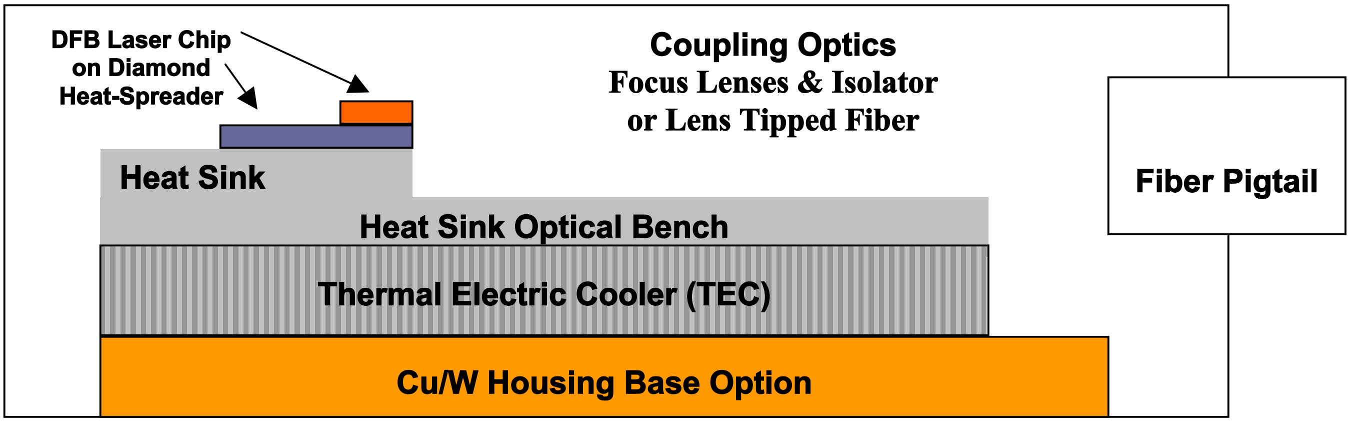
DiaTherm™ Low Cost CVD Diamond Heat-Spreaders

Heat-Spreader Function:

Heat-spreaders perform the task of quickly removing heat generated in optoelectronic and electronic chips. Heat-spreaders remove the heat by thermal conduction to a heat sink. The heat-spreader also as it's name suggests spreads the heat from the smaller area of the chip to the larger heat sink. Heat-spreaders with better performance have a lower temperature drop across their thickness and width and spread the heat flux over a much wider area.

Applications where heat-spreaders are essential for device performance and reliability include: laser diodes, laser diode arrays, LEDs, RF power transistors and other high power electronics. Optoelectronic device reliability and optical performance, such as emitted light wavelength and conversion efficiency, are dependent upon the "junction temperature" on the chip. Electronic device reliability and performance efficiency is also temperature dependent. In both cases, the lower the junction temperature the better is the device performance and longer the device lifetime.



Integration of Diamond Heat-Spreaders in Laser Packaging

Figure 1

Thermal Management:

The bottleneck for thermal management of junction temperature of optoelectronic and electronic devices is at the heat-spreader assembly. The ability of the heat-spreader to conduct heat away from the laser chip or electronic chip determines device performance and reliability. The thermal "pinch" of cooling capability of the assembly is at the heat-spreader. Therefore, successful device manufacturers pay special attention to materials choice and assembly design of the heat-spreaders.

CVD diamond is the ultimate heat-spreader by a large margin. However, due to the proprietary advantage it presents, its use has not been widely publicized. Diamond has a much greater thermal conductivity than other material choices: 3 times greater than copper, a common heat sink, 5 times greater than aluminum nitride or beryllium oxide, which are also used as heat-spreaders, 5 times greater than refractory metals such as copper tungsten or molybdenum copper used as heat sinks or heat-spreaders. See Table 1.

Use of diamond heat-spreaders in laser devices improves the cooling capability of the chip in assembled devices by 30% to 100%.

