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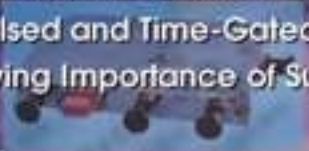

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High Frequency Circuit Materials With Increased Thermal Conductivity

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Rogers Corporation

This article describes a new microwave laminate material with enhanced thermal conductivity, which simplifies management of heat dissipation for board-mounted power devices

Thermal management has always been a major concern in the design of high frequency, high power electronic devices. Historically, in most power amplifier designs, the vast majority of the power dissipated is from the high power field effect transistors (FET) themselves. In these cases, the high power dissipation requires direct attachment of the FETs to a finned heat sink, or conduction through copper "coins" placed in areas where the polymer composite dielectric circuit substrate has been machined away. Direct connection is required because the dielectric material is two orders of magnitude lower in thermal conductivity than copper.

There has recently been increasing interest in higher *z*-axis thermal conductivity high frequency circuit laminate materials for applications where the heat removal path needs to be through the thickness direction of the dielectric material itself. A number of recent studies have modeled different applications where the thermal conductivity of the dielectric material is of interest [1-3].

One example of such an application is a high power circuit where RF trace heating can be significant [4]. In this case, in addition to high thermal conductivity, the lowest possible conductor and dielectric losses are desirable to minimize power dissipated.

Other examples include remote radio head [5] and similar applications where weight and size are critical. Lower power FET devices that may not require a thermal coin may benefit from higher thermal conductivity dielectric substrates, as well as some high speed digital devices.

In some cases, heat dissipation through a dielectric laminate is improved by the use of multiple thermal vias, also known as a "via farm." While this obviously cannot be used to control RF trace heating, many devices can be soldered to a pad connected to the thermal vias to greatly increase heat dissipation through the laminate.

In the present article, we demonstrate the large reduction in the temperature rise of a surface-mounted resistor when high thermal conductivity dielectric laminate materials are used. Surprisingly, the higher thermal conductivity dielectric materials significantly reduce the temperature rise even in the case of mounting the resistor on a via farm. The effects are demonstrated for both a Dk = 3.5 material and a Dk = 6.15 material, useful for size reduction in circuits with wavelength dependent geometries.

Material Considerations

Zweben [6] discusses a wide range of ultra-high thermal conductivity materials used in the electronics industry. CVD diamond and HOPG (highly oriented planer graphite) exhibit thermal conductivities in the range of 1100-1800 W/m-K, though the properties can be highly anisotropic. Electrically conductive metals such as aluminum, copper, gold and silver exhibit high and isotropic thermal conductivity values from 200-430 W/m-K.

PTFE (polytetrafluoroethylene) and thermoset butadiene resins are often used as the organic binders in polymer composite circuit laminates formulated for high frequency applications. In contrast to metallic conduc-

tors these polymeric materials used exhibit very low thermal conductivities of about 0.2 W/m-K. In order to achieve a good match of the in-plane coefficient of thermal expansion of the copper foil, the polymer binders are combined with woven or non-woven E-glass fibers or filled with ceramic powders.

The E-glass fibers do not substantially increase the *z*-axis thermal conductivity of the polymer composite circuit substrate in part because the thermal conductivity of the E-glass is relatively low (about 1 W/m-K) but also largely because the fabric is oriented "in-plane." E-glass fiber reinforced materials often exhibit thermal conductivities of about 0.25 W/m-K.

Polymeric composite circuit substrates are sometimes filled to control both the in-plane coefficient of thermal expansion and the dielectric constant. Low dielectric constant (Dk <3.7) materials are often filled with fused amorphous silica, which imparts a low CTE, low dielectric loss, and excellent stability of dielectric constant. While the thermal conductivity of fused silica is only about 30% higher than E-glass, the *z*-axis thermal conductivity of the composite circuit substrates ranges from 0.5 to 0.7, due to the more isotropic distribution of the powder compared to the E-glass fibers.

Other "high dielectric constant" polymer composite circuit substrates (6 < Dk < 10) are often filled with titanium dioxide powder. The titanium dioxide has thermal conductivity of 11.7 W/m-K, so these high dielectric constant circuit laminates exhibit thermal conductivities of 0.6 to 1 W/m-K.

Candidate Fillers for Higher Thermal Conductivity High Frequency Dielectrics

Since high thermal conductivity polymeric materials with low dielectric loss do not exist, higher thermal conductivity fillers are required to formulate higher thermal conductivity composite dielectric materials.

