Thermal management of microelectronics packages engineering essay

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Introduction

Thermal management is an important design consideration for number of microelectronic components and packages. Few essential ways of thermal management of microelectronic packages are efficient cooling techniques, efficient thermal interfaces and heat dissipaters. Due to the current trend of increasing heat fluxes and smaller dimensions, thermal management becomes compulsory to achieve optimum performance and reliability of the system. In order to guarantee that, modern electronic systems are characterized by increased density of circuits which is a sole cause of rapid temperature increase within the circuit. The temperature rise caused by such intensive thermal energy dissipation may be sufficiently large to cause some damage to the system. Improved functionality and efficient performance of the products require highly efficient heat dissipation mechanisms.

Literature Review

The rapid increase in the thermal issues has threatened to limit the overall performance of the system. Therefore, package-level thermal management has become a primary concern for the electronic industries. There are a number of microelectronic packages that are being designed in the manufacturing industries around the world. Flip chip packages are commonly used because of their superior electrical and thermal performance. These packages are primarily used in efficient microprocessors, digital and analog signal processors as well as networks and data storage applications [1]. In

order to achieve improved performance and sustainability, these packages are manufactured using different types of materials for example laminate coated substrates or ceramic layers for better metallization and heat spreading throughout the interface [2]. These laminated materials are highly conductive in nature and can be used in a wide variety of applications such as microelectronic packages, electrostatic discharging in electrical components, electromagnetic shielding and coating purposes, protection against sudden surge of power in electronic systems, automobile applications and wind turbine designs. It is important to research and understand how to improve the performance and reliability of the package through thermal management. This task involves considering many factors such as electrical design methods and engineering, overall thermal package layout, material properties and feasibility, manufacturing process and the production cost [3]. The electrical design of any electronic package holds a vital importance in the efficiency of the system. A finite distance below the heat source is required for the heat flux to become uniform with the ambient. Similarly, the type and location of heat sinks also have significant effects on the overall performance of the device. There have been a number of comprehensive reviews that explored various types of heat sinks designed for efficient heat dissipation [4-9]. Lelea [4] carried out research to geometrically optimize the micro-heat sink consisting of straight circular micro-channels. For all four geometries under investigation, the tangential position of the inlet cross-section to the tube axis helped reduce the overall temperature distribution across the micro channels. The temperature distribution was calculated at constant heat flux along the bottom wall at

temperature of 100 W/cm2 and 293 K respectively. The authors showed that the lowest temperature was obtained for the scenario where the width of the inlet channel covered half of the tubes' cross-section with minimum temperature of 313. 2 K and temperature difference of 10. 17 K. The authors reported that the results from tangential micro-heat sink showed significantly better thermal performance than the conventional micro-heat sink with lateral cross-section at the inlet and outlet. The fin-heat sink method showed by researchers [10-11] is one of the most reliable and cost efficient methods for efficient heat dissipation in electronic packages. Some researchers [12-13] proposed a micro-jet array cooling system for electronic packages and they found that it has more advantages over typical cooling systems for example heat pipes and regular fin-based cooling mechanisms. Jouhara and Axcell [9] presented the thermal conditions within a heat sink with rectangular fins under forced convection cooling. The authors showed a detailed parametric numerical study on key parameters of heat transfer that vary with axial distance. Near the leading edges of the fins, the heat transfer coefficient and pin efficiency changed exponentially. The authors reported that despite the exponential transformation in those parameters, good engineering accuracy for heat sink performance could be achieved using theoritical methods which take into account the average values of heat transfer coefficient and fin efficiency. Elshafei [5] carried out experiments on convection heat transfer of heat sinks with circular pin fins subject to the applied heat flux, its geometry and orientation of the heat sink. The authors found that the solid pin fin heat sink showed efficient performance in terms of upward and sideward orientations. The authors compared the values of

