

NONINVASIVE HERMETIC SEALING OF DEGASSED LIQUID INSIDE A MICROFLUIDIC DEVICE BASED ON INDUCTION HEATING

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Abstract: A noninvasive hermetic sealing approach has been introduced for the high-temperature degassing and liquid filling of a microfluidic electronics-cooling device. This approach involves melting, using induction heating, a donut-shaped preformed solder ball around the device fill-hole, which lies inside a nonmagnetic liquid-filling cavity. Inductively heated soldering experiments were performed to seal fill-hole prototypes, which were etched into a silicon substrate using TMAH wet etching. This helped to verify the efficacy of the sealing approach and characterize the induction heating parameters. Results indicated that an optimum solder mass ensures a wide enough induction-heating time window for successful sealing of both dry and wet fill-holes.

Keywords: hermetic sealing, packaging, solder, induction heating, micro loop heat pipe, electronics cooling

INTRODUCTION

Thermal management has emerged as a major challenge for the electronics industry in recent years. Due to an increase in the number of transistors per chip [1] and the miniaturization of electronic packaging modules [2], it is becoming increasingly difficult to get rid of the electronic waste heat. Conventional thermal management solutions such as conduction and convection, which provide relatively low thermal conductivities and convection coefficients respectively, can no longer keep the electronic junction temperatures within safe operating limits. A number of high-heat-flux cooling technologies such as heat pipes, microchannel heat sinks, jet-impingement, and spray cooling are being investigated. Heat pipes are already being used in laptops for cooling microprocessors.

Heat pipes, loop heat pipes, and capillary pumped loops belong to a class of capillary force-driven, passive, high-heat-flux, phase change cooling systems. Heat is transferred from the heat source to a colder heat sink by the evaporation and condensation, respectively, of the working fluid hermetically sealed inside the device. No external pumping power is required to maintain the two-phase flow loop, which is aided by surface tension-based capillary forces in the device wicking structure. Conventional loop heat pipes, which provide improved performance over heat pipes [3, 4], are bulky systems that are ill-suited for integration with planar, densely packed modern electronic substrates. In complementary efforts [5, 6], we are working to develop a silicon wafer-based planar MEMS loop heat pipe for direct integration with hot electronic substrates [7–12].

PROBLEM STATEMENT

Fig. 1(a) shows a micro loop heat pipe (mLHP) prototype that was fabricated in silicon and Pyrex wafers,

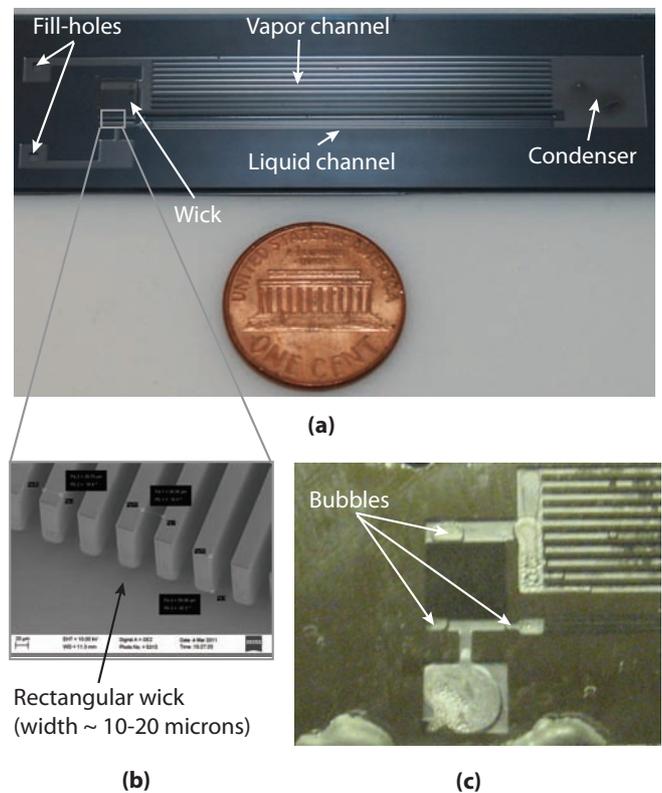


Fig. 1: Problems due to air bubbles in a two-phase microfluidic electronics cooling device: (a) The micro loop heat pipe (mLHP); (b) Narrow rectangular channels in the mLHP wick; (c) Air bubbles cause blockage in the flow loop leading to device failure.

