Electronic Packaging and Manufacturing
Prof. Anandaroop Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

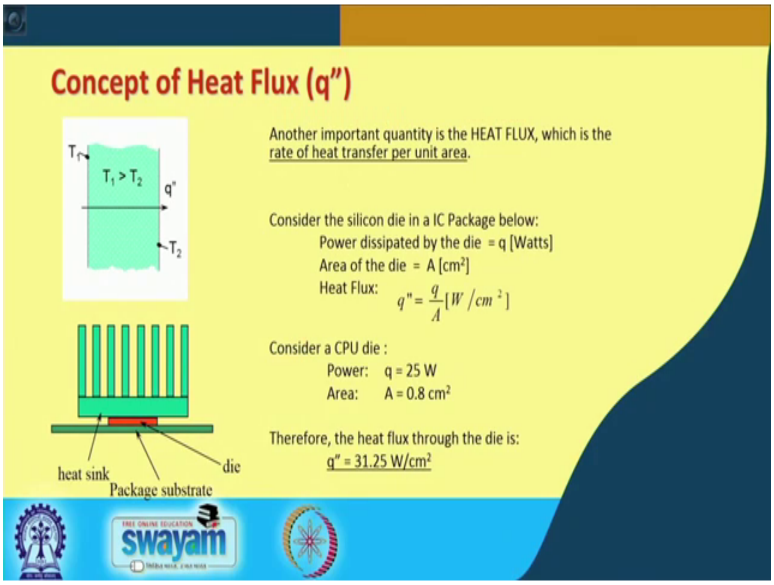
Lecture – 23
Thermal Management 2: Concepts

Welcome back to the course on Electronic Packaging and Manufacturing. In the last lecture, we have started the very important topic of Thermal Management and Cooling ok. We are introduced ourselves to the basic concept of heat transfer, and the three modes of heat transfer which is conduction, convection and radiation ok.

(Refer Slide Time: 00:48)

So, now what we will do is we will go back we will continue from there rather. And the concepts that will be covered in this lecture include the concept of heat flux and the concept of thermal resistance ok. Both are very important and we will be discussed in detail, because these are something that we are going to use very very frequently ok.

(Refer Slide Time: 01:00)



So, let us move on and look at what is heat flux what do I mean by heat flux. It is a very important quantity, because it is the rate of heat transfer per unit area. So, think about it. We were talking we were talking about a heated plate right. And let us say the heated plate is dissipating about 100 watts ok. If the heated plate is dissipating 100 watts maybe a heater is attached to its bottom and the plate is 1 meter by 1 meter ok. Can I cool it? Probably.

Now, let us say it is not 1 meter, sorry, sorry, I was wrong. It is not 1 meter by 1 meter; it is actually 1 centimeter by 1 centimeter. And then you saw my God, 100 watts over 1 centimeter squared that is going to be tough. Why? Because the amount of heat that can be dissipated either by conduction, convection or radiation what we saw in the last class. We saw that the amount of heat transfer is proportional to the surface area right.

So, therefore, whether if I may have to cool 100 watts, but if I have to cool it over 1 meter squared versus 1 centimeter squared, the challenge and therefore the technology that I need to deploy to achieve the cooling is going to be extremely to be going to be very very different. It is very very much challenging. You know the problem is why is that because heat flux which is he dissipated per unit area ok. So, it is like you know similar to if electrical wires for example, if it is a thick wire and I am passing some current that is fine. If it is a thin wire, then it becomes more difficult. So, similarly here because over there the flow is current, here the flow is heat right.

So, what I am saying is now let us say consider a silicon die in an IC package as is shown here. So, here we will see we will see this picture very often later. So, this is a CPU or a die as we are calling it. This is substrate. And on top of that I put something called a heat sink ok. People with mechanical engineer background, we have done heat transfer will definitely recognize what is a heat sink. These are typically this is a fin heat sink with parallel plate fins.