Alumina is a metal oxide that exhibits a low dielectric loss at high frequencies and a relatively high thermal conductivity value of about 30 W/m-K. It is used as a low loss ceramic circuit substrate, as well as fabricated ceramic parts for dielectric applications. As described by Bujard et al. [7], alumina has also been used as an additive to polymer composite circuit substrates to increase thermal conductivity. Although it is currently in commercial use in composite circuit substrates, alumina is very abrasive and can significantly increase drill wear. It also exhibits a comparatively high dielectric constant of about 9.8, which limits its use in low dielectric constant substrates.

Aluminum nitride is a high thermal conductivity dielectric material frequently used as a high frequency circuit substrate. The thermal conductivity of AlN substrate ranges from 170 to 200 W/m-K [8]. AlN exhibits a dielectric constant of about 8.9, though is considerably less abrasive than alumina. A number of authors [9-11] have investigated the use of AlN as a thermally conductive additive to polymeric composites for electronic applications.

While exhibiting a thermal conductivity of about 30 W/m-K [12], *boron nitride* (BN) offers an excellent mix of properties for high frequency electronic applications, both as a ceramic shape and a thermally conductive additive to polymeric composites. It exhibits a dielectric constant of about 4.1, low dielectric loss and a low temperature coefficient of dielectric constant. It is also easily machinable as a fabricated shape and non-abrasive when used as a thermally conductive additive to polymer composites.

Laminate Material	Dk 10 GHz	DF 10 GHz	TC (W/m-K)
RO3035	3.5	0.0018	0.5
RO4350B	3.5	0.0037	0.6
RT/duroid 6035 HTC	3.5	0.0014	1.4
WG-PTFE	3.5	0.0015	0.3
RO3006	6.15	0.002	0.6
RO4360	6.15	0.0038	0.8
RO3006 HTC	6.15	0.0016	1.7

Table 1 · Laminate material properties.

Laminate Materials

The current studies were conducted on 0.020" thick dielectric materials. Four high frequency laminate materials with a dielectric constant of 3.5 were included in the study: a woven-glass PTFE composite laminate, WG-PTFE (filled with a relatively small amount of titanium dioxide to increase its dielectric constant); Rogers RO3035™ laminate, a highly silica-filled, glass fabric-free PTFE composite; Rogers RO4350B™ laminate, a silica-filled hydrocarbon resin-glass fabric material; and Rogers' soon-to-be released RT/duroid® 6035 HTC laminate. Rogers RT/duroid 6035 HTC material is similar in dielectric properties to the RO3035 laminate but uses a proprietary mixed filler system that includes BN to increase the thermal conductivity without increasing drill wear.

Three high frequency laminates formulated to exhibit a dielectric constant of 6.15 were also included: Rogers RO3006™ laminate, a titanium-dioxide-silica-PTFE composite material; Rogers RO4360B™, a high dielectric constant commercial hydrocarbon-woven glass composite material; and soon-to-be released RO3006 HTC laminate. The RO3006 HTC laminate is similar in dielectric prop-

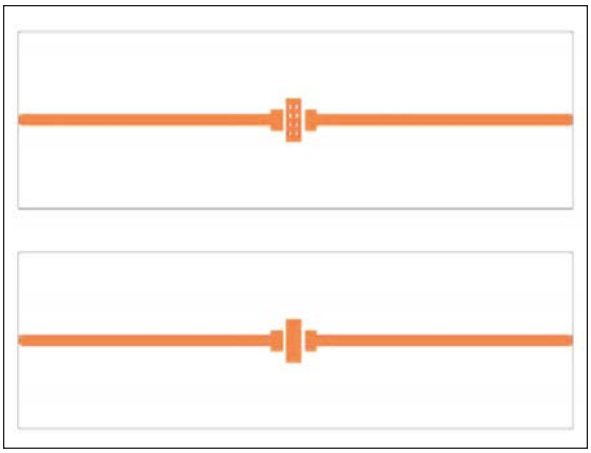

Figure 1 · Test circuits with via farm (top) and thermal pad (bottom).

