Advanced MEMS and Packaging: Photoresist, Adhesive and Thin Film Processing Solutions for Lift-Off Processing

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ABSTRACT:
Today’s wafer level processes used for MEMS and packaging must be compatible with extreme topologies. Common spin coating processes fall short for most of these applications because the photoresist layer voids or thins on the corners or edges of the higher topologies leading to unintended etching or the incomplete lift-off of thin films.

Spray coating is a solution for photoresist and adhesive application that is highly compatible with harsh topologies. This is accomplished by spraying the material with a controlled distance and angle to the substrate. The benefits of this method include significant material saving, decreased photoresist waste, coating insensitivity to particles or damage to the wafer, and can easily be used to coat partial wafers or square substrates without edge effects. This method can be used for virtually any liquid polymer including photoresists, PBO, polyimides, and adhesives to a variety of thicknesses regardless of the material’s viscosity. Spray coating can be used for many processes including photo patterning, bilayer lift-off, single layer lift-off, and bonding.

Spray coating technology has existed for over a decade and has many obvious benefits. It is gaining momentum in the industry, especially in MEMS and packaging processes, but is still as yet unknown to many companies. In this presentation the capabilities, benefits, and uses of spray coating will be expounded upon and paired with a lift off process used to pattern optical thin film coatings.

Optical thin film coatings have been paired with sensors for decades but with recent advancements in technology and processing techniques we are now able to deposit patterned low defect coatings on 3D topography wafers as well as active device wafers. This allows for drastically reduced form factor than the alternative discrete window manufacturing approach with higher quality and lower costs.

KEY WORDS:
Spray, Coating, Photoresist, Cavity MEMS, WLP

INTRODUCTION:
There are a variety of photoresist coating technologies that can be used for the application of photoresist, polymers and adhesives. Photoresist can be coated using electrodeposition, spin coating, spray coating, and even deposited using plasma [1]. Each of the methods has advantages.
Spin coating is achieved by dispensing photoresist onto the center of the wafer and allowing it to spread for a brief time, depending on the viscosity of the photoresist. After the mentioned spread step the speed accelerates and then spins to a set maximum speed for a set time period. The maximum speed is set based on the desired thickness of the coated layer. This method works well on flat substrates and with wafers that have limited topology. If the topological features are much higher than the intended photoresist thickness, then the method is not ideal.

BEOL processing steps and WLP processing for traditional semiconductors, compound semiconductors and MEMS devices typically bring a different set of challenges than the earlier layers of silicon fabrication. The challenges include trenches, blind vias, through-hole vias, V-grooves, and tall structures with sharp features. They all include more severe 3D topology that is difficult to coat with polymers, photoresists or adhesives. With many MEMS devices there are also fragile structures present that will not withstand the forces caused from traditional spin coating.

Spray coating was originally developed as a solution to provide conformal coating of features such as those described that are found on MEMS devices and WLP processing. There are other benefits that provide a marked improvement above the common spin coating method. These include:

- Coating of irregularly shaped/heavy substrates
- Reduced utilization of materials
- Coating of multiple small substrates simultaneously
- Protective coating of fragile structures
- Underfill applications

For this paper we will demonstrate the spray coating method which does not require a high speed spin and will cover well into deep trenches and over the corners of high features with significant improvement of photoresist coverage compared to the more conventional spin coating method. While spray coating improves coat conformity of both negative and positive photoresists, positive photoresist benefits more greatly because the photoresist is already cross-linked and can cover corners more readily. In this case, we will show some typical results of spray coating positive photoresist, but will also show results of spray coated nLOF 2070 photoresist, which was required for compatibility with the sputter and lift-off processing that was demonstrated after the photo processing. One hundred micrometer deep cavities will be coated with an nLOF photoresist and patterned with various sized lines and squares for use with lift off processing so the long wave antireflection coating, Cr:NiAu seal ring, and sputtering short pass coating can be selectively patterned onto the surface.

In the results section we will examine several patterns of a long wavelength anti-reflection coating from a thermal evaporation process, Cr:NiAu solderable coating from a metallization process, and lastly a sputtering short pass coating in the visible wavelength range. In the conclusion portion of the paper we will summarize the patterned coating results and its manufacturing benefits.
BENEFITS OF SPRAY COATING:
There are multiple benefits from use of the spray coating method. The first to mention is that spray coated photoresists are more conformal over tall or deep features than photo resists coated using other techniques. With spray coating one can coat to a wide range of thicknesses: It is not dependent on the viscosity of the material being coated. Some typical coat profiles with positive photoresist are shown in figure 1.

![Figure 1 Positive photoresist spray coated into a via](image)

Finally, there is a very significant savings in photoresist usage over spin coating. Photoresist waste is the biggest disadvantage of spin coating. With the spin coating process, most of the resist that is dispensed spins off the wafer into the side of the bowl. After this it is discarded as waste. On average one should expect to use only 20 - 30% of the photoresist that would be used on a spin coater when coating with the spray method. [2] The chart below shows the number of 4" silicon wafers that can be coated with 1 liter of photoresist using spin coating and spray coating with 2 different dilutions.

