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Thermal Interface Materials used for Improving the Efficiency and Power Handling Capability of Electronic Devices: A Review

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Abstract- **Thermal interface material (TIM) is used to enhance heat flow by reducing thermal resistance across the thermal interface between the heat source and the heat sink, and to minimize the variance of the interface resistance as compared to just surface-to-surface contact. In this mini review, the recent developments in the thermal properties of various used and advanced thermal interface materials are discussed with the new technologies employed for improving the performance of TIMs. Also, a brief account of the applications of thermal interface materials is presented.**

***Keywords**:* Thermal interface materials, heat flow, heat sink, interface resistance, surface-to-surface contact

I. INTRODUCTION

New gadgets are being introduced almost daily in today's world of electronics with smaller size and faster speed. A well-designed thermal management program is necessary in order to optimize performance and reliability for the smooth functioning of these electronic devices. A heat sink is joined with the semiconductor for efficient transfer of heat from the source to the environment. A Thermal Interface Material (TIM) is required to improve heat flow across this thermal interface by eliminating air voids (http://www.chomerics.com/products/documents/thermcat/heat_transfer_fund.pdf). In response to the need for improved heat dissipation, various forms of liquid cooling and refrigeration are being considered. All liquid cooling systems have significant drawbacks, including parts and labor costs, reduced reliability and increased weight. In addition, the fluid pump consumes power. Use of materials with extremely high thermal conductivities can extend the use of convection cooling, potentially overcoming the need for liquid cooling. Thermoelectric Coolers (TECs), which require power input, are widely used for temperature control of laser diodes and micromechanical devices. Materials with high thermal conductivities can improve thermo electric cooling efficiency with reduction in power consumption.

TIMs are used to eliminate interstitial air gaps from the thermal interface by conforming to the rough and uneven mating surfaces. Since TIMs have significantly greater thermal conductivity than the air they replace, the resistance across the interface decreases, and the component junction temperature will be reduced. The member of TIMs families include: Elastomeric Pads/Insulators, Thermally Conductive Adhesive Tapes, Phase Change Materials, Thermally Conductive Gap Fillers, Thermally Conductive "Cure in Place" Compounds, Thermal Compounds or Greases and Thermally Conductive Adhesives (http://www.chomerics.com/tech/Therm_mgmt_Artcls/TIMarticle.PDF). The success of any thermal interface will depend on the design, the quality of the interface material and its proper installation. There is a key difference between thermal greases, phase change materials (PCMs), thermal pads and films, adhesives, and alloy composite materials (http://www.gasketfab.com/tipdf/thermalinterface.pdf). In principle, a phase change material is a solid at room temperature and then as the device heats up, the PCM changes from a solid phase to a flowable phase, where the material can fill in all the surface roughness similar to a grease. The phase change materials tend to be much harder than thermal pads, and thus the pressure required to meet thermal targets often presents a mechanical challenge for design engineers. Manufactures developed thermally conductive compounds and thermal adhesives for the application of heat sinks to high-powered electronic components like Arctic Silver 5 (AS-5), Matrix, Arctic Alumina, Céramique, ArctiClean, Arctic Silver Thermal Adhesive and Arctic Alumina Thermal Adhesive.

The research people found that Carbon has more advantages than Silicon. By using carbon as the manufacturing material, we can achieve smaller, faster and stronger chips. A electronic Chip is manufactured using carbon as the wafer. A diamond chip works at Higher Temperature up to 1000 degrees Celsius, while silicon chips stop working above 150 degrees Celsius. Diamond can also resist voltages up to around 200 volts, compared to around 20 volts for a silicon chip. Due to this power electronics, such as an inverter, can become made much smaller in size. Due to this power electronics, such as an inverter, can become made much smaller in size. One drawback is that electricity cannot travel smoothly through diamond. As compared to Barium Oxide (BaO) substrate package, diamond substrate package shows a better mean-time-to-failure by a factor of two [1]. A novel integral dielectric heat sink material consisting of diamond deposited carbon/carbon composite with metallic layer(s) on the diamond surface is developed that provide the characteristics including microstructure, thermal conductivity, diamond coating quality and thickness of metallised layer [2].Advanced electronic devices are developed based on synthetic diamond as the semiconductor material. Chemical Vapor Deposition (CVD) process allows single crystal CVD diamond to be manufactured to a high purity and consistency. CVD Diamond is resistant to heat, radiation and acid attack and boasts the best thermal conductivity of any material near room temperature. It is a good electrical insulator but can be doped like silicon to create semiconductor devices. It is available in single crystal and polycrystalline forms.

