Arizona State University

Innovative approach to mitigate dynamic warpage in microelectronics packages by nanofluids based heat-sinks

Surya Shekhar
(ASU ID # 1215338475)

Contents:

Introduction:

With Gordon Moore’s hypothesis becoming a law, the semiconductor industry has grown exponentially with the decrease in distance between the tansistors in a last few decades. Therefore flip chip packages going down to the size of milimeters and the slilicon wafer chip thickness going down to microns, heat dissipation and managing the thermomechanical stresses has become a major challenge. The thermomechanical stresses developed because the package is made of wide range on layers of material laminated together have Coefficient of thermal expansion varying in a wide range. These stresses developed in a Flip Chip ball grid array package has demonstrated chrecteristic of dynamic warpage. As per [1] package warpage at room temperature was found to be mailny depending on die size, substrate thickness of integrated heat spreader size but classical thermal strain still occurs at die region. The warpage in the die can be measured by shadow moire` technique. This is a non-contact full field measurement method that is done by a light source creating moire pattern at the region of warpage [2].

This paper deals with mitigation of dynamic warpage by proposing various techniques of localised cooling of substrate and die in packages. The temperature rise in the silicon wafer can be indentified by deformation behaviour of MEMS gyroscope package subjected to temperature change from room temprature to 125°C, using high sensitivity moire` informatory[5]. Now, one process of cooling can be by creating microchannel heat sink with nanofluids. Nanofluids notonly have have anamolously high thermal conductivity at low volume fractions of nanoparticles but also three fold higher critical heat flux than that of the base fluds [3]. Another most convincing method of localised cooling is by thermoelectric devices fabricated from Bi_2Te_2 based thin film superlattices into electronic packages [4]. The thermo-mechanical reliability is a critical concern in wafer level packages and the limitations of the solder joints to sustain the wide range of thermal cycles have resulated in decreased number of IOs is WLPs [6]. The intrinsic difference between the coefficient of thermal expansions of silicon is ~ 2.6 ppm/°C and the PCB is ~16 ppm/°C and that is a big difference that creates a strain energy density of more that 0.6 Mpa for a WLP structure which can cause solder failures and delamination [7].

Identification of Dynamic Warpage:

Moie Experiment:

Non uniformity in a pane caused by thrmomechanical stresses can be measured by cross-line defraction grating replicated onto the cross section of the interest. The interaction between two coherent laser beams with the deformed grating produces an interferance pattern that represents the thermally induced displacement pattern. Thermally induced deformations can be extracted from the displacement fields by the below formulas:

$U(X,Y)=(1/f)Nx(X,Y)$

$V(X,Y)=(1/f)Ny(X,Y)$

Where Nx and Ny are fringe factctors in U and V firld respectively and f is grating frequency. Now in case of grating frequency of 1200 lines/mm, each fringe spacing represents 417 nm relative displacement difference [8].

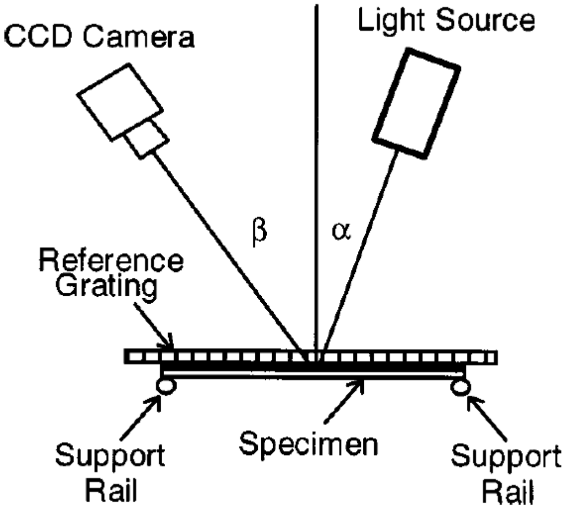

Figure 1: Schematic of shadow Moire's setup [2] Swapan K. Bhattacharya et el (2000)

A. MEMS Gyroscope Sensor

MEMS vibratory gyroscope sensors are used to detect angular rate or motion, and due to their small size they are highly sensitive. The lateral vibratory gyroscope sensors have laterally oscillated comb structures, consisting of driving spring, sensing springs, sensing combs and driving combs.