using standard MEMS microfabrication techniques [8]. To make the device operational, it has to be filled with a working fluid. A key requirement is that the working fluid should be completely degassed as the presence of any non-condensable gases (NCGs) in the working fluid can lead to blockages in the flow loop, leading to device failure. The NCG bubbles can block the flow of liquid in

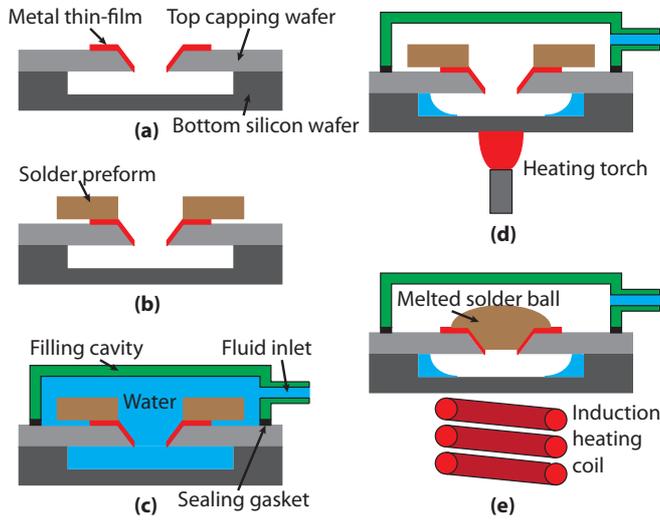


Fig. 2: A hermetic sealing approach for the high-temperature degassing and fluid-filling of the mLHP: (a) Pattern metal thin-film; (b) Place preformed solder ball; (c) Attach gasket-sealed filling-cavity, and degas and fill the device with water; (d) Boil off water from the vicinity of the fill-hole; (e) Inductively melt the solder to seal the hole.

the narrow channels of the wicking structure (Fig. 1(b)) or in the transport channels (Fig. 1(c)).

Degassing and temporary fluid-filling of the mLHP device, using a two-port thermal-flux-based system, has previously been successfully demonstrated [8, 11]. In this approach, the mLHP fill-holes (see Fig. 1(a)) are connected using metal tubing to an external heated fluid reservoir. One of the key remaining challenges is to develop a compatible process for hermetically sealing this degassed liquid inside the mLHP device. This will allow for the decoupling of the filling system from the filled device, and make it possible for the standalone device to be deployed inside electronic substrates.

MATERIALS AND METHODS

Noninvasive Hermetic Sealing Process

The mLHP hermetic sealing approach has to be non-invasive in order for it to be compatible with the thermal-flux filling system. *Induction heating* is one of the few available techniques that allow noninvasive localized energy transfer to the point of application.

Fig. 2 shows an approach, based on induction heating, to hermetically seal degassed water inside the mLHP device after the completion of the degassing and filling process. A metal thin-film is first patterned around the device fill-holes to act as a wetting agent for the solder bond (Fig. 2(a)). A donut-shaped preformed solder piece is then placed around the fill-hole and heated just enough to attach it to the metal film (Fig. 2(b)); The working concept is to provide a hole through the solder for the incoming fluid. A gasket-sealed filling-cavity, connected to the external filling

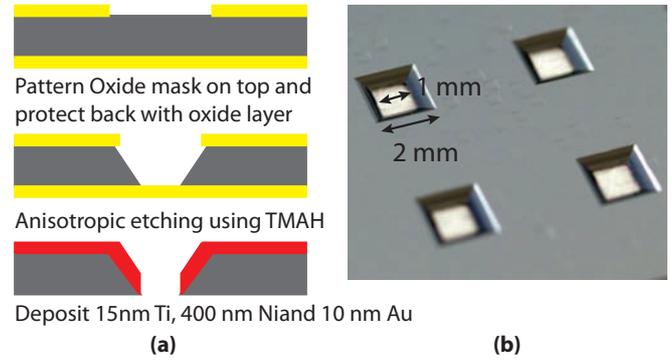


Fig. 3: Fabrication of holes in a silicon wafer for testing the inductive-soldering approach: (a) Fabrication process flow; (b) Wet-etched holes.

setup, is placed around the fill-hole, and the device is degassed and filled with water (Fig. 2(c)). After the filling process is complete, a heating torch is used to boil off the water from the vicinity of the fill-holes (Fig. 2(d)). An induction heating coil, placed under the fill hole, is used to generate eddy currents inside the patterned magnetic thin-film. This heats up the adjacent solder, which melts onto the metal thin-film thus sealing the fill-hole.

