THIN FILM THERMOELECTRIC

HANDBOOK

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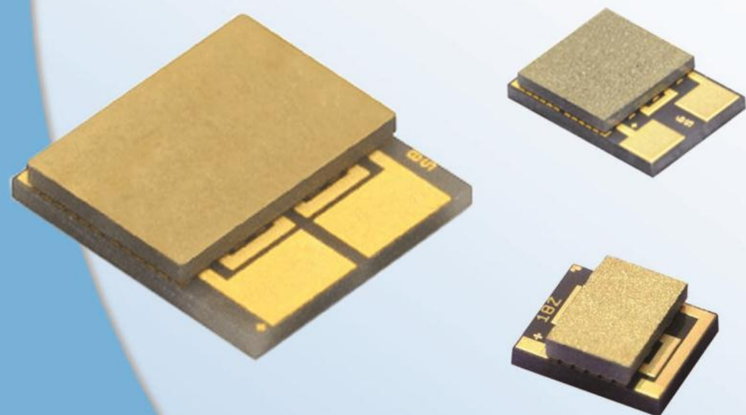

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Revision History

Revision	**Description**
1	8/30/2012 – Initial Version

Thin Film Thermoelectrics

As components, packages and systems continue to shrink in size, the heat generated in these dense electronic systems can be quite large and can lead to a significant rise in temperatures that in turn can cause device and system-level failures.

Heat has always been an issue for system designers, but only recently has the problem become so severe that thermal management solutions can no longer be introduced as an afterthought. Thermal management must be considered from the beginning of the design process in order to avoid causing severe problems at the system level. This is an important consideration because at the system level, the thermal operating space is more limited (i.e. the temperatures that can be tolerated) and any solution employed at the system is likely to be more expensive than one implemented at the chip level.

A new approach to thermal management involves embedding thermal management functionality deep inside an electronic component at the source of the heat using thin film thermoelectric devices.

Introduction

TEMs (thermoelectric modules) are solid-state heat pumps that operate using the Peltier effect. When an electric current is driven through a circuit containing two dissimilar materials, heat is absorbed at one junction (the cold side) and released at the other junction (the hot side). The design of most Peltier devices requires the use of both an n-type semiconductor and a p-type semiconductor. Since heat naturally flows down a temperature gradient from hot to cold, a TEM's ability to move heat from cold to hot in a solid-state fashion is unique. By reversing the polarity of the applied DC current, heating is also possible. This attribute is especially useful for applications requiring both cooling and heating to maintain precise temperature control.

Conventional TEMs, sometimes referred to as "bulk" TEMs, have been used for decades to control the temperature of electronics. However, as the size and power density requirements of new applications are changing, conventional bulk thermoelectric technology has not kept pace. In some instances, designers choose to place the cooling device outside the package if it is too large to be placed inside. Cooling the device by cooling the entire package is at best an inefficient method for thermal management and often leads to over sizing of the TEM and input power requirements, which results in more waste heat in the system.

Advantages of Thin Film Technology

Conversely, thin film thermoelectrics target the source of the heat flux to provide thermal management and control. These embeddable TEMs use semiconductor processing techniques to create a nano-structured thin film used for the P and N legs. Thin film TEMs are typically 5 to 20µm thick, versus 200µm for conventional bulk TEMs, resulting in several differences. The heat flux, which is inversely proportional to the thickness of the thermoelectric material, is more than 20 times greater than bulk TEMs. Thin film TEMs can also pump a maximum heat flux of 100 to 400W/cm² versus less than 10W/cm² for conventional bulk TEMs. Thin film TEMs can operate in a high coefficient of performance (COP) regime and still pump a reasonably high heat flux of 20 to 40 W/cm². COP is a measure of efficiency defined as cooling power divided by input power.

Figure 1:Ccomparison of thin film vs bulk device

Depending on the design, thin film TEMs may have thermal response times as low as milliseconds enabling very rapid cooling and heating to maintain precise temperature control. They are known to have higher heat pumping capability than standard bulk TEMs, but for temperature control applications, the superior switching speed of the devices may ultimately prove to be their most valuable asset.

Thermoelectric Cooling

The most basic representation of the operational space for a thermoelectric module is a performance chart as shown in Figure 2.

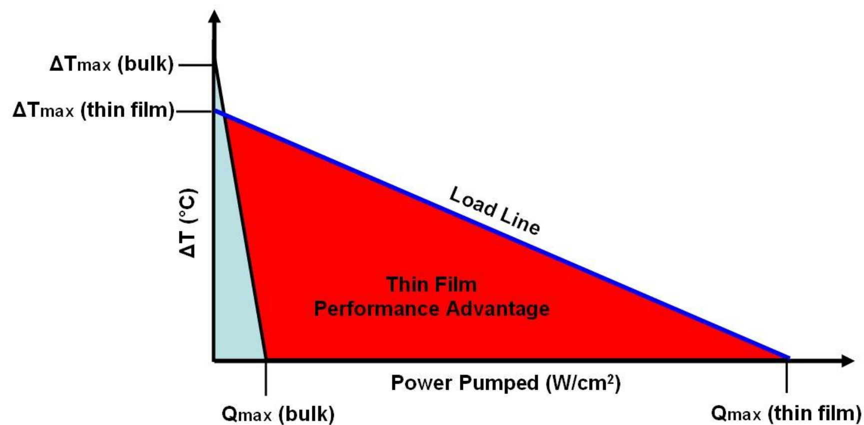

Figure 2: TEM Performance Chart.

The load line represents the ΔT and power pumped conditions possible for a given TEM drive current. At the maximum drive current for the module, the load line is generated from two key parameters: 1) the maximum power the device can pump, Qmax; and, 2) the maximum temperature difference that the device can sustain between its top and bottom substrates, ΔTmax.