the heat transfer coefficients to the perforated hollow pin fins. They found that the augmentation factor was about 1. 05 to 1. 11. According to the authors, the temperature difference between the base plate and surrounding air, at the same heat input value, was found to be less for hollow/perforated pin fin heat sink than that for solid pin heat sink. Kim et al. [7] investigated natural convection for vertical plate fin heat sinks for thermal optimization in a fully-developed-flow regime. Researchers showed the analytical solutions for high conductivity ratios, high channel aspect ratios, as well as low Rayleigh numbers in terms of velocity and temperature distributions. The authors defended the explicit correlation for optimal channel width and fin thickness. These correlations explain the minimization of the overall thermal resistance for certain geometry of the heat sink. These correlations were shown to be a function of materials conductivity, being independent of the Rayleigh number, the viscosity of the fluid, and the length of the heat sink. Huang et al [8] used square plate fin heat sinks for thermal optimization under natural convection subject to the influence of heat sink orientation. The authors examined various arrangements of seven different square pin fin heat sinks as well as a flat plate. Results showed that the upward and sideward facing orientations were of comparable magnitude and showed competitive nature. The porosity of the heat sink had a secondary effect on the performance of the pin fin. The authors found the optimal porosity of the heat sink to be around 83% for upward arrangement and 91% for the sideward arrangement. The augmentation factor for the upward arrangement was found to be approximately 1. 1-2. 5 and between 0. 8–1. 8 for the sideward arrangement. Khor et al [6] used straight-fin heat sink and

closely examined thermal radiation in order to find the correlation of it with the heat sink's thermal performance. The authors developed three different models to examine these effects simultaneously on the heat sink performance and the convection coefficient. Results show that the average convection coefficient for the case neglecting thermal radiation was largest with 30% error, followed by that with thermal radiation including view factor, and that with thermal radiation excluding view factor as the lowest with 60% error. The fin effectiveness was overrated for the cases when thermal radiation and view factor were excluded with more than 40% error. The authors concluded that it is reasonable to exclude thermal radiation under certain circumstances to be able to solely concentration on the convection heat transfer management. An essential type of electronic packages is made of ceramic. Ceramic packages show better thermal expansion and dissipation than other packages such as those made of plastic and other conventional materials. Kandasamya and Mujamdar [2] took into account major contributing factors to the thermal efficiency such as thermal conductivity of the material, thickness and the effect of void parameters during the system assembly. The authors carried out a numerical study on three different ceramic ball grid arrays (FC-CBGA) packages (35 mm, 22 mm and 18 mm) using cup lid, flat lid and no-lid configurations to simulate power dissipation of the package. They found that either eliminating the thermal interface material TIM or using one with least interfacial resistance was very effective in cooling of high power thermal applications with bare die packages. The die size plays a significant role in efficient thermal power dissipation of the package. Higher Theta-JC performance was observed for

the large die in comparison to the smaller die. In comparison to that, Mujumdar et al. [14] compared the thermal performance of a 35 x 35 mm FC-CBGA package with different die sizes that included 5x 5 mm, 15 x 15 mm, and 20 x 20 mm. The lid fitted heat sink performance was investigated in application specific integrated circuit (ASIC) chip, in correspondence with the JEDEC criteria. An exceptional agreement and consistency was found between the numerical results and the data that was measured. The thermal performance was observed with a package that was lidded as opposed to the un-lidded package. However, there was no noticeable improvement observed between lidded and un-lidded packages when they were fitted with a heat sink subjected to forced convection. The package thermal budget estimate variations with and without heat sinks was also discussed in the paper. Circuit board that was printed and package top surface patterns of temperature were analyzed and measured using an infrared thermal camera. Parametric studies were also carried out in order to understand the effect of radiation effect, die size, and gird size variations and airflow rate on die junction temperature and the thermal resistance on the package. The study incorporates the effect of substrate, lid, PCB temperatures, and die for different die sizes in natural and forced convection environments. Light-emitting diode (LED) is a type of solid-state semiconductor device that directly convert electrical energy into light. Due to their extraordinary color saturation and excellent reliability over time, these are one of the technologies with superior potential. These do not only produce great light, but also guarantee energy savings when compared to the conventional sources of light. High power LEDs are very popular in the solid illumination

