**Electronic Packaging and Manufacturing**
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**Lecture – 22**
**Thermal Management – I: Introduction**

Good evening, welcome back to the course on Electronic Packaging and Manufacturing. And today, we start on a very important topic which is on thermal design and cooling ok. Let me start by saying that if you look at electronic products and even packages or systems, and you look at the causes of failure majority of that can be attributed to overheating, due to thermal if I make use the word mismanagement, so why does this happen ok.

So, let me take a step back and try to explain, why thermal management is important. When you when you have a circuit or when you have a circuit board or a device, let us take just the microprocessor for example when you switch it on, and you have all this circuitry working inside. We know that there will be heat generation because of losses i squared r losses joule heating. So, this heat if not removed or dissipated efficiently is going to lead to a rise in temperature ok.

And finally, every device because of its material constraints as well as you know as well as the requirement for proper functioning has a certain threshold temperature beyond which it cannot operate either its performance goes down, and in the worst case it just gets damaged or if I may use loosely a term called fried ok. So, as the heat is getting generated, it is important to remove the heat efficiently, so that the temperature remains within that acceptable threshold ok.

Now, what is the problem here? If you look at this VLSI-Very Large Scale Integration ULSI-Ultra Large Scale Integration, and also if you look at the system level, so one VLSI is within the microprocessor or the chip, where we are packing in more and more circuitry right. Today, in let us say a silicon chip of 1 centimeter by 1 centimeter sometimes even less, you have millions of transistors inside ok. Each of them probably dissipating a few milli watts, but you add them up you see how much of power its dissipating ok.

Similarly, if you look at a system if you look at your laptop computer for example, we have so much of features inside, we have a microprocessor which is a CPU, we have the graphics, we have memory, we have wireless, we have this controller hub, we you have the optical disk drive ones that still come with the optical disk drive the CD drives, you have the hard drive or the flash memory or the flash drive. And then you have all these other components like the voltage regulators VR, and the passives, amplifiers, power converters. So, all these are all accommodated in that small 13 inch box.

If you look at my laptop computer here, this is one of these mini ones 13 inch a motherboard inside consisting of so many different processors, each of which is dissipating heat. So, how do I remove this heat, if I do not remove, it will keep getting the temperature will keep rising and it will come to a point, where it will fail ok. So, thermal management is about that ok.

So, one thing is it really the way I describe it, it really comes as an afterthought you know. And it is like the electrical designer or the architect as we call it the VLSI architect, he designs the microprocessor. And that dissipates let us say some x watts, when it is powered on. And then the thermal designer needs to design a cooling system, which can dissipate this x number of watts by while keeping the temperature within the acceptable limits ok.

And unfortunately, this is how for many years the design used to happen, it was called over the wall design ok. The electrical and thermal engineers would work in isolation. The electrical engineer is going to design, come up with his design and then it is over the wall means, he will just throw this design over the wall. And the other end and the other end of the wall is where the thermal engineer is present, and he takes it and tries to solve this problem ok, but things are changing now ok.

Now, the amount of power that you can dissipate, and therefore the amount of circuitry that you can pack into your microprocessor is a lot of times limited by the thermal design limited by temperature, because with products becoming smaller, thinner, etcetera. The kind of thermal solution the kind of cooling that we can offer using traditional methods is really going down.

So, therefore the thermal engineer will step up and say that look I am sorry I cannot cool beyond this ok. And therefore, I want to introduce this term today called TDP a microprocessor has something called a TDP standing for Thermal Design Power ok. So, the maximum power that can be dissipated during operation by a microchip is limited by its TDP standing for thermal design power ok.

So, you can you can understand the importance of thermals in electronics ok, thermal management is extremely critical. The unfortunate part is its not something that comes to the forefront. Number one you are not going to buy a system an electronic product, because it has a very cool thermal solution inside ok. If a product works according to its specification, then that is what the user expects. If the product does not work and gets overheated, that is when the thermal engineer gets blamed ok.

So, many a times people say that the thermal engineers job or thermal is in this industry is kind of a thankless one, it is very important, but it is a thankless job. So, one of my friends who we used to work for hp, he used to say that our work is like that of a janitor you know people will come, and you know make everything dirty, and our job is to clean it up ok.