The load line defines the operational space for TEMs and is the best and most usual way to illustrate cooling capacity for a particular temperature condition.

System Level Considerations

The TEM, being an active thermal device, creates a thermal inversion that dramatically changes the thermal profile inside the package. Figure 3 shows a comparison of the thermal profile through the cross section of the module in two cases, a) with no TEM, or in other words, a passive solution only, and b) with a TEM actively cooling the junction. It can be clearly seen that the introduction of the TEM provides a substantial net cooling benefit.

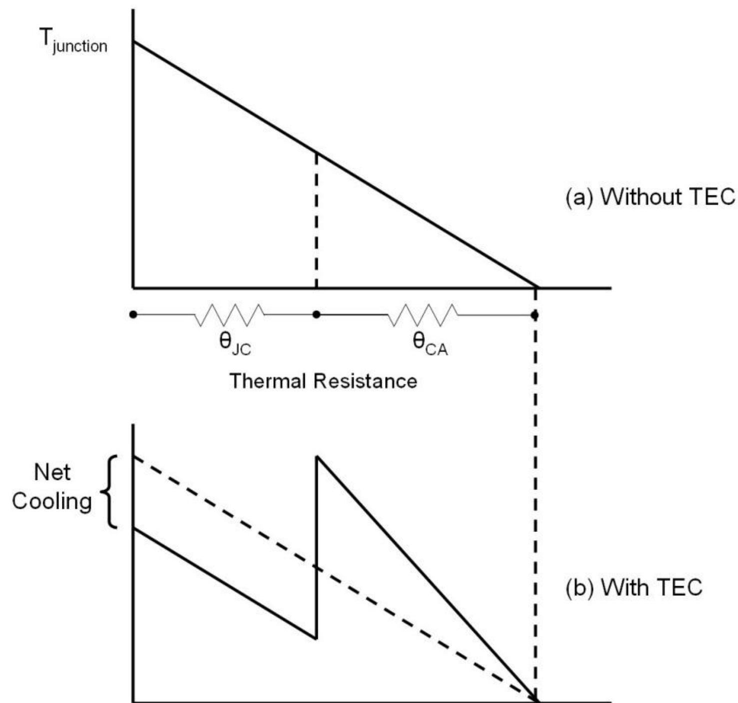

Figure 3: Temperature profiles through the cross section of a package from the junction to the case (θJC), and case to ambient (θCA) without (a) and with (b) a TEM. The temperature inversion created by the TEM lowers the junction temperature relative to the no-TEM case.

The heat that is pumped by the device and the additional heat created by the TEM in the course of pumping that heat will need to be rejected into the system. Since the performance of the module can be improved by providing a good thermal path for the heat rejected, it is beneficial to provide high thermally conductive pathways. For small packages, this is typically accomplished through the electrical connections themselves, and depending on the operating characteristics, this level of thermal management might be sufficient. For packages with higher heat densities, thermally-conductive feed-throughs or posts may be needed to remove the heat.

Thin Film Thermal Management Design

In order to understand the design challenges facing engineers in the electronics industry, we need to first look at the way heat moves or flows through a material system, and to do this we need to look at the forces that govern that movement. Heat has always been an issue for system designers, but only recently has the problem become so severe that thermal management solutions can no longer be introduced as an afterthought. Heat flux must be looked at from the beginning of the design process. Heat flowing through a material will always create a temperature gradient across that material and will do so in a continuous manner as it flows from one material to another.

Designing in a thermal management system today is a cumbersome exercise where the means for moving the heat and the manner and location in which we reject the heat must be considered early in the design cycle in order to avoid causing severe problems at the system level. This is an important consideration because at the system level the thermal operating space is more restricted with the temperatures that can be tolerated and any thermal conducted at the system level is likely to be more expensive than one implemented at the chip level.

Unfortunately the management of heat in a system is at times a lot like pushing jelly. You can press it down in one direction but it will just flow in another. To see why this is so, we will look at the rules for heat flow in a material system.

Heat Flow in a Material System

The heat equation is an important partial differential equation describing the distribution of heat (or variation in temperature) in a given region over time. For a function u (x, y, z, t), which is a measurement of the temperature T, of three spatial variables (x, y, z), and the time variable t, the heat equation is

$$\frac{\partial u}{\partial t} - k\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = 0$$

u = u(t, x, y, z) is temperature as a function of time and space; or equivalently

$$\frac{\partial u}{\partial t} = k\nabla^2 u$$

Here k is a constant.

The other important governing equation is

Q = U + W

Heat flow is equal to the work on the system plus the change in internal energy of the system. Hence, in thermodynamics, the change in heat is equivalent to the heat flowing into the system. Combining these two equations and in the absence of any work being performed, Q is proportional to the change in temperature. We won’t provide the derivation here since it is to be found everywhere in the literature but we then arrive at:

Q = kΔT

Hence for passive systems, cooling by the conduction of heat is a linear function of temperature and a constant related to the material properties of the solid. This constant k may be a function of many variables including T, P, and V.

Passive Cooling

The primary systems used for passive cooling of electronic and optoelectronic systems are materials configured as thermal interface materials (TIM), heat spreaders and heat exchangers. Each perform a different function for removing heat from a system.

Heat exchangers may be an environment (e.g. liquid or air) or object that absorbs and then dissipates heat while in physical or thermal contact. This may occur in different ways including direct and radiant transfer of heat. A heat exchanger's performance is a function of material, geometry, and the overall surface heat transfer coefficient along with the temperature of the heat sink. Generally, forced convection heat sink thermal performance is improved by increasing the thermal conductivity of the heat exchanger materials and increasing the surface area.