Fill-hole Prototype Fabrication

In order to test the inductive sealing process, $1\text{mm} \times 1\text{mm}$ pyramidal fill-hole samples were fabricated on a silicon wafer. Fig. 3(a) shows the fabrication process flow.

A $2\ \mu\text{m}$ thick silicon oxide layer was first deposited on both sides of the $\langle 100 \rangle$ silicon wafer using low pressure chemical vapor deposition (LPCVD). The top oxide was patterned using a photoresist mask and plasma dry etching. Using this oxide layer as an etch mask, the silicon wafer was wet-etched using TMAH; The backside oxide protected the other side of the wafer. The following metals were then deposited using e-beam evaporation to form an adhesion layer for the solder preform: $15\ \text{nm}$ Ti, $400\ \text{nm}$ Ni, and $10\ \text{nm}$ Au. Titanium provides an adhesion layer to the silicon substrate and the magnetic properties of the thicker nickel layer improve localized induction heating in the direct vicinity of the filling port. The thin gold layer provides an oxidation barrier for the nickel and readily dissolves into the solder upon bonding. Fig. 3(b) shows the fabricated fill-hole samples, which were subsequently diced for experiments.

Induction Heating Experimental Setup

Experiments were performed to seal the fill-hole samples by inductively melting donut-shaped solder pieces. Fig. 4(a) shows the induction heating assembly: It consists of an internally-water-cooled hollow metal coil connected to a high voltage $11.7\ \text{MHz}$ AC power source. The time-varying magnetic field generated in-

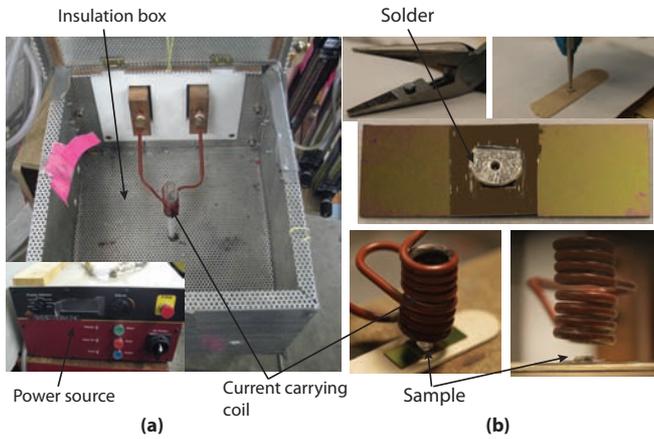


Fig. 4: Experimental setup for implementing inductively-heated solder-sealing of holes in a silicon substrate. (a) Induction heating apparatus. (b) Solder-on-hole sample preparation.

side the coil heats magnetic materials placed next to the coil by inducing eddy currents in them. The magnetic coil is placed inside a metal insulation box for protection against the high-energy fields generated by it.

Fig. 4(b) details the method for preparing the solder-on-hole test sample. A small solder piece, manually shaped into a donut and applied with some solder flux, is placed around the fill-hole on the test sample. This sample is then placed, using a wooden holder, under the induction heating coil for heating.

RESULTS

Solder-sealing experiments were conducted on a number of test samples, using different preformed solder masses and induction heating times. Fig. 5 shows the test samples before heating and the front/back of these samples after induction heating. It also gives the mass of the solder piece used, the induction heating time, and the power setting on the induction heater for each case.

