Modelling, manufacture and test of a microchannel cooling plate for microelectronics packaging

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Abstract
The modelling, simulation, fabrication and testing of a microchannel cooling plate are described in this article. The cooling component is to be used in microelectronic packaging applications. The nickel-based micro-channel cooling plate is fabricated on a glass substrate using a two-layer electroforming process borrowed from UV-LIGA. Forced convection of air or liquid is scheduled for this microchannel plate. The cooling plate was tested using a custom-made test rig to measure pressure head as a function of mass flow rate. Hydraulic performance of the cooling plate is presented.

1. Introduction
The rapid advances in transistor density and switching frequency of VLSI circuits as encountered in microprocessors have induced dramatic increases in die heat flux and power consumption at all levels of electronic packaging [1]. Such increases in thermal dissipation have motivated the demand for more efficient cooling mechanisms at the die, component, PCB and system levels [2]. Of interest in this article are heat sinks which are the most researched and cost-effective components employed for the thermal management of microelectronic equipment [3]. More particularly, the research presented in this paper concentrates on single phase forced convection heat sinks based on microchannel plates [4]. The microchannel plate is to receive forced air convection from a 3-D electromagnetic microfan manufactured using microengineering techniques. Whereas the concept of microchannel cooling is over 20 years old [5], the microchannel plate presented in this article is based on a new application of the UV-LIGA process in the growth of a doubly electroformed layer of Nickel for the base and the microchannels, respectively. In section 2, the design of the component and its fabrication are presented. Experimental set up and testing procedures and explained in section 3. A description of the flow through analytical equations is given in section 4 and is being compared in section 5 with the simulation and modelling works based on finite element analysis. Results and discussion are finally presented in section 6.

2. Device fabrication

Figure 1 Photo mask design for the microchannel plate.
The square cooling plate is 15mm wide and 130µm thick from the base of the plate till the top of the channels. The support itself is 60µm thick providing thereby 70µm of depth for the channels. The plate supports a total of 128 channels of 100µm width that radiate from its centre. The shortest channel length is 4.5mm in length and the longest is 7.6mm. The center of the plate is a 6mm diameter hole for the fan to be fitted in. The whole channel plate is made by electroplating nickel by using a 2-layer electroforming process borrowed from UV-LIGA process. The masks for the channel plate have been prepared using the CAD-software layout editor L-Edit. The software LinkCAD was employed to convert the file from GDSII to Gerber. The first mask is used for fabricating the holes as shown in figure 1, the second mask is used for fabricating the channels.

2.1 Fabrication of the first layer

The first layer is to define the base of the cooling plate and the position of the centre holes. The component is fabricated using UV photolithography and electroplating techniques. First a 3-inch glass wafer is thoroughly cleaned and then dried in oven at 60°C deg for 20min. After cooling to room temperature, 3ml of AZ 9260 positive photoresist are then deposited and coated onto the wafer in two spin cycles. For the spreading cycle, the spin speed is 380 rpm, with a ramp rate of 100 rpm/s and the spin time is 20 seconds. For the coating cycle, the spin speed is 2800rpm, with ramp rate of 600 rpm/s and the spin time of 20 seconds. A delay of 4 minutes is then allowed for the photoresist to settle down on the wafer before baking commences. The wafer is then baked on a hot plate to evaporate the solvent. This is carried out in two steps; first at 78°C for 20 seconds and then at 103°C for 330 seconds. It is then removed from the hot plate and allowed to cool down to room temperature for about 2 minutes. It is then left at room temperature for about 40 minutes before UV-exposure. The photoresist coated wafer is then exposed using the 1st layer mask (shown in figure 1) by a highly collimated UV light source at 365 nm wavelength for an energy dose of 800mJ/cm². After exposure, the wafer is developed using AZ developer for 4 minutes (the ratio of AZ developer to DI water is 1:3). As a result, approximately a 5-6µm thick layer of photoresist layer is achieved. This photoresist layer is to be sacrificed at the end of the overall process. A layer of 300nm thick titanium is then deposited onto the developed photoresist using an electron-beam evaporator. This layer constitutes the seed conductive layer for subsequent electroplating processes. The regions of photoresist that have not been protected by the titanium layer are then stripped off using an organic solvent in an ultrasonic bath for 3 minutes. These regions will define the center holes where the microfan is to be fitted. Nickel is then electroformed onto the titanium seed layer using electroplating technique. Initially, the electroplating is carried out with a low current of 68mA for 2 hours. This is to allow a slower plating rate of nickel such as to reduce internal stress within the structure and achieve better plating results. A higher current of 198mA is then applied for about 14 hours. As a result, a 60µm thick electroplated nickel layer is achieved for the 1st layer as shown in figure 2.