Thermal interface material (TIM) is used to fill the gaps between thermal transfer surfaces, such as between microprocessors and heat sinks, in order to increase thermal transfer efficiency. These gaps are normally filled with air, which is a very poor conductor of heat. The most common TIM is thermal grease, typically silicone oil filled with aluminum oxide, zinc oxide, or boron nitride.

Heat spreaders, most often simple metal plates, have high-thermal conductivity. Carbon-based heat spreaders having anisotropic characteristics are also being used. They act as a heat exchanger moving heat between localized heat and a secondary heat exchanger that is larger in area.

For all the passive components described above, heat will move through them as described by the general rules below:

1. There has to be a temperature difference; heat will only flow if there is a temperature difference

2. Heat always flows from a higher temperature to a lower temperature

3. The rate of flow is proportional to the difference in temperature

4. The flow of heat may be caused or assisted by both active and passive means

Active Cooling and Package Size

As overall sizes of electronic devices shrink, the size of the thermal management system must also shrink. Given that passive heat removal is only a linear function over distance of the temperature difference, work must be put into the system to obtain a greater rate of cooling and yield a smaller device.

One such example for optoelectronics of the continuing reduction in package size is shown below in Figure 4. In some instances, designers choose to place the cooling device outside the package because it is too large to be placed inside.

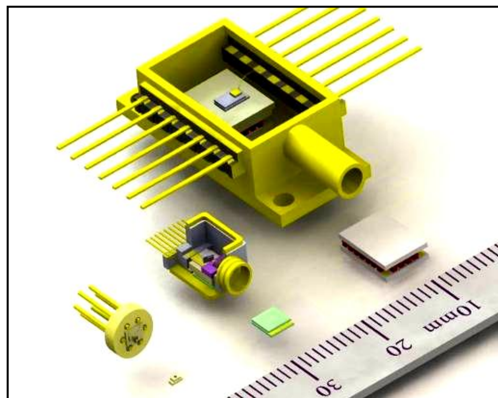

Figure 4: Size comparisons of optoelectronic packages and thermoelectric modules. From left to right, TO-56, TOSA and butterfly package

An active thermal management device, such as a thermoelectric module (TEM), has been employed to provide this additional heat pumping and temperature stabilization capability. A simple example of the type of heat pumping and temperature control offered by a TEM and its ability to cool a device is shown in Figure 5.

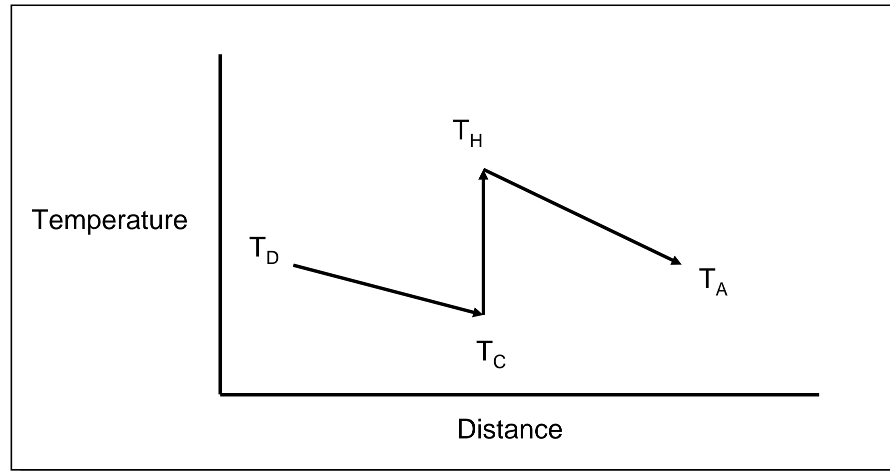

Figure 5: T_D is the temperature of the device to be cooled; T_C is the temperature of the cold side of the TEM; T_H is the temperature of the hot side of the TEM; and T_A is the temperature of the ambient or surrounding environment where the heat is to be dumped.

A Comparison of Active and Passive Cooling

As shown above, thermal management solutions for electronics may be divided into two types of systems: active and passive. With the exception of fans, which are usually combined with heat sinks, most of today's thermal management systems are passive types. Conduction-based thermal management systems, such as thermal interface materials (TIMs), are used to improve the flow of heat from one location to another and greatly enhance the efficiency of the overall thermal management system. However, convection-based systems have the drawback of allowing heat to flow in an uncontrolled manner from one level to the next.

These systems have served the industry well but have the drawback of removing not only the heat that is limiting device performance but also any of the heat from the surrounding area which likely is not limiting the device or system performance.

One solution is to apply an active device as a localized thermal management solution. This could be applied inside the electronic package. To reduce the cooling needed at the system and building levels, we need to reduce the amount of heat extracted from the die. Die are typically cooled to keep their operating frequency near its peak. However, this peak frequency is typically limited by the temperature within one of the hot spots on the die and not the temperature across the entire die.

If instead of extracting the heat from the die as a whole, we are able to extract the heat from the hot spot only, we will create a smaller system-level problem to deal with and subsequently have a smaller building thermal management problem.

Design Considerations

One of the drawbacks of thermoelectric devices is that in order to cool, they consume power. This power adds to whatever power is being pumped out of the cooling zone, so at the larger, system level more heat has to be dissipated with a TEM in operation than without one.

If TEMs are applied to cool devices in the same manner as passive thermal components, then the heat dissipation becomes a much larger problem at the system than at the chip level. A more cost-effective and efficient approach — and one that is only possible with TEMs — would be to cool only what is necessary. In other words, scale the thermal management system to the size of the heat problem.