industry and is considered as next generation device for wide variety of applications such as LCD displays, visual indicators in computers and microelectronic devices, automotive lighting including interior and exterior displays, headlights, signals and luminaries [15-18]. Majority of researchers have carried out extensive research on the thermal management of the LED packages. In those studies, these LED packages were studied for many different applications such as LED package design and analysis [19, 20], high thermal conductivity materials for thermal packaging [21, 22], thermal interface materials [23] and efficient cooling mechanisms [24, 25]. Christensen and Graham [26] showed in their report that the package temperature distributions that were of a high power light emitting diode array had been investigated using quantitative heat flow models. They combined a thermal resistor and network model with a 3D finite element sub-model of an LED structure for the analysis. In order to better understand various roles of thermal resistance in cooling, the thermal resistance network was examined to obtain ready estimates. Other researchers took the torch ahead with this study; developing unique methods to ultimately reduce packaging resistance for high power LEDs. Tsai et al. [27] conducted experiments that showed in the results that the thermal resistance of the low-cost high power LED package was similar and comparable of commercial packages. The resistances were calculated from the 3D TRC, 2D ANSYS, and 3D CF design methods. The authors found that the calculated Tj and thermal resistance values for the package were comparable to those obtained from the experimentation. There were certain differentiations between different designs for thermal analysis and the equation based convection coefficients.

The variations between the LED module and the others showed the results in the forced convection and the design parameters. Weng [28] demonstrated the cooing of LED package by 20%-30% decrease in the thermal resistance over the package geometry. The author found that by reducing thermal resistance at the interface, the cooling of the LED package is very efficient compared to that with higher interfacial resistance. This interfacial resistance plays a vital role in the heat transfer from the heat source to the heat sink. This could be complimented with the use of high thermal conductivity materials for microelectronic packages such as aluminum oxide (Al2O3, ~20 W/mK), silicon nitride (Si3 N4,~70 W/mK), and aluminum nitride (AlN, > 170 W/mK) ceramics instead of conventional flame retardant (FR-4) epoxy (0. 2 W/mK), (Pb, La), (Zr, Ti)O3 films for electro-optics, Pb(Zr, Ti)O3 films for piezoelectrics, yttria films for certain plasma coatings as well as the phase transformation of aluminium nitride package during the aerosol deposition process [29]. Cho and Kim [30] investigated, by the aerosol deposition mechanism, the heat dissipation properties of metal-core printed circuit boards (MCPCBs) with an alumina (Al2O3) layer. The authors showed that the total thermal resistance of the MCPCBs with an alumina dielectric layer in a packaged LED form was obtained to be approximately 34. 5 K/W as compared to the conventional MCPCBs with thermal resistance of approximately 38. 5 K/W. Heo et al. [29] applied high thermal conductivity aluminum nitride (AlN) films (directly deposited on the aluminum plates) to replace low thermal conductivity epoxy resin and various alumina substrates. This caused the removal of the thermal adhesives sheets which are traditionally used as thermal interface materials in metal printed circuit

boards. The authors calculated the thermal resistance of the LED package and found that the package mounted on the AlN thick film was 28. 5 K/W, while an LED package mounted on a conventional epoxy-based metal PCB and a PCB with thermal values were 47. 2 K/W and 36. 5 K/W, respectively. This shows significant enhancement in the heat transfer across the interface in the aerosol-deposited AlN-based LED package. Lu et al. [31] performed a thermal analysis on high power LED package with a flat heat pipe (FHP). The authors experimentally investigated the thermal characteristics including start-up performance, temperature uniformity and interfacial resistance of the LED package with FHP heat sink. They showed that the junction temperature for input power of 3 W, reached up to 52 °C with the total thermal resistance of the system being 8. 8 K/W. In addition to that, they indicated that the inclination angles and various filling rates of the heat sink to the overall performance should be taken into account since these parameters effect the cooling system [31]. Wang [32] investigated the thermal performance of heat sinks with one and two pairs of embedded heat pipes. The embedded heat pipes transfer the total heat capacity from the heat source to the base plate and disperse heat into the ambient. The author found that that two and four heat pipes embedded in the base plate carry 36% and 48% of the total dissipated heat respectively. It was also reported that when the total heating power of the heat sink with two embedded heat pipes was 140 W, the total thermal resistance reached the minimum value of 0. 27 °C/W, while for the heat sink with four embedded heat pipes, when the total heating power was between 40 W and 240 W, the total thermal resistance was calculated to be 0. 24 °C/W. Chen et al. [33] derived various