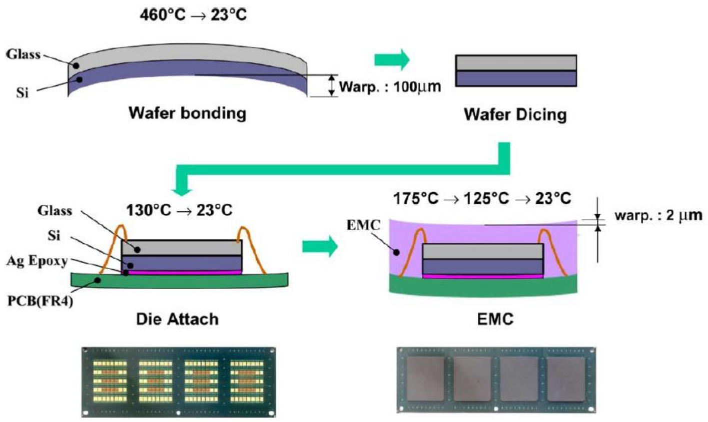

Figure 2: MEMS Gyroscope Sensor [5] Change Jin-Won Joo et el (2000)

B. MEMS Gyroscope Package

A gyroscope package is basically a diced gyroscope chip attached to a PCB or FR-4 board with silver adhesive The elctrical contac is made by wirebonding encapsulated by epoxy moulding compound. When thermal stresses are produced due to CTE mismatch bonded wafers 4 inch dimension bow upto 100 micons. Wafer bowing was measured by measuring the highest and the lowest points of the deformed surface, however the diced wafer has a deformation less than 0.1 micron which is very small. Now with the deformation of the entire package the MEMS structure also deforms resilting in a frequency shift frequency shft is observed [5].

Warpage Study:

In case of a post mold curing of epoxy molding compound (EMC), the FEA simulations donot show warpage at the centre and the largest deformations are found to be at the edges. Also Von mises stress acting in EMC top surface are larger than those in the interfaces (Path 2) between the EMC and the top of the chips. To illustrate this phenomenon an ansys simulation was performed on a closely similar flip chip package model. The temperature and stress concentration contour plots were made for Bismaleimide Triazine (BT) organic substrate for 1000 cycles of fatigue caused by thermal stresses for a range of 125°C to -40°C. BT has a CTE of 14ppm/°C , Young’s modulous 22Mpa and Poission’s ratio 0.35.

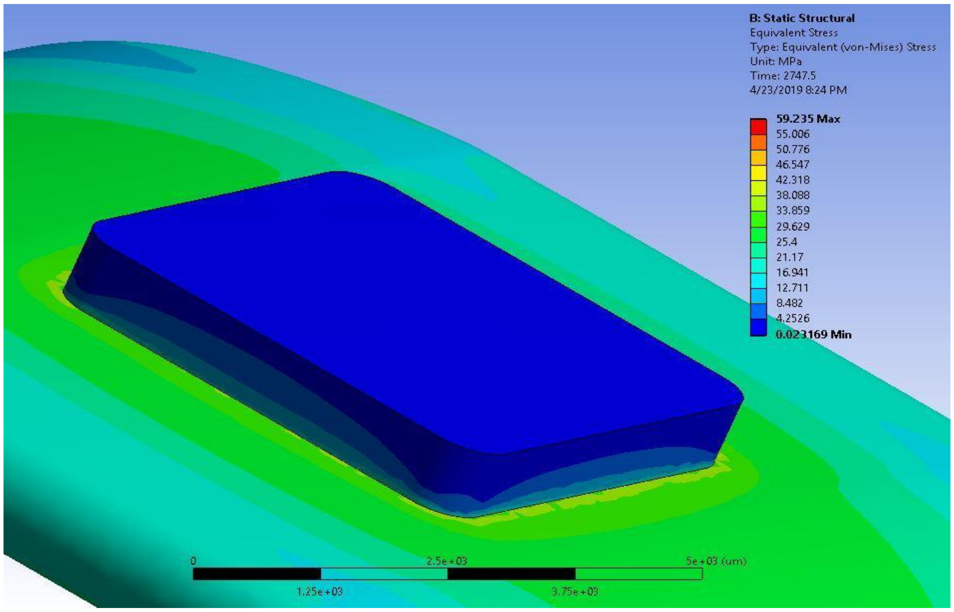

Figure 3: BT Stress Concentration at maximum temperature of 125ºC.