This can be illustrated by looking at the coefficient of performance (COP) of a TEM, which is defined as:

$$COP = \frac{Q_{pumped}}{P_{in}}$$

A TEM will pump a certain amount of heat, Q, and add an additional amount of heat, Q*COP to move this heat. This is a result of the inherent inefficiency in all engines. As a result, bulk TEMs are often sold as systems that include the TEM and a heat transfer mechanism such as a fan and heat sink or liquid heat exchanger. The value of the TEM in this case is that it can deliver sub-ambient temperatures and provide active temperature control but at the cost of increasing the system level heat transfer problem.

Because heat in the passive case flows linearly, any thermal resistance between the TEM and the heat source will have a temperature drop across it. This will act to increase the temperature difference that the TEM must pull. As already mentioned, the TEM is a heat pump removing heat in a manner whose efficiency depends upon the temperature difference it is required to generate. Minimizing this temperature difference will improve the efficiency of the TEM and reduce the additional heat added at the system level.

Integration of a TEM close to the heat source is the key to improving a TEMs operational efficiency. Adding an additional heat transfer system defeats the purpose of the integration. As such, careful attention has to be paid to the characteristics of the heat transfer problem, the design of the thin film solution and also the design of the device package. When these three issues are addressed in tandem; ideally at the time of product design and development, significant performance improvements can be achieved.

Module Handling and Assembly

Thin film thermoelectric modules have extremely small form factors with footprints smaller than 10 mm^2. These devices are only 0.6mm high, making them the thinnest thermoelectric modules available on the market today. Due to their small form factor, care must be taken when handling and assembling modules into sub-assemblies for validation testing and production use.

Figure 6 shows a typical thin film thermoelectric module. Please note the location of the primary and secondary headers, which are referenced in the assembly instructions that follow.

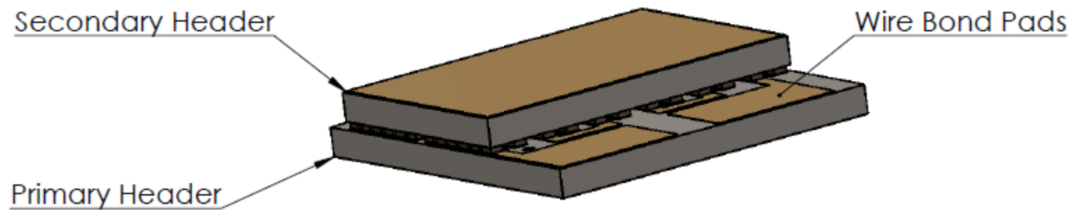

Figure 6: Typical Thin film Thermoelectric Module.

Figure 7 shows a rendered image of an HV56 in a “generic thermal package” consisting of two metal plates with spacers and the eTEC™ (with wires) sandwiched between. The lower metal plate is described as the “heat-rejection surface” while the upper plate is the “temperature controlled surface”. The figure indicates typical components used during package assembly, including spacers, hard solders, and liquid metals.

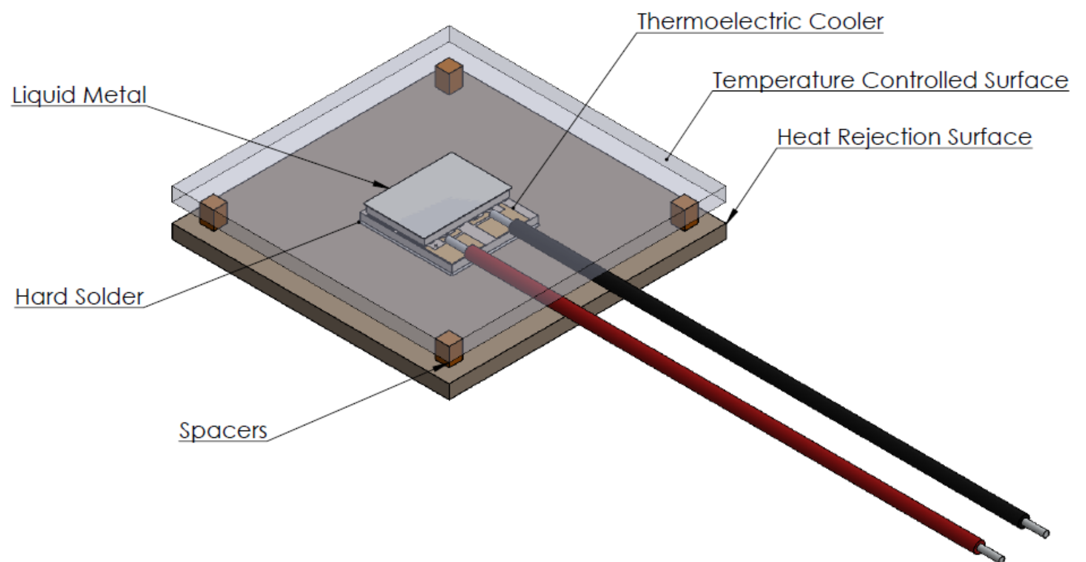

Figure 7: A generic thermal package.

The assembly procedure that follows describes a method for fabricating a thermoelectric assembly as shown in the figure above where a thin film thermoelectric device is packaged between thermally conductive plates. These plates could represent separate heat-spreaders or could be an integral part of the heat-exchangers or temperature controlled target. The package has been optimized to meet the conflicting requirements of highly conductive thermal interfaces while allowing for mechanical isolation of the eTEC™.

