ABSTRACT
The MEMS industry has gained momentum recently with significant unit growth, especially in the consumer market. While traditional MEMS devices like automotive accelerators have established high-volume manufacturing processes and packages with high reliability, most MEMS devices have been fragmented in packaging because of their unique requirements and small volumes, resulting in high packaging costs. In the cost-sensitive consumer market, emerging devices such as MEMS microphones, accelerometers, and gyroscopes in mobile devices have rapidly increased their production volume and chased lower packaging cost while accepting relatively less reliability than traditional devices. This paper will present technical requirements for dispensing sealant, volumetric accuracy, and motion systems for MEMS wafer capping to meet packaging trends and will also address manufacturing cost reductions.

Key words: MEMS, dispensing sealant, wafer capping, volumetric accuracy, motion systems

INTRODUCTION
Wafer capping technology in MEMS production has gradually become popular in many MEMS devices such as inertial sensors, oscillators, and microfluidic packages. During production, MEMS release timing is very critical. Wafer dicing and die handing are difficult after release because the MEMS devices become fragile. Wafer capping provides MEMS structure protection after release during the dicing process. A cavity wafer covers the MEMS structure by bonding the cavity wafer to the MEMS die wafer, and the two bonded wafers are diced together. In addition wafer capping can provide a vacuum or low pressure with the right material, and a hermetic or almost hermetic seal can be realized.

However, there are manufacturing challenges. First, wafer capping requires precise alignment. Second, a variety of bonding methods have technical drawbacks. Stencil or screen printing is one way to deposit sealing lines to cap wafers but consumes a relatively wide area as sealing width and may not work if the sealing line must go onto the MEMS die wafer which is not flat surface. Dispensing, an alternative to printing, can apply a conductive or non-conductive sealing line on the MEMS die wafer even if it has fragile MEMS structure. Precise alignment is still a challenge regardless of various capping methods.

Cap wafer screen printing method
Cap wafer fabrication is done to make a cavity using different etching techniques such as deep-silicon reactive ion etch (DRIE). Bonding material, like seal glass, is applied to a cap wafer as shown in Figure 1[1]. The material is applied to only the bonding area. Then the MEMS wafer and cap wafer are aligned together and bonding is completed by heating them to the fusion point of 430 °C. The bonded wafers are diced together. In some cases cap structures are partially etched and thus wire bonding pads are exposed as shown in Figure 2.

Wafer capping dispensing method
Some structures require sealant in MEMS Si wafer and it is difficult to use a printing method on a device wafer that
contains movable parts. Dispensing is attractive due to its flexibility to apply sealant in various shapes especially for areas with geometric constraint or three dimensional structure surfaces. For example, when the getter material is applied to the cap wafer, sealant material needs to be applied on the MEMS wafer. Sealant material like silver paste, bonding adhesive, UV curable material, or low-temperature solder, is applied to the MEMS wafer side. Rectangular shape sealant is common. Then the cap wafer such as a glass or silicon wafer is aligned with the MEMS wafer. When glass cap wafer is used with UV curable material, UV light penetrates the glass wafer to cure the adhesive [2]. Once the base and top wafers are bonded together, dicing is performed at wafer level while the released MEMS structure is protected. Figure 3 illustrates the sealing dispensing method.

Step 1: Released MEMS on Si wafer

Step 2: Add sealant to MEMS wafer

Step 3: Cap wafer/glass bonding

Figure 3. Wafer capping dispensing method

DISPENSING REQUIREMENTS

There are many challenges to meet packaging requirements for MEMS devices. High yield and throughput are critical to realize low-cost solutions in volume manufacturing environments. The following section details three main topics. First, the choice for dispense sealant is important for its end use. The right sealant material for the end application is selected based on defined life time, reliability concerns, and functionality of the device. Second, consistent volumetric accuracy is a must to achieve a process yield required for volume production. Lastly, the throughput impact of sealing dispense will be studied using a specific case example. Throughput study will guide manufacturer to choose right system and applicators based on their specific application requirements.

1) Sealant material

Many varieties of capping technologies are used today based on reliability requirements ranging from solder bonding, anodic bonding, eutectic bonding and adhesive bonding. Each method has different hermetic levels and different tools for bonding. The MEMS designer will choose the right material for their packaging requirements based on lifetime of the device. Dispensing can be one option if liquid-type sealant is used, like epoxy adhesive, UV cure material, silver paste and solder paste. Adhesive may not meet the hermetic requirements for medical or military applications. However, consumer devices can accept less reliable but cost-effective approaches, however, time-to-market could be much more critical. Wafer capping is attractive in high-volume production because yield can be improved by MEMS immediate protection, and handling is easier during dicing, pick and place, and wire bonding. Figure 4 shows an example of conductive adhesive jetting on wafer to create uniform thin lines of 0.3 mm width.