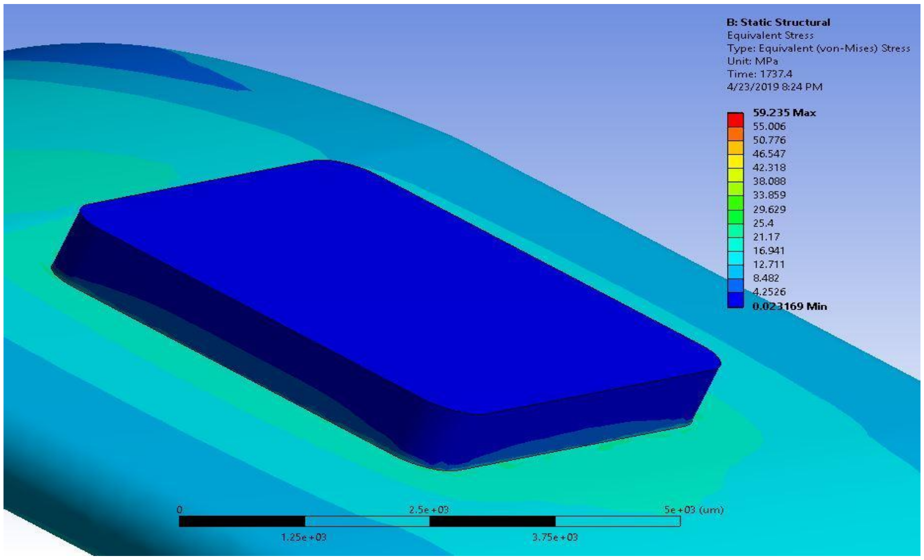

Figure 4: BT Stress Concentration at minimum temperature of 45ºC.

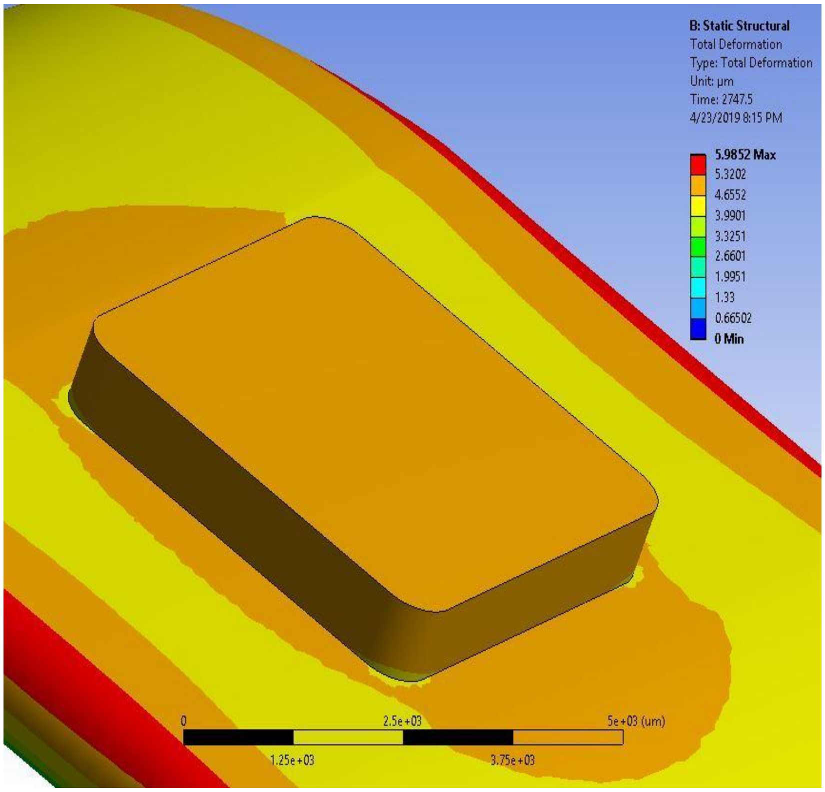

Figure 5: Package deformation at maximum temperature of 125^{o}C.