Suggested Parts and Supplies List

Solder – available from Indium Corporation in wire or foil preform

- InSn alloy #1E (52/48), MP 118°C
- BiSn alloy #281 (58/42), MP 138°C
- PbSn alloy #106 (63/37), MP 183°C

Flux – available from Indium Corporation

- For InSn and BiSn: TacFlux012
- For PbSn: TacFlux020 or 5RMA

ArticSilver Epoxy

- New Egg, catalog #N82E16835100005

Liquid Metal

- GaSn : Alfa Aesar, stock #18161
- GaInSnZn: Indium Corporation alloy #46L

3M Kapton tape

- Digi-Key # 3M541312-ND

Foam swab

- VWR, cat # TWTX751B

Mechanical Supports

- Fralock, 26 mil thick Cirlex® (custom cut)

Tweezers

- TDI International, part #5C-SA

Assembly Procedure

The recommended assembly procedure is described below:

1. Solder the eTEC to the heat rejection surface

The high heat fluxes provided by thin film eTECs require a metallic interface for optimal thermal performance. Non-metallic contacts will reduce the effective performance (ΔT) of the eTEC. Several solders and related fluxes that have been used successfully are listed in the parts list above. The bond line should be kept as thin as practical for minimal thermal resistance.

It's important to only handle the primary and not the secondary header of the eTEC. Precision tweezers that we have found to be appropriate for eTECs are recommended in the parts list above.

2. Attach the mechanical spacers to the heat rejection surface

Thermal expansion of the heat rejection and temperature controlled surfaces will differ due to different temperatures and possibly also material properties of these surfaces. eTECs are more robust in compression than in shear, due to the material properties that enable high heat flux densities. It is therefore necessary to provide mechanical spacers between the heat rejection and temperature controlled surfaces to avoid transferring shear forces to the eTEC.

There is a tradeoff between mechanical strength and thermal performance. These mechanical spacers are also a thermal shunt that can reduce ΔT if a material with high thermal conductivity is used. We therefore recommend the use of Cirlex®[1] (see the parts list above) with a thermal conductivity of 0.17 W/m-K. An epoxy that we have used successfully with Cirlex® and different metallic surfaces is also recommended in the parts list above.

3. Coat the secondary header of the eTEC with Liquid Metal

We recommend the use of GaSn or GaInSnZn liquid metal as an interface between the secondary header of the eTEC and the controlled temperature surface to provide high thermal conductivity while protecting the eTEC from high shear forces. GaSn is preferred when the controlled temperature surface is always at or above room temperature (22°C). GaInSnZn is preferred for lower temperatures because it has a lower melting point. Gold coated eTECs may need to be lightly scrubbed to wet the secondary header with liquid metal. A foam swab that we have used successfully for this purpose is recommended in the parts list above. It's important not to use so much material that the liquid metal overflows the sides of the eTEC. This can cause electrical shorts or thermal shunts. We recommend the use of Kapton® tape (see the parts list above) to protect the electrical connections.

4. Coat the temperature controlled surface with Liquid Metal

We recommend coating the portion of the temperature controlled surface that will cover the eTEC. This creates a clean void free interface for optimal thermal performance. The area coated should be approximately nine times greater than the area of the secondary header. This allows room for minor misalignments and gives a place for excess liquid metal to reside. Be careful to not coat with liquid metal any surface that the spacer will need to be attached to as the liquid metal will prevent a secure epoxy bond.

5. Attach the temperature controlled surface to the mechanical spacers

Epoxying the temperature controlled surface to the mechanical spacers completes the assembly procedure.

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[1] Cirlex® is a sheet material manufactured by Fralock made from 100% DuPont Kapton® polyimide film.

Precautions

Handling

- DO use precision tweezers for handling of the bare eTECs (see the parts list for a suggestion)
- DO grip the eTEC only by the primary header
- DO NOT grip the eTEC by both headers simultaneously
- DO NOT grip the eTEC by the secondary header

Thermal Interfaces

- DO use premium thermal interfaces such as solders and liquid metals
    - Use of thermal grease or epoxies will provide reduced performance

Liquid Metal

- **Liquid metal can be removed from delicate surfaces by using a pointed swab soaked in isopropyl alcohol. The IPA causes the liquid metal to form small spheres which can then be carefully swept away.**
- **Glass or ceramic surfaces can be cleaned with a quick etch of dilute HCl in deionized water. A concentration of 1 part HCl to 100 parts water (by volume) works in most circumstances**

Solders

- DO use a mid temp solder such as InSn, BiSn, or PbSn for the Primary Header interface
- DO keep the Primary Header thermal interface bond-line as thin as possible (approximately 12 µm or less)
    - This reduces the thermal resistance in the heat rejection path, which improves the ΔT.
    - DO NOT allow the eTEC to “float up” on puddle of solder as a large bond-line will result in excessive thermal resistance
- DO use a liquid metal solder such as GaSn or GaInSnZn, for the Secondary Header interface
- DO keep the Secondary Header thermal interface bond-line greater than 12µm but not to exceed 37µm
    - Bond-lines smaller than 12 µm expose the eTEC to damage from mechanical stresses imposed by the system
    - Bond-lines larger than 37 µm increase the interface thermal resistance
- DO NOT use a nominally solid solder on both thermal interfaces of the same eTEC
- DO use materials consisting of Cu, Ni, Ag, Au, or Sn on the surface to which the Primary Header will be solder attached
- DO use a Ni coating on the surface for liquid metal attachment of the Secondary Header
- DO NOT attempt to solder or liquid metal attach directly to aluminum
    - Soldering to aluminum requires caustic fluxes that can damage the thermoelectric material, which is exposed because sealing the device would reduce the performance due to the resulting thermal shunt
    - The Ga in the liquid metal reacts with aluminum
    - We’ve had excellent results with Ni electroplated on aluminum surfaces

Fluxes

- DO use a mildly activated rosin flux for solder attachment of the eTEC
- DO NOT use Organic Acid or other highly reactive fluxes for eTEC attachment as immediate and irreversible damage will occur due to its corrosive nature.