The heat generated within the electronic device is most often concentrated in a small area and temperatures in this region rise much higher. By spreading the localized heat generated by the device, DiaTherm™ (a diamond heat spreader) can improve cooling capability of laser die in assembled devices by 30% to 100% (Website: www.sp3diamondtech.com). In this mini review, the updates in the field of thermal properties of various used thermal interface materials are discussed with the new technologies employed for improving the performance of TIMs. Also, a brief account of the applications of thermal interface materials is presented.

II. THERMAL INTERFACE MATERIALS

A. *Selection of Thermal Interface materials*

An integral part of thermal design process is the selection of the optimal TIM for a specific product application. Having a basic understanding of their strengths, weaknesses, and applicability is a key to successful selection of the best interface material. The selection of proper TIM depends on many factors like: power density, heat dissipation, process requirements, Bond Line thickness (BLT), rework ability and user preferences.

B. *Advanced thermal interface materials*

A wide range of standard and specially designed thermal management materials which includes Silicone and Non-Silicone heat sink compounds, Pads, Gap fillers and Epoxies are available, worldwide**.** Nano-Crystalline Diamond (NCD) in an amorphous carbon matrix deposited in a nanocomposite film as well as Carbide Nano-Films (CNF) combines the properties of diamond with very low friction, high toughness and biocompatibility. A new class of Nano-Thermal Interface Material (NanoTIM) with adhesion functions is developed. Nanoparticles such as nano-silver particles, Nano-Carbon Nanotubes (CNT) and Nano-Silicon Carbide (NSC) particles can be embedded into the Nano-Fibers (NF) to enhance the thermal conductivity and to reduce the thermal resistivity (Website: johan.liu@chalmers.se). A very thin TIM composed of carbon nanotubes, silicon thermal grease, and chloroform was developed which has very low thermal impedance [3]. TSE328-G silicone adhesive is a low viscosity, thermally conductive material, which will be in an uncured state at room temperature and cure to an elastomer after application of heat (http://asia.matweb.com/search/SpecificMaterialText.asp?bassnum=PGESIL071).

Expanded flexible graphite sheet materials with high thermal conductivity have ability to conform well to surfaces [4].These sheets are porous. The graphite material containing synthetic oil reduces the contact resistance because of decrease in materials elastic modulus and increase in its plastic deformation at low pressures (<700 kPa) , shows high thermal stability than graphite material containing mineral oil. For enhancing the heat dissipation for high brightness LED (light emitting diode), thermal interface material with aluminum and graphite plate are fabricated and integrated in power LED. A large variation in junction temperature and light output among the different heat-sink modules were investigated [5].

The need to dissipate the sizable amounts of heat being generated in low-power electronic devices creates problem. To solve this 3M company provides Thermally Conductive Adhesive Transfer Tapes, Interface pads and epoxies (Website: www.3m.com). Adhesive Research offers several sophisticated bonding technologies designed for bus bar, solar cell junction box, and encapsulation applications in crystalline and thin film photovoltaic (PV) modules (Website: www.adhesivesresearch.com). Experimental thermal resistance results of some advanced thermal greases used for power electronics have been illustrated by Narumanchi, 2007 [30]. In high performance flip-chip ball grid array (FCBGA) packages for ASIC and microprocessor devices, silver filled Thermal Paste Adhesives (TPA) are used [6].

