THE PRINTED CIRCUIT DESIGNER'S GUIDE TO...™

Thermal Management with Insulated Metal Substrates

Didier Mauve and Ian Mayoh
Ventec International Group

I-007e Books

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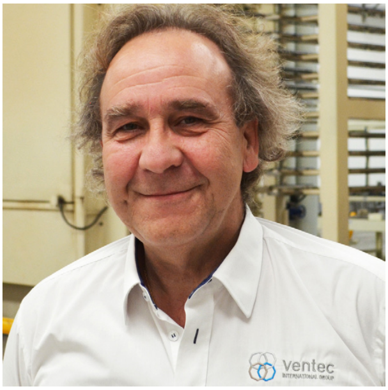

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Well known and highly respected in the printed circuit community, Didier Mauve brings over 25 years of industry experience with him. His CV includes roles such as the sales and marketing manager of one of the leading distributors in Europe, and as managing director of the largest copper-foil converting service in Europe. Mauve joined Ventec in 2015 to strategically drive European sales. His particular expertise and interest in thermal management technology has been instrumental in helping Ventec become a global leader for high-tech and high-reliability materials.

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With over 30 years' hands-on experience in PCB manufacturing following his formal education in physical science, Ian Mayoh joined the PCB industry with Hoechst AG, which was initially based in the UK. Over 10 years, Mayoh held numerous senior positions throughout Europe, Australasia, and the Far East. Since returning to the UK in 1994, he has held various positions with LeaRonal, Elga Europe, and Amphenol Invotec. Following a short period working in specialty composite materials, Mayoh joined Ventec in 2011 as technical support manager covering the European, Middle Eastern, and North African market areas. He is a key member of the global technical team with direct support from Ventec International Group's headquarters in Suzhou, China, and is also a Fellow of the UK's Institute of Circuit Technology.

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Thermal Management with Insulated Metal Substrates

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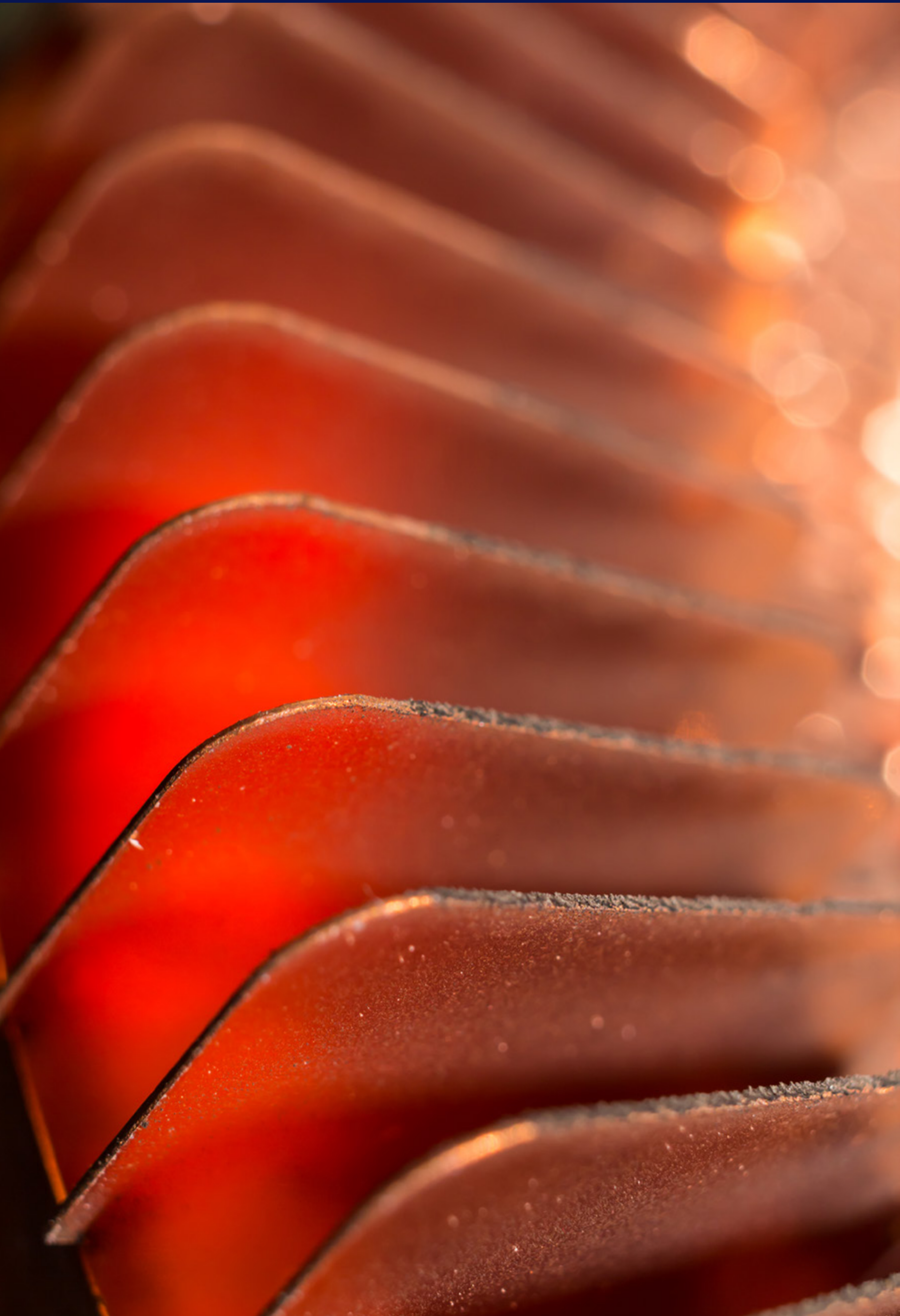


Chapter 1

Overview

Introduction

This eBook will provide the PCB designer with the essential information required to understand the thermal, electrical, and mechanical characteristics of insulated metal substrate (IMS) laminates, to select and specify the most appropriate material for a particular thermal management application, and to achieve a reliable and cost-effective design.

Thermal Management of Electronics: The Needs and Benefits

The need to dissipate heat from electronic modules and assemblies is an increasingly important design consideration. This may be just one possible consequence of the inevitable "smaller, faster, cheaper" trend for microelectronics to operate at higher performance levels. For example, in the field of automotive engineering, an increasing number of functions like braking and power steering, which were previously achieved mechanically, are now being solved electronically.

Power electronics is another area where thermal management is a critical consideration in the design of DC power supplies, inverters, power conversion systems, and electric motor control applications. Thermal management becomes especially significant in the automotive industry as electric traction systems are progressively introduced.

Recent advances in high-brightness LED technology have led to its rapid adoption in municipal, domestic, industrial, and automotive lighting applications. Effective and consistent thermal management is essential to maintain the brightness and color spectrum of an LED light. Its life expectancy is closely related to operating temperature, and can be doubled by a 10°C reduction in operating temperature. McKinsey's 2012 Global Lighting Market Model suggest that LED technology will capture over 70% of the global lighting market by 2020.

These forecasts have generated exponential growth and created huge market demands for efficient, reliable, cost-effective thermal management solutions, which in turn drive the development of thermally-conductive printed circuits as a preferred option. Keeping heat-generating components cooler increases component life, product life, and long-term reliability. The trend to increase the use of insulated metal substrates is driven by the need to reduce system costs, and reduce or eliminate the need for costly and bulky cooling fans and heat sinks. Meanwhile, a standard FR-4 laminate has a thermal conductivity coefficient of around 0.25 W/mK. Thermally conductive prepregs, laminates, and insulated metal substrates now offer thermal conductivity coefficients of up to 10 W/mK, and development will continue.

Thermal Awareness at the Design State

Dennis Price, quality director at Merlin Circuit Technology, began his presentation on heat dissipation methodologies at the 2016 Institute of Circuit Technology Northern Seminar by expressing concern that a designer survey had indicated that heat dissipation was considered a low design priority by many engineers, and that the majority of designers did not consider thermal management early enough in the design. More than one in four only considered thermal issues after the design had been completed, and more than half only tested thermal design on the first prototype, if at all. It was the view of many designers that thermal simulation techniques were too complex and time consuming! However, it is important that thermal awareness and thermal management be considered and addressed by designers.

Removing Heat: What are the Options?

There are three main ways to dissipate heat from a component: by conduction into the PCB, by convection into the local environment, or by radiation to any other surface. Conduction and convection are the only realistic methods of heat transfer, except maybe in space where radiation is probably the only option, and conduction through the substrate is likely the most efficient. Although common printed circuit laminates provide strong electrical insulation, they are generally good thermal insulators as well, so various features have been incorporated to promote heat dissipation. Features include bonded external heat sinks, through copper-invar-copper constructions that serve the additional purpose of CTE control, and heavy copper single or multiple internal heat planes.

The thermal conductivity of a substance k is an intrinsic property that indicates its ability to conduct heat. Some relevant examples are illustrated in Table 1.1.

Heat can be dissipated from QFN components by mounting them on thermal pads connected to internal copper planes by thermal via holes. Problems of solder wicking into the holes and causing voided joints can be avoided by filling the holes with thermally conductive resin and plating them over with copper, or by completely filling the holes with electroplated copper. Solid copper "coins" can be bonded into recesses milled into the PCB to conduct

Material	Thermal Conductivity W/mK
Diamond	1000 to 2200
Copper	390
Aluminum	180
Alumina	30
Water	0.59
Air	0.02
FR-4 Laminate	0.20 - 0.25
Thermal Dielectric	1.00 - 8.00

Table 1.1: Thermal conductivity of various materials.

heat away from individual power devices. All of these techniques can be effective, but they usually involve additional materials and processing, and a significant cost premium.

Many power electronics and under the hood automotive devices are built on direct-bonded copper (DBC) substrates because of their strong thermal conductivity. They are based on a ceramic tile (commonly alumina) with a sheet of copper bonded to one or both sides by a high-temperature oxidation process. The top copper layer can be formed prior to firing or chemically etched using PCB technology to form an electrical circuit, while the bottom copper layer is usually kept plain so that it can be soldered to a heat spreader by soldering the bottom copper layer to it. Beryllia, silicon nitride, and aluminum nitride are more effective heat conductors than alumina, but cost considerably more. Further, thick-film technology can be used in some high-reliability applications. Thick-film technology offers a higher degree of design freedom than direct-bonded copper, but it may also be less cost-efficient.

LED manufacturers have adopted packaging technologies from the power-electronics field with the result that they can now offer efficient thermal coupling from the semiconductor to the primary interconnecting substrate of the package. However, it remains that the only path for heat out of the LED is via the bottom of the LED package to the PCB, which must not present a thermal barrier. For high-power LEDs, the thermal conductivity of an FR-4 PCB is insufficient to enable effective heat transfer, and insulated metal substrate materials offer a better solution. These materials generally consist of a thermally-conductive dielectric layer heavily loaded with ceramic-type fillers that are sandwiched between copper foil and an aluminum or copper plate. The dielectric may be unreinforced or woven-glass reinforced.

Chapter 2

Management of Junction Temperature and the Concept of Thermal Resistance

Whether the active device is a MOSFET in a power converter or an LED in a lighting system, maintaining stable performance and maximizing reliability and product life is critically dependent on effective management of junction temperature.

Convection, even with forced air, is a very inefficient means of heat removal from the die and is not a viable option, so thermal management relies upon conduction through the base of the device (Figure 2.1).

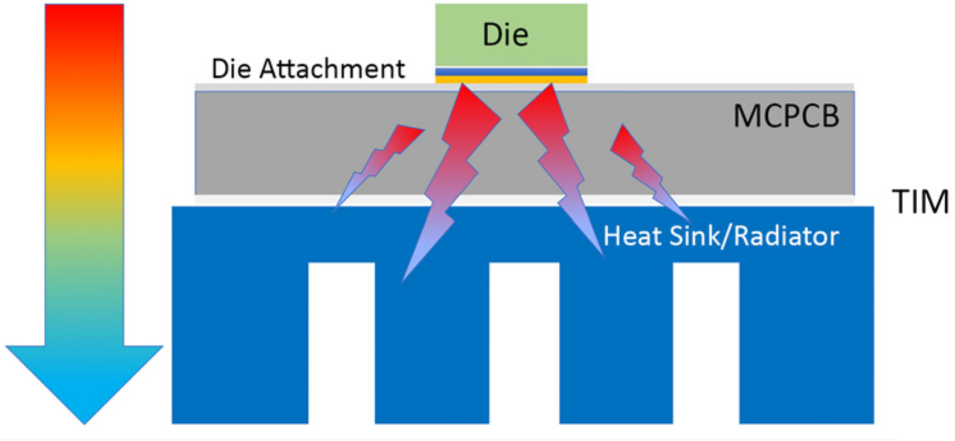


Figure 2.1: Thermal path.

Electrical Versus Thermal Analogy

Heat flow can be modelled by analogy to an electrical circuit where heat flow is represented by current, temperatures represented by voltages, heat sources represented by constant current sources, absolute thermal resistances represented by resistors, and thermal capacitances represented by capacitors (Table 2.1).

Description	Electrical	Thermal
Ohm's Law Analogy	R = V / I	R_{th} = °C / W
Resistance	R - Electrical Resistance in Ohms	R_{th} - Thermal Resistance in °C /W
Potential	V - Electrical Potential Difference in Volts	°C - Temperature Difference in Celsius
Energy Flow	I - Electrical Current in Ampere	W - Power Dissipation in Watts
Capacitance	C - Electrical Capacitance	C_{th} - Thermal Capacitance

Source: Vishay

Table 2.1: Electrical versus thermal analogy.

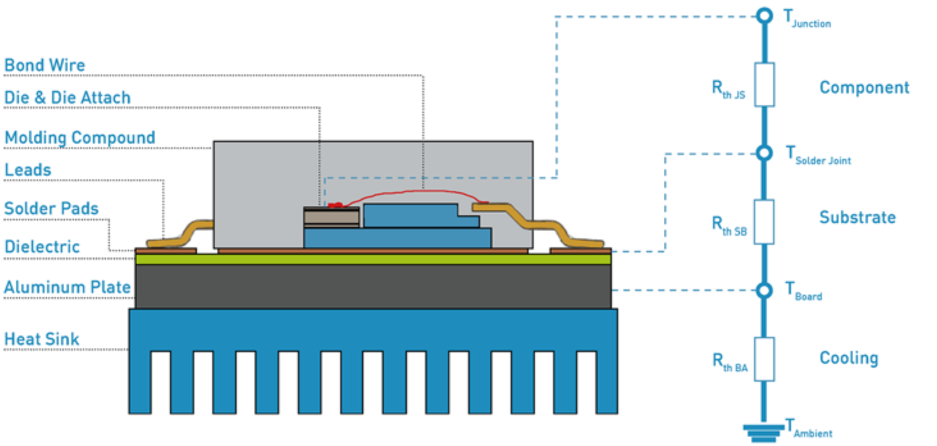


Figure 2.2: Thermal impedance, thermal system configuration, and thermal resistor network.