Solvents

- DO solvent clean any assembly to remove flux residues from inside the eTEC
- DO NOT leave residues of any kind inside the eTEC as it will become a thermal shunt path and result in degraded performance.

Mechanical Supports

- DO use a mechanical support system to carry the stresses applied to the system and also to set the bond-line of the liquid metal interface (hence mechanically decoupling the eTEC)
- DO NOT allow the eTEC to carry any mechanical load, i.e. with the system being in direct contact with both headers at the same time
- DO use thermally resistive, rigid materials for the mechanical support (see for example the spacers in Figure 2 above), e.g. Cirlex®
    - Thermal conductivity < 0.2 W/mK
    - Modulus > 2 GPa

Temperature Sensing on Thin Film Modules

Whether you need to cool a hot spot, maintain operating temperature ranges for optimal performance or channel heat away from sensitive electronics, thin film thermoelectric modules enable micro-scale thermal management products for precision temperature control.

Integrated temperature sensing of the cold-side of thin film thermoelectric modules is a challenge due to small surface area of the ceramic top substrate. Micro-scale thermistors can be mounted either directly onto the top surface of the header or on the side of the top header to enable closed-loop temperature control.

Temperature Sensing

The precise measurement of temperature is not always required. For some applications where thermal boundary conditions are known, closed-loop temperature control is not required and it is adequate to simply apply a specific current to the TEM. However, for applications that do require tight control of temperature, it is necessary to measure the temperature on the cold side of the TEM during operation. Thermistors have traditionally been used because they have the benefit of high temperature sensitivity and while their resistance is non-linear with temperature, they are extremely repeatable. In addition, thermistors have reasonably high impedance (typically 10kΩ) and are generally easier to integrate than thermocouples. Finally, many commercially available temperature controllers include thermistor connections making them the preferred measurement probe for closed loop feedback.

The integration of these devices onto a TE device is relatively straightforward if there is adequate working space. Conventional thermistors tend to be on the order of 2-3 mm2. Unfortunately, this precludes the use of these devices on thin film modules since they are as large or larger than the top substrate. Several manufacturers have begun offering small scale thermistors that provide a pathway to direct temperature sensing on a thin film module. Three examples of these micro-scale thermistors are listed in Table 1 along with their size and electrical resistance.

Manufacturer	Model Number	L x W (mm)	Resistance (k)	Comments
AdSem	GE-N-CHIP-103	0.1 x 0.1	10	Leadless device
BetaTHERM	GR10KM3499J15	0.4 bead	10	Glass encapsulated with leads
Cornerstone Sensors	T021D103	0.43 x 0.43	10	Leadless device

Table 1: Micro-scale Thermistor Products

Integration Examples

Several potential integration methods are shown below for attaching thermistors to an HV14 TEM. The HV14 has a top header that is only 1 mm x 1.5 mm in size. Placing the thermistor on the top substrate of the TEM is the most straightforward method of integration but uses valuable space (and limited) area on the header.

Figure 8 shows the packaging scheme in which a laser diode was mounted on the cold side of an HV14 in a TO-8 package. Figure 9 shows a side profile of the same package. The HV14 is thermally coupled to the chip and TO base.

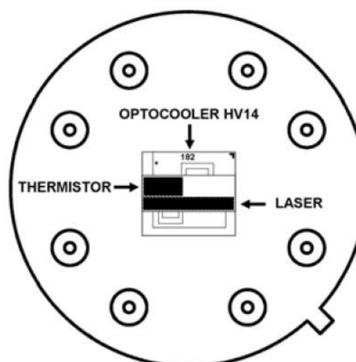

Figure 8. Illustration of a laser diode TO package with embedded HV14 TEM

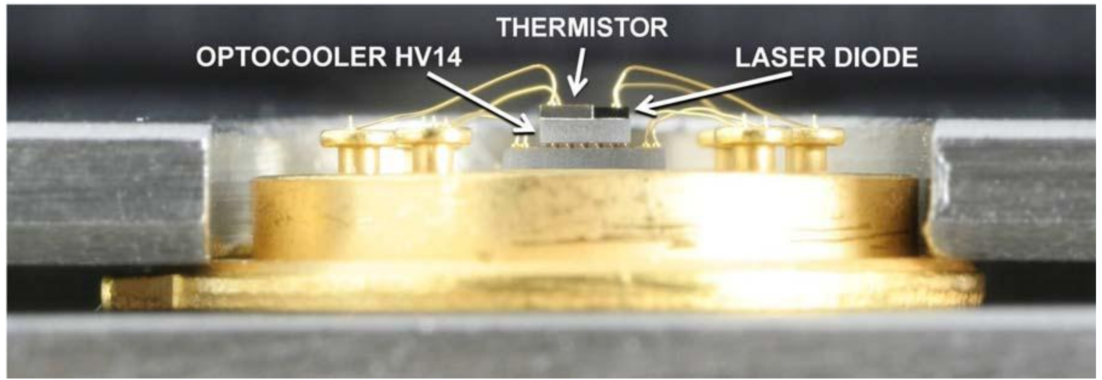

Figure 9. Side profile of a laser diode TO package (cap removed) with embedded OptoCooler HV14 TEC and thermistor

Figure 10 illustrates placement of an AdSem thermistor to the top header of the HV14 TEC. The AdSem is a leadless device and so the leads must be attached by the integrator.