The CarbAl™ heat transfer material has unique properties than conventional passive thermal management materials [7]. Only exotic and expensive synthetic diamond films, diamond composites and Highly-Oriented Pyrolytic Graphites (HOPGs) have higher thermal conductivity and closer Coefficient of Thermal Expansion (CTE) than the CarbAl™ material. Thermal conductivity as a function of coefficient of thermal expansion has been demonstrated by Narumanchi, 2007 [30].

Carbon Nanotubes (CNT) are sheets of graphite rolled up to make a tube. The dimensions are variable (down to 0.4 nm in diameter) and it exist also nanotubes within nanotubes, leading to a distinction between multi-walled and single-walled carbon nanotubes. The free-standing CNT arrays can be very good thermal interface materials under moderate load compared to indium sheet and phase-change thermal interface materials [8]. Further, combinations of CNT arrays and existing thermal interface materials can improve these materials' thermal contact conductance. The Carbon Nanotubes and polymer composites can form foams. These lightweight materials foams will be produced with improved electrical, mechanical, and thermal properties. A double layer structure of aligned carbon nanotubes array was successfully developed as a result of the sandwitch growth via thermal Chemical Vapor Deposition (CVD) method, for enhancing the performance of nanotubes-based devices [9].

Thermal tapes as a TIM function as a strong attachment between a heatsink and heat-generating component with proper heat conduction [10]. They are designed to meet the microelectronic packaging industry's strict requirements. The drawback of this tape is that sometimes the thermal resistance for a thick tape can be only slightly better than a dry joint or air gap. Thermal performance would be carefully evaluated along with shear-creep resistance data of the tapes.

A nanostructured thermal tape is created that conducts heat like a metal while allowing the neighboring materials to expand and contract with temperature changes (metals are too stiff to allow this). This ability to reduce chip temperatures while remaining compliant is a key breakthrough for electronic packaging. The nanotape performs so well is due to a combination of binder materials surrounding carbon nanotubes. This allows for very high thermal conduction while remaining flexible to adjust as required on the condition. The nanotape can replace solder pads with a thin lightweight material that improves thermal energy management. A process has been developed to integrate the high thermal conductivity of carbon nanotubes into a polymer matrix, thus creating a material with high thermal transport properties for laser and IC chip packaging.

Graphene behaves as a strong heat conductor, which could mean lower temperatures and a concrete possibility for chip manufacturers to reach higher processing speeds with relative ease. Graphene is a one atom thick planar sheet of sp2 bonded carbon atoms that are densely in a honeycomb crystal lattice packed [11]. Graphene is highly conductive, conducting both heat and electricity better than any other material, including copper, and it is also stronger than diamond. It is almost completely transparent, yet so dense that not even helium, the smallest gas atom, can pass through it. Graphene electronic devices are predicted to be substantially faster, thinner and efficient. The theoretical mobility of electrons in pure Graphene is 200 times that of silicon. This will make it extremely interesting material for future high speed electronics and sensors. Graphene Nano Ribbons (GNR) band zig-zag type structure can be semiconducting or metallic depending on width. The multiple layers of graphene show strong heat conducting properties that can be harnessed in removing dissipated heat from electronic devices

III. PROPERTIES OF TIMS

The high Coefficient of thermal expansion (CTEs) cause high thermal stresses when they are attached to the semiconductors and ceramics used in electronic and optoelectronic applications. The CVD diamond, Kovar, copper / tungsten, copper / molybdenum, and the new composites and monolithic thermal management materials show low CTE. The CTE differences may not be significant when device dimensions are small. Reliable hard solder die attach techniques is used to bond large high CTE compound semiconductor dice directly to copper packaging without compromising either reliability or thermal performance [12]. The low density of TIM materials (like CVD diamond) is useful in most packaging materials, which is important in weight-critical applications, such as aircraft and spacecraft electronic systems, notebook computers and other mobile devices. In addition, density is important even for stationary applications, because stresses arising from shock loads during shipping (50g is a common requirement) depend directly on component mass.