Figure 2.2 shows an equivalent thermal circuit for a semiconductor device with a heat sink. $T_{junction}$ is the junction temperature, $T_{ambient}$ is the ambient temperature, and the R-values are the individual thermal resistances of the die, die attach, substrate, thermal interface material, and heat sink. The thermal schematic resembles an electrical schematic with resistances in series where the substrate becomes part of the overall thermal design of the device. When it comes to defining the right substrate for the right application, the critical engineering parameter is R_{th}, the thermal resistance value, which measures a material's ability to prevent heat from flowing through it.

Thermal resistance is a function of thickness (l) in millimeters, area (A) in square meters, and thermal conductivity (λ) in watts per meter per degree Kelvin.

$$R_{th} = \frac{l}{\lambda \cdot A}$$

For a given thickness, R_{th} is expressed in units of K/W, meaning that one watt of heat will flow through the thickness of a square meter of the material if the difference in temperature between the two sides is one degree Kelvin. The R_{th} of a complex system is equal to the sum of the R_{th} values of its parts. Clearly, the most critical thermal component in the series is the one with the highest thermal resistance.

Power dissipation in a metal-core substrate structure (Figure 2.3) occurs when heat from the die components, MOSFETs, LEDs, etc., makes its path all the way through the x-, y-, and z-axes of the material and flows from the high to the low temperature level (i.e., Tambient).

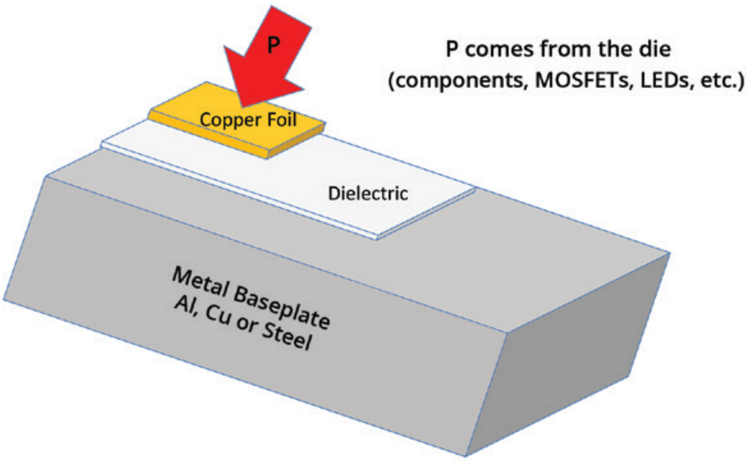


Figure 2.3: Graphic of a metal core substrate structure.

Heat conduction models are often described in terms of their equivalent electrical scheme, which introduces the notion of R_{th} and C_{th}. This results in a dipole with its own Z_{th}, being the sum of all elementary materials crossed by the heat flow. R_{th} and C_{th} are then calculated and give the equivalent circuit according to the Cauer network (Figure 2.4).

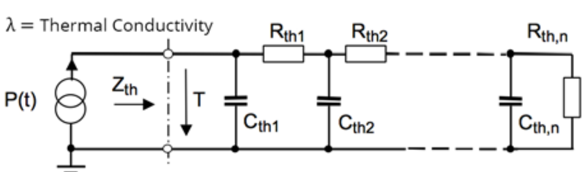


Figure 2.4: Electrical transmission-line equivalent for modelling heat-conduction properties. The physical variables are specified in their thermal equivalents.

$$R_{th} = \frac{T_a - Tb}{P_{loss}}$$

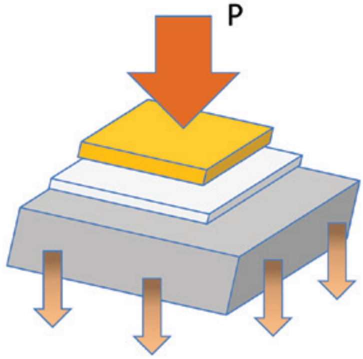


Figure 2.5: Rth and Cth are calculated, and give the equivalent circuit according to the Cauer network.

The calculation and image shown in Figure 2.5 apply to steady-state operations. Where pulse operation is to be considered, the thermal inertia of media should be taken into consideration. For example, Figure 2.6 shows what happens in a transient-state operation when a current is applied in on-off pulses and alternately begins to heat up and cool down without reaching a steady state:

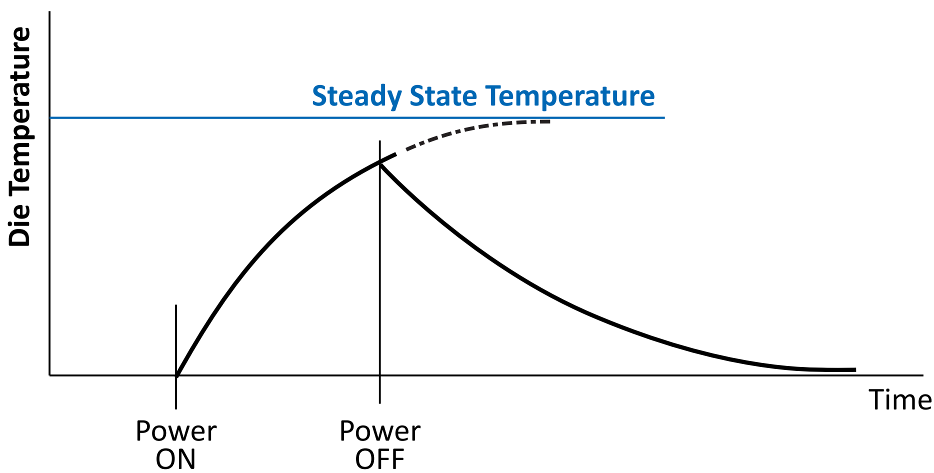


Figure 2.6: Effect of current application in on-off pulses.

Another parameter can be added called C_{th}, the thermal capacitance of the material. This can be seen in the equation $C_{th} = Cp*\rho*l*A$ in J/K where Cp is specific heat, ρ is density in kg/m^3, and (l*A) is volume in m^3. Thermal capacitance measures the ability of a material to store or release heat. It is the amount of heat energy absorbed or released by unit volume of a material per unit temperature change, effectively the thermal inertia of the material. As the pulse frequency increases, the transient state effectively becomes a steady state.

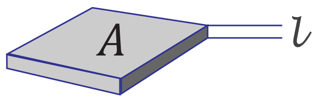
The thermal impedance of a particular assembly is the ratio of the temperature difference between two surfaces to the steady-state heat flow through them. Thermal impedance in the transient state is given by the following equation:

$$Zth(t) = \sum_{v=1}^{n} Rv \cdot \left[1 - e\left(- \frac{t}{Rv \cdot Cv}\right)\right]$$

Dielectric Consideration

When selecting a dielectric for a thermally-conductive substrate, it is necessary to consider the parameters that will have the most significant influence on the thermal resistance.

$$R_{th} = \frac{l}{\lambda . A}$$



The objective is to reduce the thermal resistance of the dielectric while maintaining reliable electrical insulation. Options for reducing the thermal resistance include reducing the thickness, increasing the thermal conductivity, and/or improving the contact surface.

Clarification of Terminology

Thermal conductivity (λ) is a fundamental property of a material that describes the ability of the bulk material to transfer heat by conduction. It is independent of the geometry of the material and does not take into account any interfacial effects. The density of heat flux is proportional to the temperature gradient. Thermal conductivity is measured in units of W/mK, or watts per meter-Kelvin. Alternative units include cal/(sec*cm*°C) and (BTU*in)/(hr*ft^2*°F). Conversion factors can be found in Appendix 1.

Thermal resistance (R) is analogous to electrical resistance and is measured in units of °C/W, or degrees-C per watt.

Thermal impedance (Z) is calculated by multiplying thermal resistance by the area of the interface. It describes the temperature gradient per unit of heat flux passing through an interface. Thermal impedance is measured in units of °C-in^2/W, degrees-C inch squared per watt, or °C-cm^2/W, degrees-C centimeter squared per watt.

It should be noted that thermal resistance and thermal impedance are related to the geometry of an assembly and can include interfacial effects. They are practical characteristics that determine the actual capability of an assembly to dissipate heat.

Thermal Resistance in the Context of Insulated Metal Substrate Materials

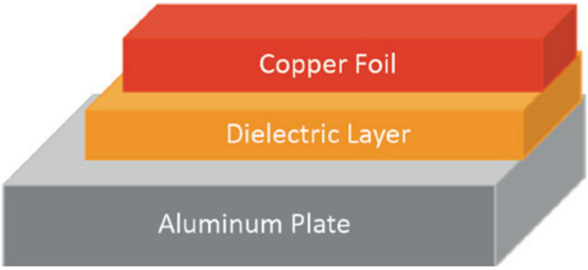


Figure 2.7: Schematic representation of an insulated metal substrate laminate.

In its simplest form, an insulated metal substrate laminate (Figure 2.7) consists of a metal baseplate (aluminum is commonly used because of its low cost and density; copper is offered as an alternative in certain applications) separated by a thin layer of dielectric from a surface layer of copper foil. The dielectric is resin-based and serves to bond to the metal layers as well as provide electrical insulation between them. The copper foil is etched to form electrical interconnection for the semiconductor devices. As already remarked, the objective is to make R_{th} as small as possible, and this can be achieved by minimizing l, and/or maximizing λ and/or A. Figure 2.8 provides a network illustration of the different media that heat will travel through.

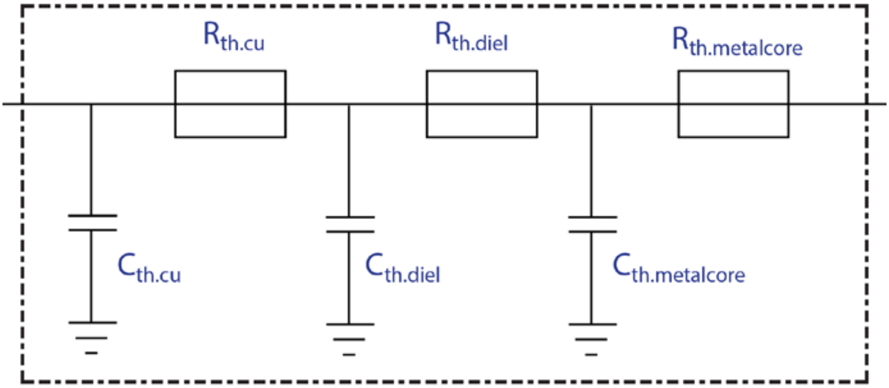


Figure 2.8: Thermal circuit equivalent of an insulated metal substrate.

Considering the thermal conductivities of the three materials, copper is around 400 W/mK and aluminum is about 180 W/mK, whereas standard FR-4 laminate can be as low 0.25 W/mK.

$$R_{\Sigma} \cdot (n) = \sum_{i=1}^{n} \cdot R_i \quad C_{\Sigma} \cdot (n) = \sum_{i=1}^{n} \cdot C_i$$

In the first instance, the area of copper should be as large as the dimensional constraints of the design will allow so the copper can distribute the heat from the device in the XY direction, and maximize the area of dielectric the heat that will pass though in the z-axis. The dielectric thickness should be as small as practicable to give the shortest thermal path consistent while maintaining acceptable electrical insulation and maximizing the thermal conductivity of the dielectric. These are the challenges addressed by the specialist laminate manufacturer.

A Note on Electrical Capacitance

Discussion so far has focused on thermal attributes and electrical analogies, illustrations, and comparisons. However, it should not be overlooked that the combination of copper foil, thin dielectric, and aluminum, which constitute the insulated metal substrate, form an electrical plate capacitor and its characteristics may need to be taken into consideration by the designer. Table 2.2 shows different e-capacitances versus dielectric types and thicknesses.

E-Capacitance	ε.A/d		ε.0 = 8,85E-12	
	Glass-Reinforced	Glass-Reinforced high-Tg	Non-Reinforced Dielectric	
Dk @ 1 MHz	5,0	4,3	4,8	
Thickness in µ				Unit
50			85,00	pF/cm2
75	59,03	50,76	56,67	pF/cm2
100	44,27	38,07	42,50	pF/cm2
125	35,42	30,46	34,00	pF/cm2
150			28,33	pF/cm2

Table 2.2: E-capacitance.

In Figure 2.9, the effect of dielectric thickness on e-capacitance is illustrated based on a selection of Ventec product examples. As shown in the example, higher dielectric thickness will achieve lower e-capacitance.

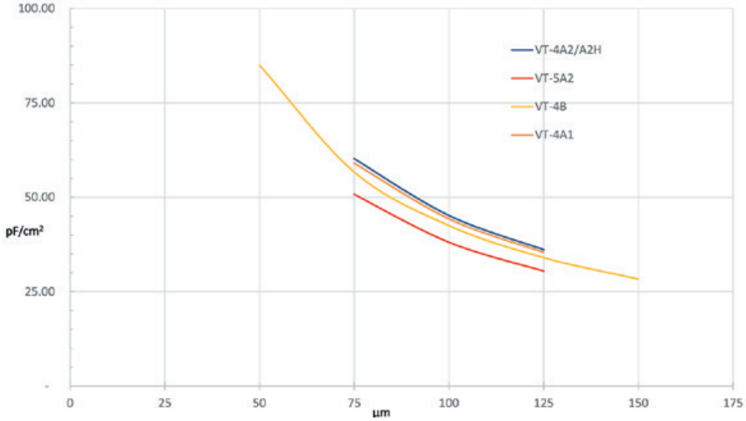


Figure 2.9: E-capacitance versus dielectric thickness.