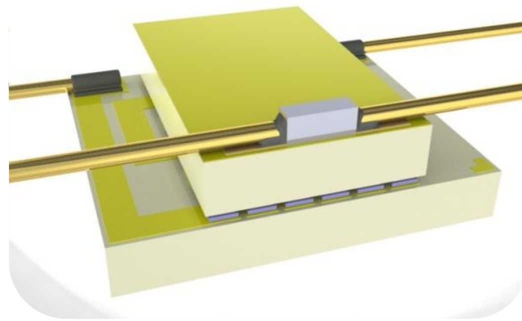

Figure 10: HV14 with AdSem thermistor attached to top header.

Figure 11 shows the placement of a Cornerstone Sensors thermistor attached to the top header. In this case, the ground for the thermistor is connected through the metallization of the HV14 header. Wirebonds are used for the connection to the package posts.

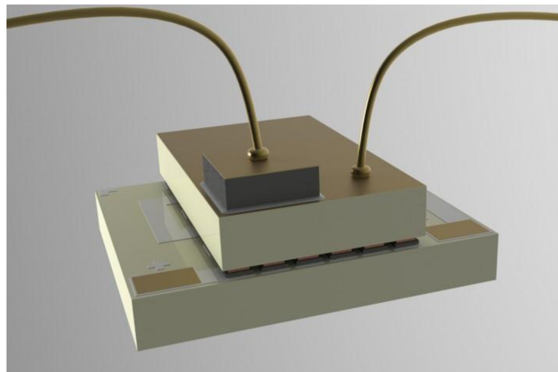

Figure 11: HV14 with Cornerstone Sensors thermistor attached to top header.

Attaching the thermistor to the top surface may not be acceptable in cases where the all the top surface is reserved for the device (e.g., laser diode, ASIC, LED). In these cases, it is possible to place the thermistor on the side of the top header as shown in Figure 12.

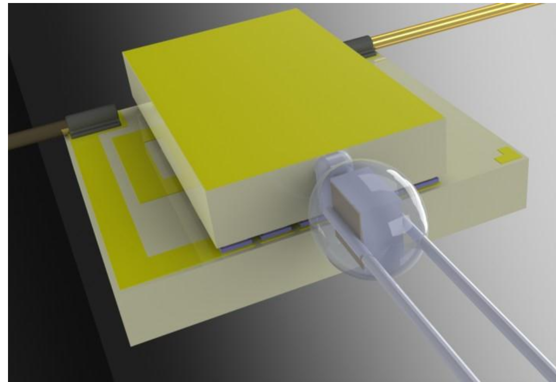

Figure 12: HV14 with BetaTHERM encapsulated thermistor attached to side of the top header.

Thin Film Module Reliability Overview

The eTEC™ Series thin film thermoelectric modules have been proven to be reliable in the most demanding applications for optoelectronic devices. Validation testing has been conducted as defined by Telcordia's GR468-CORE specification (see Table 2), which is the most comprehensive standard for reliability testing of thermoelectric modules in the optoelectronic market.

Category	Test	Level	Additional Information
Mechanical Integrity	Mechanical Shock	Required	Condition B (1500 g, 0.5 ms), 5 times/axis
	Vibration	Required	Condition A (20 g), 20 to 2000 to 20 Hz, 4 min/cy, 4 cy/axis
Non-Powered Environmental Stress	High Temp. Storage	Required	85°C, 2000 hr
	Temperature Cycling	Required	-40°C to +85°C, 500 cycles Interim read @ 100 cycles
Powered Environmental Stress	Powered Thermal Age	Optional	Tamb=85°C, 2000 hr, 5000 hr, I=Imax
	Power Cycling (On/Off)	Required	Hot-side T =85°C, 5000 cycles (90 sec on, 30 sec off)

Table 2: Telcordia GR468-CORE Test Protocol

Mechanical Integrity

Mechanical shock experiments were performed in accordance with MIL-STD-883E Method 2002.3 that defines shock of 3000 g in a 0.3 ms pulse (5 times per axis)—this exceeds the requirement in GR-468 by 100%. Figure 13 shows a g-force response curve for the testing. Shock tests were performed on 12 HV14 modules, which exhibited an average change in AC resistance of -1.9% with a range of changes from -5.8 to +3.1%. This result indicates the HV14 TEM is well within the specified range of 1500 g.

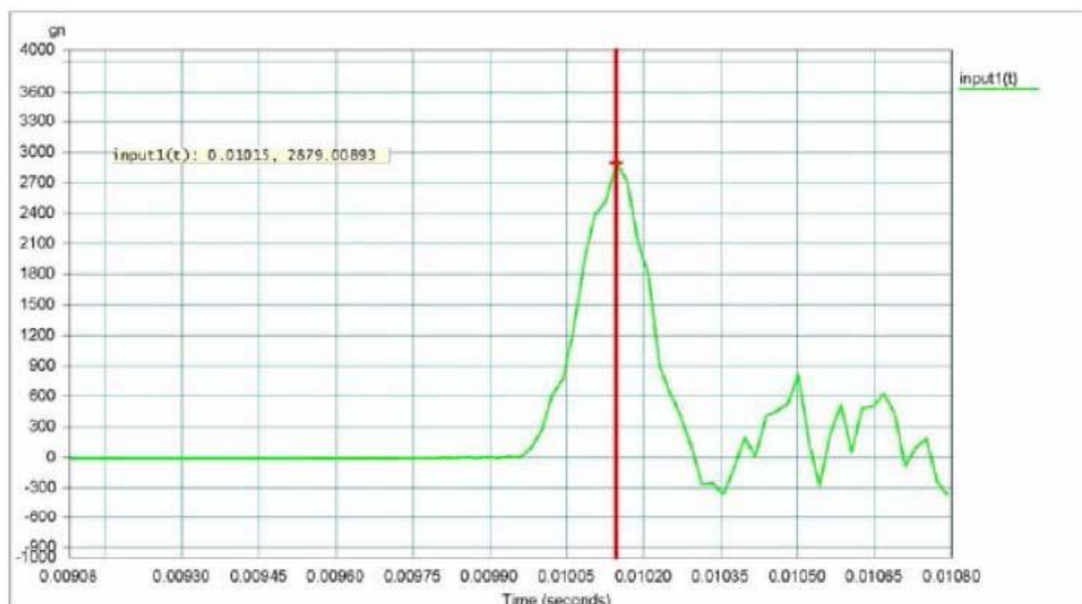

Figure 13: Shock (g-force) as a function of time showing 3000 g pulse.