A lead-free silver bearing solder ($Sn_{96}Ag_4$), with a melting point of $221\text{ }^{\circ}C$, was employed for the experiments. The power to the induction-heating coil was kept constant at 400 W , an optimum value for melting the solder in a controlled manner. When no solder flux was used, very little spreading of the solder was observed even after a long heating time (Fig. 5(a)). Further, the hole was not sealed and the solder ball came off the sample with a small applied force. For the rest of the cases, a water-soluble paste flux was employed. Using a solder mass of 0.06 g and a heating time of 2.9 sec , the hole was found to seal properly (Fig. 5(b)); However, heating a similar sample (0.09 g) for just 0.4 sec more resulted in the solder spreading away from the hole (Fig. 5(c)).

A wider allowable heating time-window was obtained with the use of a larger initial solder mass (0.16 g). In Fig. 5(d), the solder was heated just long enough (3.7 sec) for the solder ball to form, which yielded an

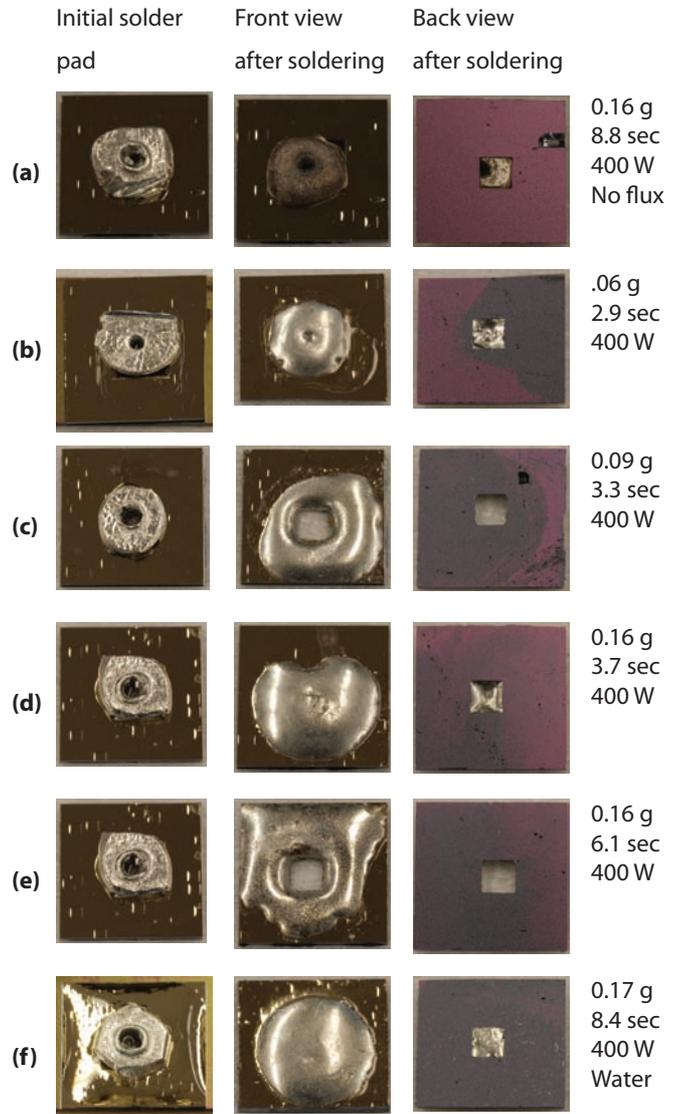


Fig. 5: Experimental results demonstrating inductively-heated solder sealing of holes. The key parameters are the initial mass of the solder preform and the induction heating time. (a) Soldering without flux is unsuccessful (b-c) Low solder mass can be unstable (d-e) Larger (optimum) solder mass ensures good sealing in a wider time window (f) Soldering in water is successful.

excellent seal. A similar sample (Fig. 5(e)) was again heated—this time for a time (6.1 sec) long enough to make the solder spread away from the hole. Comparing the two heating times, we see that by using a larger solder mass a larger heating time-window of 2.4 sec was achieved, during which the solder melted but did not spread away from the hole. Induction heating of the solder was also carried out in the presence of some water on the fill-hole sample (Fig. 5(f)). Although it took a larger heating time, successful sealing of the fill-hole was demonstrated.

DISCUSSION

The above results verify the efficacy of the induction heating approach for sealing a mLHP device fill-

hole. Under the right circumstances, the solder material melts, by absorbing heat from the magnetic thin-film, to completely cover the fill-hole. However, if we continue to heat it further, the molten solder spreads out further away from the hole, thereby leaving it exposed and unsealed. This happens because of the fact that the metal thin-film acts as a hydrophilic surface for the molten solder, and the free energy of the system is reduced as more of it is wetted.

