Technology of micromatrix posts applied to elimination of initial filling and Newton ring in a microcapillary pumped loop

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Abstract. A microcapillary pumped loop (MCPL) utilizing a two-phase heat transport has been investigated extensively because of its high heat transmission ability. Although the MCPL has been started up successfully, the initial amount of working liquid required to fill the system is so hard to control that the repeat operation of MCPL is not easy to initiate. In addition, the issue of Newton ring often occurs in the thermal bonding process of the chip and even causes the device to crack. An innovative method of micromatrix posts is proposed and confirmed by experiment for eliminating the initial filling and Newton's ring effectively. This proposed method will be useful in the operation of MCPL and all thermal bonding of microchips. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.JMM.12.3.033007]

1 Introduction

Semiconductor technology has continuously improved. The line width of an electronic chip has been reduced from 0.18 μm (1999) to 0.13 μm (2001), and the aim is to reduce it further to 16 nm. On the microscale level, good quality and low weight are important to consumers. Heat flux and heat density increase rapidly with the number of wires required and can seriously damage electronic devices.

The number and density of electronic components in VLSI chips are increasing rapidly in modern integrated circuits. The heat generated in these chips results in a high operating temperature, which, if not removed, degrades both the speed and the reliability of the devices.

The thermal stresses within a chip during its operation usually cause failure by fatigue of its mechanical devices or connections.[1] Various potential configurations should be considered in developing a microcooler. A microcooler may use a microscale phase change or single phase heat transfer, such as miniature heat pipes (HP), to remove heat from electronic packages.[2,3] Regardless of configuration, an effective microcooler must be able to fully control the movement of fluids throughout the system. The combination of microscale heat transfer and fluid dynamics along with high surface-to-volume ratios makes the development of an efficient microcooler a challenging endeavor.

The capillary pumped loop (CPL) is considered to be a reliable two-phase thermal management device, adopted mainly for the thermal control of satellites and structures. It operates passively by means of capillary forces that are generated in a porous structure situated in evaporation, which is responsible for driving a working fluid from a high-temperature source to a low-temperature sink. CPLs are part of a subject that has gained attention in the field of research into capillary-driven two-phase loops, including HP and loop heat pipes.

The CPL was first proposed by Stenger[4] and received increased attention in the late 1970s. During that decade, intensive study on the CPL proved it to be operationally reliable for thermal control and able to transport heat over a long distance with a small temperature change. Kirshberg et al.[5] were the first to present the conceptual design and fabrication of a micro-CPL, providing an initial schematic design of a completely passive three-port micro-CPL.

Great advances have been achieved in CPL setups, most related to the porous structures in the capillary evaporator. Different materials have been applied as porous wicks, including sintered nickel, stainless steel, titanium, and polyethylene, with ultrahigh molecular weight.[6–8] As the generation of capillary forces depends on the surface tension of the working fluid and size of the wick pore, CPLs have been investigated by using methanol, acetone, and anhydrous ammonia as working fluids. Various experiments using sintered nickel components with fine pore sizes have been performed.[9,10] Small pore sizes have been produced in

the manufacturing of wick structures from sintered metal components.[9] Microcapillary pumped loop systems (MCPLs) have recently undergone extensive investigation because of their importance to heat transfer. Many potential configurations and numerous challenges related to transitioning MEMS technologies have been examined to develop a microcooler. It is well known that under suitable laminar flow condition, flow pass bluff bodies give rise to hydrodynamic instabilities.[11] These flow-driven instabilities generate periodic wake behind the bluff that lead to the formation of the von Karman vortex street. Such microscale posts have recently been implemented experimentally for enhanced chemical reactivity[12,13] and for flow uniformity.[14] However, the initial filling of an MCPL cannot be easily controlled and results are very difficult to repeat. In addition, the phenomenon of Newton's ring often occurs in the thermal bonding process and even causes the device to crack, but these issues are rarely noted, even though it significantly affects experiment results. In this study, a useful method of micromatrix post will be applied to deal with the aforementioned issues.