Non-Powered Environmental Stress

High-temperature storage provides a good indicator of long-term reliability, particularly as it relates to diffusion-based failure modes and interface stability. The GR-468 test conditions were set at 85°C for 2000 hours. To further stress the module and accelerate temperature dependent failure mechanisms, modules were subjected to temperatures well above the maximum operating condition of 150°C. Figure 14 shows the results of 150°C storage with read-points on the A/C resistance at 254, 432, 1190, 1526 and 2534 hours. In all cases, the A/C resistance varied less than 1% from nominal A/C resistance. This indicates there are no temperature driven changes in the thin film material, contacts or interconnects under these conditions and the modules are very stable.

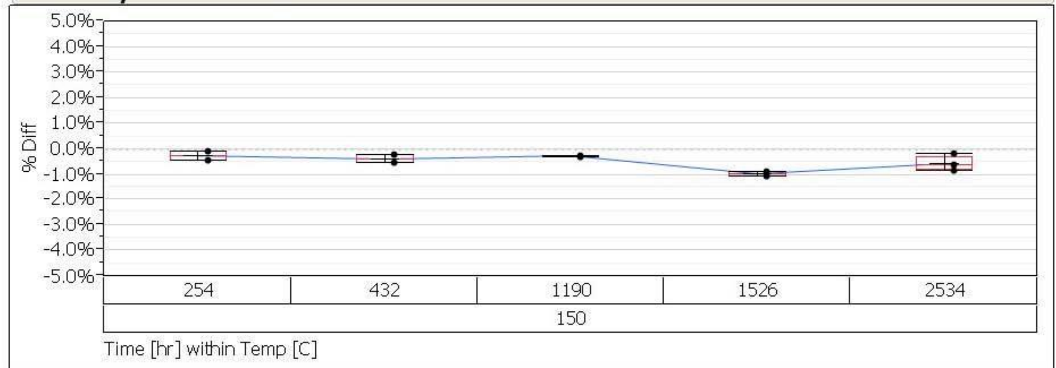

Figure 14: Percent change in AC resistance of the HV14 modules taken at different times (hours) up to 2534 hours. Less the 1% change in ACR was observed.

Powered Environmental Stress

Power cycling provides one of the most useful thermoelectric reliability tests as it simulates extreme usage by inducing large current pulses that simultaneously induce large thermal gradients in the device. These gradients produce expansion and contraction of the module that can lead to fatigue failures over time. Conducting power cycling at elevated temperatures can also induce diffusion-based failures. Figure 15 shows power cycling data of three HV14 modules at 90% of I_{max} for 100,000 cycles. In this test, the cycle period was 5 seconds on and 5 seconds off. This rapid cycling is enabled by the fast response time of the thin film module and enables more rapid accumulation of data. It also results in a rapid change in the internal stress of the devices that contributes to accelerated aging and fatigue. The ΔT of the module was monitored throughout the testing and exhibited less than a 4% change over the entire 100,000 cycle test. This far exceeded the pass/fail criteria set in GR-468 power cycling standards.

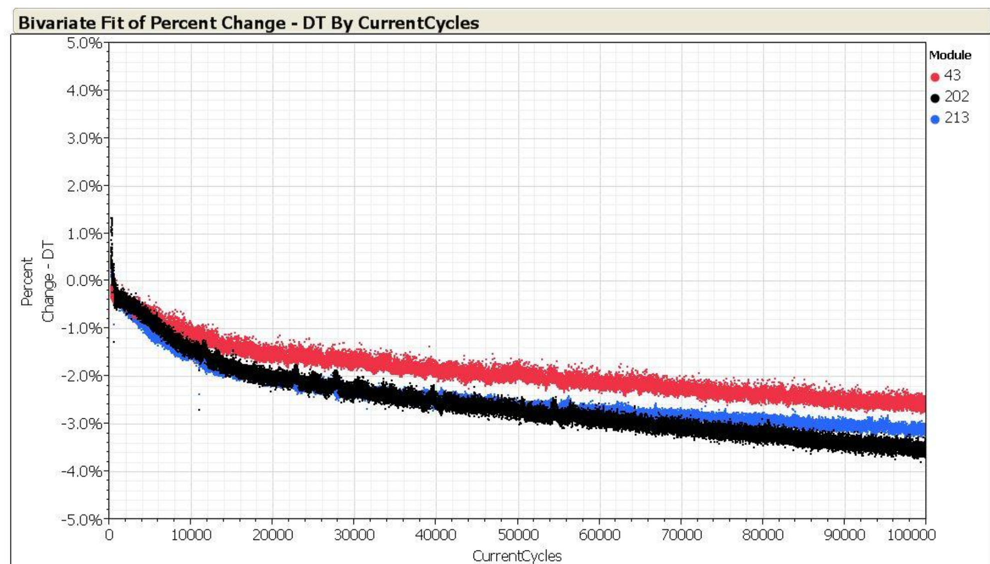

Figure 15: Change in module ΔT over 100,000 cycles at 90% of Imax.