Solder Jet Printhead for Deposition of Molten Metal Drops

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Abstract

We have developed a drop-on-demand printhead that can eject molten metal droplets. The capability to eject solder drops on an X-Y stage controlled substrate makes this new technology ideal for fast prototyping of metallic traces on planar and 3-D objects. The ejection of the conducting droplets is accomplished by the electromagnetic expulsion between two opposite flowing currents. One current path flows through the molten metal such as solder, the other through a copper stripe. The electrical connection between the two conductors was accomplished by two Ni plated vias. The expulsion force experienced between the two conductors causes the solder to squirt out of a nozzle. The size of the ejected solder drop depends on the driving energy, which was controlled by both the pulse width and the drive voltage. For successful operation of the printhead, wettability of the solder to the printhead material needs to be taken into consideration. We have constructed the solder jet printhead in both a polyimide laminates and a ceramic form that can withstand a much high temperature than the polyimide. We have ejected molten PbSn eutectic solder as well as BiSn and InSn with precision on Si wafers, over substrates with different height and connecting the traces on different levels, as well as creating free standing 3-D structures.

Introduction

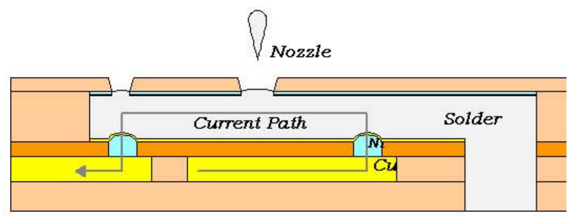
As the circuit becomes increasingly smaller in size, the requirement for interconnection has become progressively more challenging. There have been several developments for fluxless soldering of microelectronic applications using drop-on-demand jetting of small solder droplets formed by piezoelectric transducer element[1], magnetohydrodynamic force between a current flowing in between the poles of two permanent magnets[2,3], or ultrasonic generator to create ultrasonic vibrations near a nozzle[4]. In a digital fabrication of functional materials, the need to place metal trace at will without the need of a photolithography process make it highly desirable to jet metal droplets in a digital fashion.

The Marking Technology Department in HP Labs has developed a drop-on-demand printhead that can eject molten metal droplets. The capability to eject solder drops on an X-Y stage controlled substrates makes this new technology ideal for fast prototyping as well as novel bumping on 3-D objects. The self-align capability of solder reflowing process also makes it ideal for precision assembly of micro-mechanical components. This paper also describes the micro-fabrication technique used to manufacture the solder jet printhead. This same technique can be applied to other 3-D structures that require fluid channels as well as electrical connections, such as chemical sensors.

Operation Principle

The ejection of the conducting droplets is accomplished by the mutual electromagnetic repulsion between two conductors carrying opposing currents. As shown in the figure 1 below in one of the implementation, one of the current paths flows through the molten solder, the other through a copper stripe underneath. The two conductors are separated by a Kapton flex circuit, and the electrical connection between the two conductors is accomplished by two Ni plated vias. The repulsion force experienced between the two conductors with opposite current flow directions forces the liquid solder out of a nozzle, very similar to a thermal ink jet printing device.

***Figure 1**. Operation of a solderjet printhead. In actual operation, the printhead is flipped so the droplet is ejected down.*



The direction and magnitude of the repulsive force is related to the cross product of an electric current vector and a magnetic field vector(F = I x B). For parallel conductor, the expulsion force can be estimated by a simple equation:

$$f = \mu_o I^2 / 2\pi D, \quad \text{where} \qquad (1)$$

f = force per unit conductor length
D = separation between solder and copper conductor

Printhead Fabrication

There are several possible configurations as well as materials sets for a solder jetting device. One implementation of the solder jet printhead is composed of polyimide laminates and a Cu flex circuit. Figure 2 shows a cross-sectional view of a solderjet printhead. A cavity for solder channel is built on top of a flex circuit with copper traces on the back side and pairs of Ni plated vias on its front side. The solder channel is constructed by stacking up Kapton KJ/E layers. These polyimide layers are micro-machined by laser ablation with µm precision.

These layers of Kapton KJ/E and the Cu flex circuit are bonded together by hot lamination using Kapton KJ as an adhesive. Kapton KJ is a thermoplastic adhesive film with most its physical properties comparable to other polyimide films. It has been shown to bond to a variety of metallic and non-metallic substrates. Bonding is typically done at 350 °C and 3.4 MPa.