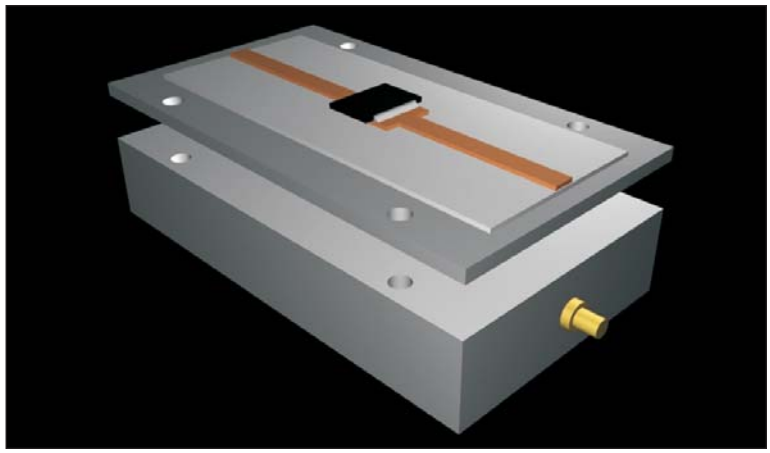

Figure 2 · Test circuit bonded to 1.25" aluminum cover and water-cooled heat sink.

erties to the RO3006 laminate, but includes the BN additive to increase the thermal conductivity.

The thermal conductivity of each material was measured with a Unitherm 2021 guarded heat flow meter described in ASTM E1530 and C-518 test methods. The results are listed in Table 1, along with the dielectric properties measured by the IPC-TM-650 2.5.5.5c X-band stripline test at 10 GHz for each material.

The power was dissipated in an American Technical Ceramics (ATC) 20 watt, 100 ohm 0.245" × 0.245" resistor. The resistive material is deposited on an aluminum nitride substrate that can be soldered to the board for good thermal contact.

Microstrip circuits consisting of 0,.065" feed lines with a 0.245" wide pad to solder the resistor to were etched on the 1/2 oz. copper foil on the 0.020" thick composite dielectric substrates. For the "via farm" tests, eight 0.030" diameter thermal vias were drilled in the pad and plated with 1 mil of copper. The patterns for the "via farm" (top) and standard samples (bottom) are shown in Figure 1.

Experimental Method

The surface temperatures were measured with a FLIR S65 IR camera, with a stated temperature range of –40°C to +1500°C and sensitivity of 0.05°C.

The samples were attached to a 0.125" thick aluminum plate using Rogers COOLSPAN™ 8322, a soon-to-be-released electrically and thermally conductive adhesive (ETCA). The ATC surface mount resistors were soldered to the leads and pad on each sample. The aluminum plate and bonded circuits were bolted to a water-cooled aluminum heat sink with an embedded thermocouple (Fig. 2). The bonded circuits were painted with high temperature flat black paint. The emissivity value of 0.95 for the painted circuits was established by holding the assembly at a known temperature and recording the thermal image.

The circuit was connected to a power supply and the power level monitored by measuring the voltage and current. The power was set at a specified level, and the temperature rise was monitored until it reached steady state. The thermal image and maximum surface temperature was then recorded. The heat sink temperature was maintained with circulating water between 25.0 and 26.7°C. The heat sink temperature was also recorded for each surface temperature measurement. The power level was then increased to the next chosen level, and the process was repeated. The power level was increased to the maximum resistor rating of 20 watts or until the temperature rise was approximately 120°C.

The thermal images of the WG-PTFE material and RT/duroid 6035 HTC at a steady state power level of 4 watts is shown in Figure 3. The temperature rise (resistor surface temperature—heat sink temperature) on the WG-PTFE substrate is 83.6°C, while that on the RT/duroid 6035 HTC laminates is 35.9°C.

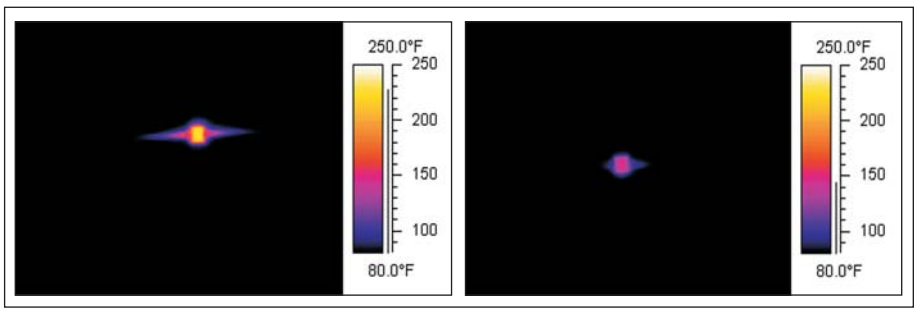

Figure 3 · Comparison of WG-PTFE (left; T_{max} = 124°C) and RT/duroid 6035HCT (right; T_{max} = 54.7°C) thermal images at 4 watts.