boundary conditions based on the heat flow and temperature to design a compact thermal model for LED packages. The authors performed finite element method modeling for simulating the LED package with different heat slug, PCB, cooling condition and chip sizes. They found surprising correlations in the thermal design with varying boundary conditions. These correlations direct to the system level thermal management for these applications. Since maximum power of the LEDs is converted to heat, it is really important to dissipate that heat. The life of any electronic package decreases exponentially as the junction temperature increases. Narendran and Gu [34] demonstrated the use of a low-operation temperature for LEDs since these have dense packaging and require high output power which contradicts between the power density and operation temperature, especially when applications require LEDs to operate at full power to produce the desired brightness. Faranda et al. [35] investigated a prototype based refrigerating liquid for heat dissipation of power LEDs. The authors carried out optimization investigation of the proposed solution to find an optimum thermal performance to be established and set as a primary boundary condition for similar systems. They performed experiments with different heights of liquid levels since the liquid determines better heat dissipation and diminution of the junction temperature. Larger operating current was supplied to the components until the junction temperature of the traditional solution was reached. By obtaining an increment of light radiation, the authors revealed that the refrigerating liquid cooling is a powerful way for heat dissipation of high power LEDs, and the fabrication of prototype was feasible and useful. Yung et al. [36] presented experimental thermal analysis

of natural convective air cooling of a high brightness 3×3 LED array package on a printed circuit board (PCB) during operation from 0 to 180° inclinations. The authors used IR camera and thermocouples to conduct thermal profile measurement for temperature distribution and heat flow analysis of the LED package. They found that the effect of position and inclination plays an important role in the heat dissipation of the LED package. The authors were able to establish criteria for not only setting up a LED array system, but also to adopt design features that would be beneficial to achieve efficiency in thermal management. Hu et al. [37] used high power light emitting diodes (LEDs) with ceramic packages to carry out thermal and mechanical analysis. The authors found that there was high level of thermal and mechanical stress even though there were less mismatching coefficients of thermal expansion compared to those in plastic packages. Usually, the performance of the LEDs is degraded as such high power operations are undertaken. In order to reduce that degradation, the application of silicon based thermoelectric cooler integrated with high power LED can be used. This LED has lower thermal resistance and the thermoelectric cooler package helps reduce the thermal resistance even further to almost zero [38]. The mismatching in the coefficient of thermal expansion can create distortions, cracks and even catastrophic damages to the microelectronic device. Hence, a good match in these coefficients of new package materials to the semiconductor device is essential. The thermal design of GaN electronic packages using new materials not only provide good match for coefficients of thermal expansion, but also have higher thermal conductivity than the current conventional materials. A number of diamond-reinforced composites

are used in the development of GaN based electronics such as GaN based high electron mobility transistors (HEMTs) and LEDs. The popularity of these materials is growing because of the high demand of power densities. Using the diamond materials, the cost constraints should also be taken into account. The reduced cost of synthetic diamond grains and latest diamond fabrication technologies have given an edge to the use of diamond composite for thermal management. In addition to that, the greater bonding between the diamond particles within the metal matrix gives it superiority over other composites to be used as an efficient material for thermal management applications. Faqir et al. [39] presented an efficient packaging solution for Gallium-Nitrogen powered systems for improved heat dissipation in high power devices. The authors carried out Micro-Raman thermography measurements to investigate the device temperature for base plates, composites made of silver diamond as well as standard Cu platted material at a range of various power levels. Since the base-plate roughness of less than 1 lm is desirable for many applications, the bare silver diamond coating was used. The authors found a significant reduction in GaN power electronics temperature by up to a factor of two, was obtained when using silver diamond composites base plates. They reported a significant improvement in the thermal management of GaN devices with respect to the existing packaging technologies. An imperative way to improve the heat dissipation problem is to improve the thermal contacts using efficient material. A vital property of any material is its thermal conductivity. All modern materials such as aluminum oxide, aluminum nitride, boron nitride, graphite and diamond powder, silver that increase thermal conductivity up to the 2 W/m-