The height of the solder channel can be easily changed by varying the number of KJ/E layers, while the width of the channel can be changed by altering the software program for the laser ablation process. The size of the nozzle can also be changed by changing the aperture during laser ablation. This approach of polyimide/ablation allows us to quickly change dimensions of the solder jet printhead and greatly shortened the development cycles.

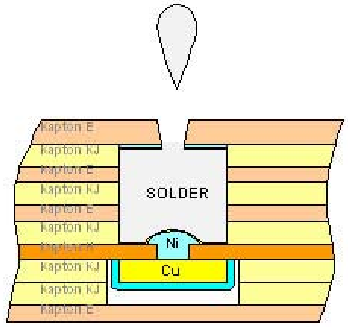


***Figure 2**. Cross-section view of solderjet laminates*

To ensure that the precision alignment between these layers is maintained during lamination, two alignment holes are precision drilled by laser ablation in each layer. Figure 3 shows an exploded view of each layer for a typical solderjet printhead. The left alignment holes are slightly undersized(~10 µm) for the alignment pin on the lamination fixture. The right alignment holes, on the other hand, are oversized in the x-direction to accommodate for any possible machining errors in the lamination fixture.

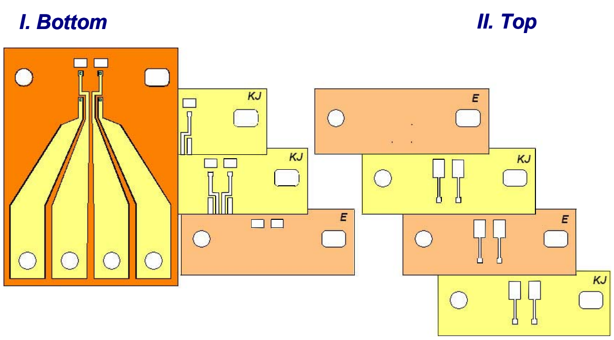


***Figure 3**. Exploded view of a solderjet printhead*

The presence of a cavity on top of the flex requires the lamination be done in two steps. The bottom part is laminated first with the flex, two KJ, and one E layers. Cutout in the bottom KJ is designed to accommodate for the thickness of the copper trace. After the bottom lamination, the top layers are fitted over the alignment pins for the second lamination. The top layers have a cutout for the solder channel. All the layers except for the top nozzle plate have two small rectangular holes for the solder to flow from the back of the printhead into the solder channel.

Metallurgical compatibility of the laminated polyimide has been continuously tested by immersing in a molten SnPb solder pot at 220 ^{o}C. No sign of any material degradation or delamination was observed for well over six months.

The flex circuit printhead is mounted on an aluminum pen body as shown in Figure 4. The backside of the solder jet printhead is attached to a solder reservoir. Solder is fed into the printhead by gravity. For successful operation of the printhead, wettability of the solder to the printhead material needs to be taken into consideration. Au and Ni thin film are sputtered deposited onto the polyimide components to assist the flow of solder in the solder channels during the initial priming of the printhead. As solder gradually fills the solder channel, the air inside is pushed out through the vent hole at the end of the solder channel. The location and the size of the vent holes are designed so that no solder will come out from the vent holes during operation.

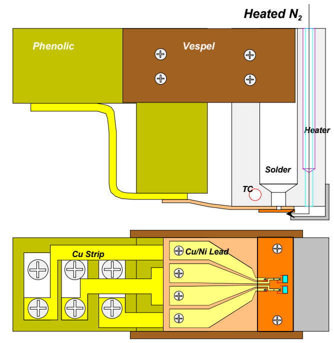


***Figure 4**. Pen body for solder jet printhead*

No active backpressure control is implemented in the printhead. Typically in an ink jet printing device such as an HP DeskJet print cartridge, a negative back pressure is required to hold back the meniscus. Otherwise the ink will drool out continuously from the nozzles. In the design of the solderjet printhead, the nozzle is shaped like an inverted funnel(Figure 2), opposite to a typical thermal ink jet printhead. The meniscus stays at the bottom of the inverted funnel. During the ejection, the high surface tension of the molten solder will pull the extended meniscus back to the bottom where the diameter is the smallest to minimize its surface energy.

