Flexible Thermal Management Circuits Bonded Directly to Aluminum Heat Sinks

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ABSTRACT
PowerFlex™ technology utilizes a flexible printed circuit, based on the all-polyimide TPI bond film, that is heat-seal laminated directly to an aluminum heat sink. PowerFlex provides excellent thermal management, while utilizing conventional circuit processing. This film-based electronic packaging system offers advantages in performance, cost and design flexibility over existing thermal management methods.

Key words: *power electronics, power device cooling, thermal management circuit, flexible circuit.*

BACKGROUND

Telcom power electronic systems, such as power converters in bay stations, have high thermal management and reliability requirements, but must be built cost-efficiently. We believe that our PowerFlex technology will assist in optimizing next-generation designs for both performance and cost.

Power electronics systems convert one form of electrical power to another, or convert electrical power to physical motion. These systems are not 100% efficient, of course, and heat is always a by-product and must be considered in design and operation.

Printed circuit boards (PCBs) in power electronics applications often generate heat, largely from the surface-mounted power device components that are soldered to the board. This heat needs to be dissipated, or the temperature rise of the power device will dramatically increase its failure rate. (As 'rules-of-thumb', failure rates for most silicon-based components double with each rise of 10°C of operating temperature, and extended exposure to 150°C+ can be imminently fatal.) A surface-mounted power device, such as a D2Pak or TO-220, is designed to have heat transfer through their solderable base into the PCB. The PCB is then often mounted onto a heat sink, generally made from aluminum. In conventional designs, heat is passed through the PCB towards the heat sink at *thermal vias*, which are drilled holes in the PCB that have been plated with copper and are generally filled with solder.

Heat can also be generated within a printed circuit by the resistance to high electric current flow within the conductors. This often is a factor in power electronic applications. Thick copper conductors reduce the amount of heat evolved.

Where conventional printed circuit boards are used, such as FR4, the PCB and its thermal vias need to be electrically-isolated from --while 'thermally-connected' to-- the heat sink. An insulation pad is placed between the PCB and the heat sink that provides dielectric strength and conforms to the surfaces to eliminate air. These pads are made from insulation material that is filled with ceramic to maximize thermal transfer. Insulation pads can have a pressure-sensitive or thermosetting adhesive to permanently bond the PCB to the heat sink. Or significant pressure must be applied to the PCB with hardware to ensure attachment and thermal transfer to the heat sink.

Many demanding thermal applications now use dielectric substrate material that has inherent high thermal transfer for the printed circuit board. Ceramic wafer (i.e., direct bond copper, or DBC) and Insulated Metal Substrate (IMS, *trademark of The Bergquist Company*) have wide acceptance. These technologies utilize the high thermal transfer and excellent dielectric properties of ceramic materials. In most DBC and IMS applications, the substrate is then mechanically attached to a heat sink, with a thermal compound material (such as thermal grease) to ensure heat transfer.

DBC and IMS require special processing to make and depanelize the circuits. Costs increase significantly where multilayer circuitry is required.

PowerFlex allows the bonding of conventional flexible circuitry directly to the heat sink, with system thermal transfer that rivals DBC and IMS.

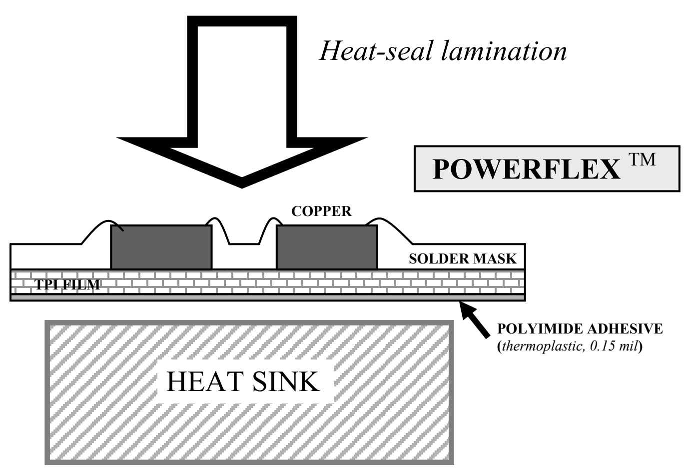

FIGURE 1: PowerFlex schematic

PowerFlex technology can reduce the cost and improve the performance of thermal management electronic packaging. The use of a film-base dielectric substrate and thermoplastic heat-seal bonding offer enhanced design options.