K. A number of researchers [40-42] used diamond with several other materials to develop a unique thermal package. Aluminum diamond was developed with a CTE of 7. 5 ppm/K and thermal conductivity of 500 W/(m K) [40]. The copper diamond composite material made with 55 vol.% of good quality diamond was developed with a thermal conductivity of 420 W/(m K) [41]. The copper diamond composites with diamond volume fraction of 62% can lead to a better performance, with a thermal conductivity of 530 W/(m K), and a CTE of 5. 5 ppm/K [42]. Some researchers developed silver diamond composites mixed with diamond particles in a matrix of silver alloy with the ultra-high thermal conductivity of 700 W/(m K), significantly larger than CuW, at room temperature and a CTE close to that of the semiconductor materials [43]. Because of ultra-high thermal conductivity and excellent bonding between these materials, they are capable of showing optimized thermal management solutions when used in microelectronic packages for high power requirements. Unfortunately, high conductive solid material alone does not contribute to the optimal system performance. Thermal resistance calculated from heat flow across the interface should also be minimized. For high thermal conductivity materials, the contact resistance may be reduced by increasing the area of contact spots. This can either be accomplished by increasing the pressure at contact surfaces and by deflecting the interfacial surfaces to reduce non-uniformity, or by reducing the roughness of the surfaces before the interface is formed by polishing the surfaces to form even layers [44]. Other properties taken into account are interfacial thickness and applied forces. In addition to thermal performance, materials for thermal packaging are selected based on their

inherent thermal properties and long-term stability (reliability). Researchers are constantly in search for superior thermal interface materials. This is usually expressed as a request for higher thermal conductivity and lower thermal resistance. Phase change materials (PCMs) have been indicated by the researchers as high storage capacity materials and significantly efficient for heat dissipation at the thermal contact. Liu and Chung [45] carried out a comparative study on phase change materials for electronic packages with various melting temperatures close to room temperature. The authors used the Parafin wax as well as the microcrystalline in their study. They found that paraffin wax was potentially good thermal interface material because of the negative super-cooling of $-7°C$, large heat of fusion (up to 142 J/g) and excellent thermal cycling stability. In the experiements, paraffin also demonstrated clear exothermic and endothermic peaks which were not found in case of microcrystalline. For microcrystalline, the incongruent melting and decomposition aspect was explained by the authors with high supercooling of 8°C and instable thermal cycling. Since most PCMs with high energy storage density have lower thermal conductivity, the authors enriched the PCM performance by mixing polymers with the PCMs and other particulate fillers of high thermal conductivity. Kandasamy et al. [46] had included in their studies the application of a novel PCM package for thermal management of portable devices. It was experimentally examined for the effects of different parameters. There was a two-dimensional numerical study that was made and compared to the experiment results. The outcome showed that the increased power inputs increased the rate of melting, while gravity had a negligible effect (on the package) on thermal performance of

the PCM package. The thermal resistance of the device and the power level applied to the package were of vital importance for the design of a passive thermal control system. The association with numerical results confirmed the PCM-based design was an exceptional candidate design for electronic cooling applications. Krishnan and Garimella [47] carried out a transient analysis of the phase change process inside a rectangular enclosure for microelectronics cooling applications with pulsed power dissipation. The experimental investigation included the melting of a pure PCM, n-eicosane, inside a rectangular aluminum container with multiple discrete heat sources mounted on one side. The authors examined the influence of frequency changes of the pulses, heat source location and aspect ratio of the containment volume on the thermal performance of the PCM unit. The performance of the PCM system was investigated by studying maximum temperature observed in the container. The heat was absorbed through the container walls as well as the heat dissipating interfaces. The authors reported that the heat source location and container aspect ratio played a significant role in the performance of the PCM system with pulsed heat input. Krishnan and Garimella [48] also performed a transient thermal analysis to investigate thermal control of power semiconductors using phase change materials. The authors compared the performance of power semiconductors to that of copper heat sinks. The authors concluded that a significant suppression of junction temperatures was achieved by the use of PCMs when compared with copper heat sinks. The researches indicated that, although the thermal conductivity of a solid material is important for microelectronic packages,

the efficiency and conductance of the plating material also plays an
important role in consenting efficient thermal management.