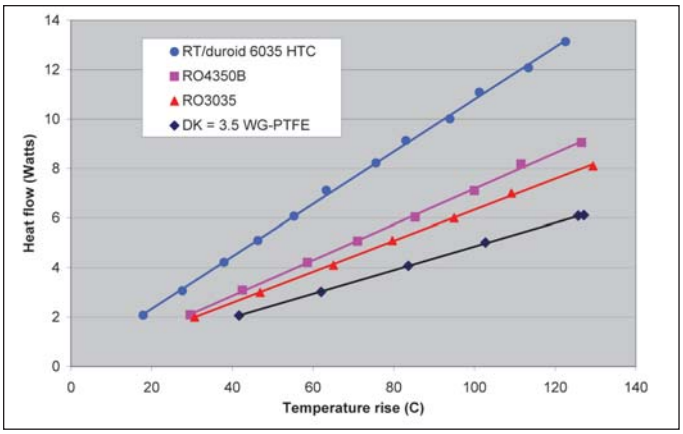

Figure 4 · Heat flow versus temperature rise; Dk = 3.5 laminates.

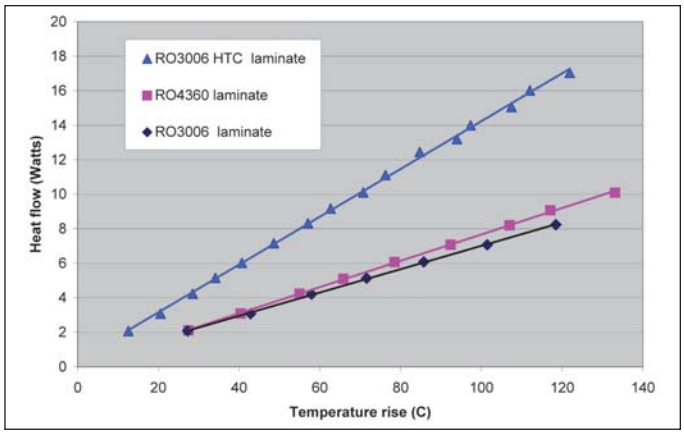

Figure 5 · Heat flow versus temperature rise; Dk = 6.15 laminates.

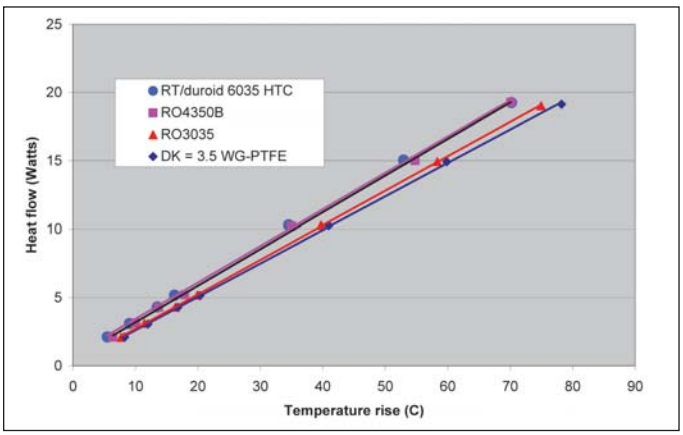

Figure 6 · Heat flow versus temperature rise; Dk = 3.5 laminates with "via farms."

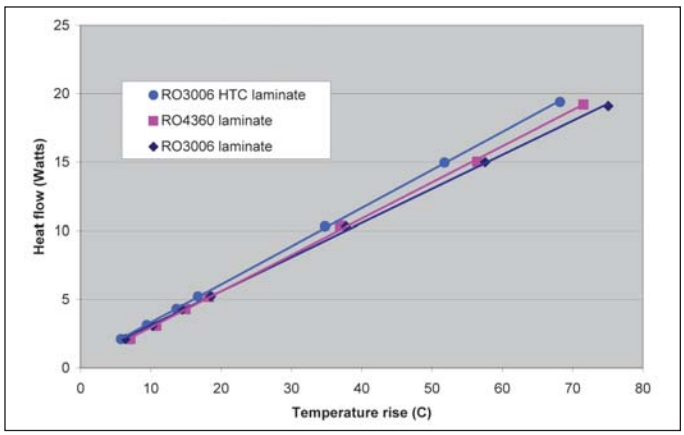

Figure 7 · Heat flow versus temperature rise; Dk = 6.15 laminates with "via farms."