Table 1
Materials and Thermal Properties for Thermal Management

Material	Function	Electrical	Composition	Thermal Conductivity (W/m$^{\circ}$C)	CTE (ppm/$^{\circ}$C)	Density (g/cm^3)
sp3 Diamond	**Heat-Spreader**	**Insulator**	**Polycrystalline diamond**	**1200**	**1.5**	**3.5**
Copper	**Heat Sink**	Conductor	Cu	**401**	17	8.9
Beryllium Oxide	**Heat-Spreader**	Insulator	BeO	**250**	8-8.5	2.9
CVD Silicon Carbide	**Heat-Spreader**	Insulator	SiC	**250**	2.4	3.2
Aluminum	**Heat Sink**	Conductor	Al	**237**	24	2.7
Copper Tungsten	**Heat-Spreader &/or Heat Sink**	Conductor	90%W, 10%Cu 75% W, 25%Cu	**200** **228**	6.4 8.1	17.3 15.7
Molybdenum Copper	**Heat-Spreader &/or Heat Sink**	Conductor	85%Mo, 15%Cu 75%Mo, 25%Cu	**155** **175**	6.9 8.0	10.0 9.8
Aluminum Nitride	**Heat-Spreader**	Insulator	AlN	**170**	4.3	3.3
Gallium Arsenide Laser Chip	**Heat Source**	Substrate Insulator	**GaAs**	**55**	**5.8**	
Indium Phosphide Laser Chip	**Heat Source**	Substrate Insulator	**InP**	**68**	4.6	
Indium "Soft" Solder	**Attachment**	Conductor	In 156°C melt point	**86**	29	7.3
Gold Tin "Hard"Solder	**Attachment**	Conductor	80%Au, 20%Sn 280°C eutectic	**57**	16	14.5
Gold Germanium "Hard" Solder	**Attachment**	Conductor	88%Au, 12%Ge 356°C eutectic	**44**	13	14.7
Alumina	**Submount or Thick Film PCB**	Insulator	Al_2O_3	**30**	7.3	3.9
Kovar	**Metal Housing**	Conductor	29%Ni, 17%Co, 53%Fe	**17**	5.1	8.0
Thermally Conductive Epoxy	**Attachment**	Usually Insulator	Particle Filled Organic Resin	**1**	65-75	1.2

Cost for Diamond Heat-Spreaders:

The cost for CVD diamond is higher on a volume basis than Cu, AlN or BeO, or refractory metals such as WCu and MoCu. However, the cost for CVD diamond heat-spreaders is small relative to the device bill-of-materials (BOM) cost and its use enables increases of device optical power of up to 300% at the same device junction temperature and device reliability. In the application of telecom laser transmitter modules and laser pump modules the cost for diamond heat-spreaders is typically 1% to 2% of the module bill-of-materials (BOM) cost, excluding the cost of the laser chip. Use of diamond heat-spreaders enable the device to operate up to 3X greater optical power at the same reliability as devices using AlN or BeO heat-spreaders.

Integration of Diamond Heat-Spreaders:

Diamond is an electrical insulator. It is metallized (typically using Ti/Pt/Au) for solder attachment to the laser chip or RF chip and for solder attachment to the heat sink on the opposite side. The top side of the CVD diamond heat-spreader is polished smooth, a result of starting with polished substrates for the CVD deposition. This smooth top side is used to solder attach laser chips or power electronic chips, whose crystalline substrate materials GaAs, InP or Si are brittle and sensitive to tensile fracture. The smooth diamond surface minimizes chip fracture issues for the assembly. The top side of diamond heat-spreaders may be pattern metallized to provide better optical and electrical chip high speed performance by providing electrical grounding and impedance control of signal lines and lower inductance wire bonds, as well as to facilitate chip attachment orientation. The rougher bottom side of the heat-spreader is used to thermally attach the heat-spreader to the heat sink and its roughness is not an issue for solder or epoxy attachment reliability.

Note that electrically conductive materials such as copper, aluminum, molybdenum copper, and copper tungsten are not suited as heat-spreaders for signal lasers and RF devices due to the complexity of adding signal trace patterning on the heat-spreader.

Attachment of Heat-Spreader:

Thermal resistance from attachment materials can contribute significantly to the assembly thermal resistance for cooling the chip. Attachment options include hard solders, soft solders and thermally conductive epoxies, see Table 1. Assembly processing in attaching the heat-spreader to the chip and to the heat sink influences the thickness of the attachment layer. Lower thermal conduction resistance for assemblies is achieved by using thinner attachment layer thicknesses and by using metallic solder attachment material rather than epoxy attachment material.