POWERFLEX TECHNOLOGY DESCRIPTION

The key to the PowerFlex technology is the unique performance of the all-polyimide TPI bond film.

The dielectric layer is 1-mil Kapton® MT film, which is filled with ceramic powder to enhance thermal transfer. The copper circuitry is bonded to the aluminum heat sink by a very thin layer of thermoplastic polyimide adhesive –0.15 mil, or 4 micron-- on either side of the MT film. This bond line is very durable physically and thermally, and its 'thinness' maximizes heat transfer.

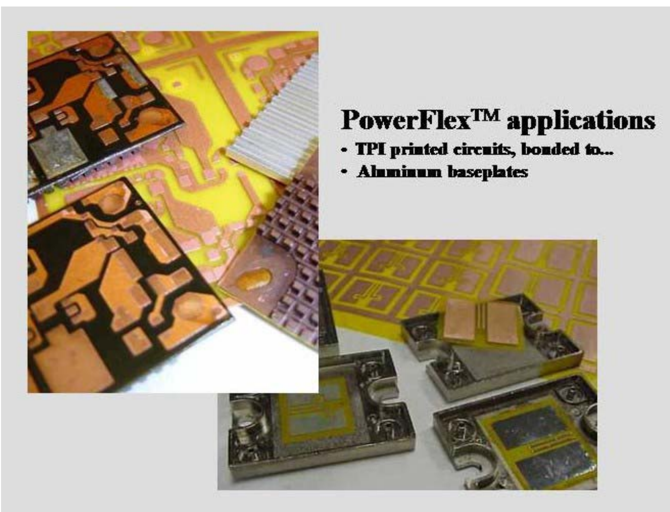

FIGURE 2: PowerFlex thermal circuits

If only single-layer circuitry is required, the copper to be printed-and-etched is laminated to the TPI at low temperature (180°C) for PCB processing. (The polyimide adhesive easily withstands the thermal and chemical rigors of masking, etching and plating, even if it is only tack-bonded to the copper foil.) The individual PowerFlex circuit is then sealed to the heat sink at high temperature (250-300°C) for the final bonding. The "heat-seal" process is short in duration due to the thermoplastic nature of the polyimide adhesive. This facilitates high-volume production and automation.

If double- or multi-layer circuitry is required, conventional flexible substrate can be used for the copper laminate. To maximize thermal transfer, thin substrates are preferred, where the dielectric layer is only 1- to 3-mil. Pyralux AP or other 'adhesiveless' film laminates, or even thin FR4, can be used for the circuitry. After the circuits have been processed, including solder-mask, the TPI bond film is tack-bonded to the 'bottom-side' of the circuit panel at low temperature. The circuits can then be depanelized and heat-sealed at high temperature to the heat sinks.

The properties of the 130TPI-2 bond film follow:

TPI bond film properties (130TPI-2)

Property	Value	Method
Thickness	1.3 mil (0.033mm)	ASTM D374
Voltage breakdown	>4000 Vac	ASTM D149
Thermal impedance [1]	0.1°C-in²/W	ASTM D5470-95 (Laminate of TPI, copper, solder)
Thermal resistance [1]	TO-220 = 2.7 °C/W TO-247 = 0.7 °C/W	Rj-s (using Anatech pulse test)
Tensile strength (TPI bond)	>600 psi at 25 °C >200 psi at 150 °C	ASTM D412
Shear strength (TPI bond)	>4000 psi at 25 °C >2000 psi at 150 °C	ASTM D412
Operating range	-65 to 200 °C	OEM testing
Flammability	V-0	UL-recognized

TECHNOLOGY PERFORMANCE

PowerFlex is thermally competitive with standard IMS substrates (based on alumina-loading) – both have thermal impedance of about 0.1°C-in²/W. Premium IMS (based on BN-loading) and DBC offer improved thermal performance, with a thermal impedance as low as 0.05°C-in²/W. Two different thermal comparisons are presented below.