And the whole idea is we use fin heat sinks to have more surface area and therefore, more heat transfer ok. We will come to this. We will talk about fin heat sinks in great details later. But you think about it, the power is 25 watts and the area is 0.8 centimeter squared. So, therefore, what is the heat flux through that its 31.25 watts per meter squared right? Now, let us say instead of 0.8 centimeter squared, I had 2 centimeter squared, then the heat flux the heat per unit area that I need to dissipate becomes 25 by 2 which is 12.5 right.

So, from 31.25 is 12.5, correct, it is almost a two and half times reduction and the challenge is so much lesser ok. So, the kind of heat sink that I need to design therefore is going to be very different from these two cases. And the heat sink here is my thermal solution, the cooling solution right.

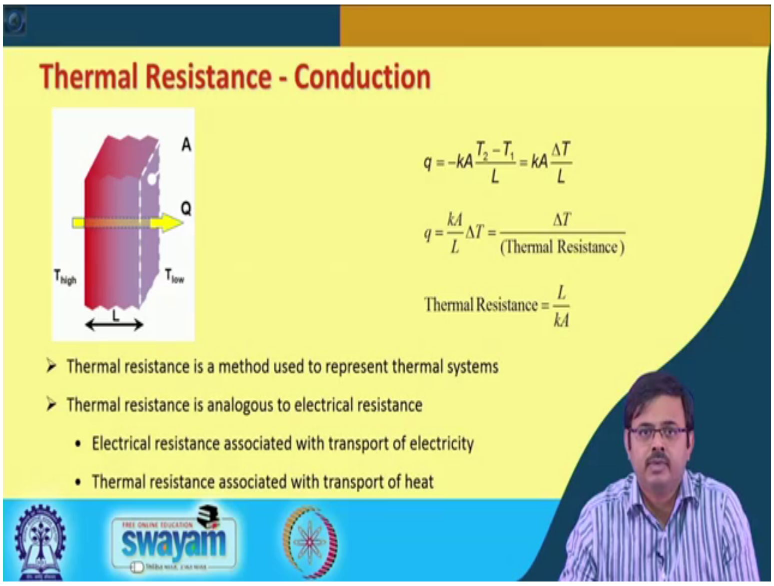
So, heat flux is very important ok. The other thing that we are going to see later is let us say for example, I am saying the die is dissipating 25 watts across an area of 0.8 centimeter squared. But you know what the challenge is this 25 watts on the dye which is probably intuitive though on the die this 25 watt is not generated uniformly, there will be areas where the heat generation will be much lesser and there will be areas that the heat generation is going to be concentrated ok.

For example, we have all heard these terms. In a CPU, you have core, you have cache. Core is where most of this computing happens. So, there is a lot of circuitry around there. Cache is where the information is stored and can be you know accessed. So, let us say you are doing a very high level computing. You need to access the data very fast right. So, the cache is the first level, where the storage happens immediately very fast right. So, the core if you if you now look into a CPU under operation and or even in the circuit, you will see a lot of the heat flux and therefore, the power and sorry the power and therefore, the heat flux is to be dissipated is concentrated over those small core regions ok.

Now, we have multi core architecture where you have multiple of there are multiple such spots where most of the heat generated and this and needs to be get this, and needs to get dissipated. So, heat flux is an extremely important term and we need to be aware of that. So, whenever somebody I mean and if you are already a thermal designer you know this. And if you once you get into this field, you will get a little more experience, this will become a very very important; this will become your friend ok. Somebody tells you oh there is this that is you know that application is a big challenge in terms of cooling.

So, really what are the kind of heat fluxes you are talking about there is the first thing I am going to ask and the second thing I am going to ask is what are the kind of temperatures that need to be cooled that that need to be maintained ok. Why is that important? We will see.