2 Fabrication Issues and Design of Micromatrix Post

In this study, the main topic will be focused on addressing the application of using micromatrix posts to eliminate the issue of Newton's ring and solving the problem of initial filling in all microflow chips, especially for MCPL. Here, the MCPL would be just acting as a platform for addressing the technology of micromatrix post applied to elimination of initial filling and Newton's ring. Of the main elements of MCPLs, four elements, including evaporator, vapor line, condenser, and liquid line, would be utilized and different from previous CPLs that are used in macroscale/miniature devices. The startup of the first MCPL was successfully carried out by the authors.[15] However, control of the initial filling and uniform distribution in MCPL (excluding the vapor line) is key and difficult to execute for the operation of the system. Another serious problem is the Newton's ring that drastically affects the fabrication of microchip, especially for MCPL. Therefore, the geometric design of MCPL will need to be revised and previous problems will also need to be solved through the use of a new method in this study. Concerning the practical operation of the initial filling in MCPL, a flow uniform distribution required would be difficult to control. The geometric design of MCPL will be revised and the Newton's ring often occurs in the thermal bonding process of chip, even causing device cracking. Therefore, a useful approach of micromatrix posts applied will be addressed and verified in this study.

2.1 Design of Micromatrix Post in Evaporator

The evaporator is the most important element of MCPL because it fundamentally affects the velocity of flow and heat transmission because the two-phase bubbles with high latent heat generated in groove structures would be acting as a driving force of flow transmission by the capillary force in MCPL. Therefore, the geometric structure of the evaporator is scaled down to fulfill the requirements of a heat transfer system for electronic devices. The area of the hot spot used to imitate the heat source is also limited. The contour dimensions of the miniaturized evaporator are 7.2 mm × 4.0 mm,
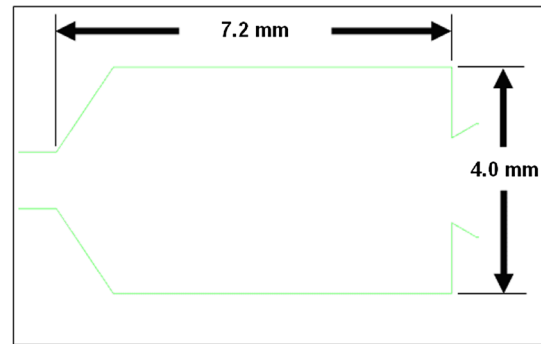

Fig. 1 The contour dimensions of evaporator.

as displayed in Fig. 1. The type of groove structure shown in Fig. 2 is parallel with a length of 5.6 mm and width of 40 μm and depth of 40 μm, respectively. As for fabrication of MCPL, it was fabricated by using the standard MEMS technology. Two pieces of glass, Pyrex 7740, each measuring 76 mm × 26 mm with a thickness of 1 mm, were utilized as the substrate and applied to the design of micromatrix posts at the inlet region of evaporator (see Fig. 2) and outside region of MCPL system (see Fig. 3) for solving the issues of initial filling and Newton's ring, respectively. Although the MCPL has been started up successfully,[16] the initial amount of working liquid required to fill the system is so hard to control that the repeat operation of MCPL is not easy to initiate.

The new design of the evaporator differs from that of first-generation evaporators. A useful method based on micromatrix posts with dimensions of 40 μm × 40 μm for each port shown in Fig. 2 was embedded in the inlet region of evaporator and utilized to solve the problems of initial filling and Newton rings. Experimental results validating the use of micromatrix posts are as follows.

2.2 Design of Condenser

The condenser condenses the vapor coming from the evaporator and transfers heat to the surroundings. A condenser with a rectangular area measuring 7.2 mm by 4.0 mm is used in the study. Groove structures used in the condenser region provide enough time and space to condense the vapor
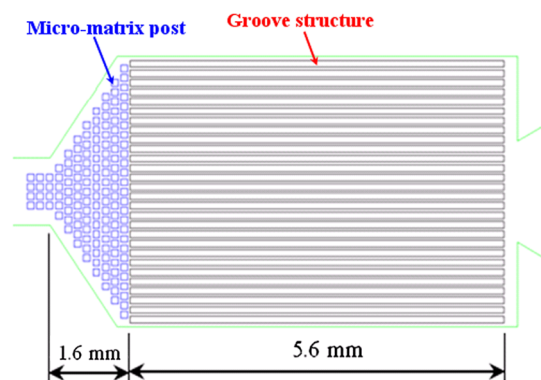

