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Packaging a liquid metal ESD with micro-scale Mercury droplet

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Abstract

A liquid metal ESD is being developed to provide electrical switching at different acceleration levels. The metal will act as both proof mass and electric contact. Mercury is chosen to comply with operation parameters. There are many challenges surrounding the deposition and containment of micro scale mercury droplets. Novel methods of micro liquid transfer are developed to deliver controllable amounts of mercury to the appropriate channels in volumes under 1 uL. Issues of hermetic sealing and avoidance of mercury contamination are also addressed.

ACKNOWLEDGMENTS

I would first like to thank Paul Galambos, whom has been my primary advisor on this project. He has provided guidance and assurance when the world of micro fluidics has brought frustration. Thanks to Austin Welborn, who assisted in the filling of channels and provided sound advice for my many ideas. Also thanks to Ron Renzi, who fabricated many of the specialized valves and fittings, making new methods possible. Additionally thanks go out to Adrian Casias, whose response to changing designs helped greatly in developing the new packaging methodology. And thanks to Katie Francis, who had to deal with our changing demands for the centrifuge testing process.

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NOMENCLATURE

ESD	Environmental sensing device
Psig	Pounds per square inch gauge
uL	Milliliter
g	Standard acceleration rate due to gravity
EDS	Energy dispersive X-ray spectrometry
DOE	Department of Energy
SNL	Sandia National Laboratories

1. INTRODUCTION AND SETUP

A liquid metal environmental sensing device (ESD) is being designed to act as an electrical switch under a variety of acceleration loading conditions. Liquid metal is being used over alternative methods for a variety of reasons. Fully electrical systems are more prone to malfunction or being tampered with. Mechanical systems suffer from degradation over time under general use. The use of liquid metal as both the proof mass and electric switching mechanism will allow for a device with a high level of repeatability and tolerance to shock damages. Mercury was chosen because it will remain in its liquid state over the full range of expected temperatures and accelerations.

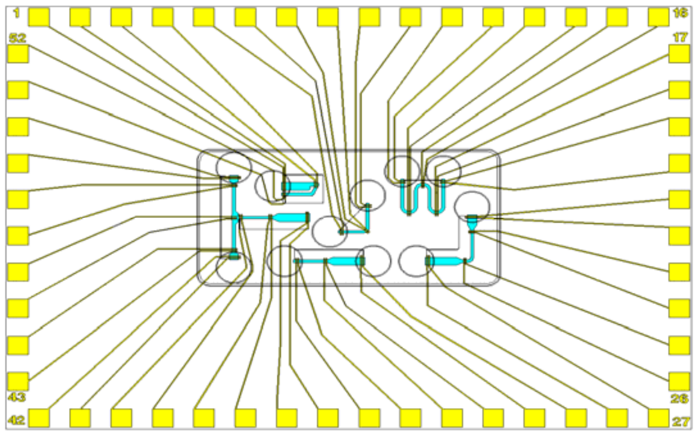

FIGURE 1: Layout of channels and associated electrical traces for current device. The channels are highlighted in blue.

At this stage of development a number of different channel designs are being evaluated. What is essential, regardless of the eventual channel layout chosen, is a method for packaging the device once it has been fabricated. Mercury must be delivered in precisely controllable amounts, as the total volume is directly correlated to movement as a result of inertial forces. The mercury must also be delivered free of contaminants. Epoxy is used in a number of the packaging steps, and its introduction to any of the channels severely affects the mechanics to render it useless in practice. Similarly, if the mercury is packaged in an ambient air environment oxidation can occur. Furthermore, once the device has been fully assembled the mercury must be sealed with the channel. Any leakage of mercury creates an unacceptable hazard, as well as compromising device performance.

2. PACKAGING METHODOLOGY

The first step of packaging the device is to attach the die to a suitable handling substrate. It is essential that when the device is attached that a hermetic seal is formed between the die and handle. As the device is fabricated the channels are open to the air, thus to prevent leakage between channels and from the device the space in between the channels must be eliminated. Several options have been explored.

