otherwise, the chip will not work. Multiple chip modules MCMs pack as many as 130 chips onto a single substrate and imagine each one each one of them is reaching a temperature level of 85 degrees centigrade, so you have to have a lot of cooling arrangement and this is where the heat sink comes into picture.

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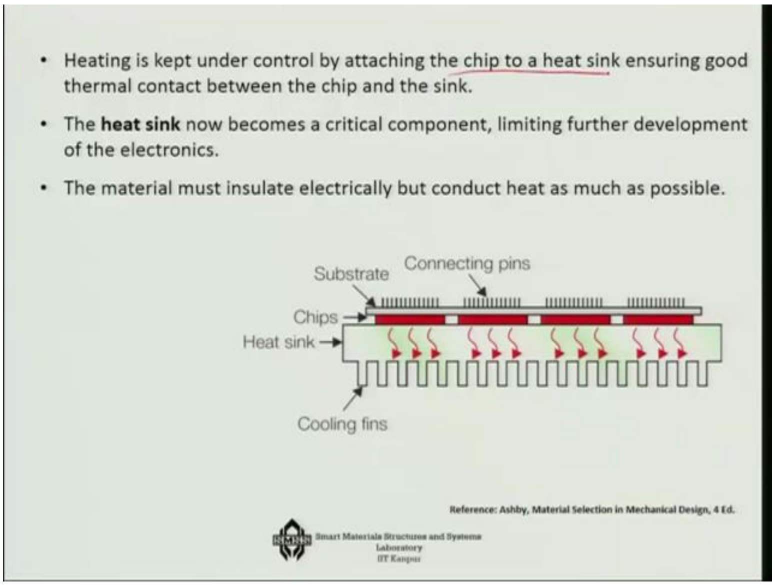

- Heating is kept under control by attaching the chip to a heat sink ensuring good thermal contact between the chip and the sink.
- The **heat sink** now becomes a critical component, limiting further development of the electronics.
- The material must insulate electrically but conduct heat as much as possible.

Reference: Ashby, Material Selection in Mechanical Design, 4 Ed.

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So as you can see here, so suppose this is the chip here okay and then there is a substrate, they are connecting pins with which it is, one side is fixed the circuit and towards the computer, the backside of it you have the heat sink and the cooling fans in the backside of the heat sink. Now, when we have to select a material here, the heating is kept under control by attaching the chip to this heat sink which ensures a good thermal contact between the chip and the sink. So the heat sink has now become a critical component, limiting the further development of the electronics.

If your heat sink is if you can make it more efficient, then you can have you can pack more electronic circuit in a smaller area. So the choice of material for the heat sink is very-very important. Now what is the contradiction here, that it must insulate electrically, but conduct heat as much as possible? That means from the chip, it should only conduct the heat but not the electricity that is what we will see is very important.

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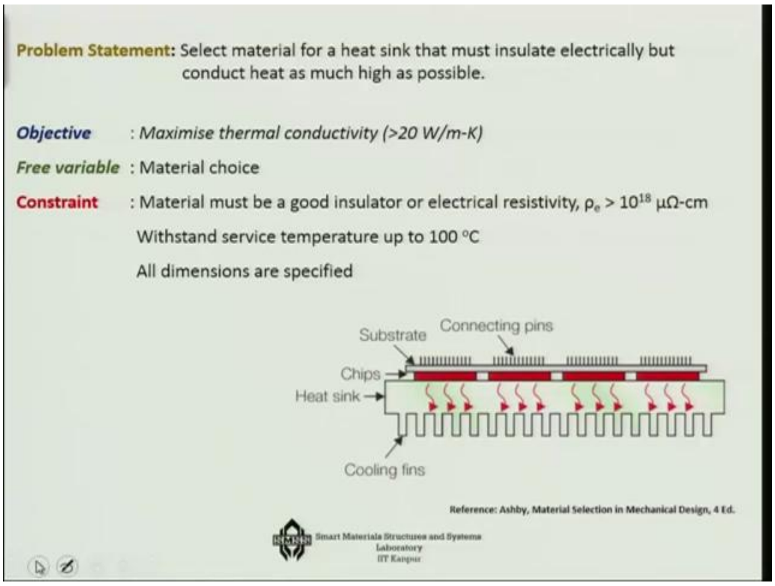

Problem Statement: Select material for a heat sink that must insulate electrically but conduct heat as much high as possible.

Objective : *Maximise thermal conductivity (>20 W/m-K)*

Free variable : Material choice

Constraint : Material must be a good insulator or electrical resistivity, $\rho_e > 10^{18}$ µΩ-cm

Withstand service temperature up to 100 °C

All dimensions are specified

Reference: Ashby, Material Selection in Mechanical Design, 4 Ed.

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So select a material for a heat sink that must insulate electrically but conduct heat as much as possible. In other words, you have to maximise the thermal conductivity, but minimise the electrical conductivity or at least say that the electrical conductivity something less than something like you know, resistivity is greater than 10 to the power 18 micro Ohms centimeter. So also, the temperature it has to withstand is something like 100 degree centigrade. So with this type of condition, here we can directly actually use the Ashby chart.