One of my favorite analogies is if you think of a building ok, if you think of a building, and it is a very nice one and you go and you like it, you give compliment to the architect and to the builder right. But, what we what we forget is the building is running efficiently, and there are lots of other things that is involved there. There is a play the plumbing lines, there the electrical lines, there the fire safety and water lines, and all these I mean if they are there you are they are expected to be there. If they are not working of course, all hell breaks loose ok.

So, the role of a thermal designer is similar to that electrical designer in the building or the or the you know hydraulics engineer, so the one who designs his water system and so on ok. So, what I am trying to say, it is extremely important, you cannot imagine a building without electricity, you cannot imagine a building staying in a nice building, but where there is no water right you expect that. But, if it is there yes, I mean you do not say what a wonderful job, you know this designer has done we do not do we do not say that right.

So, similarly so that is there it is important, we have to do it. And we have to understand that a thermal designer even though it is very critical and important. You ask anybody they will they will anybody who works in that industry, he will say yeah its very very important.

Some people will say you thermal engine is a very painful, you do not let us add more features to the circuitry, we know how to do it. I can I have space I have the I know of an architecture, where I can have more and more features, I can have more speed, but you are not allowing us to do that, so that is the way it is alright. What I am trying to say is the importance of thermal designer in this industry that is what I have been doing for the last 20 years or so. So, you can see so if I get a little biased, and if I talk a little more passionately than the other topics, then I hope you will excuse me for that ok.

So, thermal design let us get into the topics now. The first thing that we need to understand is heat transfer ok. I think for people with mechanical engineering backgrounds, this may come as a repetition or as a recap. But, for people from other backgrounds I will try to make it I will try to brush up the essential concepts, so that when we come to electronics cooling you understand what we are trying to do ok.

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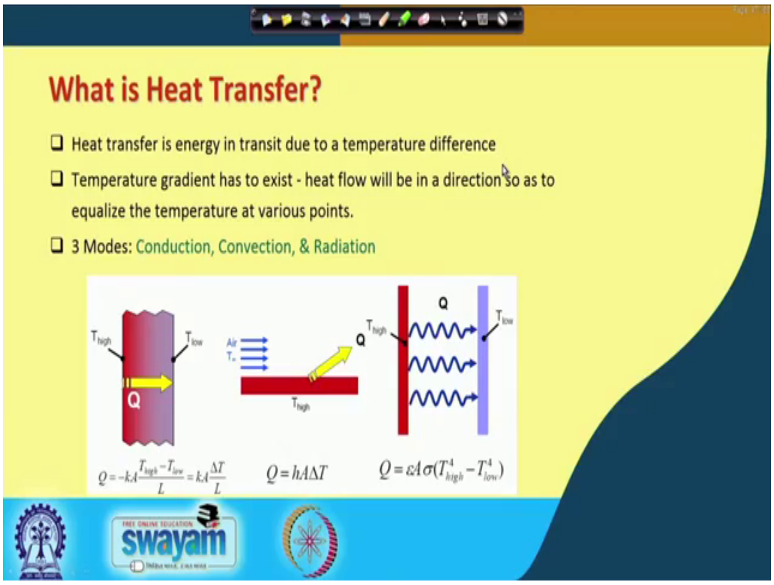


So, first we will talk about what is heat transfer ok. So, what is heat transfer? Heat transfer is energy in transit due to temperature difference, it is also thermal energy we call it. So, heat flows or thermal energy flows from a higher temperature to a lower temperature ok. And for heat to flow a thermal gradient, which is a difference in temperature, a temperature gradient must exist.

So, if you have two bodies and bring them in contact, two bodies at different temperatures, one at a higher and one at a lower, and you bring them in contact. Then we know that heat will flow from the hotter body to the colder body right. And how long will that flow, the heat will flow till the to let temperatures get equalized clear, so that is what we mean when we say that a temperature gradient has to exist, when for heat to flow.