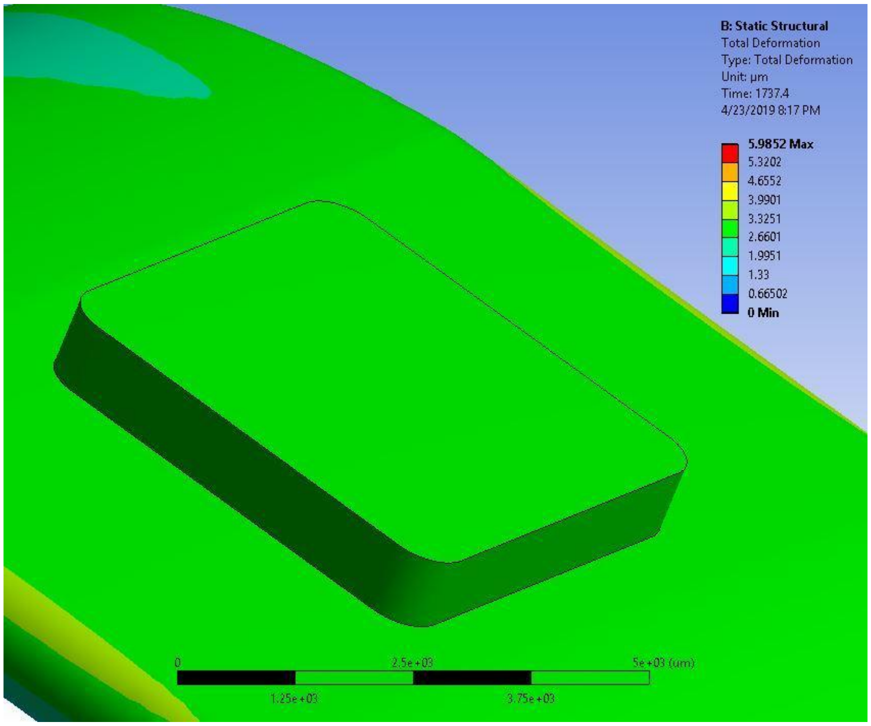

Figure 6: Package deformation at minimum temperature of -40^{o}C.

Now from the above contour plot we know the regions of maximum stress concentration and maximum deflection, which is the edges of the die and substrate interface.

Hoever this is a condition when there is no integrated heat spreader, but when we introduce a heat spreader to the system, a huge amount of heat flux is rejected from the top of the die (which happens during operation) and the package waprs with a ‘M’ shaped topology. This happens because the HIS constraints the package from deforming freely.

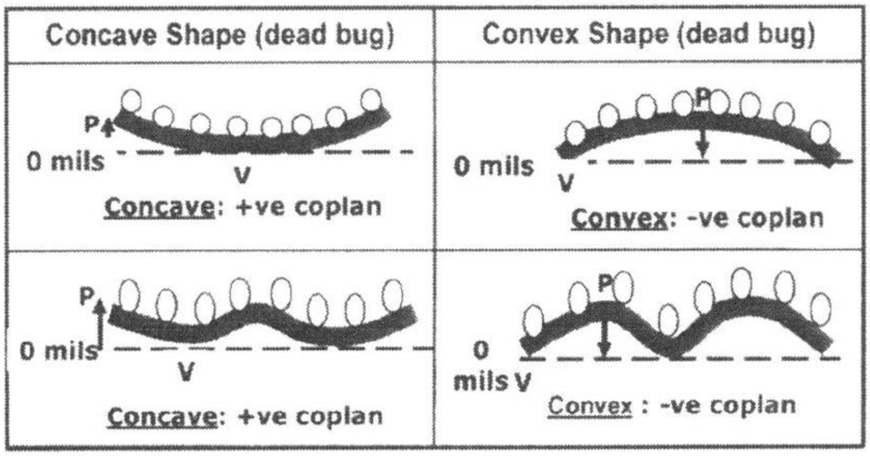

Figure 7: Substrate warpage convection [1] Chee Kan, Lee et el (2006)

A flip chip ball grid array package flattens as temperature increases, this is because at room temperature with a HIS the package warpage depends mainly on the dimensions of the package. Thus the heat spreader gives a constrain to the size of the package [1].