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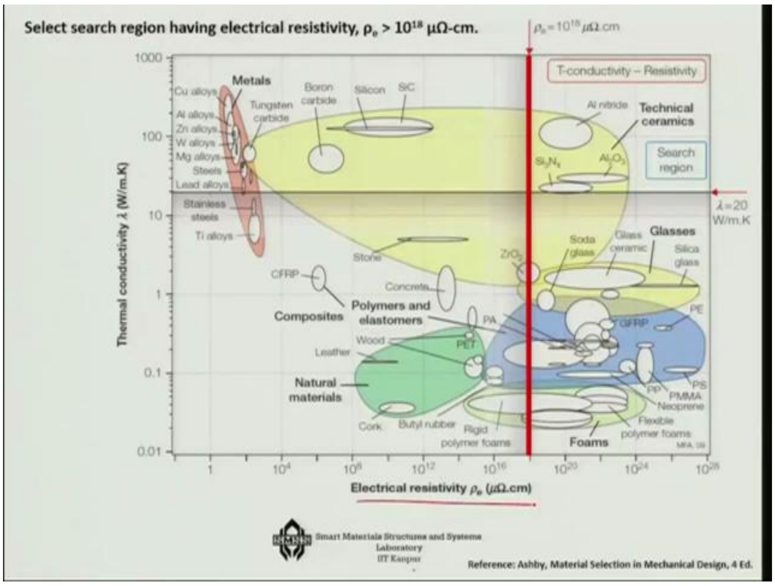

Select search region having electrical resistivity, $\rho_e > 10^{18}$ µΩ-cm.

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Reference: Ashby, Material Selection in Mechanical Design, 4 Ed.

So we need a plot of electrical resistivity in our X axis and the thermal conductivity in our Y axis, so what we want to do here is that we want to maximise the thermal conductivity and we also want to maximise the electrical resistivity because that means it will be more like an insulating material. So, if you choose certain like border like 10 to the power 18 micro ohms centimeter, then it is the top part of the curve this is where we are interested in, where you get high value of thermal conductivity and high value of electrical resistivity.

Just the opposite is this region where you get low value of electrical conductivity and low value of thermal conductivity, so low value of electrical resistivity and low value of thermal conductivity. But it is the top part we are looking at and here, what are the possibilities for us? Aluminium nitride you will see, technical ceramics like Al2O3, Si3N4, and these are the things that you will see in the top part. Now, if you further expand this you will see that there are 3 materials which will come to your focus; one is aluminium nitride, then the silicon nitride and aluminium oxide.

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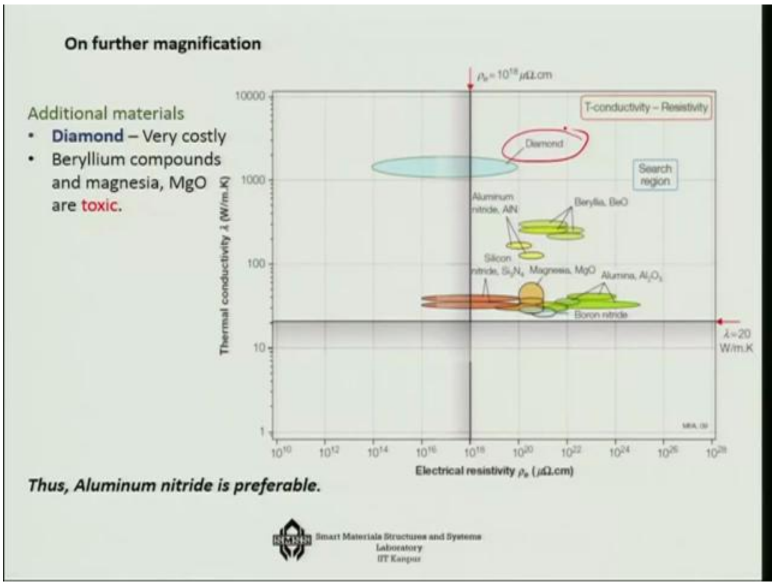

On further magnification

Additional materials

- **Diamond** – Very costly
- Beryllium compounds and magnesia, MgO are toxic.

Thus, Aluminum nitride is preferable.

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So these are the materials which are which gives you a high this electrical conductivity or so to say the resistivity, so you will get a better resistivity that is 10 to the power 18, but the thermal conductivity so which is greater than 20 watt per meter Kelvin. So with that we can get such materials for us and if you further magnify it, you will also see that there are some materials which also comes inside like diamond for example okay, which is slightly better in terms of the thermal conductivity but not in terms of electrical resistivity. Of course, diamond is very-very expensive, then the beryllium compounds are also there beryllia, but I told you that beryllia is toxic.

Magnesium oxide is also there, that is also generally not used as that is also toxic. Thus, we can see that the safe bid is actually the Alumina, so alumina or silicon nitride either of them is the safe bid for us, so this is how we can select the material. Now in the next lecture we will learn about the magnetic properties of a system, thank you.