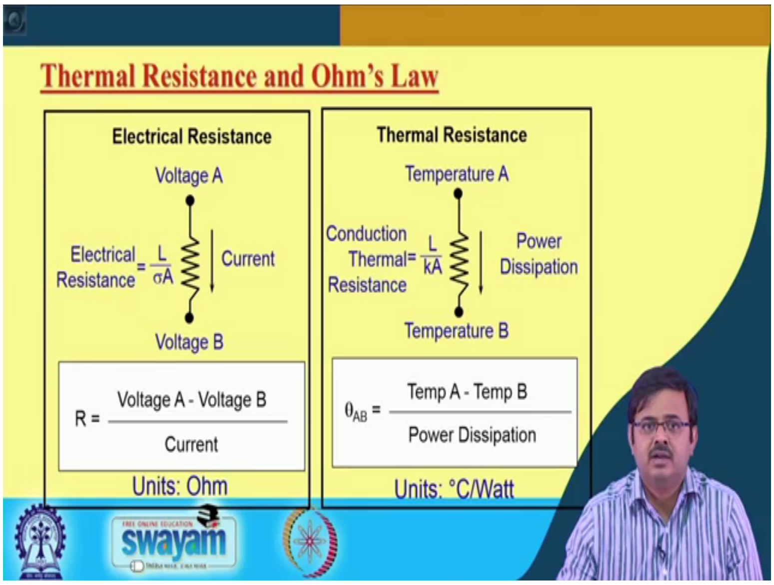
(Refer Slide Time: 07:34)



The next thing that we want to introduce is the concept of thermal resistance ok. So, let us take this conduction as the example, we saw this cartoon in the last lecture, q is ka delta T over L ok. If I you know do some rephrasing or basically rearranging the terms, I can write q is delta T over divided by L over k A, and the L over k A will call the conduction resistance. This is an extremely important concept and a tool because it helps us we will see that in the next slide. It is analogous to electrical resistance.

Now, let us look into this if you look at my second bullet point thermal resistance is analogous to electrical resistance. How, because electrical resistance is associated with transport of electricity or other electric current and thermal resistance is associated with the transport of heat or thermal energy.

(Refer Slide Time: 08:53)



Let us look at term by term what I am talking about. In an electrical circuit, what happens you need a current to flow or rather for a current to flow you need a potential difference. If it is between point A and point B, the potential of point A must be higher than point B or the potential of point B.

So, the voltage of A is greater than voltage of B, and as a result of this difference potential difference or voltage difference I have a flow of electric current. Now, how much is going to be the electric current? Well, that just does not depend just not on the delta V or the voltage difference, but also on the resistance that exists electrical resistance that exists between point A and point B. It can be electric load like a bulb or a fan or something else, a resistance.

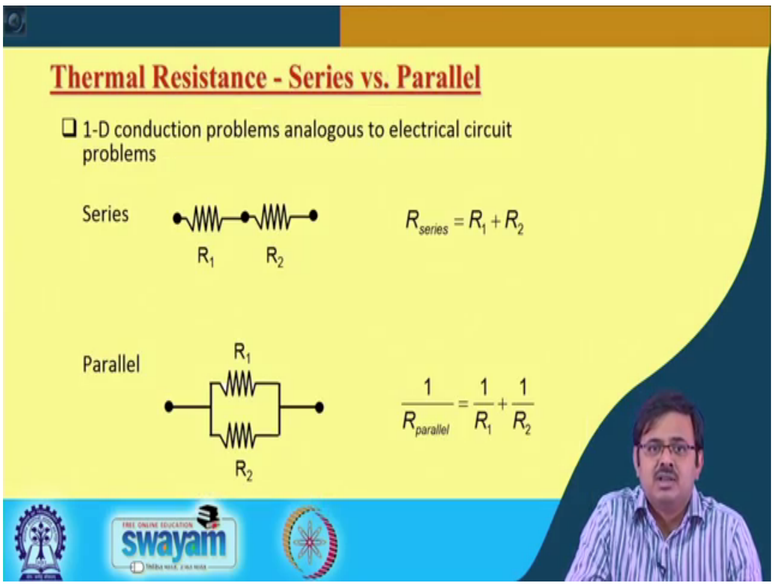
So, what is resistance from Ohms law, we have V equals to I R or R is delta V over I voltage difference divided by current. What is the voltage difference that is the driving that is the driver because of which the current flows, and the current is the, what is the parameter that gets transported or that flows ok. So, similarly if you look at thermal the conduction from temperature what is the driving force there, the temperature difference between point A and point B. And what flows so analogous to current the parameter is heat or in this case power heat per unit time ok.