Chapter 3

Developments in Insulated Metal Substrate Laminates

The insulated metal substrate concept is not new. Materials were available as long ago as the mid-1960s for specific niche-market applications. However, the exponential growth in LED lighting has been the main driver for the development of improved versions in volume manufacture. Insulated metal substrate laminates are now firmly established as the preferred base material for the fabrication of printed circuits for high-brightness LED lighting and DC power conversion applications because they offer cost-effective performance with straightforward fabrication, good mechanical stability, and a range of thermal conductivities to suit particular configurations.

Although thermal PCB design technology has been predominantly single-sided, multilayered constructions are now possible through resin-coated foil and resin-coated film options. The use of thermally conductive prepregs and copper clad thin laminates manufactured with them, which can be bonded to the insulated metal substrate or co-laminated with high Tg or low Dk and Df cores and prepregs, have also made multilayered constructions possible.

The recent progress made by these thermal prepregs and thin cores allow engineers to design multilayered PCBs with integrated thin thermal layers. This opens up many possibilities, particularly when convection is not an option due to space, or real estate, and the cost of additional radiators is a concern.

Dielectric Layer

The key element of an insulated metal substrate material is the thermally-conductive dielectric layer between the copper foil and the aluminum plate. This may be a woven-glass reinforced-resin composite (prepreg), as in a conventional laminate construction, or a layer of unreinforced resin. The resin itself is typically a halogen-free epoxy-laminating resin. Whereas a conventional FR-4 laminate would have very poor thermal conductivity, the thermal conductivity of the resin component is significantly improved by loading it with up to 70% of a thermally-conductive ceramic filler. The resin must also continue to serve the fundamental purpose of reliably bonding the insulated metal substrate construction together under potentially severe thermal-cycling conditions.

The thermal conductivity of glass-reinforced materials is still limited by the nature of the glass, so it is the non-reinforced dielectrics that have the lowest thermal resistance. However, they demand critical control in manufacture to maintain consistency of dielectric thickness, whereas glass fabric provides a natural mechanical spacer.

In accordance with Table 3.1, one can compare the difference in thermal impedance between a 1.5-mm FR-4 and different 1.5-mm thermo-conductive non-glass-reinforced insulated metal substrates. As you can see, the thermal impedance at the same thickness can be dramatically reduced by using a metal base substrate.

Item / Product	Standard FR-4 0.3W/mK	3 W/mK	4.2 W/mK	7 W/mK	7 W/mK Cu Base
Copper Thickness (mm)	0.035	0.035	0.035	0.035	0.035
Dielectric Thickness (mm)	1.550	0.050	0.050	0.050	0.050
Al-Plate Thickness (mm)	n/a	1.5	1.5	1.5	1.5
Total Thickness (mm)	1.535	1.585	1.585	1.585	1.585
Total Thermal Impedence (°C .in²/W)	7.750	0.042	0.035	0.028	0.017

Values are calculated with 5052-grade aluminum.
The thicknesses of FR-4 versus IMS vary, for an accurate real-life example.

Table 3.1: Thermal impedance comparison of standard FR-4 with Ventec materials.

Filler Type	Thermal Conductivity (W/m*K)	Breakdown Voltage (Based on 70% Filler)
Al_2O_2	25~40	+ +
MgO	25~50	+
SiO_2	9.6	+
Si_3N_4	50	-
BeO	270	-
SiC	25~100	- -
AIN	120~220	+
BN	100~250	+

(Key: ++ Better + Good - Bad -- Worse)

Table 3.2: Effect of filler on thermal conductivity and breakdown voltage.

The filler blend needs to be carefully selected with regard to ultimate performance requirements balanced against long-term reliability, and represents a compromise between thermal conductivity, electrical insulation, and cost. Table 3.2 indicates that aluminum nitride and boron nitride give a combination of high thermal conductivity with good breakdown voltage, whereas alumina gives a higher breakdown voltage but with lower thermal conductivity.

Glass-reinforced dielectrics are available with thermal conductivities as high as 3–4 W/mK in plane and 2.2 W/mK in the z-axis, but the presence of glass fabric imposes a lower limit on a thickness of 80 microns. Table 3.3 shows properties of thermal conductive cores. Therefore, the resulting thermal resistance, expressed in °K*in²/W, is around 0.056, which is adequate for lower-power applications. With a hi-pot withstand voltage of 4,500 volts on glass-reinforced materials, the material benefits from extremely good electrical insulation. By comparison, the thermal resistance of a 50-micron non-reinforced dielectric can be as low as 0.011 °K*in²/W, but with hi-pot, withstand reduced to 2,000 volts DC.

Test Condition (IPC-TM-650)	Unit	Std- and High-Tg Thermal Conductive Cores		
		Dielectric Thickness		
		80 µm	100 µm	150 µm
		Glass Fabric Reinforced		
ISO22007-2	W/m*K	2.2		
ISO22007-2	°C*in²/W	0.056	0.07	0.106

Table 3.3: Properties of thermal prepregs versus dielectric thicknesses.

Another basic difference between reinforced and non-reinforced dielectrics is their ability to be mechanically formed (Table 3.4). Many LED assemblies need to be post-formed into three-dimensional shapes, often with sharp bend radii. Non-reinforced materials are preferred for these applications.

It is clear that the choice of dielectric for a given application is a balance of the requirements of thermal conductivity, dielectric strength, reliability, and unit cost.

Property	Reinforced	Non-Reinforced
Breakdown Voltage	+ + +	+ +
Cost	+ +	+
Thickness Evenness	+ +	+ +
Thermal Conductivity	+	+ +
Bendability	- -	+ +

[Key: ++ Better + Good - Bad -- Worse]

Table 3.4: Effect of reinforcement on properties.

A Reminder About Thermal Conductivity and Thermal Resistance

To avoid confusion when referring to insulated metal substrate suppliers' datasheets, it should be remembered that thermal conductivity (λ) is a value that defines an intrinsic characteristic of a material.

Thermal resistance is not a simple reciprocal of thermal conductivity, because it is a calculated value directly proportional to the thickness of the material. Therefore, for example, a thick layer of dielectric with a high thermal conductivity could show a higher thermal resistance than a thin layer with a lower thermal conductivity.

Details of the wide range of available dielectric thicknesses and thermal characteristics, together with their physical, mechanical, and electrical properties, can be found in suppliers' datasheets. Typical values are shown in Appendices 2–6.

Aluminum Layer

Various ANSI grades of wrought aluminum, generally from the 1000 series, 5000 series, or 6000 series, are used as the base in insulated metal substrate materials. Three examples include 1100, a commercially-pure aluminum, 5052, which is alloyed with magnesium and chromium, and 6061, which is alloyed with silicon, magnesium, and copper.

These various grades of aluminum have similar coefficients of thermal expansion, around 25 ppm/°C, but differ somewhat in their thermal conductivity: 220 W/mK for 1100, 138 W/mK for 5052, and 157 W/mK for 6061. In the context of an insulated metal substrate material, their ultimate thermal conductivity is probably not the primary concern—clearly the commercially-pure metal is the best—but their mechanical properties, like hardness and tensile strength, and their corrosion resistance may be important in particular applications. The 5052 series is the generally accepted industry standard aluminum grade, because it is readily available and offers a compromise between performance and price.

Figure 3.1 provides an overview of key specifications when choosing the right grade for a specific application. Depending on the application, the aluminum thickness can be specified in increments from 0.5–3.0 mm with the most commonly specified being 1.5 mm.

Major Chemical Composition

Alloy Code	Major Chemical Composition	Alloy Code	Major Chemical Composition
1100	Al, Si, Fe, Cu, Zn, Mn	5052	Al, Mg, Fe, Si, Cr, Cu, Zn
3003	Al, Mn, Si, Fe, Cu, Zn	6061	Al, Mg, Si, Fe, Cr, Cu, Zn, Ti, Mn

Calorific & Electrical Performance

Alloy Code	Melting Point Range (°C)	CTE(ppm/°C)		Cp(J/g-°C)	Thermal Conductivity (W/m-K)	Resistivity (Ω-cm)
		20~100°C	20~300°C			
1100	643~657.2	23.6	25.5	0.904	220	3.00×10^{-6}
3003	643~654	23.2	25.1	0.893	163	4.16×10^{-6}
5052	607.2~649	23.8	25.7	0.880	138	4.99×10^{-6}
6061	582~651.7	23.6	25.2	0.896	167	3.99×10^{-6}

Mechanical Performance

Alloy	Hardness (HB)	Ultimate Tensile Strength (MPa)	Tensile Yield Strength (MPa)	Elongation at Break 1.6mm (%)	Modulus of Elasticity (GPa)	Poisson Ratio	Fatigue Strength (MPa)	Shear Modulus (GPa)	Shear Strength (MPa)
1100H24	32	124	117	9	68.9	0.330	48.3	26.0	75.8
3003H24	40	152	145	8	68.9	0.330	62.1	25.0	95.5
5052H32	68	262	214	10	70.3	0.330	124	25.9	145
6061T6	95	310	276	12	68.9	0.330	96.5	26.0	207

* Number of cycles: 5.0E+8.

Figure 3.1: Aluminum grade selection.

Insulated metal substrate laminates are generally supplied with the outer surface of the aluminum coated with a peelable protective film to prevent chemical attack during the processing of the printed circuit pattern. Depending on the application, typical films are either polyester or polyimide.

Copper as an Alternative to Aluminum

In instances where the highest thermal conductivity is required or the CTE mismatch is of high concern, copper may be substituted for aluminum, although with weight and cost penalties. Table 3.5 shows this comparison between copper and aluminum.

Alloy	Thermal Conductivity W/mK	CTE ppm/°C	Density g/cm³	Modulus GPa	Yield Strength MPa
Cu - C11000	386	17	8.9	44	310
Al - 5052H32	138	25	2.7	26	215

Table 3.5: Physical properties of copper and aluminum.

Designers should also make the right choice of peelable protective film available for copper or aluminum depending on the temperature cycles during PCB process (Table 3.6).

Type	Material	Maximum Operating Temperature
Standard	Polyester	170°C
High Temperature	Polyimide	270°C

Table 3.6: Peelable protective film for copper or aluminum.

Copper Foil Layer

The copper layer is generally a standard HTE (high-temperature elongation) ED (electro-deposited) foil as used in regular copper-clad PCB laminates. It can be specified in thicknesses from 18 microns (½ oz/ft²) to 210 microns (6 oz/ft²) depending on the application, and can be imaged and etched by normal PCB processes to form conductor patterns as required. Super-elongation foil can be specified where extreme CTE mismatch is an issue. When the maximum amp per square unit is clearly a determining factor for foil thickness, one should bear in mind the mechanical characteristics of copper-foil. Elongation, for example, is a key factor and should be carefully monitored.

Availability of Insulated Metal Substrate Materials: Sheet and Panel Sizes

Insulated metal substrate materials are typically available in various sheet sizes, which offer the designer many panelization options. Careful selection of the panel sizes will allow significant cost savings by optimizing the yield of the board/panel (Table 3.7). This can dramatically influence the cost.

	Panel Size					
Imperial (inches)	18" x 24"	20" x 24"	21" x 24"	18" x 48"	20" x 48"	21" x 48"
Metric (mm)	457 x 610	508 x 610	533 x 610	457 x 1220	508 x 1220	533 x 1220

Note: The designer is advised to discuss preferred sizes with the PCB fabricator and EMS provider before committing to a particular panel format. A popular working panel size for PCB fabrication is 18" x 24".

Table 3.7: IMS panel sizes.

To enable multilayer constructions with enhanced thermal performance, such as in power conversion applications, prepregs are available in pressed thicknesses of 75, 100, and 125 microns, and resin-coated film with 50-micron dielectric in corresponding sheet sizes. Table 3.8 summarizes typical properties of commercially-available insulated metal substrates.

Thermal Conductivity (W/m*k)	Thermal Impedance (ºC*in²/W)	Dielectric Break Down (Volt)	Tg (DSC) (ºC)	Td (TGA) (ºC)	Dk (@1 MHz)	Df (@1 MHz)	MOT (ºC)	Flammability (UL 94)
Thermally-Conductive Insulated Metal Substrates, Glass-Reinforced								
1.6	0.074	6000	130	380	5.0	0.015	90	V0
2.2	0.054	6000	130	380	5.1	0.014	90	V0
2.2	0.054	6000	130	380	5.1	0.014	105	V0
Thermally-Conductive Metal Substrates, Without Glass-Reinforcement								
1.0	0.116	6000	100	380	4.8	0.016	130	V0
3.0	0.040	7000	130	380	4.8	0.016	130	V0
3.0	0.040	7000	130	380	4.8	0.016	130	V0
4.2	0.029	7000	120	380	4.8	0.016	130	V0
7.0	0.017	7000	100	380	4.8	0.016	130	V0

Table 3.8: Typical IMS laminate properties.

Latest Developments in Thermally-Conductive Laminates

There is a growing demand for thermally conductive laminates capable of operating at higher temperatures, applications in power converters, hybrid multilayers, and high-power electronics with heavy copper designs to provide enhanced signal stability in harsh environments. Maximum operating temperatures for insulated metal substrate laminates are usually about 130 °C, although they can be as low as 90 °C for certain glass-reinforced grades.

A new generation of high-Tg thin laminates and prepregs with maximum operating temperatures increased to 150 °C, and thermal conductivity of 3–4 W/mK in plane and 2.2 W/mK in z-axis (eight times that of the equivalent FR-4 material) was recently introduced to the market (i.e., Ventec's VT-5A2) (Table 3.9). This material is compatible with epoxy and polyimide-based materials, including the latest high-speed grades in the fabrication of hybrid multilayer boards.

Properties	Test Method	Ventec VT-5A2
Tg (°C)	DSC	190
Td (°C)	TGA	375
Z-axis-CTE before Tg (ppm/°C)	TMA	29
T260 (min)	TMA	>60
T288 (min)	TMA	>30
Peel strength 1oz (lb/in)	As received	6.8
Thermal conductivity (W/mK)	ASTM E1461	2.2

Table 3.9: Properties of newly-developed high-Tg thermally-conductive dielectrics.

Chapter 4

Application Examples

Main Application Areas

Insulated metal substrates find many applications in automotive and industrial LED, power conversion, general lighting, street safety, backlight unit, and e-vehicle sectors (Figure 4.1).