Thermal conductivity, describes the material’s ability to conduct heat. Thermal resistance is a measure of how a material of a specific thickness resists the flow of heat. Thermal conductivity and thermal resistance describe heat transfer within a material once heat has entered the material. The thermal impedance, of a material is defined as the sum of its thermal resistance and any contact resistance between it and the contacting surfaces. This type of data can be used to generate information about the ability of a material to conform to surfaces to minimize contact Resistance. One study shows that the thermal conductivity of TIM changes with temperature. When temperature increases, surface contacts between two surfaces where TIM are applied could be better or worse, and consequently the thermal resistance variation of a package may increase or decrease. The thermal conductivity variation in the LED chip area changes the thermal resistance coefficient of the LED.

IV. TECHNOLOGIES USED FOR IMPROVING THE PERFORMANCE OF TIMS

The CVD processes used by Element Six allow the growth of polycrystalline and single crystal CVD diamond films with consistent characteristics and few defects. By controlled manufacturing process, the synthesized material can be tailored to a particular application at attractive costs. The diamond-like carbon (DLC) film is deposited by radio frequency plasma-enhanced chemical vapor deposition (rf-PECVD) on silicon (100) wafers using methane (CH4) and hydrogen (H2) as the precursors. Two new microwave plasma reactors, excited with a hybrid “TM013 plus TEM001” mode are designed and developed which are operated in the 200-400 Torr pressure regime. High quality single crystal diamond (SCD) and polycrystalline diamond (PCD) is synthesized with deposition rates that exceed 100 microns/hr and reactor power efficiencies range from 6 – 25 mm3 of diamond per kW-h over a 25 mm diameter synthesis area as pressure, power density and gas chemistry are varied [13].

An isolated Nanocrystalline Diamond (NCD) fibers are produced at high growth rates by high-power microwave plasma enhanced chemical vapor deposition technique (MPECVD) [14]. The developed nanocrystalline nature of the diamond material has perfect crystallinity of the sample. The applications of this novel material are in cold-cathode devices, heat sinks in microelectronics and structural materials in micro- and nanoelectromechanical systems. The nanodiamond particles act as seeds for the further growth of NCD on the nanofibers. The reasonable volume-averaged velocity and temperature distribution were obtained by treating the microchannel as a fluid saturated porous media. This methodology is not limited by assumptions on the laminar or fully developed nature of the flow and is able to predict the total thermal resistance of any microchannel heat sinks satisfactorily [15].

Adhesive research unveils new bonding method in a name of Pressure Sensitive Adhesive (PSA) technology for Photovoltaic(PV) manufacturers which deliver added functionality for enhancing the capabilities and performance of a variety of PV modules including ease-of-handling, continuous roll formats, and no messy clean-up (Website: www.adhesivesresearch.com). Three different cooling methods are used using heatsink, thermoelectric cooler (TEC) and fan in order to solve the heat dissipation problem [16]. By this technique the thermal resistance reduces and the cooling capacity improves.To built three dimensional (3-D) MultiChip Modules (MCMs) for high-power high-density light-weight electronic systems, large area free-standing CVD-diamond is deposited on Si and Cu substyrates as heat spreading material [17]. The relative properties of diamond and certain package materials have been presented by Xie et al., 2005 [17].

For the purpose of graphite foam thermosyphon design in electronics cooling, various effects such as graphite foam geometry, sub-cooling, working fluid effect, and liquid level were investigated [18].The use of graphite foam as the evaporator in a thermosyphon enables the transfer of large amounts of energy with relatively low temperature difference and without the need for external pumping [19]. The graphitized carbon foam used is an open-cell porous material that consists of a network of interconnected graphite ligaments whose thermal conductivities are up to five times higher than copper. While the bulk graphite foam has a thermal conductivity similar to aluminum, it has one-fifth the density, making it an excellent thermal management material.