TEST 1: Thermal transfer comparison shows that PowerFlex and standard IMS have equivalent thermal resistance (junction-to-baseplate).

The following test was run with single power devices mounted to small aluminum plates (1.5" x 1.5"), which in turn was bonded to a large pin-fin heat sink with conductive adhesive. The amount of power dissipation in the PowerFlex single-sided construction was comparable to that given by the equivalent IMS format.

THERMAL PERFORMANCE:
Maximum Power Dissipation [2] at Tj = 150 °C

Interface Material	TO-220 (watt)		TO-247 (watt)	
(*Air Flow, lfm =>*)	0	100	0	100
IMS	16.6	23.1	25.4	40.1
PowerFlex	16.8	23.7	24.2	38.0

It is important to note, however, that if the PowerFlex was bonded *directly* to the pin-fin heat sink, the power dissipation would be even greater, as there would be less material and interface thermal barriers. In addition, this system also would have no attachment hardware or pressure dependency.

TEST 2: Thermal transfer comparison shows that IMS has a slight advantage over PowerFlex, but this is moderated by the addition of the heat sink to baseplate.

THERMAL PERFORMANCE:
Thermal Resistance [2a] **(TO-220: Rj-s, °C/W)**

Interface	*Thermal resistance to:* Baseplate	*Thermal resistance to:* Heat sink	Comment
All-metal	1.35	*1.35*	Theoretical limit
IMS – premium	1.80	*2.00*	Baseplate req'd
IMS – standard	1.94	*2.14*	
PowerFlex *(filled)*	2.10	*2.10*	No baseplate
PowerFlex *(unfilled)*	2.28	*2.28*	

NOTE:
- The *all-metal construction* is a TO-220 soldered directly to a copper heat sink. It has no conventional "interface". Its thermal resistance would be the sum of the silicon die junction, the device case, and the solder joint -- these are common to all the insulated interface formats listed.
- IMS is only available on a flat baseplate, which typically needs to be adhered to a heat sink with attachment hardware and thermal compound. In determining the thermal resistance to the heat sink, the additional resistance of the IMS baseplate and thermal compound is estimated at 0.2°C/W for a TO-220.
- PowerFlex is typically made with alumina-filled Kapton® MT film. Tests were also run with unfilled Kapton as well, for reference.
- PowerFlex can be bonded directly to heat sinks. A baseplate is not required.

TECHNOLOGY FEATURES

The unique characteristics of the PowerFlex system based on TPI bond film offer the following performance and design advantages:

- ***Higher thermal transfer*** *than conventional mounting methods of flexible and rigid printed circuit boards to heat sinks at comparable cost.* The thermal resistance of a PowerFlex construction (from the heat-producing electronic components and conductors on the circuit board to the heat sink,) is a fraction of the thermal resistance of conventional circuit board mounting methods, which include various tapes and adhesive sheets.

Better thermal transfer can provide the following performance advantages:
- ⇨ lower electronic component temperatures (increasing reliability),
- ⇨ reduction in component and/or heat sink rating and cost (less-expensive devices and/or heat sinks can be used),
- ⇨ increase power output from same system (ex., more Watt output from same power supply unit).

- ***Elimination of assembly hardware*** – the PowerFlex printed circuit construction is bonded directly to the heat sink with very thin, thermally-activated polyimide adhesive on the TPI film. In many applications, printed circuit boards are merely pressed against heat sinks with electrically-insulating and thermally-conductive interface material between the PCB and the metal heat sink. Insulated metal substrate (IMS) and direct-bond copper ceramic (DBC) constructions also often need to be mechanically-attached to a heat sink. In addition, a thermally-conductive interface material is required between the IMS or DBC and the heat sink.

- ***Higher thermal transfer*** *than more-expensive IMS and DBC constructions in many applications.* The PowerFlex printed circuit can be bonded directly to the heat sink -- the thermal interface resistance resulting from the mechanical attachment of the IMS and DBC to the heat sink is eliminated.

- ***Excellent durability*** – the all-polyimide TPI bond film withstands a wide-temperature range, thermal shock, heat+humidity, shock-and-vibe, and solvents. The bond strength of the polyimide adhesive on the TPI film is resilient up to, and beyond, its glass-transition temperature.