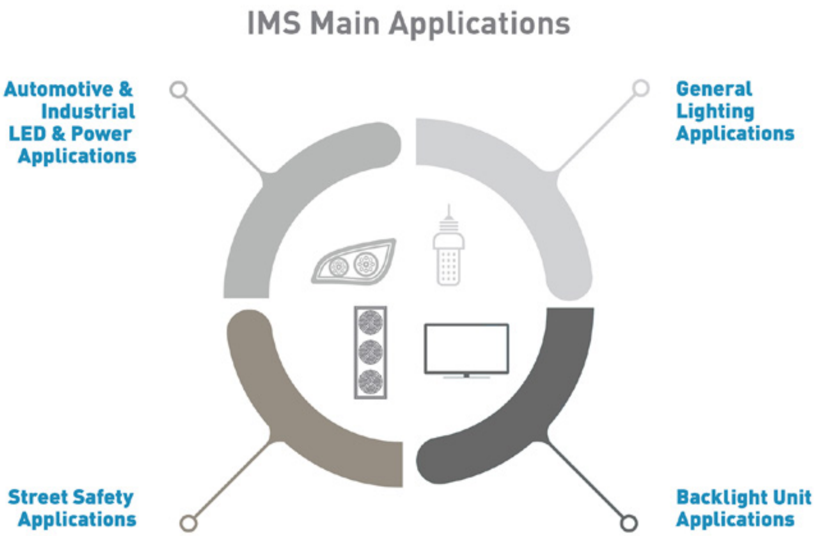


Figure 4.1: Primary applications for IMS.

Headlamps

Compact LED lamp units give car stylists extra freedom. Bright lighting at near-daylight color temperatures gives drivers a clear view. However, as much as 80% of the electrical power supplied is dissipated as heat, which presents engineers with severe thermal management challenges.

Matrix headlamps feature multiple closely-spaced emitters on a single substrate. A substrate of high thermal conductivity, featuring either an aluminum or copper baseplate, and dielectric thickness of about 0.002” (0.05 mm) is a typical choice to ensure long-term reliability. A non-reinforced dielectric minimizes stressors due to CTE mismatch between the copper foil and aluminum baseplate. A copper baseplate may be used if the matrix density is extremely high and the power is very high to address potential CTE mismatches.

Spotlights with multiple boards, each containing two or three emitters, concentrate the thermal challenge on smaller substrates featuring an aluminum baseplate and 2–3 W/mK overall thermal conductivity including the dielectric layer, which is typically about 0.003–0.004" (0.075–0.010 mm).

Automotive Turn Signals

LEDs for turn signals are typically in the 3W power range. A three-emitter unit dissipates about 7 watts of thermal energy that must be extracted from the component. IMS is often the most efficient and cost-effective thermal connection to the metallic chassis. Extreme size and shape constraints can direct designers toward a substrate with 3 W/mK thermal conductivity and 0.002" or 0.003" (0.05–0.075 mm) dielectric.

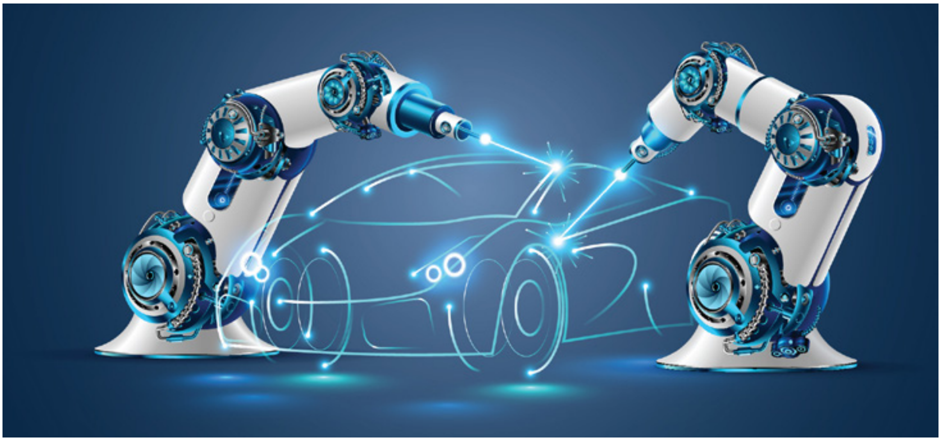
High-Power Motor Drive for Electric Power Steering

Electric power steering (EPS) and other motor-driven mechanisms, including high-power electric-traction inverters in EVs, can present even tougher thermal management challenges. Targets for module size and reliability can be met cost-effectively using a high-performing IMS with thermal conductivity of 3–4.2 W/mK and 0.004"–0.006" (0.10–0.15 mm) dielectric. Direct bonded copper (DBC) is an alternative. In extremely high-power applications, such as inverters, power transistors may be soldered to the IMS/DBC circuit layer as bare die, and a liquid-cooled heat sink attached to the baseplate. In some modules, such as combined on-board charger (OBC) and DC/DC-converter units for EVs, the baseplate is integrated with a cast metal chassis, and the specification determined in consultation with the foundry.

Street Lighting

Marshalling every last lumen from each LED in the array is key to providing safe, economical illumination for tomorrow's smart cities. Long life and high reliability are critically important, as recommended replacement intervals can be three years or more to help trim municipal maintenance costs. Thus, a high-performing IMS specification combining thermal conductivity, typically about 3 W/mK with 0.003"–0.004" (0.075–0.10 mm) dielectric, ensures low LED die temperatures and consistent CCT at the high current needed to maximize luminous flux.

Non-Automotive Examples



Welding Power Sources

IMSs play a crucial role in high-power welding applications, like power sources for industrial MIG, TIG, or plasma welding gear. Depending on the equipment and application, IGBTs (insulated gate bipolar transistors) or MOSFETs in chopper or inverter circuits must ultimately deliver anywhere from 50A to 400A or more to the torch. Robotic welders can sustain high power demands for long periods.

Among multiple thermal management techniques needed, IMSs engineered with heavy-duty copper foil, high-voltage dielectric, and a high-conductivity baseplate extract heat quickly from the hard-working power transistors and diodes, and transfer it efficiently into heat sinks and oil cooling.

Air Conditioners

High-power air conditioners, although often mounted on an external wall or roof, need to keep power inverters and triac circuits within temperature limits to ensure longevity and reliability. IMSs featuring an aluminum baseplate and conductivity of up to 10 W/mK provides the essential link between power semiconductors and air-cooled chassis/heat sinks.

Electrification in Demand

While electrification continues to increase and expand applications—bringing weight savings, cost reductions, and greater energy efficiency—typical appliance electrical power ratings are also increasing. More power means more intense thermal design challenges. Engineering a successful solution requires access to a broad choice of baseplate metallurgies, dielectric formulas, circuit foil properties, and expertise to optimize the composition and dimensions.

Assistance is often needed to create a custom solution. As industries such as automotive and lighting are moving quickly to acquire electrical/power-electronic design expertise, material suppliers are often required to provide the thermal management knowhow to help meet stringent demands on end-product size, performance reliability, cost, and time to market.

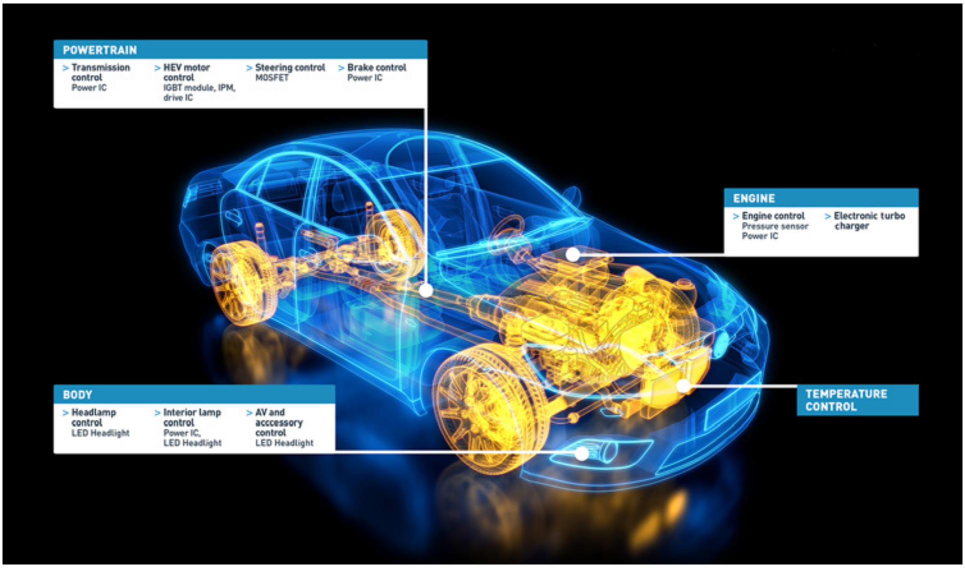


Figure 4.2: Example of a current automotive powertrain.

Automotive: The Driving Force

The electronic thermal management landscape in automotive has drastically changed due to the advent of hybrid-electric and pure-electric vehicles (Figure 4.2).

Apart from power requirements of lighting and accessories, the power drive chain includes features such as AC/DC converters for regenerative braking and on-board charging, DC/DC converters for dual-battery management and bi-directional power supply, high-voltage batteries, and traction motors (Figure 4.3). The MOSFET and IGBT semiconductors associated with these electronics can dissipate from several hundred watts up to tens of kilowatts of total power, and demand specialized thermal design and management.

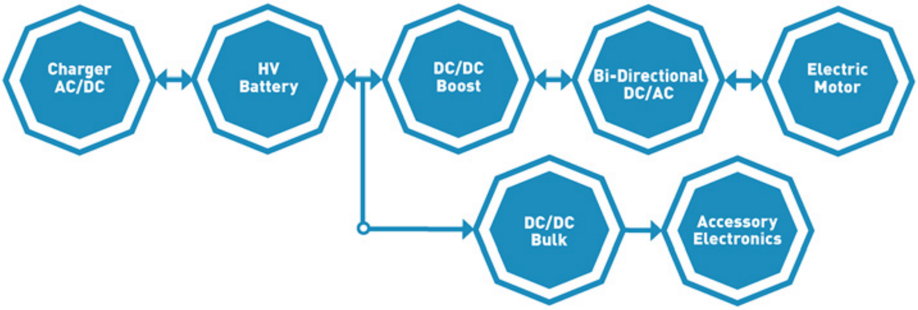


Figure 4.3: Electric vehicle electrical power scheme.


BE
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Chapter 5

Design Considerations

Choosing the Material to Suit the Application

By proactively considering thermal issues at the earliest stages of the design process, designers have the opportunity to improve the efficiency and reliability of their devices.

Martin Cotton, director of OEM Marketing at Ventec International Group, said, “At the end of the day, the solution needs to suit the product and be cost-effective, and not belt and braces because we don’t understand the parameters at play. Shortcuts will result in one of two outcomes: a product that isn’t fit for the purpose, or a product that is so over-engineered that it fails to be a cost-effective solution.”

A Word of Caution

It is advisable to systematically evaluate and characterize an insulated metal substrate material for a particular application rather than rely entirely on datasheet information, which may overstate certain critical parameters or be difficult to use comparatively as a consequence of different manufacturers using in-house test methods to generate critical datasheet values. Until the insulated metal substrate market matures and a universally accepted set of test methods emerges, inconsistent test methods will result in some anomalies and make direct correlation of datasheet values difficult.

Electrical Performance: Design Considerations

Order of Precedence

The initial consideration is whether the dielectric will provide sufficient electrical insulation based on breakdown voltage versus dielectric thickness (Table 5.1).

	IPC-TM-650 method	50 micron	75 micron	100 micron	125 micron
Glass-reinforced insulated metal substrate					
Hi-Pot Withstand Volts	1.5.7.2		4500	5000	6000
Breakdown Voltage	2.5.6.3		6000	7500	9000
Non-reinforced insulated metal substrate					
Hi-Pot Withstand	2.5.7.2	2000	3000	4000	
Breakdown Voltage	2.5.6.3	4000	7000	8000	

Table 5.1: Electrical insulation characteristics of typical glass-reinforced and non-reinforced dielectrics.

Second is to select copper-foil weight based on the required current-carrying capacity of the conductor (Table 5.2). Keep in mind that the heat-sinking effect of the insulated metal substrate material will effectively reduce I^2R heating.

Temp Rise	10 °C			20 °C			30 °C		
Copper	1/2 oz	1 oz	2 oz	1/2 oz	1 oz	2 oz	1/2 oz	1 oz	2 oz
Trace Width (inch)	Maximum Current Amp								
0.01	0.5	1	1.4	0.6	1.2	1.6	0.7	1.5	2.2
0.015	0.7	1.2	1.6	0.8	1.3	2.4	1	1.6	3
0.02	0.7	1.3	2.1	1	1.7	3	1.2	2.4	3.6
0.025	0.9	1.7	2.5	1.2	2.2	3.3	1.5	2.8	4
0.03	1.1	1.9	3	1.4	2.5	4	1.7	3.2	5
0.05	1.5	2.6	4	2	3.6	6	2.6	4.4	7.3
0.075	2	3.5	5.7	2.8	4.5	7.8	3.5	6	10
0.1	2.6	4.2	6.9	3.5	6	9.9	4.3	7.5	12.5
0.2	4.2	7	11.5	6	10	11	7.5	13	20.5
0.25	5	8.3	12.3	7.2	12.3	20	9	15	24

Table 5.2: Current-carrying capacity of copper foil.

Copper Foil Layer: Design Considerations

Because of their ability to efficiently dissipate heat, insulated metal substrates significantly reduce I2R heating effects in copper conductors, as Figure 5.1 demonstrates for different copper weights. As a result, this increases their effective current-carrying capacity. It is logical that conductors should be as wide as the design constraints allow, both to spread the heat from the heat source and to maximize the area of dielectric through which the heat is transmitted by the insulated metal substrate. In some cases, very heavy copper can be utilized along with bare die to eliminate the need for a standard packaged component.

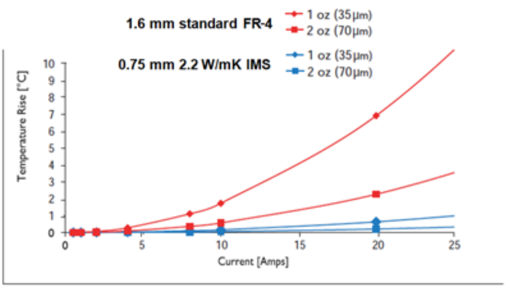


Figure 5.1: Temperature rise in copper conductor with resistive heating.