A unique pin-fin carbon fiber epoxy composite material heat sink is used for surface enhancement at the evaporator of thermosyphon [20]. A thermosyphon is a passive means of utilizing two-phase flow in a system, similar to a heat pipe, with the only difference being the absence of capillary action. The carbon-fiber heat sink exhibited thermal performance below that of the carbon foam due to a smaller surface area resulting from the pin fin design. However, the thermal performance is improved when compared to the other traditional pin-fin evaporators. The adhesion functions are incorporated into the developed nano-TIMs using lamination or direct mixing methods. To achieve this, hotmelt adhesive is directly laminated into the nano-TIM materials to achieve adhesion function. Thermally Conductive Resins provide fast heat dissipation for a variety of electronic and industrial applications (Website: www.epoxies.com). For the study of thermal performance of solar air collector system, neural network (NN) software is used for simplification of performance analysis. This new formulation can be employed with any programming language or spreadsheet program [21].

V. APPLICATIONS OF TIMS

The miniaturization and increased functionality of electronic devices is causing manufacturers to seek new thermal management solutions. When compared to conventional materials, chemical vapor deposition (CVD) diamond is emerging as an effective heat spreader. A developing application of CVD diamond as a thermal management tool for both power devices and processors is the work being done with Diamond-On-Silicon (DoS). Both laser and Light Emitting Diodes (LED) device manufacturers are using CVD diamond thermal submounts. Even in low-cost LED packages, small segments of diamond is used to enhance color output stability (http://www.electroiq.com/index/display/packaging-article-display/276420/articles/advanced-packaging/volume-15/issue-10/features/cvd-diamond-solves-thermal-challenges.html).The ultra-high thermal conductivity (up to 200 W/m-K) of CVD-diamond enables increase in microprocessor frequency and output power of microelectronic and optoelectronic devices such as radar and other radio-frequency (RF) devices, power semiconductors, laser diodes and LEDs . High-power military and space applications, challenged for size and weight, have found diamond to be a useful material. CVD diamond also has found its way into the designs of RF Power packages, amplifiers, radar devices and infrared cameras. CVD Diamond used in the development of high-power, high temperature semiconductor devices for microwave power electronics (Website: www.e6cvd.com).

Grease materials have been successfully specified into servers, desktops, and notebook CPUs (central processing units) in the computer industry. They are also widely used in displays, automotive control units, and communications equipment. Typically, greases are specified when an application demands high performance and thin bond lines. Thermal pads are effectively employed in a wide range of low thermal demand applications such as disk drives, chipsets, communication equipment, and general Printed Circuit Board(PCB) protection. Phase change materials (PCMs) are designed to offer the thermal performance of greases, with the advantages of pre-cured thermal pads, in a single material. Phase change materials are widely used for memory modules, graphics chips, and notebook computers. Polymer solder hybrids and metal matrix TIMs are most often found in high-end processor chip packaging. Their cost limits their use to highly specialized chips. Polymer solder hybrids are available in the form of greases, PCMs .and pads. CVD polycrystalline diamond films are used as heat spreader for heat sink applications [22].

The TIMs are used in some specific applications like-Thermally conductive adhesives [23] are used as the interface between silicon chip and heat spreader. These conductive adhesive can also replace solder, screws, bolts, clamps or other form of mechanical attachment devices for cost savings or other reasons. Some thermally conductive adhesives with electrical conductivity can be used to conduct heat away and as an electrical ground to the board. Because of loading of conductive filler particles, these adhesives are harder and less elongation than their unfilled counterparts. Thermal interface material using Carbon Nanotubes (CNT) can maintain an acceptable operating temperature for power electronics. CNT explored in realistic IGBT package configuration. The optical performance of High-Brightness Light-Emitting Diode (HB-LED) packages using the aligned CNT-TIM was greatly improved with the use of the CNT-TIM [24]. Cool silver thermal grease is used in the cooling aspect of PC in place of arctic silver (Web site: www.altechnology.com).