![Figure 4](image)

2) Volumetric accuracy

There are many variables to control the flow of the material to dispense tight sealant lines. Fluid pressure, needle diameter, length of needle, and fluid viscosity determine volumetric flowrate shown in Figure 5.

\[
Q = \frac{\pi d^4 \Delta P}{128 \mu L}
\]

\[
\begin{align*}
   \Delta P & = \text{pressure drop} \\
   \mu & = \text{fluid viscosity} \\
   L & = \text{length of needle or nozzle} \\
   Q & = \text{volumetric flow rate}
\end{align*}
\]

Figure 5. Volumetric flowrate - Poiseuille’s law

Many varieties of materials have a pot life and viscosity will change over time. This changes the flowrate for a given setup. Along with flowrate change, dispensing volume changes if dispensing parameters are fixed. Thus dispensing parameters need to be adjusted to keep dispensing volume consistent, which calls for the use of a flowrate compensation tool. Dispensing uniform lines can be a
challenge due to material characteristics if a flowrate compensation tool is not applied. Figure 6 shows an example of two-part silicone flowrate changes over a 4-hour period (after fluid mixed) while dispensing parameters were fixed.

Once flowrate over time is characterized, the weight calibration tool can be applied at a given frequency for routine maintenance. Examples of variables for calibration are dispensing on-time, fluid pressure, or the number of shots (when jetting), depending on available tools and chosen applicators.

![Figure 6. Flowrate change over time](image)

### Dispensing by auger or time-pressure valves

Certain materials are suitable for needle-type dispensing, like solder paste or dam epoxy material. There have been many efforts to create uniform thin lines and to dispense consistent volume at the knitting point for sealing. Sealant tends to come out slowly from the needle at the beginning and more excessively at the end of the sealing line. These inherent effects make it challenging to dispense a uniform knitting point. When the needle dispenses the sealant on the surface, controls at the starting and ending points are critical to make volumetrically consistent dispensing. Figure 7 shows the typical dispensing point when dispensing parameters were not optimized on the left (a) and improved case on the right (b).

![Figure 7. a) Typical starting point; b) A few variables were adjusted to minimize “dog-bone” effect](image)

Fluid will start to flow once fluid pressure is on. The duration between the valve turning on and sealant coming down to the surface depends on viscosity of fluid, fluid pressure, valve motor speed and signal delay from the system. Somewhat uncontrollable flow time through the needle tip can change the volumetric consistency. Initial flow of sealant material takes time to reach the surface.

- **Coordination with motion control**

The dispense head starts to accelerate at the first dispensing location to reach dispensing velocity. It requires a certain distance in order to reach pre-defined dispensing velocity. At the first starting point, the system will put down more material at given flowrate because applicator velocity is initially slow. Plus, the applicator decelerates to stop at the end position and thus more fluid will be dispensed at a given flowrate by ramping down applicator velocity. For instance, if a 5mm line is dispensed from start to finish at given motion profile (Figure 8) to reach 35mm/s dispensing velocity, it takes 0.173s to dispense one straight line. During this time 0.53mm distance is used for acceleration (31ms) and 3.95mm distance is used for constant velocity.

![Figure 8. Motion profile](image)

- **Fluid break-off**

When the needle is close enough to the substrate surface with certain dispense gap (the distance between needle tip and substrate) during dispensing, fluid is still in contact with the surface. Fluid can break-off when the needle moves up. The amount of fluid in the needle tip and the amount of fluid on the surface are difficult to control when the fluid break-off point is inconsistent.

**Solutions:**

There are two issues to address: knitting point and inconsistent volume. Precise time control of turning fluid pressure or valve motor before the dispense head reaches the first dispensing location or turning on delay time before dispensing begins would minimize the “dog-bone” shape line. This timing is critical to control the amount of material volume. Timing control of pressure off before the end of the sealing line could eliminate the excessive amount of sealant at the knitting point due to slow response time of the flow similar to start location. In addition, motion parameters should provide needle move-up distance, acceleration and velocity control for consistent fluid break-off. Those three parameters can be optimized based on sealant type. The shortest needle move-up distance with optimized maximum acceleration and velocity for a given application setup.
would result in high throughput if needle move-up and -down time is a significant portion of total dispensing time.

**Jetting small uniform droplets**

Another dispensing applicator can eliminate the “dog-bone” issue fundamentally: the jet applicator. Jet dispensing delivers small droplets, without contacting the substrate. High energy is delivered by a piston to the tip of the nozzle and fluid is ejected through the small nozzle orifice as Figure 9 shows. An array of small dots can be connected to form a uniform line as shown in Figure 10. Precise valve control of a millisecond achieves consistent volumetric accuracy, and eliminates “dog-bone”-shaped lines. Jetting can be optimized by moving the dispense head to compensate for acceleration distance. Thus, at the starting point, dispensing already reaches constant velocity when it begins to dispense dots continuously.

![Figure 9](image1.png)

**Figure 9.** Mechanical jet applicator ejecting small droplets. The jet uses a pneumatic piston with a ball tip to raise the piston by air pressure and to push fluid through a narrow orifice at the jet nozzle. As the ball tip on the end of the piston engages in a seat at the nozzle, the fluid is energized and shoots a droplet from the end of the jet [3].