So, similar to we can therefore write that there exists a thermal resistance, we can define something called the thermal resistance which is the delta T or the temperature difference divided by the power or q that flows a rate of heat transfer ok. And that as we saw in the previous slide comes to be L over k A. What is L? L is the distance through which the heat has to flow ok; the thermal energy has to flow. A is the cross sectional area; and k is the thermal conductivity.

And what is the expression of electrical resistance it is L over sigma A or rho L over A, where sigma is the electrical conductivity or rho is the electrical resistivity. If I wrote it as rho L by A, it rho is the electrical resistivity, sigma is an electrical conductivity. So, look at the look at the analogy L over sigma A, L over k A electrical conductivity, thermal conductivity.

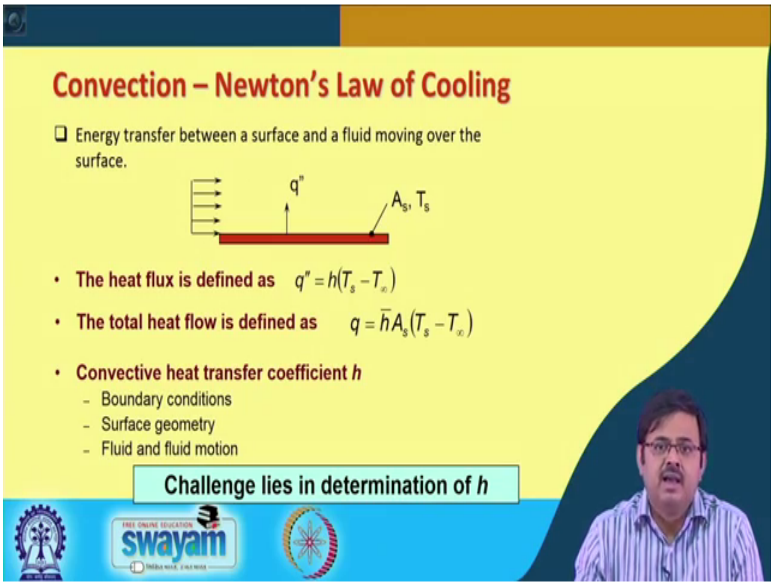
Now, unlike electrical resistance where we the unit is named after the person who first introduced this which is Ohm. Thermal resistance we really do not give credit to somebody specific to for coming up with this concept it just came out naturally it came naturally. And therefore, the units remain degree c per watt or Kelvin per watt ok. Ohm is actually what volt per ampere ok, so here it is degree c per watt, so that is the thermal resistance.

(Refer Slide Time: 12:45)



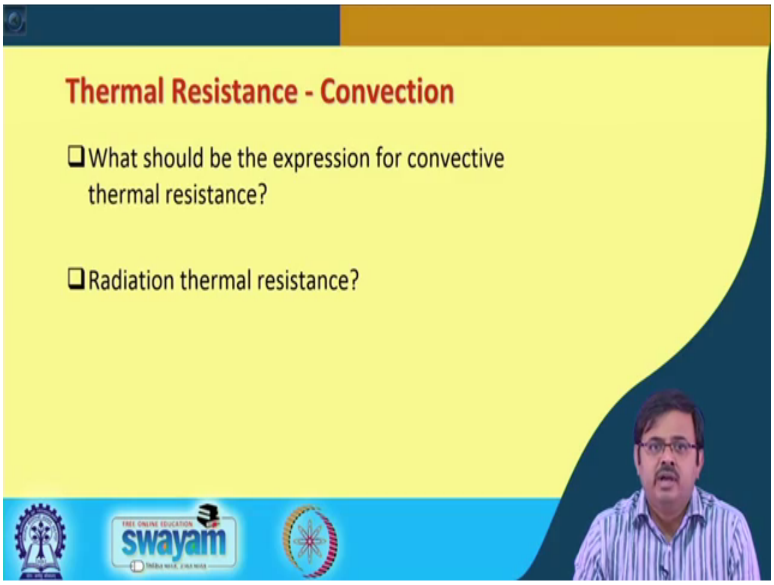
And the analogy of thermal resistance electrical resistance clear this is going to be very important, because similar to electrical resistance I can also have thermal resistances in series in parallel ok. If there is a heat generation at a certain point and the heat can flow in two parallel paths, then these are thermal resistances in parallel all right now. So, what we will do is later we will see these examples. So, right now, we are not going to talk about that.