Solder attachment enables high reliability of the assembly. Laser chips and high frequency RF chips are fabricated on crystalline substrates such as GaAs or InP and are sensitive to potential fracture with assemblies that exceed the chip's substrate tensile fracture load. Diamond has a lower coefficient of thermal expansion CTE 1.5 ppm/^{o}C than these substrates and shrinks less than the chip upon solidification of the attachment solder. High temperature attachment solders of AuSn and AuGe (280^{o}C and 356^{o}C eutectic) have a higher Young's modulus and a larger CTE, 13-16 ppm/^{o}C, than the chip CTE, 5.8 ppm/^{o}C for GaAs. The stiffness of these hard solders help minimize transfer of tensile load to the laser chip from the differential thermal contraction of the chip and the diamond heat-spreader.

The magnitude of tensile load on the chip depends upon: chip size; CTEs of the chip, heat-spreader, heat sink and, solder; solder solidification temperature; thickness of each layer of the assembly, i.e. chip, heat-spreader, heat sink and, solder; assembly flatness and solder thickness uniformity between the chip and heat-spreader. The chip edge quality, chips outs and micro-cracking, from chip singulation also affects potential chip fracture. Thermo-mechanical finite element modeling (FEM) can predict maximum chip size for use of diamond heat-spreaders with hard solder attachment. Thermal cycling is used to verify survivability of assemblies and to detect latent chip fractures in assemblies design or processed such to exceed chip tensile fracture loads. In practice, due to the small size of laser chips, typically less than 1mm, laser chips integrated on diamond heat-spreaders with hard gold solders survive telecom reliability requirements of Telcordia. Use of lower cooling performance heat-spreaders that have CTEs equal to or higher than the chip CTE, such as with AlN, BeO, WCu, MoCu, diamond-metal-composite DMCs, SiC, is not necessary with single laser chip modules in order to avoid reliability issues.

High temperature hard solders are needed for laser chip attachment to the heat-spreader as this is the initial solder process in the hierarchy of solders used in process assembly of laser transmitter and pump laser modules. Solder attachments that occur later in the assembly process sequencing require a lower solder melt temperature so that the previous solder joints do not reflow. Note that in packaging optoelectronic modules maintaining the laser chip position for optical coupling to optical fibers requires that the laser chip does not change position upon later assembly process temperature profiles. Gold enrichment of AuSn and AuGe solder, caused by diffusion of gold from the chip's and heat-spreader's solder pads' oxidation protection layer, raise their remelt temperatures significantly, allowing the use of the same solders in subsequent steps. Note that integration of thermo-electric coolers (TECs) in laser transmitters for laser temperature wavelength control requires the use of lower temperature solders so as not to damage the TEC. Also note that use of flux for improving solder wetting may cause reliability problems for laser devices.

Integration of heat-spreaders in the packaging of DFB edge emitting lasers is shown schematically in Figure 1. The laser chip sits upon its heat-spreader, both of which rest on top of a heat sink submount and optical bench. The optical bench provides the mechanical platform for alignment of coupling optics, such as lenses, to couple the light emitted from the laser chip to a device's fiber optic pigtail or pluggable fiber optic connector. Underneath the optical bench a thermo-electric-cooler (TEC) is placed for active temperature control laser devices. The heat sink optical bench or TEC is attached to device package base through which heat generated by the laser chip and TEC is discharged to the PCB board mount. High powered laser devices often use a copper tungsten base braised into the lower thermal conductivity Kovar package for better device cooling. These laser devices are typically hermetically sealed in a metal housing for the device to pass Telcordia reliability requirements of telecom applications. Hermetic sealing involves metallization and soldering or glass frit seal of the fiber pigtail to the package or a window in the package wall and leak testing of the sealed laser device. Common device configurations are butterfly, DIL, and mini-DIL Kovar packages as well as small form factor configurations.

Assembly of these DFB lasers involves multiple subcomponent attachment process sequences requiring a hierarchy of solders for sequential assembly with the need that earlier solder attachments do not reflow in later soldering operations. Attachment of the laser chip to the heat-spreader is at the top of this solder hierarchy with AuSn or AuGe hard solders. Devices with fewer assembly attachment steps may use lower temperature solders. Heat-spreaders commonly used include Diamond, AlN and BeO. High powered laser chips such as pump lasers typically use copper heat sinks.