If a sealant fluid contains fillers, then the choice of nozzle size will be limited by particle size distribution. Larger nozzle choices due to filler size can make it challenging to put down a fine line width. Figure 11 shows the droplet of non-filled material forming 100um diameter dot in the air using non-filled material. Thus a nozzle with small inner diameter of 50um was used. If sealant volume control is inconsistent and more sealant is applied in one line, then excessive material can contaminate wire bonding pads or other components near the sealant material after capping. This is a typical failure and re-work can be difficult. When sealant is disconnected due to material void or line width is inconsistent due to un-optimized parameters, this will be a critical failure when it requires certain hermeticity or low vacuum after capping (Figure 12).

![Figure 11](image2.png)

**Figure 11.** Jetting non-filled material 100 um diameter dot in the air

**Potential issues**

If sealant volume control is inconsistent and more sealant is applied in one line, then excessive material can contaminate wire bonding pads or other components near the sealant material after capping. This is a typical failure and re-work can be difficult. When sealant is disconnected due to material void or line width is inconsistent due to un-optimized parameters, this will be a critical failure when it requires certain hermeticity or low vacuum after capping (Figure 12).

![Figure 12](image3.png)

**Figure 12.** a) Disconnected sealant line (yellow box); b) Optimized sealant line

**3) Motion systems – throughput requirements**

This section evaluates the impact on throughput by changing motion parameters such as maximum velocity. In addition two different applicators were used for the experiments. The sealing line width requirement is driven by the geometric constraint of a package structure. Thus a certain needle/nozzle inner diameter, fluid pressure, line speed, and others were selected for this study.

**Experiment setup:**

Two different motion parameters were set up. Motion 1 used normal mode and motion 2 applied high-performance parameters. Motion 1 with a single applicator was used as a baseline. Table 1 shows the setup. “Dual” in this case means moving two applicators simultaneously that dispense different MEMS sealing lines in parallel.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Motion Type</th>
<th>Applicator</th>
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</thead>
<tbody>
<tr>
<td>Scenario1</td>
<td>Motion 1</td>
<td>Single</td>
</tr>
<tr>
<td>Scenario2</td>
<td>Motion 2</td>
<td>Single</td>
</tr>
<tr>
<td>Scenario3</td>
<td>Motion 1</td>
<td>Dual</td>
</tr>
<tr>
<td>Scenario4</td>
<td>Motion 2</td>
<td>Dual</td>
</tr>
</tbody>
</table>

**Table 1**
Height sensing and vision:
It was assumed that the wafer had good alignment and flatness. Thus three points of height sensing (HS) per substrate and two fiducials (alignment mark) were applied.

Dispensing dimensions:
5mm X 5mm square sealing line was used per unit. One panel included 100 units. Each unit spacing was 5mm pitch.

Non-contact jetting case:
Putting down sealant in the desired location can be a challenge when there are tight tolerance and dimension requirements. It is important that the dispensing system provides constant velocity during dispense in order to put down the droplet at consistent distance intervals. Cycle time per unit is shown in Figure 13. Total time of handling and dispensing includes handling, vision, height sensing and dispensing time.

\[
\text{Cycle time per unit} = \frac{\text{Total time of handling and dispensing}}{\text{Number of units per tray}}
\]

**Figure 13.** Cycle time

Applicator velocity during dispensing was determined by flowrate and other requirements such as line width. In this case it required a 0.3mm line width and thus a small orifice nozzle was needed to make the small volume droplet. Work-time dispensing means the duration of the applicator putting down sealant material. Applicator velocity was locked to 42mm/s during dispensing patterns of square sealing units as work-time dispensing. Motion-time dispensing is defined by non-dispense move time between square sealing units. Non-dispense moves of 5mm were used in this experiment as each unit pitch and two different motion parameters showed significant difference in cycle time by reducing motion-time dispensing. Figure 14 shows that high throughput can be achieved by high-performance motion parameters or normal motion parameters with dual applicators. A large portion of motion-time dispensing (51%) is allocated in Motion 1 and thus a dispensing system with high-performance motion parameters can increase unit per hour (UPH) in this case. Certain dispensing system accuracy is required for the dual applicators to meet tight geometry constraints.

Conclusions:
MEMS wafer capping has been seen in many devices such as inertial sensors, oscillators, and microfluidic packages. This paper presented technical requirements for dispensing sealant, volumetric accuracy, and motion systems. Sealant
material choice depends on the lifetime of the end application, reliability, and functionality. This paper also addressed challenges of volumetric accuracy when dispensing sealant and then presented solutions to improve dispensing consistency. Throughput optimization was studied by using specific MEMS applications by varying motion control parameters and dispensing parameters.

FUTURE WORK
Future work will include investigating the impact on the throughput model due to size reduction efforts in packaging. More dies can be produced per given wafer size, which means there is more dispensing area per wafer. In addition, sealing line requirements will be more challenging, and so further work will address these demands.

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REFERENCES