Initially the silicon piece was aligned onto the glass chip using a specially fabricated holding mount. While under compression beads of Epo-Tek H74 epoxy were used around the base of the device, which creates an edge seal after proper curing. A Sandia designed die level anodic bonder has also been utilized. Under slight pressure and thermal loading the inter-channel spacing is removed, and as voltage is applied the resulting material interface closes off each channel from the others.

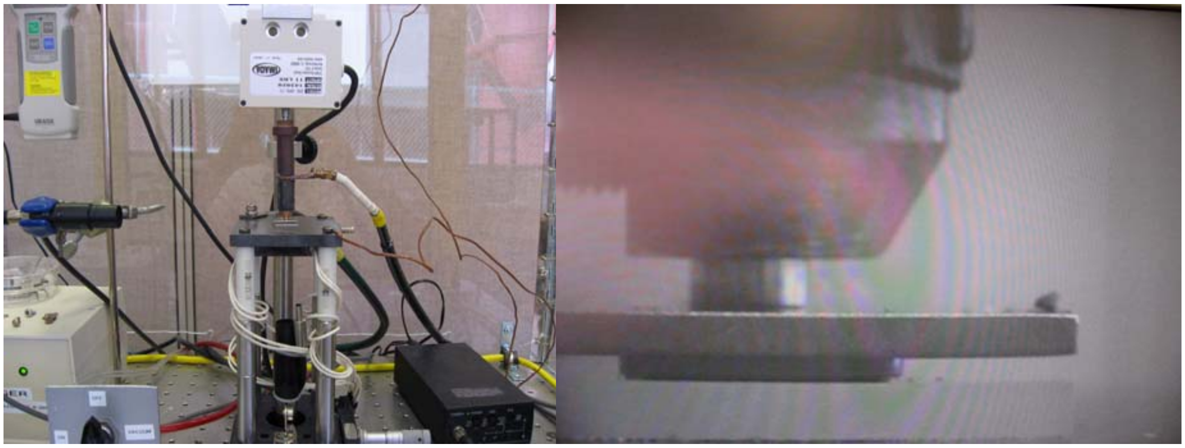

FIGURE 2: (1) Die level anodic bonder. (2) Close up of bonder chuck compressing device against glass substrate.

Numerous substrates have also been used. Some have been glass, patterned with gold traces and bond pads. These devices have been used to evaluate the concept of conductivity through the mercury. Other glass pieces have been devoid of any patterning, allowing for testing with reduced concerns over material interactions.

To allow access to the channels themselves, during fabrication holes are etched into the backside of the die. A series of copper tubes are modified to fit within these into these holes. The tubes are 1/16” outer diameter, and are cut and bent into a specific shape which allows a user to easily reach the ends away from the device.

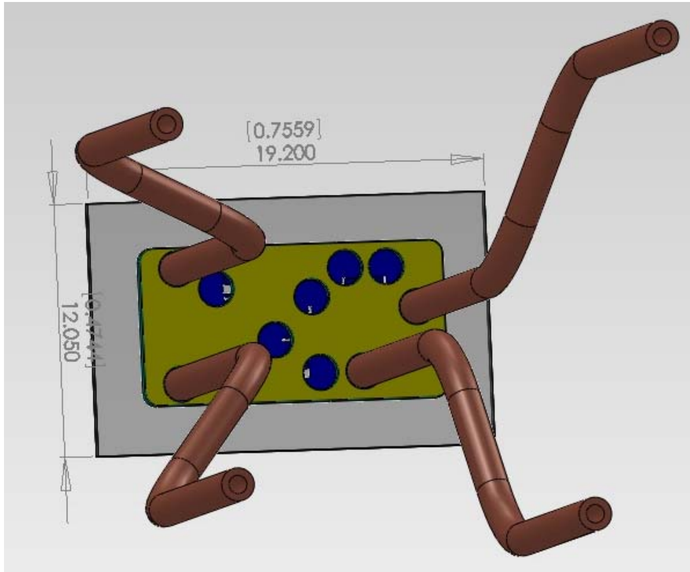

FIGURE 3: Model view displaying the tube bending design for easy access.