In a personal computer, laptop and portable electronics, better the thermal interface material, the smaller the heat sink and overall chip-cooling systems have to be. The forests of tiny cylinders called carbon nanotubes are grown onto the surfaces of computer chips to enhance the flow of heat at a critical point where the chips connect to cooling devices called heat sinks. This nanotube layer makes possible the low-cost manufacturing approach to keep future chips from overheating and reduce the size of cooling systems. Nano tape consists of a vertically aligned carbon nanotube forest at its central core, with carefully chosen alloys on both the top and bottom that wet the carbon nanotubes and also will contact to the heat sink and the chip. The nanotape will look like a conventional solder pad, and will work with in same equipment, but it has the mechanical characteristics of an aerogel and the thermal conductivity of a metal. The nanotape can more reliably transfer heat to thermoelectric generators, enabling greatly improved fuel economy [25]. The metallic adhesion layers on each side of the central core of the carbon nanotube forest have been displayed by Johnson, 2011 [25].

High Thermally Conductive Graphite Foams are used for Compact Lightweight Radiators [26]. The graphite foam material keeps high-intensity LEDs as cool as those used for front-panel indicators, thereby reclaiming their long lifetimes [27]. The graphite foams are used in commercial LED lighting systems such as in the large arrays for street lamps and parking garages [28].

A. Future Prospects

Researchers develop thermal nanotape to help cool future Central Processing Units (CPUs) and Graphics Processing Units (GPUs) . The Graphene could be used to produce ultra capacitors with a greater energy storage density than is currently available. Solar cells and fuel cells are further potential areas of application of carbon based nanomaterial in the field of energy related applications.

B. Economic status of thermal interface materials

Thermal conductivity is the most important requirement in thermal management applications. Values in excess of 8 W/cm °K (about twice the value of copper) are adequate and routine in most applications. Higher thermal conductivities are possible but, to achieve them, films must be grown at lower rates. Therefore, production costs increase to the point where film prices can be prohibitive. Films must also be reasonably thick in order to spread the heat properly. As the typical thickness required is 300 to 500 μm, deposition techniques must have high enough rates to keep deposition times within practical limits. The process techniques which eliminate cracks are in the way of development.

About 20% to 35% of the total plant cost goes to construct air cooler heat exchangers in geothermal power plant. Two layers of hot screens above the electric heater in different height enhanced the average air velocity at the inlet of the model from 1.05 to 1.64msec^{-1} and more. This imposed design of the cooling system increased the plant performance and decreased the installation cost [29].

The films require lapping or polishing after deposition (usually on both sides). Polishing significantly impacts production costs, (due to the hardness of some TIM like diamond) and new polishing techniques are constantly being developed in an effort to reduce these costs. The thermal properties of diamond permitted a cost reduction of the overall device package even though the price of the diamond substrate was higher than the previous substrate. AT&T announced that thermal management comprised the largest active CVD diamond market today. The greatest impact on the price of bulk diamond is still to come. The prospect for lower costs in future advanced systems is excellent, with diamond production costs predicted to drop to less than $10/carat before polishing. Production costs at this level will open up new markets which are price sensitive.

VI. CONCLUSION

The survey of existing literature on this subject reveals that the TIM materials with high thermal conductivities have a variety of potential benefits that can contribute to reduced total cost of ownership, including: elimination of the need for liquid cooling; reduced system cooling power consumption; reduced building power consumption and increased operational lifetime. To minimize cost it is important not to over specify the requirement for thermal conductivity, planar dimensions, and thickness. More intensive research in this direction is needed to make the thermal interface materials more efficiently applicable for power handling capability of electronic devices.

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