Fig. 2 Parallel structure of groove and micromatrix posts in evaporator.
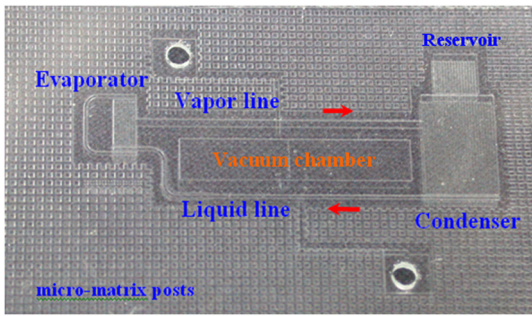
Fig. 3 A sketch of MCPL and microstructure image after fabrication of MEMS technology.

coming from the vapor line, which then changes into the state of subliquid in the outlet of condenser.

2.3 *Design of Vapor Line/Liquid Line*

The vapor line and liquid line are applied to connect the evaporator and condenser. The key elements of the design are the internal diameter of the connector, length of line, and the height between the vapor line and liquid line. The internal diameter of the vapor line must be larger than that of the liquid line to ensure that enough heat is transferred from the vapor originating from the evaporator. The position of the outlet of the vapor line must be higher than that of the inlet of the liquid line to eliminate backflow by exploiting gravity force. Based on all of these considerations, the dimensions of the liquid line are set to 28 mm × 1000 μm, and those of the vapor line are set to 74 mm × 2000 μm.

2.4 *Fabrication Process of Micromatrix Post and Issue of Newton's Ring in MCPL*

This work utilized MEMS technology, comprised primarily of lithography, wet etching, and thermal bonding. Fused silica glass, whose thermal conduction coefficient is $K = 1.4$ W/m · K at $T = 300$ K, was used as the substrate because it has a low coefficient. The dimensions of the substrate are 76 mm × 32 mm × 1.1 mm, and elements of MCPL are shown in Fig. 3. However, the issue of Newton's whose phenomena in which an interference pattern is created by the reflection of light between a spherical surface and an adjacent flat surface often occurs in the thermal bonding process of chip and even causes the device to crack. Here, a clean surface of glass tested is a very important requirement for thermal bonding within the wet etching process for chips because organic residue and particles prevent close contact of the glass, resulting in air gaps, which are indicated by interference fringes (Newton's rings). The appearance of stress concentration originating from Newton's ring will make the chip crack seriously and needs to be solved by using a matrix post in this study before thermal bonding of the chip, especially for MCPL. Therefore, micromatrix posts were built throughout the region, excluding the MCPL area, to address the appearance of Newton rings because they often occur in the bonding process and can even cause the device to crack. Here, the vacuum chamber will be fabricated for eliminating the heat conduction by way of a solid substrate and decreasing the inaccuracy of the MCPL heat
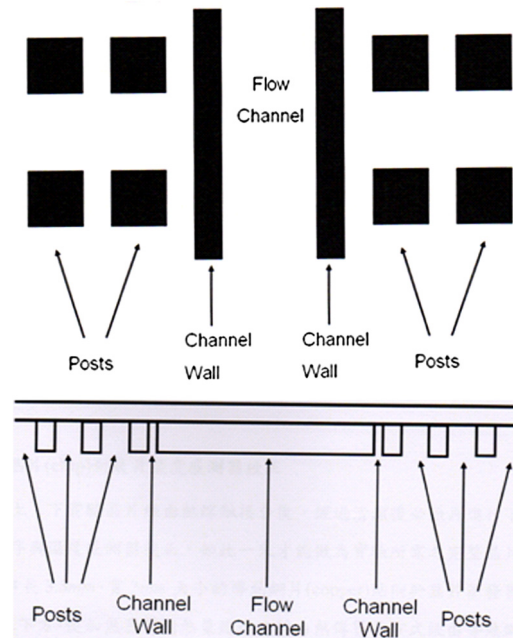

Fig. 4 A layout of micromatrix post and flow channel in MCPL (upper: top view; bottom: side view).

transmission. Figure 4 shows the layout of micromatrix posts in MCPL.