Solder oxides and impurities can clog the printhead if they enter the solder channel or form in the nozzle. To prevent this, two steps were taken in more recent implementations. First, the reservoir was filled with a solder slug, which was pre-formed in a flowing N_2 atmosphere. Second, the printhead assembly and the substrate were placed inside a box with flowing N_2 gas before the aluminum pen body is heated to melt the solder. Although the box is partially open to allow for microscopic observation of the jetting process, the flowing N_2 reduces the oxygen concentration sufficiently to prevent noticeable oxidation at the nozzle. With a short working distance of < 5 mm, the N_2 also helps prevent oxidation of the solder droplets during flight before they solidify.

In the present implementation, there are two solder channels with one nozzle each in a printhead. It is possible to design more than two solder channel in a printhead. It is also possible to design multiple nozzles within one solder channel.

Experimental Results

Successful ejection of PbSn eutectic solder drops has been demonstrated. The size of the ejected solder drops depends on the driving energy which was controlled by both the pulse width and the drive voltage, as shown in Figure 5. The solder droplets were deposited on a Au/Ni coated Mylar sheet in 5 x 5 array patterns. The average diameters of deposited solder drops were plotted. The wettable surface resulted in a flattened solder bumps with dimples in the middle of each bump. Some solder drops were also ejected into water which resulted in spherical solder balls. A 200 µm diameter solder bump on a Au/Ni coated Mylar sheet roughly corresponds to a 120 µm diameter solder ball. Bump diameters increased with increasing applied voltages and pulse widths.

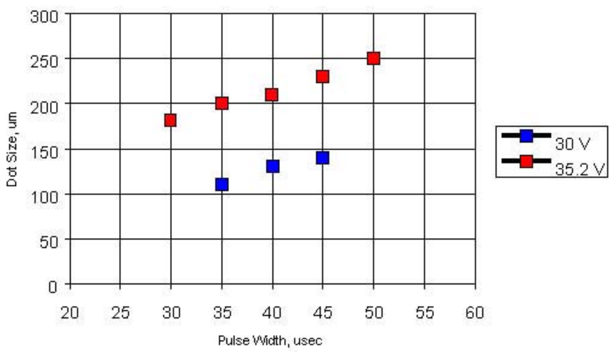


Figure 5*. Effect of pulse width and voltage on drop size*

Both the drive voltage and the pulse width vary with the energy delivered to the printhead Figure 6 shows a summary of the total energy for all the experiments conducted on the same printhead(same color) for two printheads with different nozzle sizes, one 100 µm and the other 50 µm. For the same printhead all data points fall roughly in a continuous curve.

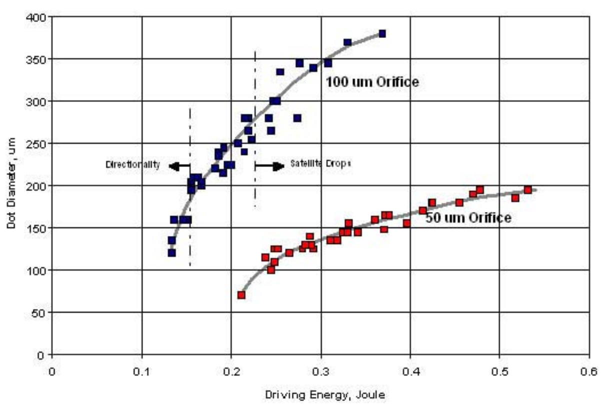


Figure 6. Effect of driving energy on drop sizes

Typically there is an optimal operating conditions for a given printhead. Operation with energies above that range will result in satellites. On the other hand, operation under the optimal range produces an under energy droplet and results in directionality problem. As expected, a smaller nozzle produced smaller solder drops.

However, contrary to what may be expected from intuition, a smaller nozzle requires a substantially higher energy than a large nozzle to eject solder. The turn-on energy of a 50 µm nozzle is almost double the turn-on energy of a 100 µm nozzle. The increase in drop size per unit energy for a smaller nozzle is also shallower than a larger nozzle.

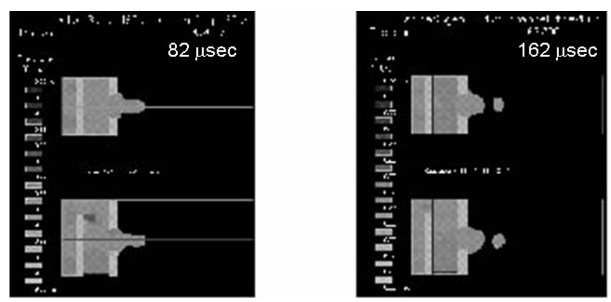
Discussion

Extremely stable operation has been observed in some cases. We have been able to pile up several hundred solder drops into one single long straight column while printing at a working distance of 2 cm, with succeeding droplets just landing directly on top of the preceding ones. But, significant directionality variation has been observed with other printheads.