I am sure you have all studied thermodynamics basic thermodynamics, and you recall second law, and this essentially tells the same thing ok. For heat to flow spontaneously the direction is from higher temperature to a lower temperature second law one of the statements suggest that for the heat to flow in the opposite direction that is from heat to flow from a lower temperature to a higher temperature that cannot happen, unless you do external work on the cycle right around the system work done on the system not by the system right.

So, we will talk about that because when we talk about cooling techniques, we are going to talk about refrigeration. And refrigeration is an example, where we use it every day when our refrigerators in our air conditioners, where we know that the direction of heat flow is actually from the lower temperature to the higher temperature. And that is possible, because we have a compressor which does work on the system you spend energy to make it happen, otherwise spontaneously it will not going to happen ok, so that is there is a little bit of digression, but talking about temperature gradient ok.

Now, what are the three modes of heat transfer, we know from our class 12th physics, it is conduction, convection, and radiation so conduction, convection, and radiation. So, these are the three small cartoons that I have I am showing at the bottom of the slide, which tries to give you the essence of what each of these heat transfer modes mean or imply. So, let us spend a little bit of time on this slide ok, because this is kind of I am trying to brush up an entire undergraduate, at least one half of an undergraduate heat transfer course in one slide.

So, let us try to do this. On the left hand side, what you see is conduction. Why does conduction happen, conduction happen because of you know movement of molecules or lattice vibration of molecules or lattices ok. So, so the molecules at higher temperature, vibrate with higher amplitude, and pass on the energy to the neighboring molecules, which are at a slightly lower temperature. And this is how the energy gets passed from the hotter temperature to a colder temperature ok.

So, if you have a slab over here, as I am showing you can think of it as a wall. If you look at the if you look at a cross section of a wall ok, and there exists a temperature gradient across the wall. So, you have a higher temperature on this left hand side, and a lower temperature on the right hand side. If you do that, there will be there is a temperature gradient that exists across this solid wall, as a result of which heat is going to flow ok. So, there is going to be conduction through this solid.

Now, how much heat is going to flow, there is the next question, per unit time what is going to be the heat flow ok. So, the first thing is so that is given by this expression k A delta T over L ok. So, I will take a step back and say let us go back to the drawing board.

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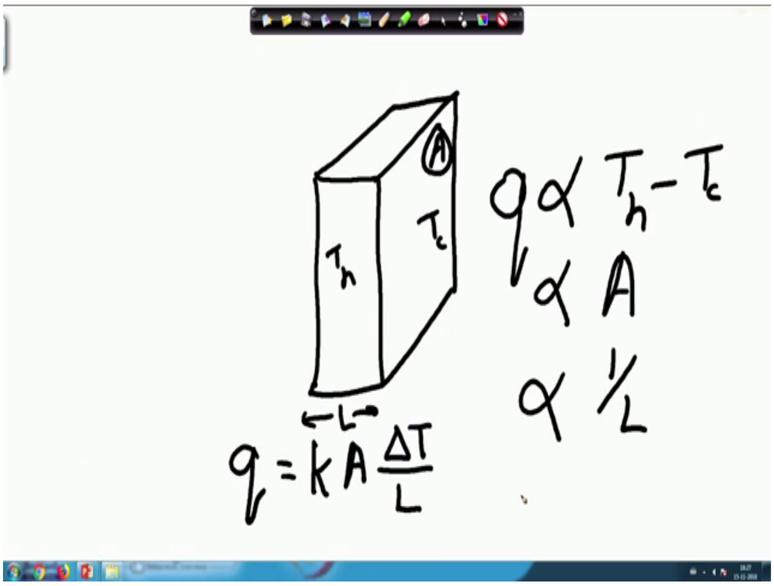


The surface area is A, this thickness is L, this face is a T h, this face is a T c. Then q is going to be proportional to number one T h minus T c or delta T, it is going to be proportional to the surface area A, and it is going to be proportional to 1 over L. So, therefore the final expression that we write is A delta T, delta T is T h minus T c over L, and the proportionality constant is written as k, and k is known as the thermal conductivity ok.