In addition a couple of other tube modifications are made. To ensure that, when placed inside the die holes, the copper does not seal off the micro channel from the outside the inserted end is first shaved down to an angle. This is achieved either by hand file, or table grinder, and gives the tube a roughly 10 degree angle end. Tube ends are then deburred and filed to ensure a smooth fit free of contaminants. The tubes are then annealed in an effort to increase sealing effectiveness later in the packaging process.

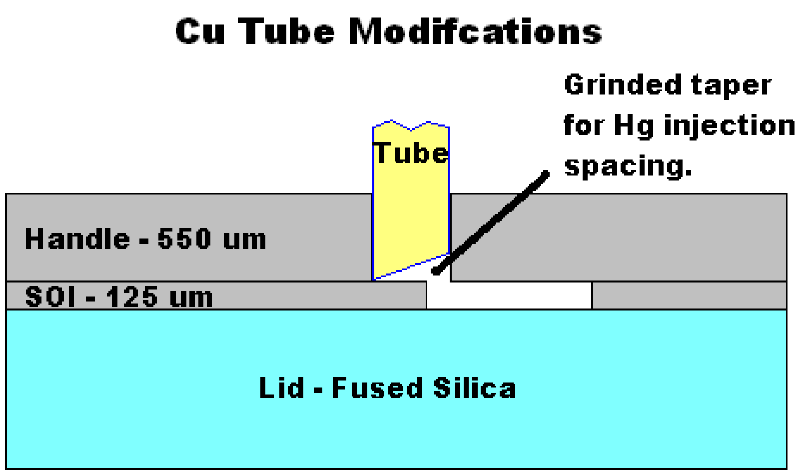

FIGURE 4: Cross sectional view of angled tube end.

Attaching the tubes to the device requires the fabrication of a holding mount. While holding the device in place, the mount aligns the tubes above the different holes, allowing them to be securely dropped into place. Once there, H74 epoxy is used around the base of the copper, sealing them to the device. Care is taken to ensure epoxy is not pressed down in between the copper and the device to avoid leakage into the channels.

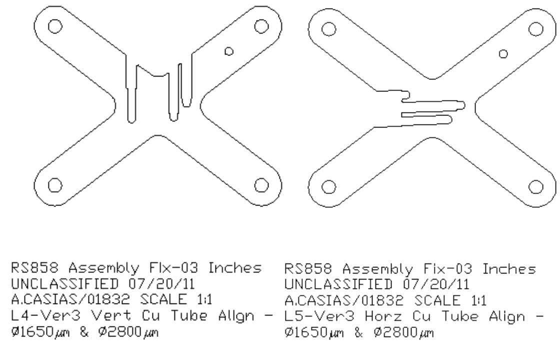

FIGURE 5: Two of the mounts pieces that slide in from the sides to hold copper tubes in place.

The next major step is filling the channel with the appropriate amount of mercury. To this end, a novel micro fluidic dispensing system has been developed. The system starts with a specially modified syringe, originally from Hamilton Co., and fitted with tip piece that directly connects to a small ferrule. From this ferrule there is a small piece of tubing, which in turn connects to a fabricated 3 way valve. The valve itself is unique in that it has been designed to have zero dead volume.