From the extensive literature study it has been found that there is a good scope of research in methods of mitigating dynamic warpage of wafers by methods of localised thermal management. With a proper localized thermal management the thermomechanical strain can be checked and package reliability can be increased.

Heat dissipation through nanofluids

Fluid with nanoparticles(with an average crystaline size below 50 nm) suspended in them are called nanofluids. The larger surface area of the nanoparticles compared to conventional particles notonly incerases the heat transfer capabilities but also incerases the stability of suspension. Successful employment of nanofluids in microelctronics packages can prove to be good for local heat exchanger systems for heat dissipation.

Thermal Conductivity:

From extensive literature survay it has been found that there is no formula for calculating thermal conductivity of nanofluids, it mainly depends on thermal conductivity of the base fluids and the nonoparticles. However there exist a number of semi emperical correlation to calculate the apparent conductivity of a two phase mixture, this is called the effective thermal conductivity (k_{eff}) [3].

$$k_{\mathrm{eff}} = \frac{k_{\mathrm{p}}\phi_{\mathrm{p}}(\mathrm{d}T/\mathrm{d}x)_{\mathrm{p}} + k_{\mathrm{b}}\phi_{\mathrm{b}}(\mathrm{d}T/\mathrm{d}x)_{\mathrm{b}}}{\phi_{\mathrm{p}}(\mathrm{d}T/\mathrm{d}x)_{\mathrm{p}} + \phi_{\mathrm{b}}(\mathrm{d}T/\mathrm{d}x)_{\mathrm{b}}} \tag{1}$$

The maxwell’s model for solid liquid effective conductivity of a solid liquid mixture is given by

$$k_{\mathrm{eff}} = \frac{k_{\mathrm{p}} + 2k_{\mathrm{b}} + 2(k_{\mathrm{p}} - k_{\mathrm{b}})\phi}{k_{\mathrm{p}} + 2k_{\mathrm{b}} - (k_{\mathrm{p}} - k_{\mathrm{b}})\phi} k_{\mathrm{b}} \tag{2}$$

Where, kp is the thermal conductivity of the particle, kb is the thermal conductivity of the base fluid and φ is the particle volume fraction of the suspension. Yu and Choi proposed a modified Maxwell model to account for the effect of the nano-layer by replacing the thermal conductivity of solid particles kp by modified thermal conductivity of of solid particles Kpe [10].

$$k_{\mathrm{pe}} = \frac{[2(1-\gamma) + (1+\beta)^3(1+2\gamma)\gamma]}{-(1-\gamma) + (1+\beta)^3(1+2\gamma)} k_{\mathrm{p}} \tag{3}$$

where $\gamma = k_{layer}/k_p$ is the ratio of nano-layer thermal conductivity to particle thermal conductivity and $\beta = h/r$ is the ratio of the nano-layer thickness to the original particle radius. Ttherefore the maxwell’s equation can be modified as:

$$k_{\mathrm{eff}} = \frac{k_{\mathrm{pe}} + 2k_{\mathrm{b}} + 2(k_{\mathrm{pe}} - k_{\mathrm{b}})(1-\beta)^3\phi}{k_{\mathrm{pe}} + 2k_{\mathrm{b}} - (k_{\mathrm{pe}} - k_{\mathrm{b}})(1+\beta)^3\phi} k_{\mathrm{b}} \tag{4}$$

However, having produced the above methods of heat transfer it is true that these traditional computational methods donot charecterize the fluid flow nature and heat transfer charecteristics of nano-fluids. And the Latice Boltzmann equation can address this problem.

Lattice Boltzmann Model for Nanofluids:

Nanofluids experience a number of forces like buoyancy and gravitational force, the brownian force, the drag force and the dispersion force resulting from repulsive potential in case of no other active external fields. If the browninan force is dominant the nanoparticles may tend to aggregate and forming clustors resulating in blocking the cappilary. The forces acting on each nanoparticle can be expressed as a vector sum of Browninan force. The buoyance force is given by the equation:

$$\mathbf{F}_H = -\frac{4}{3}\pi a^3 g \Delta\rho' \tag{5}$$

And the drag force is given by :

$$\mathbf{F}_{\mathrm{D}} = -6\pi\mu a \Delta\mathbf{u} \tag{6}$$

Where α is the radius of the suspended nanoparticle, Δρ′ is the mass density difference between the paticles and the base liqud, μ is the viscosity of the fluid, Δu is the viscocity difference between the particle and fluid [11].