(Refer Slide Time: 13:19)



But let us move on to the next slide then and talk about convection Newton's law of cooling. So, Newton's law of cooling is that h A delta T and the heat flux therefore, is h delta T ok, the convection expression that we saw, so that is actually Newton's law of cooling ok. And as I said before the convective heat transfer coefficient h depends on a variety of factors, and important among them being boundary conditions surface geometry fluid properties and fluid motion ok. And the challenge lies in determination of these heat transfer coefficient.

(Refer Slide Time: 14:08)



Now, if I ask you what should be the expression for convective thermal resistance? For conduction resistance, we knew it was sorry it was L over k A. So, for convective resistance what is there going to be right important. So, let us go back to this expression q is h A T surface minus T ambient. Now, what is thermal resistance, it is a temperature difference over the rate of heat transfer which is q. So, this T s minus T infinity over q what is that going to be, it is going to be 1 over h A right, it is 1 over h A. So, thermal convection thermal resistance is therefore 1 over h A.

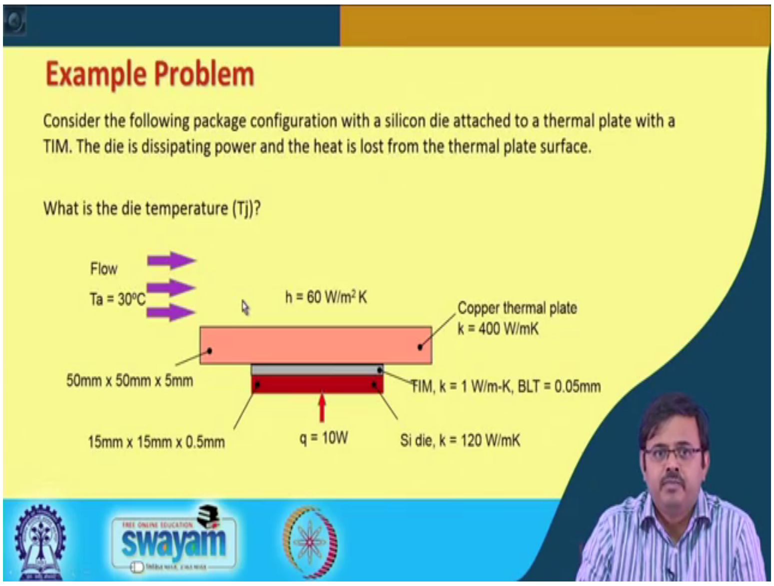
What about radiation thermal resistance. So, radiation thermal resistance is complicated, because the heat transfer unlike conduction, convection, the rate of heat transfer or q is not directly proportional to delta T, but it is proportional to the difference of the fourth power of their absolute temperatures. So, if you now want to have a parameter in terms of degree c per watt, the radiation thermal resistance is also going to be a function of the temperatures of the two of the two surfaces that are exchanging heat. Clear? L over k A.

If I give you a solid block and you know the geometry, the thickness and the surface area and the material, and therefore, a thermal conductivity in the range of temperature that we are talking about. You can say oh thermal resistance is going to be this, it does not matter what is the temperature on both sides as long as it is within the limit, as long as the thermal conductivity value is applicable or relevant within the temperature range 1 over h is similarly. The h is going to be a function of fluid properties and some other things, but which has some dependence on temperature, but otherwise it is independent of the temperature difference or the individual temperatures of the hot surface and the fluid, only a weak dependence in terms of the fluid properties, but radiation thermal resistance, no.