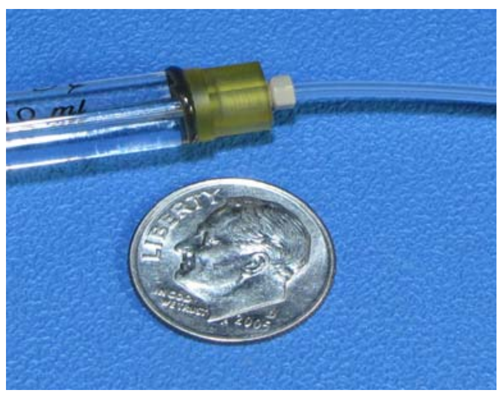

FIGURE 6: Specially modified syringe tip allowing for direct connection to desired tubing.

Mercury is drawn into the syringe in small amounts, totaling less than 1 uL in volume. The syringe tip is then attached to the fitting and tubing on one side of the valve, followed by depressing of the plunger which drives the mercury slug past the valve. At this point the valve is switched, allowing positive pressure to be supplied from the external nitrogen tank. Manipulating a fine level regulator pressure is very gradually increased, usually to around 2-3 Psig, until movement of the slug is observed. Once the mercury begins moving the pressure is held constant until the slug reaches the copper. At the copper interface a ferrule has been fitted, forcing the mercury to directly deposit into the copper and subsequently the micro channel.

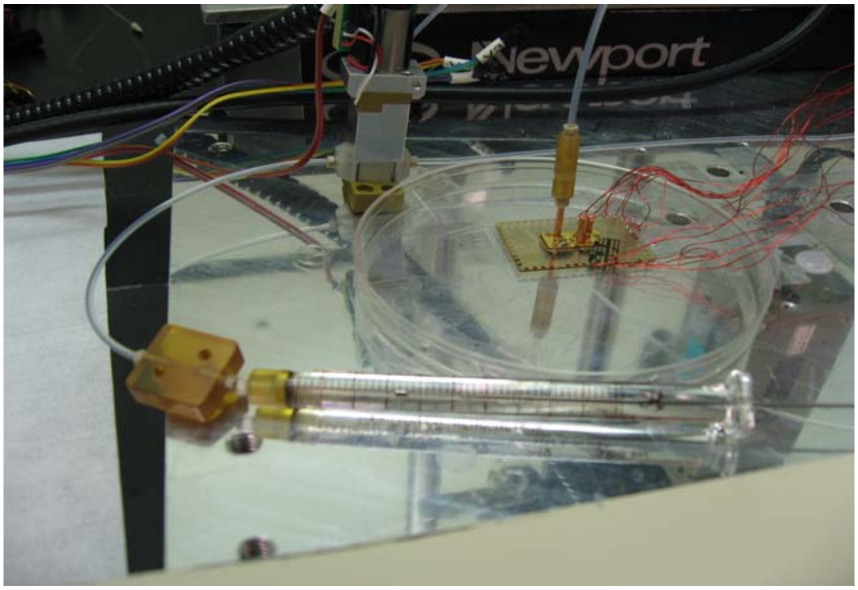

FIGURE 7: Components of filling setup. The zero dead volume fittings are seen in brown. The zero dead volume valve is seen in the back.

The dimension of all fittings and tubing ensures that the largest diameter region the mercury encounters is within the initial syringe. This forces the mercury slug to remain as a single droplet though out the line, with minimal dead volume regions for portions of mercury to escape. Pressure is then varied, and alternated between sides of the channel, until the droplet remains inside the channel. Because the mercury fills to the confines of the line it is much easier to move the slug back and forth to achieve the proper location. However, difficulties still remain, including the mercury's tendency to wick back into the copper tubing. If only a small part of the mercury slug is forced into the channel, while the bulk remains within the copper tube, the metal's intense attraction to itself draws the smaller portion back up. By controlling the size of the droplet so that its entirety fits within the channel this concern is alleviated. Fittings are detached from the device, and if the mercury remains the channel is considered filled.