Thermal conductivity and heat transfer through nanofluids notonly depend on the diameter of the nanoparticles but also on the temperature concentration. Thermal conductivity incerases with the increase in concentration of nanoparticles and temperature and decrease with the increase in size of the particles. Now since the nanofluids exhibit enhanced thermal conductivity with increase in temperature they are more effective in higher temperature [15].

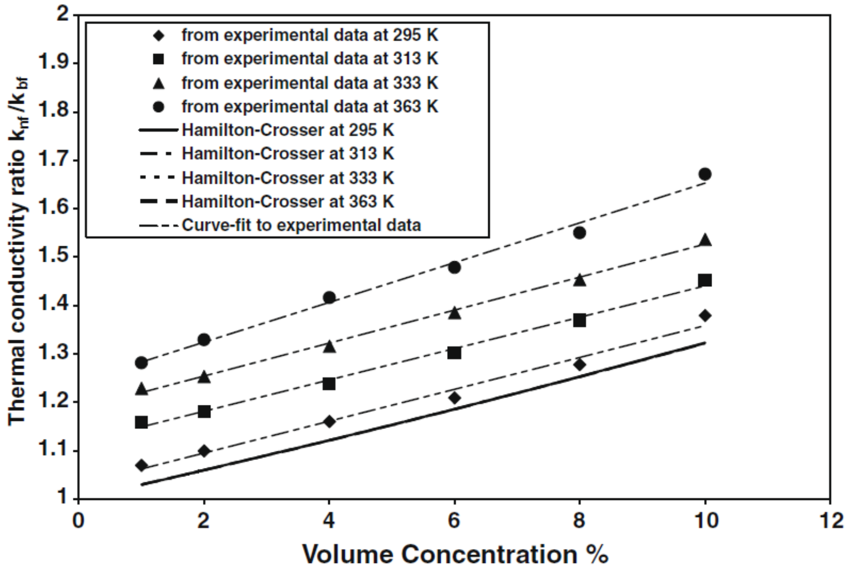

Figure 8: Relation between thermal conductivity and volume concentration of nanoparticles in nanofluids [15] Vajjha, R.S et el (2009)

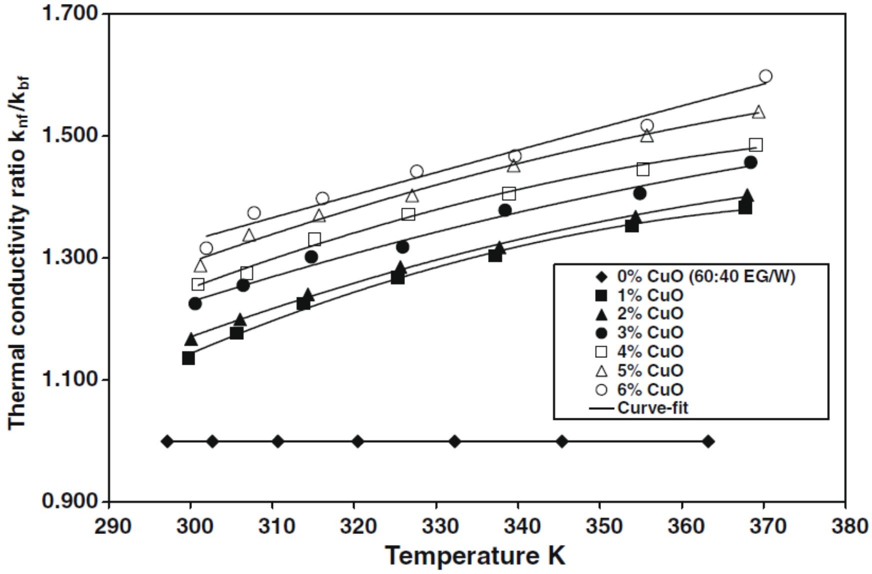

Figure 9: Relation between thermal conductivity and temperature of nanofluids acting as heat sink material [15] Vajjha, R.S et el (2009)

Therefore it can be concluded from this study that nanofluids can act as good heat exchanger material, but creating heat sink cavities still remains a challenge. Furher in this paper we would know about fabrication of heat sinks for nano fluids.