3 Experimental Verification

Comparing the experimental verification of micromatrix posts, Fig. 5 reveals that the Newton ring resulting from the residual stress is formed and can be clearly observed on the chip that is bonded without micromatrix posts, but is absent on the chip, as shown in Fig. 3, when the micromatrix posts are used and embedded in the outside region of MCPL device. These evidences show that the residual stress could be eliminated by using a micromatrix post and were confirmed by finite element analysis, ANSYS 5.7 (results not shown).

In addition, Fig. 6 shows a nonuniformity of velocity distribution indicated by the arrow at the cross-section AB during the initial filling and without micromatrix posts. The results in Fig. 7 demonstrate that the parallel form performed superbly in terms of uniform distribution of the initial filling and controlled effectively using the micromatrix posts. These findings based on micromatrix posts will be useful for elimination of initial filling and Newton's ring in all microfluid devices, especially for MCPL.
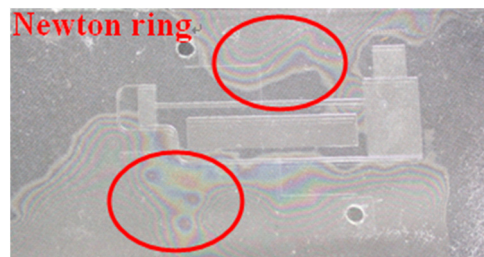

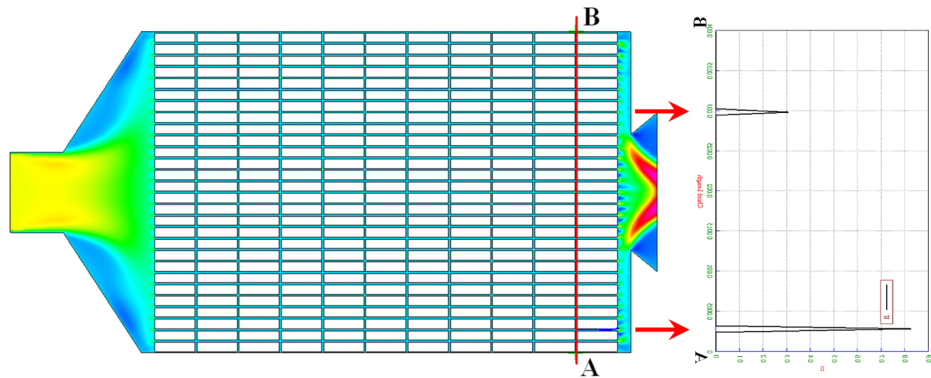**Fig. 5** Photograph of MCPL chip without using the micromatrix posts.

Fig. 6 Numerical velocity distribution in evaporator region without micromatrix post structures was executed at Re = 100.
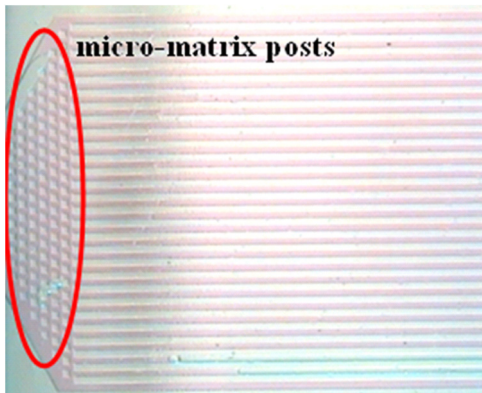

Fig. 7 Photograph of initial filling for parallel form in evaporator region.

4 Conclusions

This study presents a useful method for an MCPL, whose effectiveness in solving the problem of controlling the initial filling and Newton's ring was rectified by using micromatrix posts. The experimental verification indicated that the method of micromatrix posts is excellent at solving the problem of Newton's ring and offers outstanding control of the initial filling. This newly proposed method is very useful for eliminating Newton's ring during the thermal bonding process of microchip and the initial filling operation of MCPLs.

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