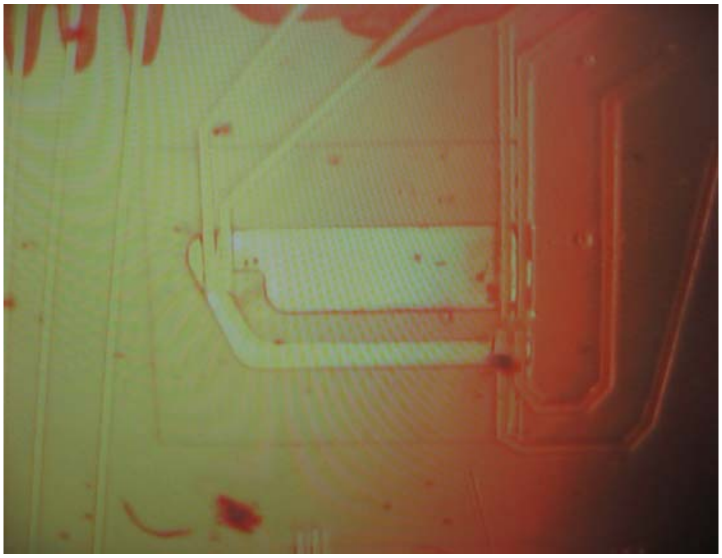

FIGURE 8: Channel filled with new methodology.

Once a filled channel is produced the copper tubes must be closed off to keep the mercury contained. This is achieved by ‘pinch-off’ of the copper tube end. Previous annealing of the copper helps this process, as the metal is more prone to being smoothly pressed. Squeezing the tube closed creates a hermetic seal at the once open end, and the package is then considered fully sealed. Pinch-off is achieved in one of two ways. A hand tool can be utilized, which provides ease of use, but concerns exist over its effectiveness. At the time of use if the tool is too sharp it will cut through without sealing the tube. Too dull and it will not fully close off the copper, or will impart a high level of stress that can damage the device. Alternatively a hydraulic pinch-off tool is used. The hydraulic tool uses a rolled clamping edge, which reliably cuts and closes the copper tubing with a steady pressure.

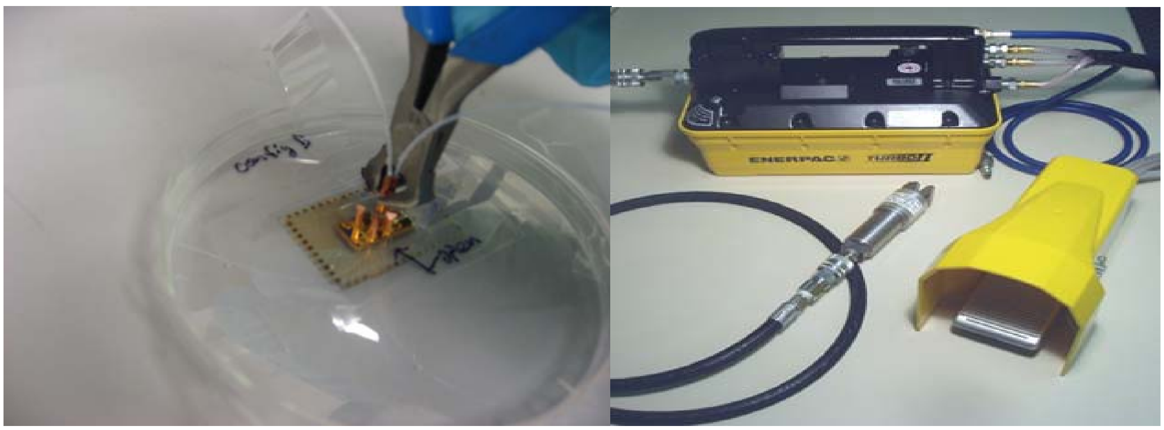

FIGURE 9: (1) Hand crimping tool being used to pinch off tubes. (2) Hydraulic pinch off tool.

After all intended channels have been filled and closed off the device is considered packaged for testing. Depending on overall configuration it is fitted inside a specific mount designed for the centrifuge, and acceleration analysis can begin.