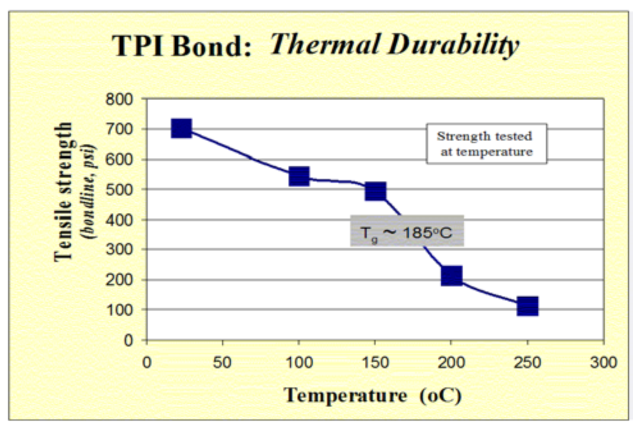

FIGURE 3: TPI tensile strength vs temperature [3]

- ***Lower cost than IMS and DBC constructions***. IMS and DBC use expensive materials and processes that have limited availability. PowerFlex uses conventional printed circuit processes that are widely-available.

- ***Greater design flexibility than IMS and DBC constructions***. Both IMS and DBC technologies are based on flat plates, requiring all circuitry and components to be on one plane only. Circuitry can only extend to the edge of the planar substrate (metal sheet in IMS, ceramic wafer in DBC). Adding multiple conductor layers is an expensive process in both IMS and DBC. DBC is also very brittle and has a limited process size (maximum of 4" x 4"). PowerFlex has significant design advantages over IMS and DBC in that it can produce thermal management assemblies that:

- ⇨ are physically flexible (plastic film dielectric),
- ⇨ can be bonded directly to practically any shape or size or material type heat sink (assuming that the heat sink can withstand the lamination process),
- ⇨ allow circuitry to extend past the edge of the heat sink (perhaps connecting to other subassemblies),
- ⇨ use conventional circuit processing equipment and materials,
- ⇨ are physically robust (plastic film dielectric and metal heat sink), and
- ⇨ can be made into literally any dimension (width or length).

The advantages of PowerFlex are summarized below:

PowerFlex Advantages	
Features	**Benefits**
Any printed circuit configuration on any heat sink (*within reason*):	• Optimized manufacturing: *Circuits made by PCB mfgr, heat sinks made by metal mfgr*
⇨ Circuits can be heat-sealed to heat sinks at OEM (or subcontractor)	• Manufacturing flexibility • Tailored product offering: *Different heat sinks for same circuitry* • Cost savings
⇨ Circuit footprint SMALLER than heat sink	• Lower cost: *Don't pay for circuit area that you don't need*
⇨ Circuit footprint LARGER than heat sink	• Electronic components and connections beyond the heat sink plane
⇨ No baseplate-to-heat sink interface possible	• Enhanced thermal transfer to ambient --*higher power output possible*-- with no attachment hardware required
Conventional materials for circuitry and heat sink (*in addition to TPI bond film*)	• Lower cost • Enhanced supply options
Conventional manufacturing processes	• Lower cost • Enhanced supply options
Excellent thermal transfer	• Resistance = $0.1^{o}C\text{-}in^2/W$ [1] across the TPI bond film (*for single-layer design; multilayer designs will have higher thermal resistance*)
Physically-robust all-polyimide construction	• All-polyimide durability • >4000V dielectric strength • Reliable in operation at 200^{o}C (continuous exposure) • Survives 300^{o}C exposure • No cracking • No handling issues

TECHNOLOGY COSTS

Cost is a critical consideration in designing power electronic systems for telcom applications. PowerFlex should reduce cost versus the other high-performance insulation systems, IMS and DBC.

As expected, cost is very application- and volume-dependent. Therefore, a relative cost table follows for various formats. The cost of a single-layer PowerFlex is designated as '*1*'. A system with approximately double the cost on an area basis would be designated as '*2*'.