A Note on Creepage Distance

Creepage distance (also known as leakage distance) is the shortest path between two conductive parts measured along the surface of the insulation. This is different from clearance, which is the shortest distance in air between two conductive parts. Creepage distance is related to the comparative tracking index (CTI) of an insulating material, which is a measure of a material as an electrical insulator and is expressed as the voltage at which the surface of a material breaks down under a standardized test (ASTM D3638). Published CTI figures for insulated metal substrates generally indicate a withstanding voltage of 600 volts, which is the highest rating (category 0). By comparison, conventional FR-4 has a CTI in the range 175–249 volts, which places it in category 3.

Creepage distance should be taken into consideration when designing for power applications where the thick aluminum baseplate becomes part of the mechanical assembly and the power stage of the device fitted with MOSFETs or IGBTs is soldered to the metal substrate baseplate while the logic is connected and tightened to the baseplate by the use of pillars and screws.

Typical creepage distances are shown in Figures 5.2 and 5.3 for a range of operating voltages in DC and AC modes.

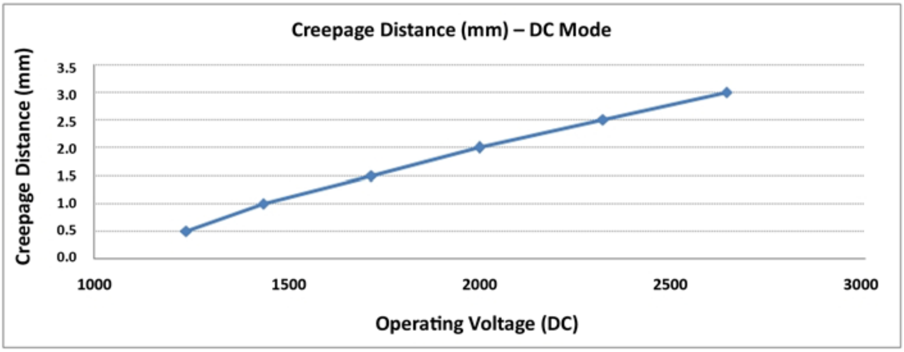


Figure 5.2: Creepage distance (mm) DC mode.

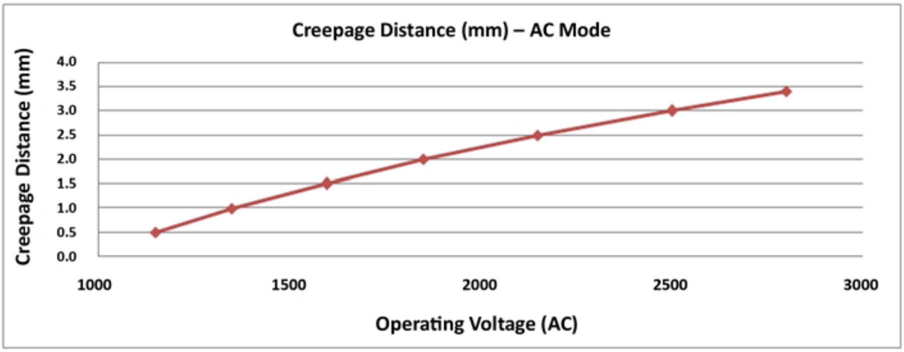


Figure 5.3 : Creepage distance (mm) AC mode.

Base Metal Layer: Design Considerations

Although the choice of base metal layer may be primarily governed by cost and essential mechanical considerations such as strength, rigidity, and weight, the CTE value may be significant when considering solder joint reliability under thermal cycling conditions. Solder joint fatigue can be minimized by selecting the correct base layer to match component expansion. Large devices, extreme temperature differentials, badly mismatched materials, or lead-free minimum solder thicknesses may all contribute to increased cyclic shear stress on solder joints.

Besides fulfilling the basic design requirements of strength, rigidity, and weight in the specification of base layer materials, consideration should be given to their mechanical performance in machining and post-forming operations (Table 5.3).

Electrical Connection to the Base Layer

If it is required to make electrical connection to the baseplate, then copper is the preferred material for reasons of processability and reliability, particularly

Metal Base Material	Thermal Conductivity W/mK	Thermal Expansion ppm/°K	Density g/cc	Notes
Aluminum 1100	218	23.5	2.7	Pure Al: Good thermal conductivity, worst for CNC machining. Lower cost.
Aluminum 5052	138	25	2.7	Al-Mg-Cr alloy: Best for bending and mechanical forming, punchable. Medium cost. Most popular choice.
Aluminum 6061	167	25	2.7	Al-Mg-Si-Cu alloy: Best for CNC machining and V-cut scoring. Higher cost.
Copper	386	17	8.9	Pure Cu: Low CTE, high thermal conductivity. High cost.

Table 5.3: Comparison of base metal layer properties.

if connection is to be made by plated-through holes. Copper will enable standard printed circuit plating processes to be used, and will match the CTE of the circuit layer so that the shear stress on via holes is minimized during thermal cycling.

Cost Considerations

Cost is a key factor in the choice of an insulated metal substrate material, especially in the LED market where competition is fierce and a low unit price is critical. Therefore, selection is usually based on the lowest cost option that will achieve the required overall performance.

Aluminum and copper are the industry-standard base materials for insulated metal substrate substrates. Comparing like-for-like thicknesses, copper is more expensive than aluminum. However, if the design requirements can be realized with a thinner layer, it may be a less expensive option. For example, for a given area, the cost of 1-mm copper is roughly equivalent to the cost of 3.2-mm aluminum (based on the LME in January 2018). Aluminum is $2,235 per ton where copper is $7,049 per ton with the density of copper being 8.9 and aluminum being 2.7 (the cost-ratio is approximately 1 to 10).

Thermal Considerations

For a given application, the choice of dielectric is determined by the need to achieve a balance between thermal conductivity, dielectric strength, reliability, and unit cost. In general, the reinforced dielectrics have lower thermal conductivity, but higher breakdown voltage and slightly better thickness uniformity. The cost of glass-reinforced dielectrics is generally lower than the non-reinforced grades, which demand extremely critical manufacturing control to ensure uniformity of filler dispersion and the absence of traces of particulate foreign material that could lead to premature dielectric breakdown. Also, due to thickness distribution considerations, many manufacturers can only laminate non-reinforced materials in smaller panel sizes, which increases unit cost and potentially limits applications.

Frequently Asked Questions: A Couple of Reminders

What does "watts per meter-Kelvin" signify?

Thermal conductivity (λ), also known as the coefficient of heat conductivity, is generally measured in units of watts per meter-Kelvin (W/mK). Because it is a coefficient, it needs to be considered in conjunction with thickness. Its reciprocal, thermal impedance, is a function of thickness. Rather than just demand a high W/mK value, the PCB designer should consider whether a lower W/mK at a lower dielectric thickness would give the same thermal impedance at lower cost, provided that the dielectric strength was sufficient, and would only become a serious consideration at high-operating voltages. Thus, for most LED and low voltage applications, the lower W/mK materials may be adequate.

If I halve the dielectric thickness, will it halve the thermal impedance?

As indicated earlier, the thermal conductivity value alone does not tell the whole story. Halving the dielectric thickness would in turn halve the thermal impedance. In effect, it would double the thermal capacity, but this also brings practical challenges in terms of thickness control of the dielectric and the risk of dielectric breakdown and hi-pot failure. Leading manufacturers are now producing commercial quantities of insulated metal substrate materials with dielectric thicknesses of 50 μm and below. This has only been made possible by substantial investment in specially-developed dedicated treaters and coaters, ultra-purity fillers, superfine filters, and proprietary modifications to resin-supply lines. As a result, manufacturing capability has been established to produce thin cores down to 35 μm guaranteed against hi-pot failure in commercial quantities.

Chapter 6

Specifying the Right Substrate

Matching Material Characteristics to End-Use Requirements

For all applications, it is essential to plan from the outset and define the right material for the particular application. Various end-use requirements will demand particular key parameters (Table 6.1).

	R_{th}	Breakdown Voltage	Tg	Relative Temp Index / Max Operating Temp	PTH Processing
LED Headlights	+++	0	0	++	-
Power Applications	++	+++	0+	+	-/+
Hybrid Multilayer Applications	++	0	+++	+++	+++

[Key: +++ Great ++ Better + Good - Bad -- Worse -/+ Equal 0 not applicable 0+ Potential]

Table 6.1: Key parameters to consider.

Similarly, the effect of dielectric thickness on thermal resistance for both aluminum (Figure 6.1) and copper (Figure 6.2) will determine the right substrate for the particular application under consideration.

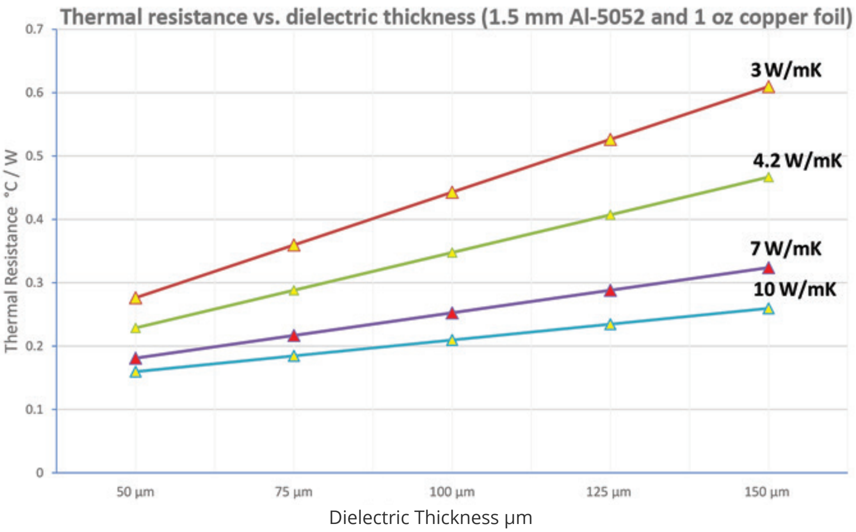


Figure 6.1: Thermal resistance versus dielectric thickness for aluminum and copper-based laminates.

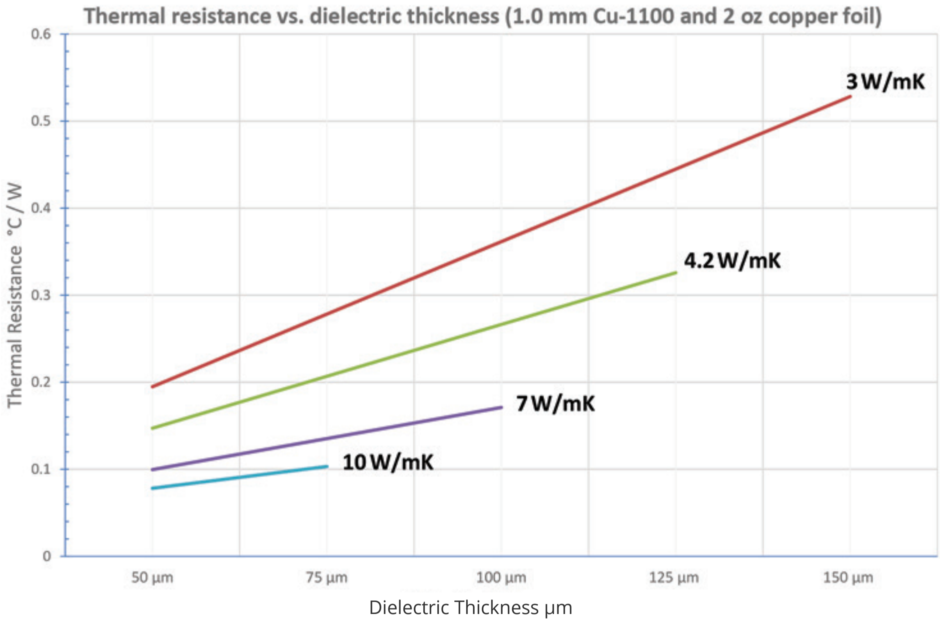
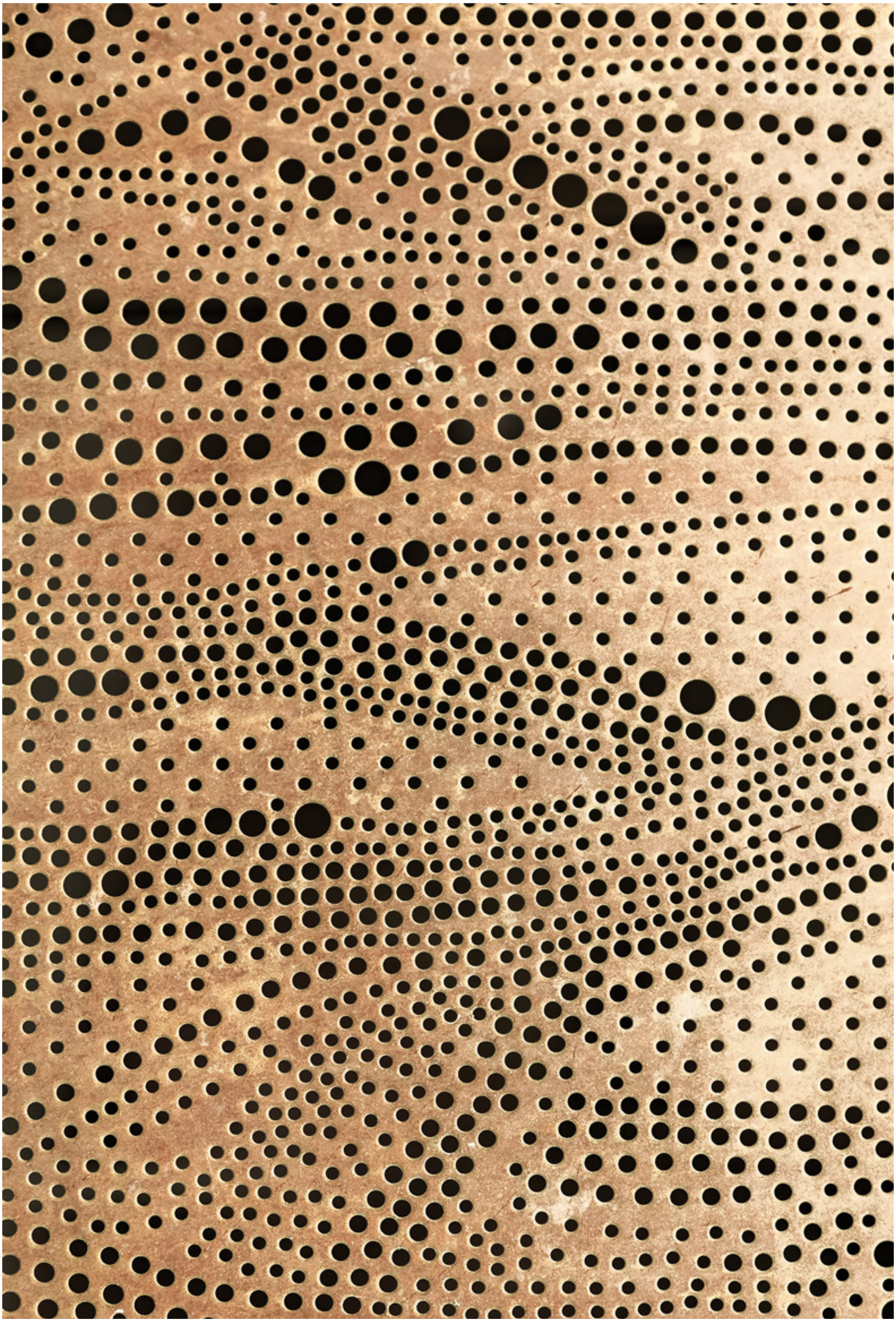


Figure 6.2: Thermal resistance versus dielectric thickness for aluminum and copper-based laminates.