Clearly, increasing the dielectric material's thermal conductivity makes a big difference in the device's temperature rise.

It is instructive to plot the data for each material as the heat flow, Q, versus the temperature rise (Figs. 4, 5). The decreasing temperature rise with increasing dielectric material thermal conductivity is clearly demonstrated. Even at moderate power levels, the difference in temperature rise can be significant. For instance, with 1 watt of power dissipated in the surface mount resistor (or about 2.58 watts/cm^2) the temperature rise in the RT/duroid 6035 HTC laminate is only 7.4°C, compared to a rise of 19.4°C in the WG-PTFE material.

Similar plots of Q versus temperature rise for the test samples with the via farms show that the thermal vias dominate performance and substantially reduce the temperature rise at a fixed power level (Figs. 6 and 7). Table 2 shows the temperature rise for 10 watts of dissipated power (25.8 W/cm^2) for the tested materials with and without the via farm. While it is clear that the thermal vias dominate the temperature rise, it should be noted that the higher thermal conductivity material still exhibit a measurably lower temperature rise. For instance, with the via farm, the RT/duroid 6035 HTC substrate temperature rise at 10 watts is 34.6°C,

Laminate Material	Temperature rise (°C) Without via farm	With Via Farm
RO3035	159	39.0
RO4350B	139	35.4
RT/duroid 6035 HTC	93	34.6
WG-PTFE	208	40.3
RO3006	144	37.7
RO4360	131	36.7
RO3006 HTC	69	34.1

Table 2 · Temperature rise with 25.8 W/cm^2 dissipated power.

compared to 40.3°C for the WG-PTFE substrate. In some critical cases, a 5°C difference in temperature rise can be significant.

Calculation of Effective Thermal Conductivity

Wilcoxon [4] demonstrates that for the situation of free convection in air, the heat loss from the top of the substrate is essentially negligible. In this case, the unidirectional steady state heat conduction equation applied to these structures gives a good, though slightly conservative estimate of the temperature rise using the measured thermal conductivities of the laminates shown in table 1. The following equation:

$$Q = \frac{k}{t} A \Delta T \quad (1)$$

where Q = heat flow, t is the dielectric thickness, k is the thermal conductivity, A is the area, and ΔT is the temperature rise, can be rearranged to predict the temperature rise as a function of dissipated power and the measured dielectric material properties.

$$\Delta T = Q \frac{t}{kA} \quad (2)$$

Equation 2 tends to "overpredict" the temperature rise, particularly for lower thermal conductivity substrates, since it does not account for the lateral or "in-plane" conduction of heat. In Figure 8, we have calculated the expected temperature rise for several selected materials from Table 1, using the measured sample thickness and thermal conductivity and compared the curves with the measured values, replotted from Figures 4 and 5. Given the simplicity of Equation 2, the agreement is quite remarkable.

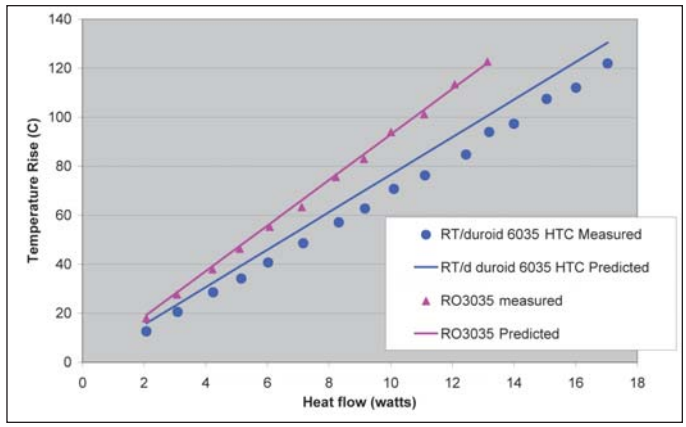

Figure 8 · Predicted and measured temperature rise versus heat flow.

Conclusion

Polymer composite circuit dielectric materials are inherently low in thermal conductivity when compared to conductors and ceramic substrates. However, increasing the thermal conductivity of these materials can substantially decrease the temperature rise of power dissipating components when the heat must be removed through the dielectric material itself.

The use of thermal vias substantially decreases the temperature rise in those design situations where their use is possible even for low thermal conductivity laminates. However, higher thermal conductivity materials offer an even larger improvement.

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