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Designing Down Temperatures for Embedded Resistors

Rick Ulrich

Two months ago, in the first of three articles about the thermal environment of embedded resistors, we discussed the difference between temperature and heat and why the former is the more important quantity. In this article, I want to address some of the basic design strategies that can be used to minimize component temperature without changing the power level. In the final installment, we'll look at the state of the art in thermal modeling for embedded resistors.

Some design tradeoffs are obvious: increasing the area of an embedded resistor would dilute the heat flux, resulting in a lower local temperature. This doesn't have anything to do with the types of resistors or boards involved, it's just easier to push the same heat through a larger area. There are two ways to go about this, and one has more thermal advantages. Let's start with a 1000 Ω resistor made from 100 Ω/sq material and using a 10 mil line; the length would be 100 mils and the area 1000 mil^2. You could increase its area by a factor of four by doubling the line width to 20 mils, which also doubles the length to 200 mils, or else by switching to 25 Ω/sq material and staying at 10 mils, so that the resulting length would need to be 400 mils. There are two advantages to the second route. First, the resulting structure is longer and skinnier, which enables the same amount of heat to be dissipated by conduction with a lower temperature driving force than a shorter, fatter line of the same area. Furthermore, some embeddable material manufacturers report that, in general, lower Ω/sq films can dissipate more heat flux than higher Ω/square formulations regardless of their geometry. Looking at the spec sheets for a couple of well-known commercialized materials, if you drop from 100 to 25 Ω/sq, the listed maximum allowable heat flux almost doubles. Increasing the area by using a lower-resistance material can lead to a considerably reduced temperature for both of these reasons.

Another related strategy is to use linear vs serpentine resistors, the former will almost always be cooler. As an example, Ohmega Technology's "built-in-trace" resistors will, as the name implies, simply replace a portion of the interconnect with resistive material. The result will be a long, thin resistor with no doubling back.

Nearby vias can significantly cool embedded resistors. Since Cu has around 1000 times the thermal conductivity of FR4 in the z direction, a 10 mil plugged Cu via would have the same ability to conduct heat as a circle of organic board material about 1/3 inch in diameter, which is probably far larger than the resistor embedded beneath. Even a 10 mil via with one mil of Cu plating would have the same heat conduction as a 140 mil diameter solid circle of FR4. However, some companies recommend that you may want to go the other way and purposely space embedded resistors away from vias in order to shield the resistor material from the heat of solder reflow, drilling effects, and contamination by chemicals used in board processing. One manufacturer recommends 10 mils separation from any via.

Placing embedded components near Cu layers can reduce local temperatures significantly. Of course, this is again due to the large difference in thermal conductivities, Cu is at least 500 times higher than FR4 in the x and y directions, but the effect can be very non-isotropic. Imagine 1/2 oz Cu lines running in the x direction with width equal to spacing (the actual measurements don't matter as long as they're equal) on a 2 mil organic board. Relative to the same board with no Cu lines, the thermal conductivity in the y direction, perpendicular to the lines, is doubled but in the x direction, parallel to the lines, it's increased by a factor of about ninety. Furthermore, a 1/2 oz solid plane, such as a ground or a power layer, would increase the thermal conductivity in both directions by double even that, or about 180X. Measurements at Gould Electronics Inc. show that even the Cu lands defining the ends of the resistor can effectively dissipate heat. As resistors are made shorter than one square, Cu is brought closer to the center of the material – the hottest part. Trimming also creates a local hot spot which you could, in principle, move closer to the Cu by trimming near one end. But, the area where embedded resistor material joins conductor is a preferred site for some failure mechanisms, so you might do more harm that good by further heating this region.

Finally, I've seen two modeling studies, and did another myself, that indicated lower temperatures for resistors buried deeper in FR4 relative to those near the surface. The reason for this perhaps counterintuitive trend is that even a poor solid conductor like FR4 still has an order of magnitude higher thermal conductivity than air. However, these studies were done on fairly isolated resistors that could utilize the entire board as a heat sink. If embedded resistors are highly concentrated, this trend might not hold. Would a buried resistor be, in general, hotter or cooler than surface mount? The answer is just starting to emerge and will probably be so full of qualifiers that it is very application-specific.

These complex tradeoffs underline the need for integrated board design software that will evaluate and optimize the layout of embedded components from the point of view of not just achieving the required electrical nets, but would also address thermal issues. It would have to possess some knowledge of the type of layout hints described here and would also have to incorporate some kind of thermal evaluation software, perhaps a 3-D finite element solver. In November we'll wrap this up by looking at what's going on in detailed thermal modeling for embedded resistors.