RELATIVE SYSTEM COST (Area Basis)			
	PCB layers:		
Interface	*Single-*	*Double-*	Comment
PowerFlex	*1*	*1.5*	No baseplate, Bonding req'd
IMS (standard)	*1.5*	*3*	With baseplate, Hardware req'd
DBC	*2.5*	*5*	Hardware req'd

NOTE:

- IMS baseplate and DBC need to be adhered to a heat sink with hardware and thermal compound.
- PowerFlex can be bonded directly to a heat sink.
- The cost of heat sink processing (bonding the PowerFlex, or hardware-attaching the IMS or DBC) are application-dependent and are not considered above.

TECHNICAL CHALLENGES

Adoption of new technology is a typically a slow process, especially in the thermal management of power electronics. Conventional PCB (both FR4 and flex), DBC and IMS thermal management systems have been used –and have performed adequately in applications-- for decades. The following technical challenges must be addressed for PowerFlex technology to become the "new standard":

- Technology inertia – a lot rides on proper thermal management of electronics….change can be daunting.
- Heat-seal processing – the only special equipment is the platen press, capable of bonding at up to 300^{o}C. Large and/or finned heat sinks would require special tooling.
- Compatible PCB materials – solder mask and copper solderability treatment must withstand the high-temperature lamination.
- Heat sink surface quality –good surface finish on a heat sink is required for good PowerFlex bonding. Chromate coating, anodization and/or priming is highly recommended.
- Volume drives cost – to ensure widespread use, the cost of PowerFlex technology needs to be small in comparison to the value that it delivers. High volume production ensures low unit costs.

TECHNOLOGY FORMATS

PowerFlex circuits can be manufactured in single- and multi-layer formats in any thickness copper. As earlier noted, the only special material is the TPI bond film.

In single-layer circuits, the TPI film serves both the laminate and bond film functions. In multi-layer circuits, off-the-shelf copper+dielectric laminates should be as thin as possible to ensure thermal transfer. Recommended substrates: ‘adhesive-less’ polyimide flex, thin FR4.

In multi-layer circuits, plated-through-hole thermal vias are extremely important to maximize thermal transfer, as they carry the heat generated by the power devices down to the TPI bond film, which attaches the heat sink.

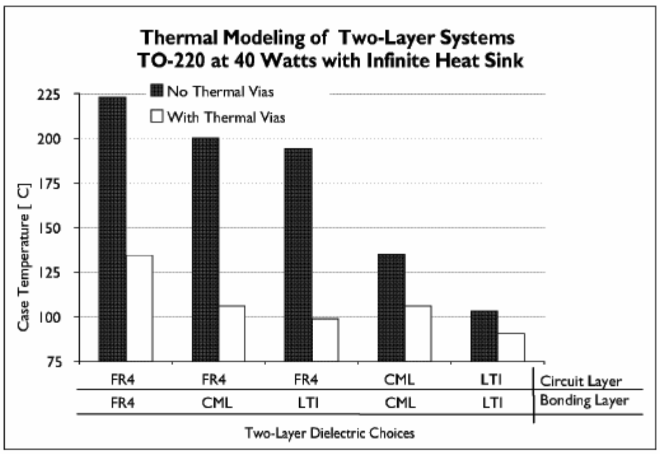

FIGURE 4: Relative importance of thermal vias and bond film (*The Bergquist Company chart*[4])

The above chart illustrates that 1) the presence of thermal vias and 2) the thermal transfer performance of the bond film are much more critical than the thermal transfer of the laminate dielectric, on which circuitry is etched and power devices are mounted. (*The white bars have thermal vias, while the dark bars have no thermal vias.* FR4 is standard hardboard PCB material. CML and LTI are types of IMS material.)

Manufacturing the PowerFlex circuit board and heat sink separately, and then bonding them together, offers design advantages:

- PowerFlex can be applied to only a portion of a heat sink. This can save material cost and improve thermal performance.
- PowerFlex TPI insulation can extend beyond the edge of the heat sink, to ensure greater dielectric reliability.
- PowerFlex can be used in a ‘rigid/flex’ format, with interconnection circuitry extending beyond the plane of the heat sink.

TECHNOLOGY APPLICATIONS

PowerFlex technology can improved performance and enhance design capabilities in the following applications:

- Power supplies
- Portable devices
- Automotive controls
- Multi-chip modules
- Other thermally-demanding applications, where cost and reliability are critical.

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