Silicon Reentrant Cavity Heat Sinks Using Anisotropic Etching

Certain areas of the package can produce high amount of heat flux and nanofluids based heat exchangers fabricated on these areas can prevent dynamic warpage by dissipating heat from those locations. But the challenge here is fabrication of heat exchanger cavities and this can be achieved by silicon reenant cavity heat sink fabricated using a two step anisotopic etching process followed by silicon direct wafer bonding.

Heat sink fabrication process:

A reentrant structure of pyramid-shaped cavity can be created by two sided etching process through silicon wafers. Silicon dioxide layers of 150 nm thickness can be first grown in both the surfaces of a 75nm silicon wafer and polished. Photolithography followed by chemical etching can produce 2.5 cm X 2,5cm array of square openings in the oxide nitride layers on one side of the wafer. Further a KOH-alcohol-DI water solution can be used to etch the cavities into wafer and the designs can be made such that they stop at 50 μm from the other edge. By this process a variety of heat sink cavities can be fabricated with mouth opening of size 8 to 500 μm. The base of each pyramid can be of 400 μm with a cavity spacing of 80 μm. The etched wafer can be bonded to a second silicon wafer using direct wafer bonding techniques and after cleaning using nitric acid treatment and deionizing water wash [12],[13].

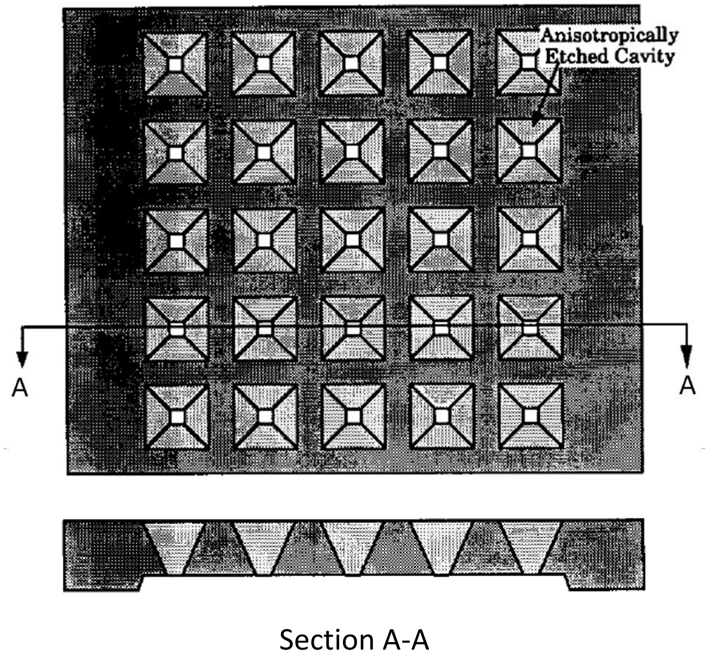

Figure 10: Reentrant cavity heat sink structure [12] Goyal, A et el (1993)

Therefore silicon reentrant cavity heat sink for enhanced liquid cooling can be fabricated on silicon multchip substrate with 420 cavities/cm^2 of mouth opening 15 µm. As per [12] the reentrant cavities suppress the temperature overshoot.

From the above procedure it is clear that heat sinks can be fabricated but we are yet to discuss the compatibility of nanofluids with these heat sink cavities. The further study deals with this part.

Characteristics of nanofluids in microchannel heat sinks:

To fabricate a nanofluid heat sink it is important to understand the characteristics of nanofluids in microchannels. Stokes and non-stokes fluid flow and heat transfer in microchannels heat sinks considerably depends on the thermo-physical properties of the liquid. For a silicon based heat sink a finite difference numerical code developed using a Tri-Diagonal Matrix Algorithm (TDMA) to solve the governing equations and its validation can give a detailed temperature and heat flux distribution in microchannel heat sinks. Moreover, the effect of channel geometry and the thermophysical properties of the fluids and the heat transfer can be estimated by a thermophysical property method [14],[16].