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Chapter 7

Scope for Design with Insulated Metal Substrates

PCB design with insulated metal substrates is by no means limited to single-sided and single-layer circuits (Figure 7.1), although these are predominantly used in the LED lighting industry.

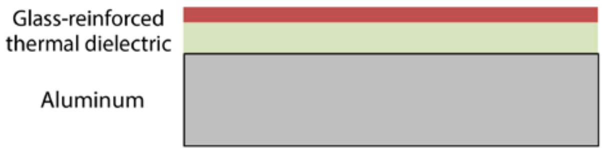


Figure 7.1: Single-sided single layer.

If a formable grade of laminate (e.g., aluminum 5052 with a thin non-reinforced dielectric) is specified, a single-sided circuit can be post-formed into three-dimensional shapes. The aluminum layer is machined to reduce its thickness in the bend area.

Insulated metal substrates can be built into multilayered structures (Figure 7.2) with thermally conductive laminates and prepregs using plated-through holes for z-axis interconnection.

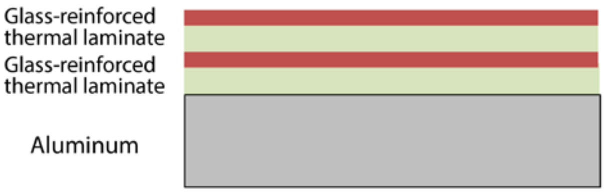


Figure 7.2: Single-sided double layer.

They can be incorporated into flex and flex-rigid designs (Figures 7.3 and 7.4) with many degrees of freedom in single-axes or multiple-axes configurations.

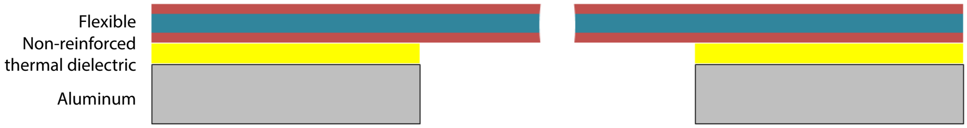


Figure 7.3: Double layer flex on an IMS.

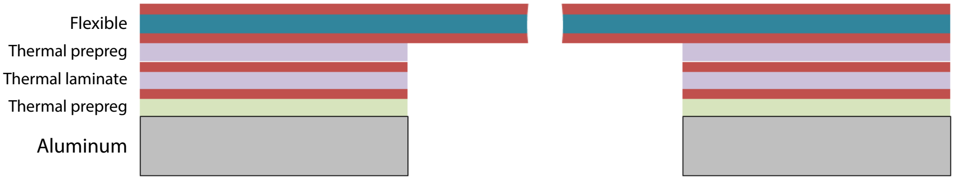


Figure 7.4: Four layers on an IMS.

Thermal prepregs can be used to aid heat dissipation in embedded-component designs (Figures 7.5 and 7.6).

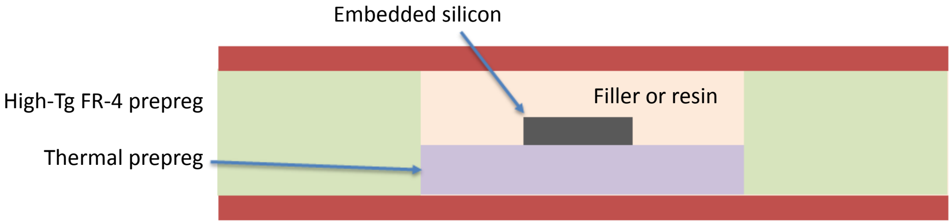


Figure 7.5: Embedded component design example.

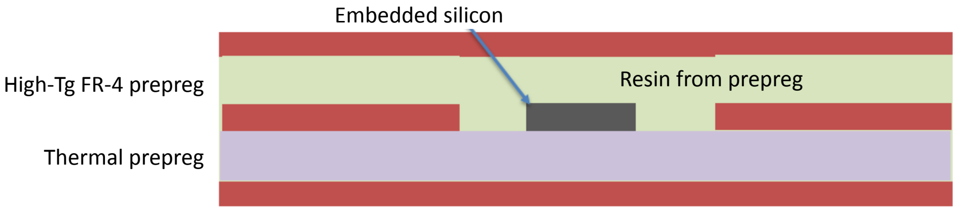


Figure 7.6: Embedded component design example.

Where the joint requirements of high-frequency signal performance and thermal management need to be addressed, insulated metal substrates and thermally-conductive prepregs can be used in combination with low-loss laminates in hybrid constructions (Figure 7.7).

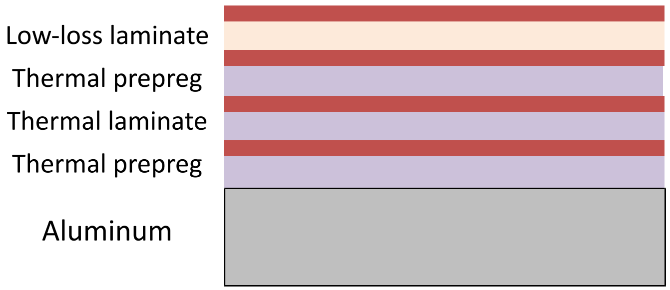


Figure 7.7: Thermally-conductive prepreg and core combined with thermal vias.

When ideally located, the thermally conductive core and prepreg–with or without the help of thermal vias–will efficiently drain the heat out of the die/chip through the thermally conductive prepreg and core (Figure 7.8)

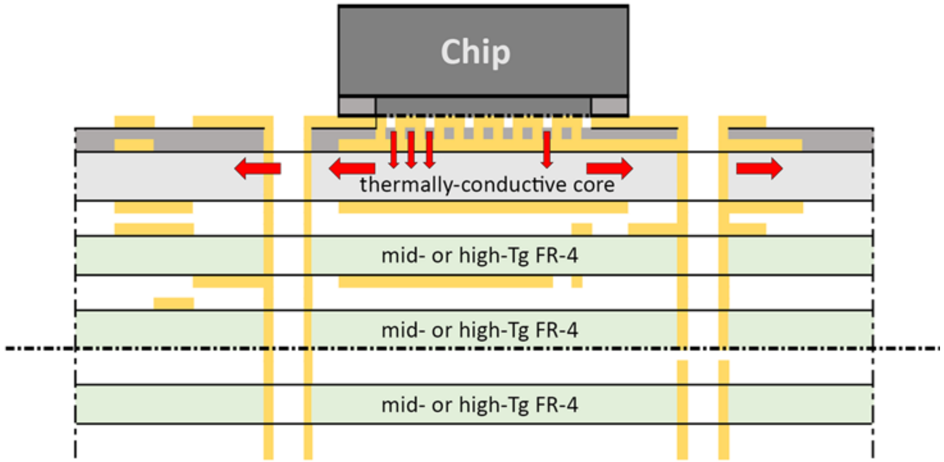
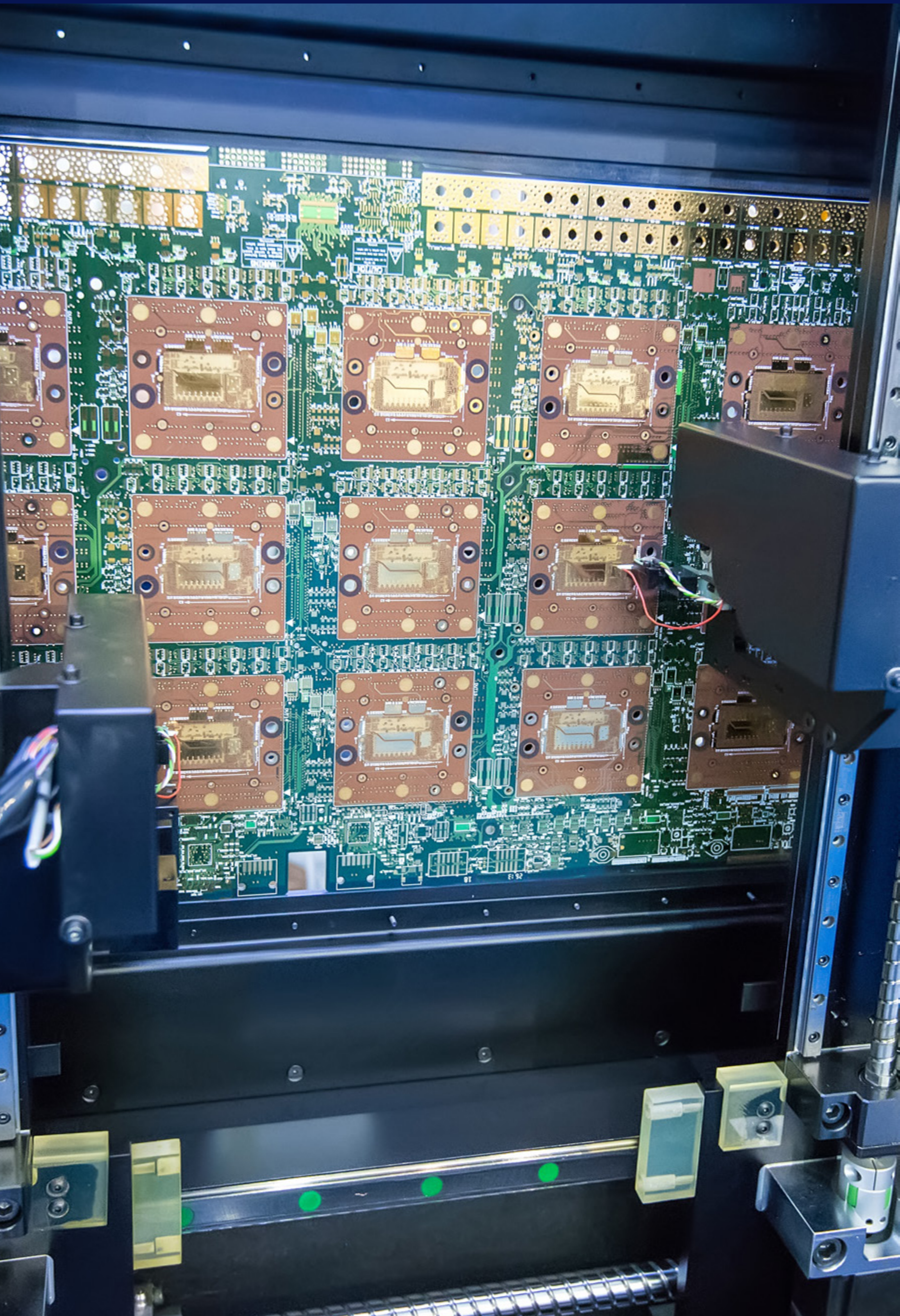


Figure 7.8: Heat flow of thermally conductive prepreg and core.



Chapter 8

Manufacturing and Assembly Considerations

Manufacturability Issues and Engineering Limitations

The designer should be aware that, although the fabrication of printed circuit boards from insulated metal substrate laminates is within the manufacturing capability of most professional PCB shops, some processing parameters require modification to suit the characteristics of the materials, and certain manufacturers have developed specialist skills and techniques in these areas.

The majority of designs are single-sided, which can be fabricated straightforwardly by conventional print-and-etch techniques. Machining of insulated metal substrate materials may require specific tools, modified feeds and speeds, and additional cooling, but the material supplier will be pleased to provide the relevant datasheets on request.

Multilayer manufacture may require optimization of the press cycle and the desmear process to suit the characteristics of thermally-conductive laminates and prepregs. Due to the low-flow nature of thermally-conductive prepregs, they are limited in their ability to encapsulate copper innerlayer features heavier than two ounces per square feet or better than 70 microns. However, there are exceptions to the rule, such as Ventec's thermally-conductive (8 x FR-4) high-Tg thin core and prepreg material (VT-5A2), which has been proven to encapsulate 3 oz/105 μm copper and is ideal for hybrid multilayer low-loss constructions.

To maximize material utilization, it is recommended that the designer discuss and agree to a matrix panel layout and profiling method with the PCB fabricator and the assembler. V-scoring is the most preferred process for rectangular shapes and is suitable for both low and high volume. It also allows the best yield per production panel because no spacing is required between circuits. Scored profiles generally enable an easier separation of boards than the equivalent routed profiles. For high-volume production of simple single-sided circuits, punching is an option both for holes and profiles if the numbers are high enough to justify the cost of tooling.

The insulated metal substrate frequently becomes part of a mechanical assembly where it may be necessary to insert screws into the substrate. It has been demonstrated that the application of maximum torque will result in breakage of the screw before any damage is caused to the dielectric. For example, where the recommended torque for an M4 steel screw is 12–16 kgf*cm, the screw can be tightened to 20 kgf*cm and break without damage to the dielectric.