Student: (Refer Time: 16:53).

So, you will have this t, t squared plus t 1 square plus t 2 square or t hot squared plus t cold squared times t hot plus t cold right; t hot to the power 4 minus t s cold to the power four or t c to the power 4 is t h squared plus t c squared times 2 h squared minus t c squared which again can be further broken down into t h squared plus t c square times t h plus t c times t h minus t c. And this t h minus t c will go on this side and what you will get in the denominator is all these other terms involving the temperature absolute temperatures ok. So, radiation thermal resistance is a little more complicated, but convection and conduction we saw.

(Refer Slide Time: 17:37)



So, what we will do is in the last few minutes of this lecture, we will just go through an example problem very simple ok, because it is electronic packaging class we will take a similar relevant example. Let us say I have a silicon die.

Student (Refer Time: 17:53).

And the dimensions are given 15 centimeter millimeter, 15 millimeter, 0.5 millimeter, cross section is 15 by 15, thickness is 0.5, the thermal conductivity is also given as 120 watts per meter Kelvin ok. You also be a little you know just pay some attention on the units that we are talking about thermal conductivity units is watts per meter Kelvin. Convection coefficient unit is watts per meter squared Kelvin ok. And it directly comes from the expressions, q what is q which is in watts is h A delta T or k A delta T over x, well delta t or l yes accordingly you can work out the units all right.

So, the configuration is as follows. It is a silicon die attached to a thermal plate which is copper 50 mm by 50 mm by 5 mm. And then we have something called a TIM which stands for thermal interface materials, thermal interface materials. It is typically in the form of a grease or a gel or sometimes something called phase change material, but it is ok. But essentially why we need it is because see however polished two surfaces are, if you bring them in contact they are never in perfect contact, there will be some air voids inside ok. These are two solids.

If you look at do a surface profile ohmmeter, there is a lot of surface roughness ok; it is never absolutely smooth. So, there will be air voids. And if there are air voids, air is one of the worst conductors ok. Here thermal conductivity is 0.026 and room temperature 0.026 watt per meter Kelvin. Silicon is 120, copper is 400. So, imagine if you have this insulating layer or insulating pockets in between, it is going to be a very bad conductor, it is going to be a real resistance, real blockage in the path of heat transfer.

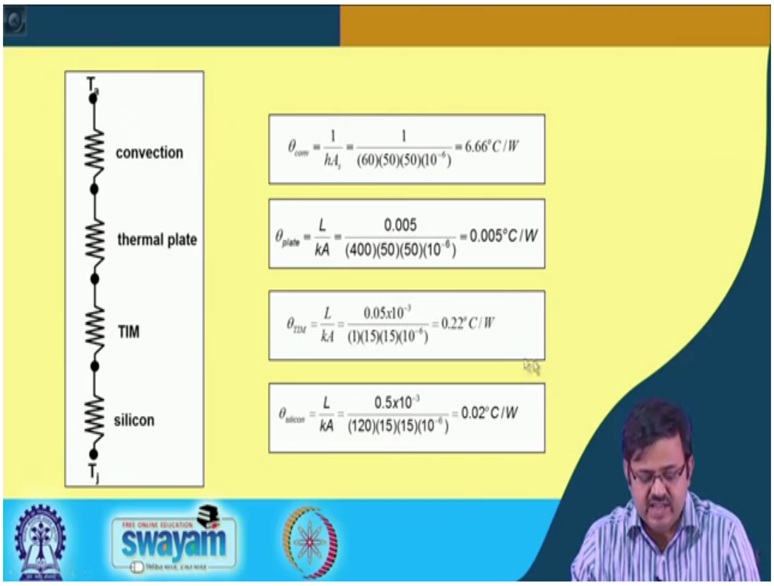
So, therefore, of course, I cannot replace the air with a solid like copper which is very high conductivity or diamond which is even high conductor which is even higher and extremely high cost. But I can fill it with something which flows and which can just flow and fill up all these voids. So, one of the thermal interface material which is very common and popular is called thermal grease or thermal paste. And then there are more sophisticated ones, we will probably discuss about them later ok, but I am talking about why thermal interface materials are TIM is important all right.