So, if we go back to this slide that is what you see here, k A delta T over L ok. So, now this thermal conductivities is a parameter of importance. If the thermal conductivity is high, then it is a good conductor thermal conductor ok. So, copper is a good thermal conductor, aluminum is a good thermal conductor, but let us say brick is not a good thermal conductor, rubber no, thermal coal very low; it is an insulator right, so that is what it is. Now, let you also say that conduction also happens in a liquid or a gas, and the same expression holds good there as well. However, there may be other modes that may become predominant alright. So, this is conduction heat transfer.

Now, what is convection heat transfer, which is what is shown on the second picture over here second cartoon. Convection is when apart from just molecular vibrations, we also have what is called a bulk flow of a fluid the solid cannot flow a fluid, let it can be liquid, it can be a gas. So, therefore the heat transfer is not just happening because of vibrations of molecules and transfer of internal energy from you know one layer of molecule to the next. But, along that along with that there is some bulk movement of the fluid molecules so; that the heat is taken away ok.

So, one example over here is let us say you have a plate or a surface at a high temperature as shown here ok, and then we have as it is placed in a in an ambient of at a lower temperature. And we have a stream of air blowing above it ok, so the air is at a temperature T infinity, which is lower than T high. So, therefore there is going to be heat transfer from this higher temperature to the lower temperature, high temperature plate to the low temperature gas air or if it can be liquid as well. So, the fluid that is flowing over it ok.

If that is the case how do I quantify, the amount of heat that is dissipated. So, again the amount of heat dissipated is going to be directly proportional to the temperature difference, it is also going to be directly proportional to the surface area of the plate ok. So, if this is my plate, then and it is held like this, then this is the surface area of the plate ok.

And it is going to depend on this parameter small h, which is known as a heat transfer coefficient. And this heat transfer coefficient unlike thermal conductivity which is a material property, this heat transfer coefficient h depends on a variety of parameters. It is going to depend on the thermal on the properties of the fluid, whether its air, whether it is water, and those properties include we will see later that properties include thermal conductivity, viscosity, density, specific heat ok.

And it is also going to be a function of the geometry whether it is a flat plate or whether it is a cylinder or whether it is a sphere, whether it is a flat plate of infinite dimensions or whether it is a flat plate of finite dimensions, so all those things. So, it depends on geometry, it depends on the fluid properties ok. And it also depends on boundary conditions, in terms of what is the temperature, whether it is uniform temperature, whether it is non-uniform temperature so on and so forth, we will look at all those later ok.

But, what I am trying to say is unlike a solid, where I say copper ok, the thermal conductivity is 400 watts per meter Kelvin at a certain temperature. But, for heat transfer coefficient if you ask me, oh I am having air flow over a flat plate, what is going to heat transfer coefficient, I will tell him ask you airflow I know at least of you have told me the fluid medium. But, what is the temperature ok, if you tell me the temperature will ask ok. What is the viscosity, and specific heat, and density, and thermal conductivity of air at that temperature you tell me that.

Then I will say alright what is the velocity at which the air is coming ok. Then what is the temperature of the difference between the plate and the air. Finally, what is the condition of the flat plate, are you maintaining at an uniform temperature or are you is a boundary condition something else, and what are the dimensions of the flat plate ok. So, so many questions on which heat transfer coefficient is going to depend on ok, so it is not that easy.

In fact, people who do research on heat transfer, and convective heat transfer a lot of it a lot of research goes into determination of this parameter h or heat transfer coefficient or some form of heat transfer coefficient alright. Then what we are going to then the 3rd mode of heat transfer is called radiation. Now, what is radiation? If first of all what is radiation ok, it is an electromagnetic waves that is generated by any surface which is at a temperature above absolute 0 ok.

If a surface by virtue of being at a temperature, above absolute 0 emits radiations ok. Now, the amount of radiation that it emits depends on several factors, but also is proportional to the 4th power of its absolute temperature ok. Now, similarly if you have another surface, which is at a different temperature that also emits radiations ok. And that emitted radiation is going to depend or is going to be proportional to the 4th power of the absolute temperature of this second surface ok.