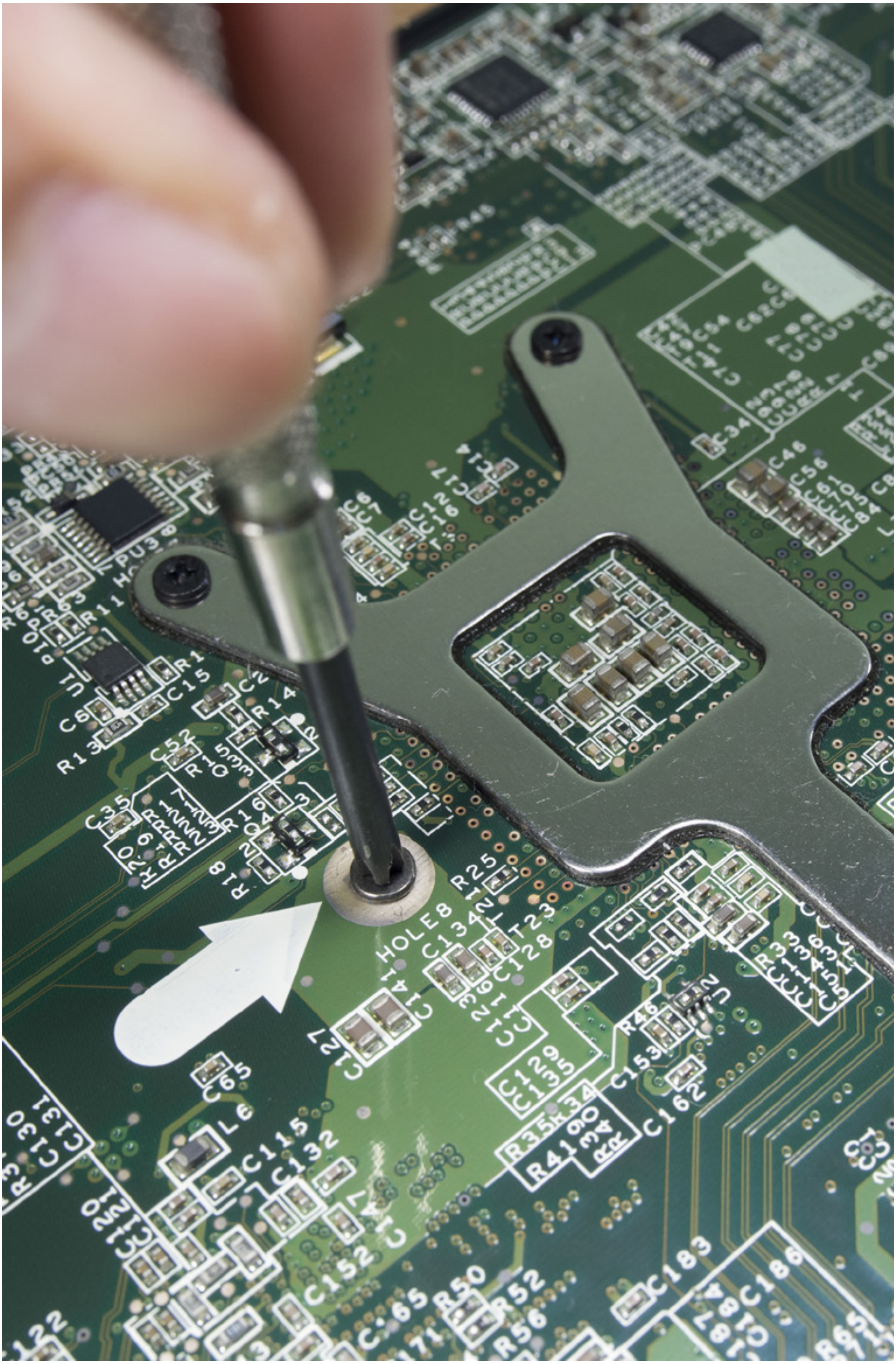
Standards for insulated metal substrate and thermally-conductive substrates are being developed, but as of now, there are no international standards other than those for PCBs in general.

Assembly Considerations for Solderable and Solder Resist Finishes

Solderable Finishes
All popular PCB finishes can be used on insulated metal substrate circuits. Organic solderability protective (OSP) and lead-free hot-air solder levelling (LF HASL) are probably the most popular for LED applications. Immersion silver and immersion tin are also used. Electroless nickel/immersion gold (ENIG) or electroless nickel/electroless palladium/immersion gold (ENEPIG) can be used for wire-bonding applications.

Solder Resists and Ident Prints
Solder resist can be applied by standard PCB screen-printing or photo-imageable processes. A range of color-stabilized white solder resists is available specifically developed for LED applications. Ident can be applied by standard PCB silk-screen or inkjet printing processes.

Assembly Considerations
Insulated metal substrate boards can be soldered by standard techniques and will withstand lead-free soldering temperatures. However, the assembler may choose to optimize the reflow profile to take into account the heat capacity of the substrate. For improved solder joint reliability under thermal cycling conditions, a minimum joint thickness of 100 microns after reflow is recommended. This will help minimize shear stresses during thermal cycling.


HOLE8
R25
C65
C115
C132
C152
C183
C129
C135
C162
R50
R52
C34
C46
C35
C52

Chapter 9

Reliability Considerations

In typical LED street-lighting applications, the main reliability issue for insulated metal substrates is not dielectric breakdown, since operating voltages are relatively low. Rather, the main issue is the shear stress from CTE differences between copper, dielectric, and aluminum during the severe thermal cycling between power-on and power-off. Humidity and temperature variations due to the day/night cycle and the seasonal environment can also cause problems.

Test conditions and typical test results are shown in Table 9.1 for hi-pot and peel testing after dry heat, damp heat, and thermal cycling for non-reinforced 3.0 W/mK and 4.2 W/mK examples with dielectric thicknesses of 50 and 75 microns (Figures 9.1– 9.5).

Test Method		IEC 60068 2-2	IEC 60068 2-14	IEC 60068 2-78
Sample	Ventec Product	VT-4B3 / VT-4B5		
	Aluminum Thk (mm)	1.5	1.5	1.5
	Dielectric µm	50 / 75	50 / 75	50 / 75
	Copper Thk	2 oz	2 oz	2 oz
	Size (inches)	4" x 4"	4" x 4"	4" x 4"
Condition	Temperature	+150 °C	-40°C / +125 °C	+80 °C
	Humidity	/	/	85% RH
	Duration	3000 hrs	3000 hrs	3000 hrs
Testing Items		Hi-pot / Peel	Hi-pot / Peel	Hi-pot / Peel
Test Frequency		Every 250 hrs	Every 250 hrs	Every 250 hrs

Table 9.1: Testing content.

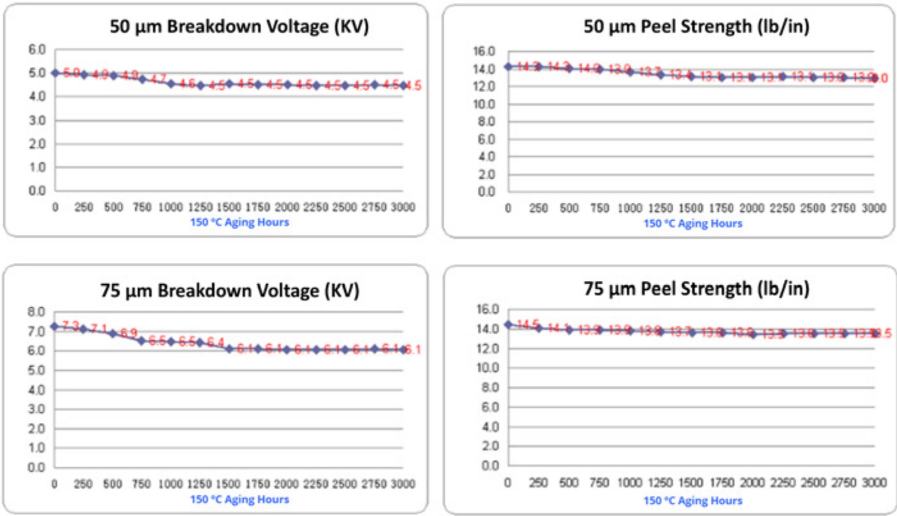


Figure 9.1: Non-reinforced dielectric 3.0 W/mk and 150 °C aging.

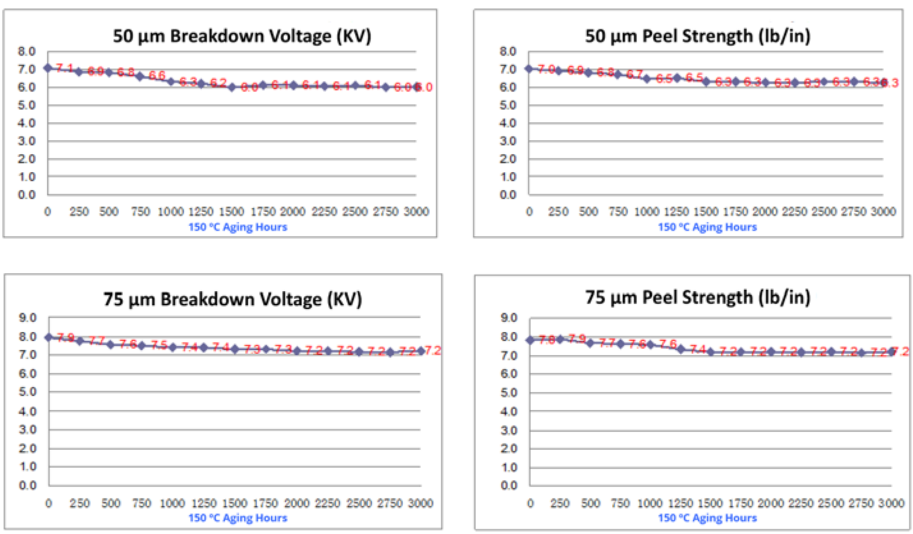


Figure 9.2: Non-reinforced dielectric 4.2 W/mk and 150 °C aging.

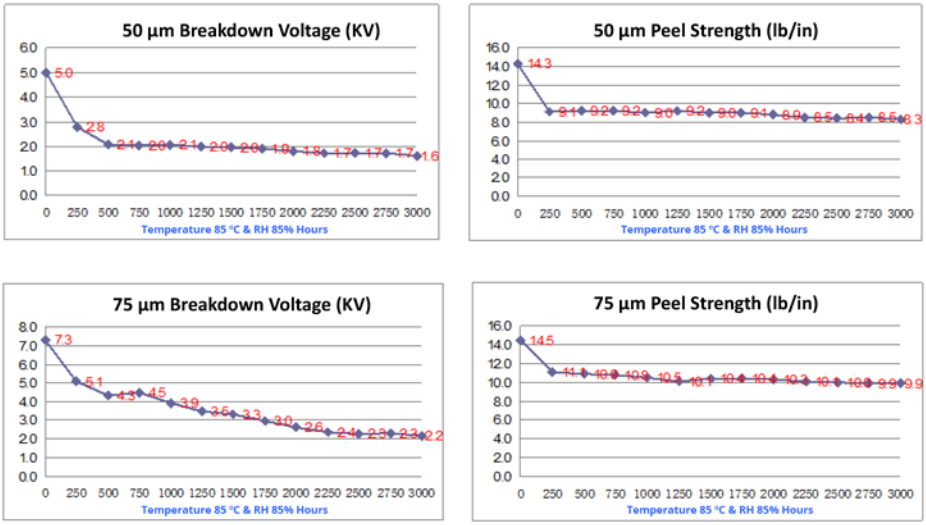


Figure 9.3: Non-reinforced dielectric 3.0 W/mk and damp heat.

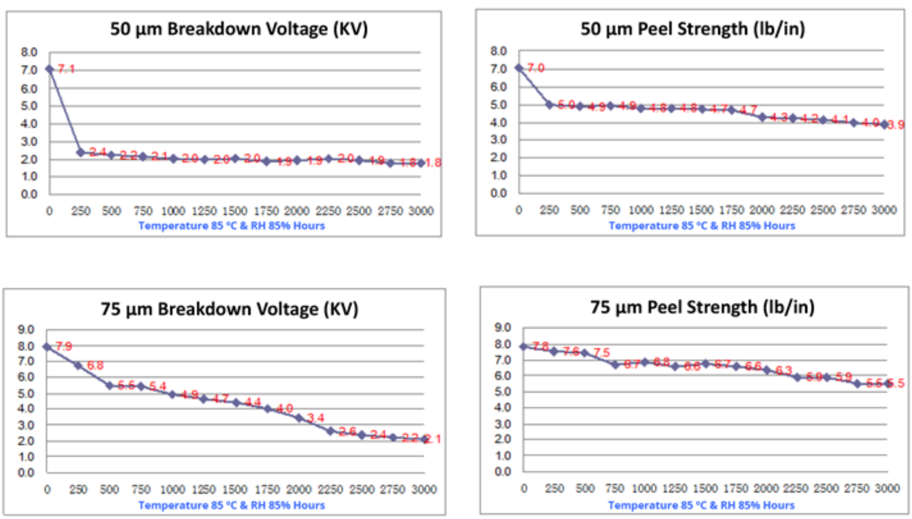


Figure 9.4: Non-reinforced dielectric 4.2 W/mk and damp heat.