The lessons we learned so far indicated that we need to pay attention to priming and servicing of the printhead for reliable operation. The placement accuracy can also be improved by reducing the working distance.

A finite difference fluid model has been employed to characterize the architecture of the solder jet printhead, as well as strobe investigation of how solder drops formed. One major difference between solderjet and HP's highly successful thermal ink jet is the high surface tension of the eutectic PbSn solder. As the solder is being pushed out of the nozzle, the high surface tension affects how the solder column narrows down its tail, how the tail snaps, and how the satellite drops may form. Figure 7 shows one of the modeling results in two cross-sectional views.

Figure 7 Finite difference modeling of solder jet ejection



The surface tension also dominates the energy required to push solder out of the nozzle. It is interesting to note that in thermal ink jet printing, a smaller nozzle requires smaller resistors to print. Less energy is needed to push aqueous ink out of smaller nozzle. Figure 6, on the other hand, indicated that higher energy is required to push solder out of smaller nozzles.

The high surface tension also dictates that the wetting characteristics of the printhead should be designed to facilitate the priming the solder into solder channel. Without a wettable coating, or if the coating is contaminated, the molten solder would not be able to migrate down the solder channel in the printhead.

Figure 8 shows some of the examples of applications enabled by the stable operation of the solderjet printhead. The optical micrograph on the left is a 3-D ring with a 2 mm diameter. The ring was built up from successive solder drops landing on top of each other while moving the substrate table in a circular motion. The micrograph on the right shows the direct writing of conductive traces between bonding pads of two chips separated by a 350 µm step between two chips.

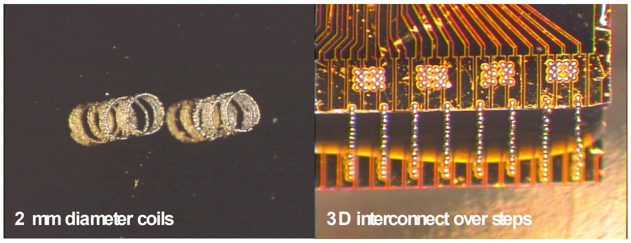


Figure 8 Examples of solderjet applications

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Author Biography

Alfred Pan received his Ph.D. in Materials Engineering from the University of Illinois at Urbana-Champaign and M.S. in Material Science from Syracuse University. He has been involved with thermal ink jet printing and other non-impact printing technologies since joining HP Labs in 1984. Previously he worked in the R&D in IC processing technology in Philips Research Lab. His interests in HP Labs have also been in the emerging technologies including direct methanol fuel cell power sources for portable devices and printable semiconductors using nanotechnology. He was the Program Chair for Americas for NIP 19 in 2003. He holds 41 US patents.

Eric G. Hanson received his undergraduate and graduate degrees in Physics from the University of California at Berkeley. After his Ph.D. in 1976, he joined HP Labs where he started in optical fiber fabrication and optical switching components. Since 1984 he has managed a research team investigating advanced non-impact printing. He is currently manager of the Marking Technology Department of the Digital Printing and Imaging Laboratory. His primary focus is on technology advances to enable higher performance liquid electrophotographic printing and thermal ink jet printing. He has also investigated several other non-impact marking techniques and analyzed technical trends in the major printing technologies. Dr. Hanson has served the IS&T as Vice President for Conferences, General Chair for NIP 11, Chair of the NIP Technical Council and is currently Executive-Vice President. He has been awarded 16 US patents.

Michael H. Lee received his B.S. with Highest Honors in Engineering Physics from the University of California at Berkeley in 1971 and his M.S. and Ph.D. in Physics from the University of Illinois at Urbana-Champaign in 1972 and 1974, respectively. He went to the IBM Research Division in 1975 in San Jose working in various fields, including magnetic and optical recording, corrosion, and displays before embarking an a career in non-impact printing in 1983. He joined HP Labs in 1994 and is now focused on its liquid electrophotography project. He was the NIP15 General Chair in 1999 and is currently an Associate Editor of the Journal of Imaging Science and Technology.