3. RESULTS AND DISCUSSION

Testing is performed inside a centrifuge. The devices are aligned so that acceleration occurs in the direction of one of the two principal axes. Video feedback is provided in real time to the operator. Centrifuge speed is gradually ramped up, in 5g increments, until bulk motion of the mercury is observed. Rotational speed is then ramped down until reaching a stop.

Early testing with devices packaged on glass patterned with gold traces show interesting results. Although under acceleration loads the mercury droplet does eventually move, it does not do so immediately or with the free flowing movement profile observed during filling; when initially pushing mercury through the channel the droplet slides back and forth with relatively low pressure. Frictional forces are evidenced by requiring pressure to move, but the mercury does not 'stick'. After remaining in the packaged state some time before testing however, new phenomena are encountered. As acceleration is increased the leading and trailing edges of the droplet are compressed. The mercury is moving at its edges, but not as a whole slug. When a certain threshold g-level is reached a sudden and complete movement of the mercury occurs. Although the mercury droplet has moved, a film is left behind where the mercury had been resting.

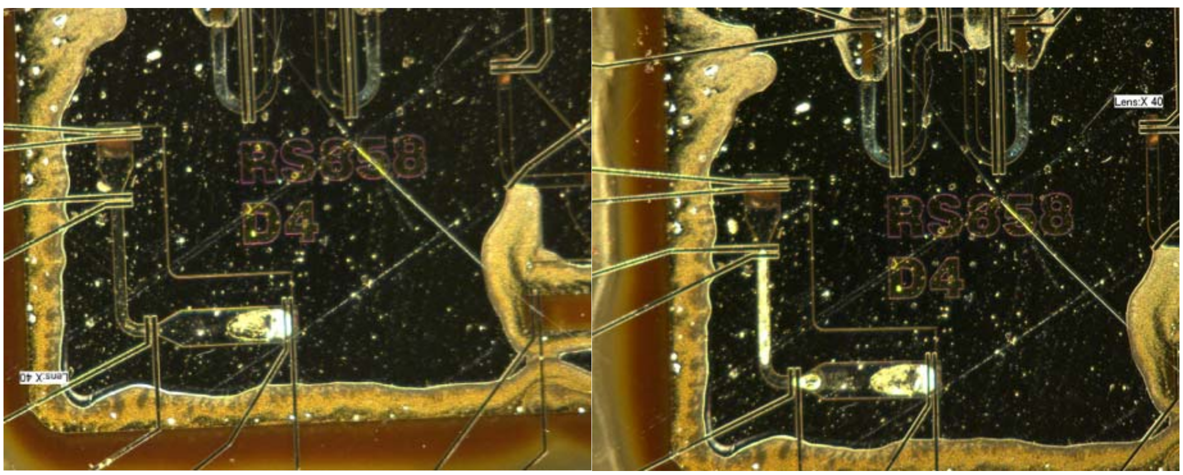

FIGURE 10: (1) Mercury droplet before application of acceleration. (2) The mercury has moved within the channel. Some film has been left behind.

While investigating possible causes of this 'sticking' it became apparent that the gold traces were reacting significantly with the mercury. External tests were done by rolling a mercury drop over exposed traces. Almost immediately the mercury was pulled up along the trace, including areas where the bulk drop had not touched. Energy dispersive X-ray spectrometry (EDS) testing of these areas confirmed that the light gold patterning had been replaced with a mostly mercury amalgamate.