2.1 Fabrication of the second layer

The second layer is to define the microchannels. After finishing the electroplating of the first layer, the wafer is then cleaned and dried with DI water. 3ml of AZ photoresist are then deposited and coated onto the wafer. A 2-cycles spinning process is required for the fabrication of the channels. For the spread cycle, the spin speed is 250 rpm, the ramp rate is 100 rpm/s and the spin time is 10 seconds. Later the spin speed is ramped to 1000rpm, with a ramp rate of 200 rpm/s and the spin time is 8 seconds. A delay of 6 minutes is then allowed for the photoresist to settle down. The wafer is then baked on a hot plate to evaporate the solvent. This is carried out in three steps: first at 68°C for 30 seconds, then at 80°C for 20 seconds and finally at 103°C for 3 minutes. The wafer is then allowed to cool down to room temperature for 3 minutes. In order to achieve the desired thickness
of 70µm, a second layer of photoresist is coated using the same parameters as in the first spinning process, except that the hot plate baking time at 103 °C is increased to 6 min. After baking, the wafer is removed from the hot plate and allowed to cool at room temperature for 3 minutes. The wafer is then left at room temperature for 1 hour before exposure. The exposure of the two layers of photoresist is carried out with the Tamarak mask-aligner. The second mask is aligned with the first pattern with the help of mask alignment marks on the wafer and mask. The wafer is then exposed to UV light with an energy dose of 2200mJ/cm². After exposure, the wafer is developed in AZ 400K developer for 12-16 minutes. Nickel is then electroplated again to obtain a microchannel thickness of 70µm. Initially, the electroplating is carried out with a current of 68mA for 2 hours and later with a current of 128mA for 16 hours. The photoresist is then stripped off using an organic solvent in an ultrasonic bath to obtain the desired microchannels. Finally the electroplated nickel microchannel device structure is lifted off resulting in the successful fabrication of the cooling plate as shown in figure 4.

Figure 4 Microchannel cooling plate after lift off from the glass substrate

3. Experimental set up and testing procedure

Description of apparatus:
Figure 5 shows the schematic of the experimental set-up used in the measurement of pressure drop in the microchannels with different flow rate (m/s). The pneumatic system supplying nitrogen to the test sample consists of a standard oxygen free nitrogen supply with regulator, a second regulator for fine pressure control, a gas flow meter, pressure gauge and purpose built fitting to supply the gas to the sample aperture. The fine adjustment regulator is a Parker PD3 diaphragm type; the flow transducer is Weber type 3202 meter and the pressure meter is a Sandhurst LH44. All the components are connected in series using 5mm ID flexible plastic tubing. The design of the supply tube allows for the gas to be supplied at one end and the opposite end mates with the central aperture and seals with a fitted rubber ‘O’ ring. The tube is mounted vertically and attached to a micrometer translator, which allows the tube end to be held firmly and pushed firmly against the sample without leaking. The full picture for the experimental set-up is presented in figure 6.

Figure 6: Picture of the experimental set-up

Description of the test procedure
The microchannel sample was mounted on a firm glass substrate base, with the channels facing towards the substrate; this effectively closes the channels and allows the gas to flow from the central cavity, through the channels and out into free space. Gas flow was then initiated and the pressure adjusted to produce the maximum gas flow to give a full scale reading on the flow meter. A flow of 5m/s corresponds to a 20mA reading from the output circuit. A pressure reading is then taken. The regulator is then adjusted to reduce flow by a small amount and a new pressure reading is taken. This process was then repeated over many times until the readings reached a zero flow measurement. A graph of pressure against flow rate (m/s) was then plotted. Several identical tests were conducted on the same sample to check for repeatability. An additional test was conducted to check the flow from the device and establish that all channels were operating and that
there were no leaks at the device inlet. This was done by submerging the entire micro-channel device in a few centimetres of water to allow a visual check for bubbles from all channel ends. Several different samples of the same microchannel device were evaluated and the results from these are discussed in the results section.