This leads to the conclusion that time is an important factor in this process. As soon as the solder melts, the hole in the donut-shaped solder closes very quickly due to its inherent surface tension. The fill-hole gets exposed as the meniscus of the molten solder starts traveling outwards, thereby sucking out the solder from above the hole, which does not provide a favorable wetting surface unlike the rest of the sample. Given that the meniscus travels with a finite speed, using a larger initial solder mass provides a larger solder mass above the hole, thereby increasing the time it takes for the hole to get exposed.

Sealing a wet fill-hole takes a longer time due to the fact that energy is expended in evaporating the water before the solder (with a melting point much higher than 100 °C) actually melts.

CONCLUSIONS

A noninvasive induction heating-based approach was introduced for the purpose of hermetically sealing degassed liquid inside a microfluidic electronics cooling device. Inductively-heated soldering experiments conducted on fill-hole samples demonstrated the efficacy of this approach; Using an optimum initial solder mass, inductive heating of the sample within a given time window lead to a complete sealing of the fill-hole. Successful sealing of the fill-hole in the presence of water was also demonstrated. This noninvasive sealing technique will enable the hermetic filling of a wide range of microfluidic devices where the presence of non-condensable gases is a concern.

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REFERENCES

- [1] Krishnan S, Garimella S V, Chrysler G M, Mahajan R V 2007 Towards a thermal Moore's law *IEEE Transactions on Advanced Packaging* **30** 462–474
- [2] Faulkner D, Khotan M, Shekarriz R 2004 Managing electronics thermal management *Heat Transfer Engineering* **25** 1–4
- [3] Feldman Jr K, Noreen D 1980 Design of heat

pipe cooled laser mirrors with an inverted meniscus evaporator wick. *AIAA Paper*

- [4] Liepmann D 2001 Design and fabrication of a micro-CPL for chip-level cooling *American Society of Mechanical Engineers, Heat Transfer Division, (Publication) HTD* New York, NY, United states vol. 369 51 – 54
- [5] Kirshberg J, Liepmann D, Yerkes K L 1999 Micro-cooler for chip-level temperature control *Aerospace Power Systems Conference* SAE International, Mesa, Arizona SAE Technical Paper Series
- [6] Kirshberg J, Yerkes K L, Liepmann D 2000 Demonstration of a micro-cpl based on mems fabrication technologies *Proceedings of the Intersociety Energy Conversion Engineering Conference* Las Vegas, NA, USA vol. 2 1198 – 1204
- [7] Dhillon N S, Pisano A P, Hogue C, Hopcroft M A 2008 MLHP: A high heat flux localized cooling technology for electronic substrates *ASME Conference Proceedings* **2008** 621–630
- [8] Dhillon N S, Hogue C, Hopcroft M A, Pisano A P 2010 Geometric control of the fluid-transport meniscus in a passive phase-change microfluidic electronics cooling device *Proceedings of Power MEMS* Leuven, Belgium 15–18
- [9] Dhillon N S, Hogue C, Chan M W, Cheng J C, Pisano A P 2011 Integrating coherent porous silicon as a wicking structure in the mems based fabrication of a vertically wicking micro-columnated loop heat pipe *Proceedings of ASME International Mechanical Engineering Congress and Exposition* Denver, CO, United States
- [10] Dhillon N S, Cheng J C, Pisano A P 2011 Minimizing the wick thickness in a planar microscale loop heat pipe using efficient thermodynamic design *Proceedings of ASME International Mechanical Engineering Congress and Exposition* Denver, CO, United States
- [11] Dhillon N S, Cheng J C, Pisano A P 2011 Device packaging techniques for implementing a novel thermal flux method for fluid degassing and charging of a planar microscale loop heat pipe *Proceedings of ASME International Mechanical Engineering Congress and Exposition* Denver, CO, United States
- [12] Dhillon N S, Cheng J C, Pisano A P 2011 Heat transfer due to microscale thin film evaporation from the steady state meniscus in a coherent porous silicon based micro-columnated wicking structure *Proceedings of ASME International Mechanical Engineering Congress and Exposition* Denver, CO, United States