Different analysis made in [16] give the different paraments that effect heat transfer for nanofluids in microchannel heat sinks, which are type of the nanoparticles (Al_2O_3, ZnO, CuO, SiO_2), volume fraction, nanoparticle diameter, and the type of base fluid. Figure shows a relation between these parameters and Nusselt's number. With the increase in Nusselt's number thermal resistivity of the nanofluids decrease. And the final results and comparisons show that the performance of triangular grooved microchannel heat sinks (TGMCHS) give the best groove geometrical configuration for Al_2O_3-H_2O nanofluid.

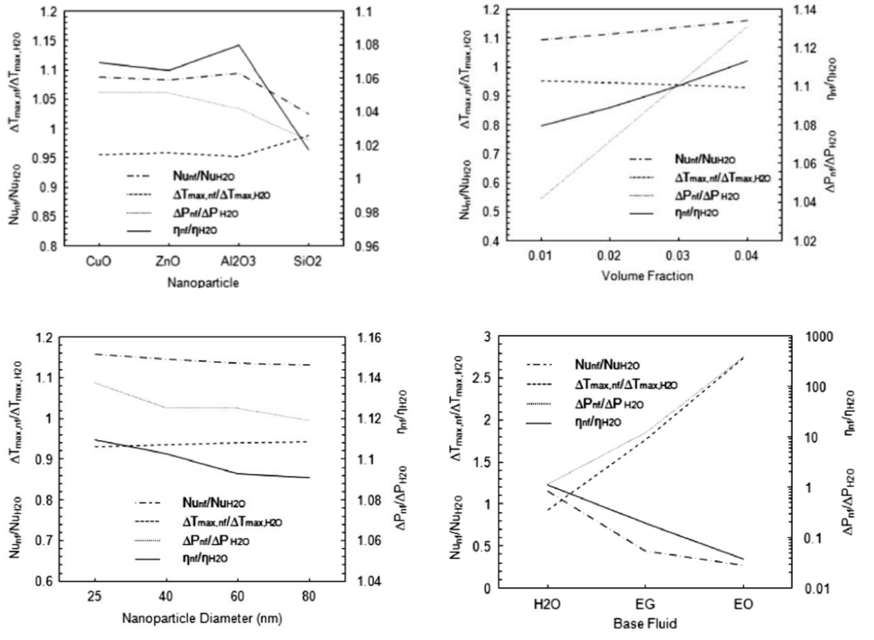

Figure 11: Relation of thermal flow performance and efficiency of TGMCHS for different parameters of nanofluids

Table: Comparison TGMCHS with Al_2O_3*–*H_2O *(Ø = 0.04,* d_{np} *= 25 nm) and simple MCHS with water [16].*

Improvement	Nu^a	ΔT_{max} (K)^b	η^a
	189.84	24.5	179.55

Where:

^{a} : Increment

^{b} : Reduction

Therefore, TGMCHS helps in redeveloping thermal and hydraulic boundary layers, vortices generation and increased heat transfer surface at the groove area for the nanofluids flowing through. The entire phenomenon enhances the heat transfer but also results in pressure drop.

Conclusion and Future Scope:

By this study it can be concluded that nanofluids used as heat sinks can be a good method of localized heat dissipation in microelectronics packages. Starting from the study of dynamic warpage its detection and analysis give us the locations of maximum thermal stress concentrations, these are the regions which if cooled or heated to certain values shall reduce the warpage due to CTE mismatch. Going further the concept of using nanofluids in TGMCHS cavities fabricated in the silicon substrate as heat exchangers to dissipate heat locally can be proposed. Finally various parameters of nanofluids are discussed that effect the thermal efficiency and the optimum results were found to have been achieved.

However, for the implementation of this idea a huge scope of research is required in different fields. Firstly, a nanofluid hydraulic circuit is needed for a particular flip chip model (CAD parametric model precisely made) on which the entire research can be done. Secondly a thermal simulation needs to be done to check if the desired values of maximum stress and temperature are received. Finally optimizations need to be done on different fields to get the perfect fluid pressure and TGMCHS dimensions. Localized thermal management can also done by thermoelectric materials [17] and a literature study can also be done on that to compare the effectivity of the two process.

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