So, what is the configuration therefore, we have a silicon die dimensions of which are given. It is dissipating 10 watts, and then it is attached to a copper plate with a thermal interface material in between. And the dimensions are the same as that of the silicon die as you can see. And then we have a flow of air at 30 degree centigrade such that and this is given to you normally this is something which we need to calculate. But over here the heat transfer coefficient is given to you as 60 watts per meter squared Kelvin. This is the very realistic numbers by the way ok.

And then what I am asking is, what is the die temperature T j? Why T j, we will talk about that at this point let us let us just say it is T j. The temperature of the die right at this location at the bottom which is going to be the hottest temperature is T j what is its value? Can I solve this, how do you solve this problem? Ok, it is a very simple one. So, what we will do is, we are going to draw we are going to see how is the heat going to flow. The heat is generated at 10 watts over here, and it is going to flow first through this silicon die, then through this interface material, then through this copper plate, and finally to the gate dissipated to the air by convection.

The heat transfer through the silicon through the thermal interface material and through the copper plate is going to be by conduction and then it is convection ok. And all these are coming one after the other, first silicon, then TIM, then copper, then convection. So, therefore, heat is flowing through each of these and therefore, these are all resistances in series. Agree?

(Refer Slide Time: 22:30)



So, I will draw a resistance network like this. My T j is the junction temperature or the die temperature. And then I have a thermal resistance because of conduction through silicon, then another thermal resistance because of conduction through TIM, then a thermal resistance because of conduction through the thermal plate or the copper plate and then convection.

Agree? So, we agree that we can draw a thermal resistance network like this exactly analogous to electrical resistance work, because the heat is flowing in one direction and through each of these one after the other. And each of these offer a resistance to the heat flow because none of them have infinite thermal conductivity and neither is a convection coefficient in finite ok, but so they are not infinite. So, the resistance is not 0.

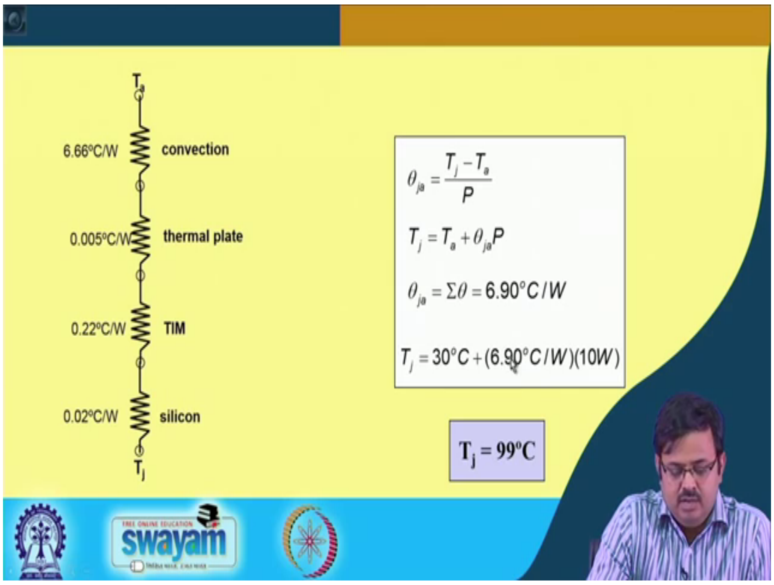
But what are those? Let us look at each of them going from bottom the theta or the thermal resistance through the silicon is going to be L over k A, any conduction resistance is L over k. So, for the silicon it is L over k A, recall the thickness was 0.5 millimeters and the area was 15 by 15 millimeters, 15 millimeter by 15 millimeters.