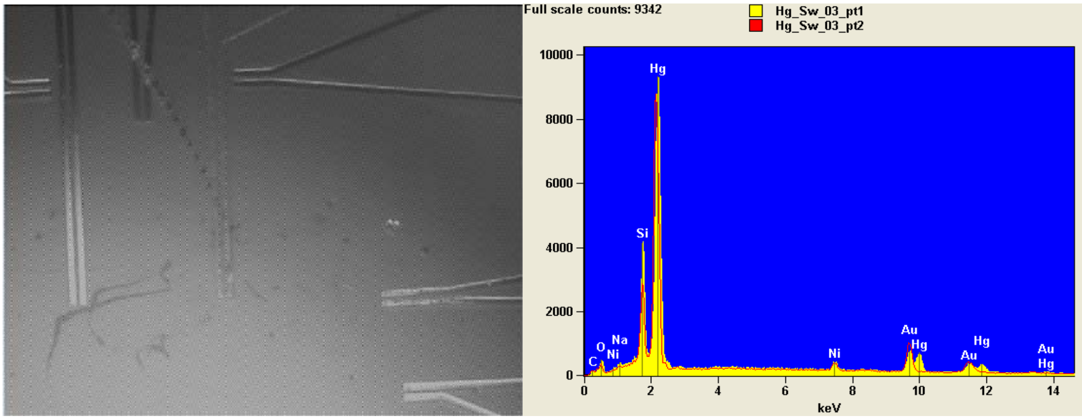

FIGURE 11: (1) Exposed gold traces that have interacted with mercury. (2) EDS results of traces.

While the gold-mercury interaction is cause for concern, other doubts were raised over the possible inclusion of epoxy into the channels. These devices had been packaged with an older method which included the application of epoxy to the filling line and copper tube interface. This same phenomenon is confirmed in later testing in the same channel design with different amounts of mercury. Despite mounting concerns over contamination during packaging, the testing provided positive results as well. Bulk mercury movement was achieved within the channel at the lowest recorded g-levels, approximately 25g. In addition a degree of repeatability was achieved, moving the mercury back and forth within the same channel in sequential testing runs.

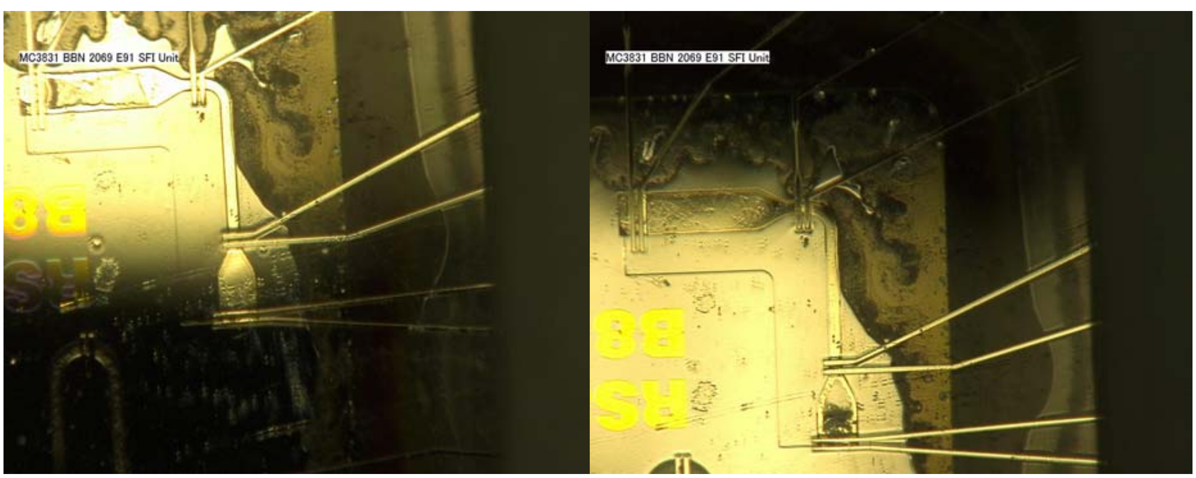

FIGURE 12: (1) Channel mostly filled with mercury. Film persists along all sides of channel not filled with bulk mercury. (2) Repeatability of mercury movement is attained.

After recent testing there has also been no indication of mercury leaks. Both the pinch off of the copper tubes and the bonding to the glass substrate appear to be hermetically sealed, or near enough approximations that no mercury escapes during the entire testing process.
Overall initial results with the new filling mechanism are very promising.