Optimal Heat-Spreader Dimensions:

Heat-spreader size and thickness may be optimized for each application using thermo-mechanical FEM modeling of the assembly. Optimal CVD diamond heat spreader thickness is 400μm based on improved performance and cost.

Rules of thumb for sizing of heat-spreaders are 2.5 times the lateral dimension for edge mounted chips such as edge emitting laser chips, and 5 times the lateral device dimension for chips mounted in the center of the heat-spreader such as for RF power transistor chips.
In the case of lower thermal conductivity heat-spreaders such as AlN and BeO, heat-spreader thickness contributes significantly to assembly thermal resistance and heat-spreader thickness is usually chosen to be between 1/4 to 1/2 the thickness of chip. Heat sink dimensions are on the order of 10 times or more the size of the chip in lateral and depth directions.

Application to High Powered Solid State Lasers:

Larger laser chips such as diode array lasers for high powered applications have one dimension longer to form a laser bar of edge emitting lasers. One method of attachment of laser diode arrays, or laser bars, to diamond heat-spreaders using hard gold solders is to segment the diamond heat-spreader underneath the laser bar such that the larger length of the laser bar does not experience tensile loads beyond the fracture limit of the chip. The strain from differential shrinkage of the chip relative to the diamond heat-spreader is limited to each section of the diamond heat-spreader. This allows large laser arrays to be integrated with optimum thermal cooling capability without chip fracture issues.

Application to High Powered Electronics:

Large electronic chips, such as for RF power transmitters and computer CPU processor chips, may be integrated with large area diamond heat-spreaders using lower temperature soft solders such as indium and indium or bismuth solder alloys. These soft solders have a low Young's modulus and the ability to creep to relieve strain in the solder due to differential thermal contraction of the chip to diamond heat-spreader. These solders, particularly indium, are used for low strain attachment of large area brittle material slabs, such as optical windows or RF windows.

Solder attachment of the chip and heat sink to the heat-spreader provides a more efficient cooling capability of the assembly. Alternative attachment methods using thermally conductive epoxies result in substantially higher thermal resistance for the assembly. Epoxy attachment, if designed correctly, can mechanically isolate the chip from differential thermal expansion tension strains on the chip from the heat-spreader and heat sink, and eliminates metallization costs required for solder attachment, but may have significant reliability issues for laser devices due to organic contamination. In cases where efficient thermal management and reliability of laser chips or power electronic chips is necessary epoxy attachment should not be considered.

Application to Bright LEDs:

LED optical output is constrained by thermal power dissipation (reference: “LEDs Make the Spot” Marsh D., EDN Europe, December 2004). LED lifetime, at 50% lumen depreciation, is related to junction temperature as: 75k hours at 40°C, 50k hours at 75°C, 30k hours at 100°C, 10k hours at 125°C, with maximum LED junction temperatures of 105°C to 135°C.

Replacement of copper heat-spreaders used in bright LED devices with diamond heat-spreaders enable greater than 200% increase LED optical power output at the same junction temperature. Diamond heat-spreader replacements fit directly in LED device assembly processing with solder attachment to the LED die and PCB or heat sink. The small size LED die with brittle substrate materials of InGaN and AlInGaP survive the differential thermal contraction to diamond heat-spreaders by solder attachment. Cost increase for replacement of copper heat-spreaders with diamond heat-spreaders is relatively small as the CVD diamond heat-spreaders cost about \$1.50/mm^3 metallized.

The superior thermal management of LED junction temperature by use of diamond heat-spreaders enables designers to provide both increased LED optical power output and longer LED device lifetimes.

Summary:

Diamond heat-spreaders provide superior thermal cooling of laser chips and high power electronics than other packaging configurations. Typical performance increase is up to 300% in laser or LED optical power output over other material choices. The increase in thermal management of device junction temperature allows the designer to trade improved device reliability margin, i.e. longer lifetime, while increasing laser and LED optical power. Diamond heat-spreaders are configured for integration in standard electronic and optoelectronic device assembly processing, are used in devices in market applications, and provide dramatic device power and reliability performance improvements at small fractional increase in total device BOM cost.

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