So, you have a 10 to the power minus 6 over here. We are doing everything in terms of meters. And thermal conductivity was given as 120 watts per meter Kelvin ok. So, the silicon thermal resistance comes out to be 0.02 degree c per watt. The TIM resistance remember what was the dimension of the TIM 0.05 millimeters 0.05 millimeters, 50 microns ok, really small, but the thermal conductivity just 1 meet watt per meter Kelvin.

So, look at this the thermal resistance is 0.22. So, imagine a very thin layer of thermal interface material 50 microns results in 0.22 degree c per watt. So, if 10 watts is flowing, then that itself results in a temperature gradient of 2.2 degrees across the thermal interface material and that is after we have put a thermal interface material with a thermal conductivity of 1 watt per meter Kelvin. Imagine if you had air instead conductivity of 0.026, 40 times less. So, this thermal resistance would have been 40 times more understand.

So, this you see a small air gap can be such a killer, and these are very realistic dimensions I am talking about that 15 by 15 actually actual dies or even less, agree, all right. Next the theta plate is copper 400 expected to be very low and it is very low. It is a large plate number 1, and that is why we have it right. We have we need a large surface area, and then the theta due to convection 1 over h A, which is this all right.

(Refer Slide Time: 26:03)



So, we have all these numbers over here that we calculate it. And what is the total thermal resistance from T j to T a, it is the addition of all these four. The sigma theta 6.9 out of h 6.66 actually comes from the convection resistance itself. And the next bottleneck is the TIM ok. So, what is the total power that I can dissipate p or q whatever if we talk about sorry, the total q was given as 10 watts, therefore the junction temperature becomes 99 degrees c ok. So, this is an example problem that we solved.

But one of the things that you see here is, this apart from being just a numerical problem it gives us some insights. If this is a real problem, what are my bottlenecks? Let us say instead of 10 watts now the electrical designer comes out of 10 watts is to less we I can hardly do anything, I wanted to a 20 watts, and that junction temperature cannot exceed 100 degrees ok. So, 99 is a maximum or maybe 100 is the maximum you can go to.

So, 6.9 cannot go up sorry, what I am trying to say is the 6.9 is not going to work anymore, because it is not 20, 20 times 6.9 plus 30, you are going to exceed by 68 degrees. It is going to be 168 degrees not acceptable, yeah. So, therefore, what do I need to do I need to reduce the thermal resistance and bring down the 6.9 to around half such that this calculation the 6.9 has to be adjusted, so that this does not exceed 100 degrees.

How do I do that? I have to look into this and see that you know what thermal plate is also already very low, silicon is already very low, let us not try to work on these. I will try to do things such that my convection heat transfer is more efficient, and my thermal interface resistance also comes down.

So, either by use of better materials over here, and by use of some better thermal dissipation techniques ok and these are the ones that we are going to talk about as part of our cooling strategy when we talk about thermal cooling solutions as part of this whole module on thermal management, we are going to discuss quite a few of these innovative thermal solutions that people have been working on ok, all right.

Thank you very much that brings us to the end of this lecture. So, in this lecture, we actually covered two very important concepts clear. We covered the concept of heat flux, which is heat transfer per unit area. So, imagine if this 10 watts was not over 15 over by 15 millimeters, but over 10 by 10 mm right, the heat flux would have gone up, and my delta T would have also gone up the thermal resistance would have gone up. And therefore, my temperature of the junction would have gone up as well, the die temperature T j would have gone up ok.

And then we introduced a very important topic of thermal resistance. And we showed through an example how thermal resistance can be a great tool to solve problems like these. We have to understand the heat flow paths. We have to understand what is in series, what is in parallel. If there is any and then use this technique to calculate temperatures, calculate thermal resistances, identify what are the critical bottlenecks where a thermal designer need to work and come up with better solutions right ok.

Thank you very much. And when we come back in the next lecture, we will continue from here and talk more about thermal management.

Thank you.