4. CONCLUSIONS AND FUTURE WORK

There are three primary issues of concern while packaging these devices. First and foremost is controlling the size of the mercury slug. The novel method of micro scale liquid movement has been streamlined to deliver the selected amount to the channel. Minute amounts of dead volume still exist, mainly within the valve. Replacement of the valve with a two-to-one line reduction fitting may go further in solving this issue. However, there is still some uncertainty in droplet size selection. Utilizing the syringe volumes less than 1 uL are easily obtained, yet due to a human operator the uncertainties are difficult to fully quantify. Other methods which contain very precise amounts of mercury should be explored if able.

Second, and most troubling at this time, is the issue of contamination. It is clear that the use of gold as the electrical traces is not the most satisfactory choice. Literature review and early testing with platinum shows a much lower degree of reactivity, while maintaining good conductivity through the mercury. Device scale testing should be performed with platinum, and other metal alternatives, to further evaluate this situation. It is also imperative that the method for attaching the copper tubes is refined. Small operator errors during processing has resulted in epoxy within the channels. Streamlining this process should be a priority.

Third is the issue of creating a sealed product. At this time there is no indication that the current design and packaging method results in any mercury leaks. If the copper tube method of mercury delivery continues there is no indication of continuation with the current method posing any problems. However, there is concern over the use of epoxy to bond the die to the glass substrate. This method has shown to be ineffective at times, creating gaps between the two surfaces at the center of the device. Thus, it may be prudent to continue on using anodic bonding as the primary method for attaching the chip to glass.

In addressing these issues and as the design process develops, different channel layouts will be considered. One possible alteration is to move the holes for die access further away from the channels of interest. Mercury would be forced through a secondary smaller channel before being deposited into the main channel. To prevent mercury from escaping during the remainder of packaging and testing the smaller channels could feature significant area reductions, making it difficult for the mercury to re-enter. Alternatively passive MEMS valves could be used to allow one way passage of the mercury slug. This channel layout would provide more visual space for the operator to determine whether the size of the mercury slug is acceptable, and more options in changing that size if it is not. In addition, any epoxy leak around the tube attachment areas will be removed from the channel, mitigating contamination concerns. Furthermore it would add another layer of protection from leakage. If the copper posts were to break off the mercury would not be immediately exposed to the ambient air.

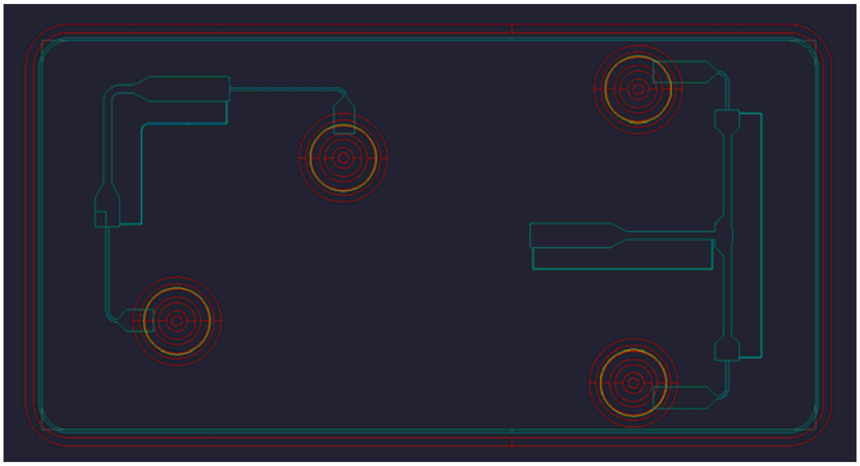

FIGURE 13: Modified channel layout. Copper tubes are attached a distance away from the main channel design.

Although some issues still exist, there is much evidence that variations of this new method for fully packaging micro channels will be very effective as work progresses into the future.

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