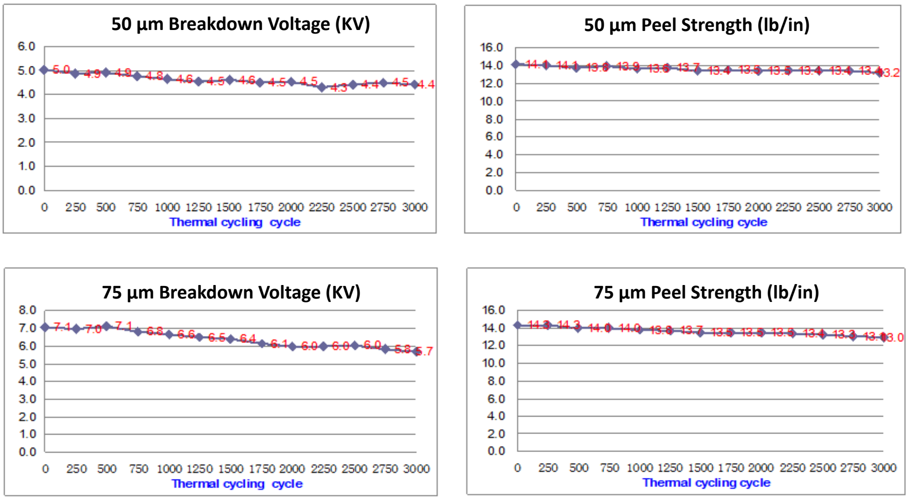


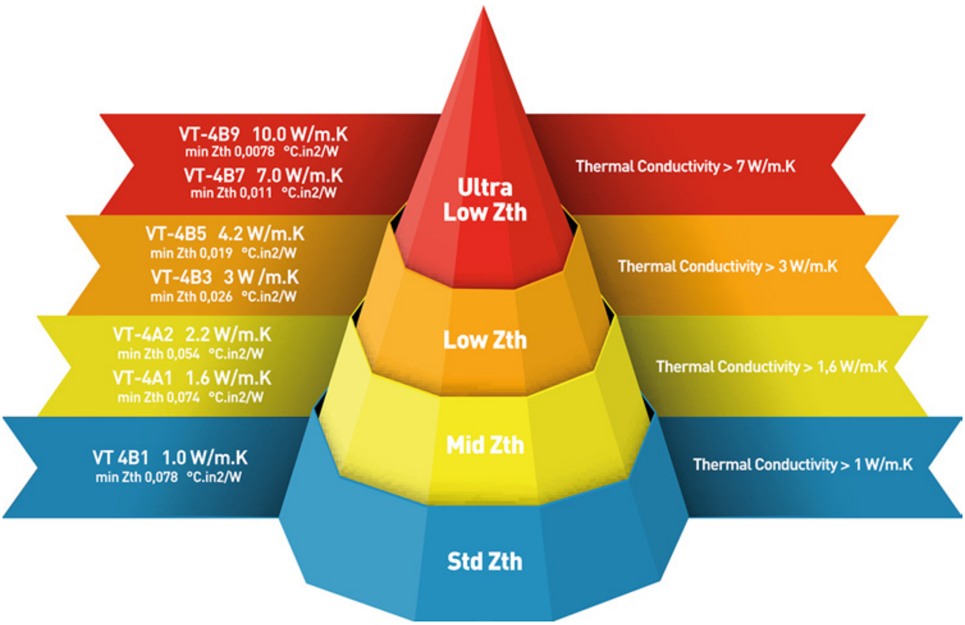
Figure 9.5: Non-reinforced dielectric 3.0 W/mk and thermal cycling.

Conclusion

The authors trust that you have found this book interesting and informative, and hope that it has helped you to develop a comprehensive awareness of the physical realities of insulated metal substrate laminates and their applications in the thermal management of electronic assemblies, and that it has aided the selection and specification of materials to achieve reliable and cost-effective performance.

The market for insulated metal substrates continues to grow exponentially, together with an ongoing demand for enhanced thermal, mechanical, and electrical properties. Over recent years, a number of lesser known manufacturers have entered this specialized market and there are some concerns about the long-term reliability of their products, particularly where these are offered at low prices.

Leading manufacturers of insulated metal substrates are committed to making substantial ongoing investments in product development and production infrastructure, as well as providing a high level of technical support for engineers and applications backed with meaningful test and reliability data. Whereas their prices may not be the lowest, they remain very competitive in real terms based on cost-reliability/reputation analyses.



For PCB designers, the Ventec IMS product pyramid is a quick and useful reference tool for IMS material selection.

Appendices

Appendix 1: Thermal Conductivity Conversion Factors

From	Cal / sec-cm-°C		BTU-in / hr-ft-°F		Watt / m-K	
Multiplier	4.2×10^2	2.9×10^3	0.14	3.4×10^{-4}	6.94	2.4×10^{-3}
To	Watt / m-K	BTU-in / hr-ft-°F	Watt / m-K	Cal / sec-cm-°C	BTU-in / hr-ft-°F	Cal / sec-cm-°C

Appendix 2: Typical Properties and Applications for Mid-Z_{th} Aluminum-Based Laminate or Prepreg

Properties: high breakdown voltage, cost-effective insulated metal substrates.

Applications: ultra-bright LED substrate, power conversion, power distribution panel, regulator for TV, monitor drives, rectifier, power supply.

Item		Test Method (IPC-TM-650)	Unit	Glass-Reinforced 2.2W/mK			
				75 um	100 um	125 um	150 um
Thermal Conductivity		ISO 22007-2	W/m*K	2.2			
Thermal Impedance		ISO 22007-2	°C*in2/W	0.054	0.072	0.089	0.107
Tg	DSC	2.4.25	°C	130			
Td	TGA	ASTM D3850	°C	380			
Thermal Stress	Solder Dip @ 288°C	2.4.13.1	Minute	>=5			
Hi-Pot Withstand	DC	2.5.7.2	V	4500	5000	6000	8000
Breakdown Voltage	AC	2.5.6.3	V	6000	7500	9000	10000
Dk @ 1 MHz	C-24/23/50	2.5.5.3	-	5.1			
Df @ 1 MHz	C-24/23/50	2.5.5.3	-	0.014			
Volume Resistance	After Moisture	2.5.17.1	MΩ-cm	5.1E+8			
	E-24/125			3.1E+7			
Surface Resistance	After Moisture	2.5.17.1	MΩ	2.3E+7			
	E-24/125			5.2E+6			
Peel Strength (1 oz)	As Received	2.4.8	lb/in	12			
CTI	As Received	ASTM D3638	V	600			
Flammability	As Received	UL94	Rating	V0			
RTI	Electric	UL94	°C	90			
	Mechanical	UL94	°C	90			

Appendix 3: Typical Properties and Applications for Low-Z_{th} Aluminum-Based Laminate or Resin-Coated Film

Properties: 3.0 W/mK, non-reinforced, ceramic filled, halogen free, MOT 130 °C, UL94 V0.

Applications: ultra-bright LED substrate, power conversion, power distribution panel, regulator for TV, monitor drives, rectifier, power supply.

Item		Test Method (IPC-TM-650)	Unit	Typical Values: Non-Reinforced 3.0 W/mK						
				50 um	75 um	100 um	125 um	150 um	180 um	230 um
Thermal Conductivity		ISO 22007-2	W/m*K	3.0						
Thermal Impedance		ISO 22007-2	°C*in2/W	0.027	0.040	0.053	0.067	0.080	0.095	0.130
Tg	DSC	2.4.25	°C	130						
Td	TGA	ASTM D3850	°C	380						
Thermal Stress	Solder Dip @ 288°C	2.4.13.1	Minute	>=5						
Hi-Pot Withstand	DC	2.5.7.2	V	2000	3000	4000	5000	6000	8000	10000
Breakdown Voltage	AC	2.5.6.3	V	4000	7000	8000	9000	10000	11000	13000
Dk @ 1 MHz	C-24/23/50	2.5.5.3	-	4.8						
Df @ 1 MHz	C-24/23/50	2.5.5.3	-	0.016						
Volume Resistance	After Moisture	2.5.17.1	MΩ-cm	5.0E+8						
	E-24/125			3.0E+7						
Surface Resistance	After Moisture	2.5.17.1	MΩ	2.0E+7						
	E-24/125			5.0E+6						
Peel Strength (1 oz)	As Received	2.4.8	lb/in	11						
CTI	As Received	ASTM D3638	V	600						
Flammability	As Received	UL94	Rating	V0						
RTI	Electric	UL94	°C	130						
	Mechanical	UL94	°C	130						

Appendix 4: Typical Properties and Applications for Low-Z_{th} Aluminum-Based Laminate or Resin-Coated Film

Properties: 7.0 W/mK, non-reinforced, ceramic filled, halogen-free, MOT 130 °C, UL94 V0.

Applications: super bright lighting, power conversion, power distribution panel, regulator for TV, monitor drives, rectifier, power supply.

Item		Test Method (IPC-TM-650)	Unit	Typical Values: Non-Reinforced 7.0 W/mK		
				50 um	75 um	100 um
Thermal Conductivity		ISO 22007-2	W/m*K	7.0		
Thermal Impedance		ISO 22007-2	°C*in2/W	0.011	0.017	0.022
Tg	DSC	2.4.25	°C	100		
Td	TGA	ASTM D3850	°C	380		
Thermal Stress	Solder Dip @ 288°C	2.4.13.1	Minute	>=5		
Hi-Pot Withstand	DC	2.5.7.2	V	2000	3000	4000
Breakdown Voltage	AC	2.5.6.3	V	4000	7000	8000
Dk @ 1 MHz	C-24/23/50	2.5.5.3	-	4.8		
Df @ 1 MHz	C-24/23/50	2.5.5.3	-	0.016		
Volume Resistance	After Moisture	2.5.17.1	MΩ-cm	5.0E+8		
	E-24/125			3.0E+7		
Surface Resistance	After Moisture	2.5.17.1	MΩ	2.0E+7		
	E-24/125			5.0E+6		
Peel Strength (1 oz)	As Received	2.4.8	lb/in	4.5		
CTI	As Received	ASTM D3638	V	600		
Flammability	As Received	UL94	Rating	V0		
RTI	Electric	UL94	°C	130		
	Mechanical	UL94	°C	130		

Appendix 5: Typical Properties and Applications for Super-Bendable Aluminum-Based Laminate or Resin-Coated Film

Properties: 1.0 W/mK, non-reinforced, ceramic filled, halogen-free, MOT 130 °C, UL94 V0.

Applications: 3D lighting, power conversion, power distribution panel, regulator for TV, monitor drives, rectifier, power supply.

Item		Test Method (IPC-TM-650)	Unit	Typical Values: Super-Bendable 1.0 W/mK		
				50 um	75 um	100 um
Thermal Conductivity		ISO22007-2	W/m*K	1.0		
Thermal Impedance		ISO22007-2	°C*in2/W	0.078	0.116	0.166
Tg	DSC	2.4.25	°C	100		
Td	TGA	ASTM D3850	°C	380		
Thermal Stress	Solder Dip @ 288°C	2.4.13.1	Minute	≥5		
Hi-Pot Withstand	DC	2.5.7.2	V	2000	3000	4000
Breakdown Voltage	AC	2.5.6.3	V	3500	6000	7500
Dk @ 1 MHz	C-24 /23 / 50	2.5.5.3	_	4.8		
Df @ 1 MHz	C-24/ 23 / 50	2.5.5.3	_	0.016		
Volume Resistance	After Moisture	2.5.17.1	MΩ-cm	5.0E+8		
	E-24/125			3.0E+7		
Surface Resistance	After Moisture	2.5.17.1	MΩ	2.0E+7		
	E-24/125			5.0E+6		
Peel strength (1 oz)	As Received	2.4.8	lb/in	11		
CTI	As Received	ASTM D3638	V	600		
Flammability	As Received	UL 94	Rating	V0		
RTI	Electric	UL 94	°C	130		
	Mechanical	UL 94	°C	130		

Appendix 6: Typical Properties and Applications for Copper-Based Laminate

Properties: 3.0-7.0 W/mK, non-reinforced, ceramic filled, halogen-free, MOT 130 °C, UL94 V0.

Applications: ultra-bright LED substrate, power conversion, power distribution panel, regulator for TV, monitor drives, rectifier, power supply.

Item		Test Method (IPC-TM-650)	Unit	3.0 W/mK			4.2 W/mK			7.0 W/mK		
				50 um	75 um	100 um	50 um	75 um	100 um	50 um	75 um	100 um
Thermal Conductivity		ISO 22007-2	W/m*K	3.0			4.2			7.0		
Thermal Impedance		ISO 22007-2	°C *in2/W	0.027	0.040	0.053	0.020	0.029	0.038	0.011	0.017	0.022
Tg	DSC	2.4.25	°C	130			120			100		
Td	TGA	ASTM D3850	°C	380			380			380		
Thermal Stress	Solder Dip @ 288°C	2.4.13.1	Minute	>=5			>=5			>=5		
Hi-Pot Withstand	DC	2.5.7.2	V	2000	3000	4000	2000	3000	4000	2000	3000	4000
Breakdown Voltage	AC	2.5.6.3	V	4000	7000	8000	4000	7000	8000	4000	7000	8000
Dk @ 1 MHz	C-24/23/50	2.5.5.3	-	4.8			4.8			4.8		
Df @ 1 MHz	C-24/23/50	2.5.5.3	-	0.016			0.016			0.016		
Volume Resistance	After Moisture	2.5.17.1	MΩ-cm	5.0E+8			5.0E+8			5.0E+8		
	E-24/125			3.0E+7			3.0E+7			3.0E+7		
Surface Resistance	After Moisture	2.5.17.1	MΩ	2.0E+7			2.0E+7			2.0E+7		
	E-24/125			5.0E+6			5.0E+6			5.0E+6		
Peel Strength (1 oz)	As Received	2.4.8	lb/in	11			7			4.5		
CTI	As Received	ASTM D3638	V	600			600			600		
Flammability	As Received	UL94	Rating	V0			V0			V0		
RTI	Electric	UL94	°C	130			130			130		
	Mechanical	UL94	°C	130			130			130		

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Ventec International Headquarters, Suzhou, China

About Ventec International Group

Ventec International Group is a world leader in the production of polyimide and high-quality, high-performance copper-clad laminates and prepregs used in a wide range of PCB and associated applications. Ventec is a global company with an extensive footprint of manufacturing, distribution, technical service, and sales centers throughout Asia, Europe, and the United States. A fully owned and managed global supply chain allows Ventec to readily and consistently supply quality products to all markets in all geographic areas.

Ventec's solutions include the latest advances in high-performance IMS materials that deliver exceptional thermal performance, reliability, and quality that is particularly demanded by automotive, medical, aerospace, and military markets, including LED lighting and DC power conversion applications. With tec-speed©, Ventec offers an advanced range of PCB materials for high-speed, low-loss applications. Its latest tec-speed 10 ultra-low Dk material with Dk values between 2.3 and 2.8 achieves lower losses, lower system power requirements, while balancing performance and cost. PCB base materials are also part of the Ventec portfolio, including complementary products such as flex- and rigid-flex circuit board materials, back-up, entry and routing materials, foils and coatings.

Wherever technology takes you, Ventec delivers! For more information, visit www.venteclaminates.com.