Now, what is the net exchange between the two? If you have two such surfaces, then what happens is the radiation emitted by surface-1, part of it falls on surface-2. Similarly, the radiation emitted by surface-2, part of that falls on surface-1. And the net exchange therefore is the difference of the two ok. In a very simple case, where you know the it is it is one surface that is emitting radiation, and which is received by a large surface around it there in that case a simple expression as shown over here sigma epsilon e which is a surface area of that plate that is emitting radiation, and that is at the higher temperature times the difference of the 4th power of their absolute temperatures ok.

But, mind you this is a very specific case, so we need to keep that in mind alright. So, actually there is also something called a shape factor or view factor that comes in into this expression, and which is important. Because, shape factor determines that how much of the radiation emitted by surface-1, actually reach a surface-2 ok, so that is one.

The other thing that I want to tell you is the fact that let us also talk about what each of these each of these terms mean epsilon is known as emissivity ok. So, the amount of heat that is emitted apart from depending on the 4th power of its absolute temperature also depends on the emissivity of the surface ok. And emissivity typically lies between 0 and 1. When the emissivity is 1, it is known as a black surface sometimes also called a black body.

But, radiation when we talk about radiation heat transfer, it is more about surface, so we will call it black surface. And something that is whose emissivity is lower than one is a non-black surface ok. Emissivity can be a function of wavelength, and sometimes what we do is we take an average value of the emissivity over the wavelength the thermal wavelength over the range of thermal wavelength, and we give it a constant value and at that time, and that is called a gray body approximation ok.

So, the emissivity of a surface typically is a function of the wavelength, but if it sometimes what we do is we plot emissivity as a function of wavelength, and give it and give it an average value, and call it the gray body approximation and we say ok. So, this surface is a great body with emissivity of 0.7 ok. So, 0.7 is actually mean value, and it helps us in calculations that is it ok.

So, I think I am giving a little more details than then required, but what I am trying to do here is give you a recap of the basic modes of heat transfer ok, because this is very important. I will just end this slide, and probably this lecture as well with a last point which is on convection. So, convection again as I said is of course, when there is a bulk movement of the fluid, and the bulk movement of the fluid can happen either by spending external energy.

For example, I am saying showing here that air is flowing. And why how can this air flow the air we can flow, because if I put a fan let us say at this point, and blow air or compressor and blowing compressed air or a pump and blowing and you know pumping a liquid right. And I am doing external work on that, and I have to spend energy to do that. And that is called forced convection, because I am somehow forcing the fluid to flow over this heated surface. So, it is called forced convection.

But, sometimes if I do not do anything right, if I just take a our experience say is that right. If I just take a solid heated solid surface, and place it on my table it is going to get cooled, how? It is going to get cooled because of natural convection. I am not blowing air on that, but it gets cooled why, because the air that is right next to the hot surface will pick up heat.

And as it gets heated, its density goes down, it becomes slighter, it moves up. As it moves up, there is a partial vacuum created, and cold air from the surrounding comes over here comes down to occupy that void, which in turn again gets heated and rises up. So, this is natural convection driven due to occurring due to density difference right. So, it is also the technical term is buoyancy induced flow because of the buoyancy forces resulting from difference in density alright.

Of course, natural convection is a less efficient means, but it comes for free you do not do anything. Force convection definitely the rate of heat transfer will be much faster, but then you are having to use external energy either to power the fan or power the pump or the compressor whatever it is, whatever is your prime mover ok.

So, I will just end this lecture on this topic of force and natural convection by this analogy. You take a you have a very hot cup of tea, and they give it to you, and it is so hot that you cannot drink. What will we do, we are going to either leave it on the table, so that it gets cooled with time and that is going to be natural conversion. But, if I am in a hurry let us say I have to go to a class or have to go to a meeting, and I want to have the tea, so that I am alert (Refer Time: 30:13).

So, in such case what I will do, I will try to take it in blow air and top, what am I doing. The second one is force conversion not by a fan not by a pump, but I am using the energy from my lungs to blow this air above the hot liquid, so that the amount of heat transfer, the rate of heat transfer is increased it would get cooled faster, and so I can drink it, and go to my meeting alright. Thank you very much. And when we come back next class, we are going to take off from here and talk about the concept of heat flux and thermal resistance.

Thank you very much.