4. Analytical expression of the fluid flow through one microchannel

Considering the dimensions of a microchannel as shown in figure 7, the volumetric flow rate \( Q \) (m/s) of a fluid in one channel as a function of pressure in Pascal (N/m²) can be expressed as [6] [1]:

\[
Q = \frac{4ba^2}{3\mu} \left[ \frac{dp}{dx} \right] \left[ 1 - \frac{\tanh(b/2a)}{b} \sum_{i=4,3,2,1} \frac{\tanh(i/4,3,2,1)}{i^2} \right]
\]

where \( \mu \) is viscosity in (N.s/m²) and \( i \) must not be less than 51. There are a total of 128 channels, with 32 channels for each quadrant of the device. Taking advantage of symmetry, only 16 channels, that is one eighth of the total number of channels, is considered for this analytical calculation. The shortest channel (channel 1) of 4.5mm and the longest channel (channel 16) of 7.6mm. It should be noted that these channels are only 50μm in width unlike the rest of the channels that are 100μm in width. These two channels are therefore analysed as half size. For example, if an input pressure of 0.245 bar is applied to the centre aperture of the device, the dp/dx term in equation 1 would range from 5.44 × 10⁶ Pascal/m for the channel 1, to 3.22 × 10⁶ Pascal/m for the channel 16. The total volumetric flow rate for channel 1-16 is the 6.76 × 10⁶ m³/s. Assuming that the fluid has a density of 1.123 kg/m³ at the exit end, the mass flow rate (kg/s) for the channels 1-16 is then 7.6 × 10⁶ kg/s. Noting the one eighth symmetry, the total mass flow rate for the whole device with all 128 channels is then 6.076 × 10⁶ kg/s. By following the above method, the rest of the calculations for mass flow rate with different input pressures are then plotted. Results of the analytical calculation are then plotted in the results section.

5. Modelling and simulation of the device

Modelling and simulation of the micro-channels device is carried out using finite element analysis (FEA) software from ANSYS Inc. Figure 8 shows the complete process for the modelling and simulation of the device. The FEA analysis consists of 3 major steps: 1) model creation, 2) model simulation and 3) post-processing analysis. Model creation begins with the definition of element type, material properties and model parameters. Density and viscosity are defined as well as the material properties to be used for the simulation. Definition of model parameters includes dimensions of the device, width, length and thickness of the channels. The element used consists of fluid 142, that is normally used for 3-D thermal-fluid and pressure type of analysis problems. After definition of various parameters, the model of the micro-channel device is generated using the ANSYS macro commands. Material properties attributed to the model are then set. The meshing controls of the model is the next step to be considered. A suitable meshing density is utilised so that an accurate simulation analysis is achieved. The boundary conditions for the model are then defined. The input flow rate, which is the velocity of the fluid (m/s), is next applied to the centre aperture of the device. The output condition is set at the end of all 128 channels by the four sides of the device. Computational Fluid Dynamics (CFD) solving options within the ANSYS software, such as fluid properties, type of flow (laminar or turbulent) are set. For this simulation, the compressible fluid is nitrogen and the flow is considered laminar. With all the settings ready, the simulation for the model is then executed. Should there be errors, the CFD solving option, boundary condition settings and device parameters need to be checked again. Errors are then corrected and the
simulation is executed again. Once the results are considered to be meaningful, post-processing analysis of the model, data collection and verification are then carried out. Results are then discussed.

Figure 9: (a) Ansys pictorial results for pressure, (b) vector speed of the fluid

Figure 9 shows the pictorial simulated results of pressure and speed vector distribution on the microchannel device. Figure 9a indicates that the pressure distribution on the centre aperture of the device ranges from 0.18 to 0.23 bar for an input flow rate of 1.5625 m/s. Figure 9b shows the speed vector distribution with an input flow rate of 0.3125 m/s. This process of simulation is repeated for different steps of input flow rate, while the output pressure is noted. A graph of pressure against flow rate (m/s) is then plotted.

6. Results and discussion

Figure 10 presents the experimental, analytical and simulation results for the full working device. Two sets of results are presented. Set A presents the experimental and simulation curves of pressure (bar) against input flow rate (m/s) of the fluid that is applied to the input aperture. Set B consists of the experimental and analytical curves of the pressure (bar) against mass flow rate (kg/s). The analytical expression as described in equation 1 does not account for entry losses from the centre aperture into each of the micro-channels. The assumption of incompressible flow embedded in equation is also breaking down at high pressure values. Therefore caution must be observed when using the analytical expression above 0.3 bar.

7. Conclusion

A novel method of fabricating micro-channel cooling plate using the cost effective technique of UV-LIGA process has been demonstrated. Testing of the device have been successfully carried out using in-house built test rig. Modelling and simulation of the whole device have been carried out using the FEA method by using the ANSYS software. Good agreement were found for experimental and simulation results. More experiments need to be carried out to analyse the thermal performance of the microchannel cooling plate.

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