![Chart 1 Demonstrates the photoresist savings realized using spray coating compared to spin coating](image)
WAFER PREPARATION:

100 micrometer deep cavities, ranging from 50 micrometers squared up to 350 micrometers squared, were patterned into boron doped <100> silicon wafers using a nitride hard mask and then a wet etch in a KOH solution. This produces a very distinctive sidewall of 54.7 degrees along the <111> plane of the silicon as shown in figure 1.0. Profilometer results showing the cavity depth are shown in Fig 2. Optical photographs of the cavities follow in Fig 3 and finally, the completed test wafer for use in our spray coating and patterning demonstration, is shown in Fig 4.

![Figure 2 Profile showing KOH silicon etch results along the <111> silicon plane](image1)

![Figure 3 Profilometer measurement showing cavity depth](image2)
The one hundred micron deep cavities created using this technique are common in the production of MEMS devices. They can be used to make V-grooves and trenches as well as the cavities. This topology, specifically at a one hundred micrometer depth is not suited for spin coating. With spin coating, in order to achieve the required photoresist thickness, or even decent photoresist coverage at the top surface of the wafer, the resist thickness would have been significantly higher at the bottom of the cavities. The thicker resist along with the high distance between the photomask and the bottom of the cavity would have made achieving a ten micrometer resolution with a contact printer difficult or impossible, especially without over-exposing the patterns at the top of the cavities and causing loss of control over critical dimensions.

Figure 4 Cavities after wet etch and nitride removal
METHOD:
For this paper a test mask was designed with features that fit with the cavity patterns. We used this mask along with the spray coated wafers to demonstrate patterning capability on the surface of the cavity test wafers that were created as described. The patterns of this test mask were designed to demonstrate patterning within the bottom of the cavity as well as varied width, ten to 50 micrometer, lines running from the top of the silicon wafers, along the sidewalls, and in to the bottom of the cavities. Some of the multi designs of interest on the test mask are shown in Figure 6.
OPTIMIZATION OF SPRAY COATING:
The first step of the photoresist patterning of the test mask onto the wafer was the spray coating. The spray coater utilizes an atomizing ultrasonic nozzle to produce tiny droplets that are carried in the direction of the wafer by a stream of nitrogen to coat the droplet materials onto the wafer. With adjustments to the solids/solvent ratio of the material, the coating properties will be affected. A more conformal coat can be achieved using a lower ratio of solids to solvents. A less conformal coat will be achieved by adjusting the ratio in the other direction. See table 1 [3] for a basic list of parameters adjusted for coating optimization.

<table>
<thead>
<tr>
<th>Coat Parameters</th>
<th>Characteristics Affected</th>
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<tbody>
<tr>
<td>Scan speed</td>
<td>Resist thickness</td>
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<tr>
<td>Nozzle pressure</td>
<td>Resist uniformity of planar areas</td>
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<tr>
<td>Solvent amount</td>
<td>Resist uniformity</td>
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<tr>
<td>Solvent type</td>
<td>Coverage over corners</td>
</tr>
<tr>
<td>Solids content</td>
<td>Coverage along sidewalls</td>
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Table 1 Coat parameters and characteristics

Fig. 7 shows an example of a spray coat nozzle coating a layer of AZ nLOF2020 for a bi-layer lift-off photolithographic process.

The wafers for this paper were spray coated to two target thicknesses one group was coated to a 4 micrometer thickness target while the other group was coated to a 14 micrometer thickness target. The required photoresist thicknesses were determined taking the desired metal stack and AR film thickness into account.
A sector exposure shutter, shown in Figure 8, with multiple exposures was used on the initial wafers to determine the best exposure dose to use for each thickness. With the negative photoresist, the selection of exposure was achieved by balancing two opposing undesirable affects. The first is bridging pattern from overexposed photoresist. The second being developer undercutting of the photoresist. Over-exposure causes cross-linking of the negative photoresist in areas that were meant to be clear of photoresist, while under-exposure stops the negative nLOF2070 from cross-linking in the deeper areas which leads to some photresist undercutting during development. See photos of the defect extremes below in Fig. 9A and 9B.
RESULTS: The results of the group with a 4.0 micrometer targeted thickness of nLOF 2070 coating are shown in Figures 10A, 10B and 10C. The results of the 14.0 micrometer targeted coating are shown in Fig. 11A, 11B and 11C.

**Figure 10A** SEM micrograph of 30 micrometer lines patterned into 4 micrometer thick nLOF2070

**Figure 10B** SEM micrograph of 10 to 25 micrometer lines patterned into 4 micrometer thick nLOF20

**Figure 10C** SEM micrograph of 25 micrometer width line patterned into 4 micrometer thick nLOF2070

**Figure 11A** Thick photoresist at the top, just outside of the 200 micrometer square cavity

**Figure 11B** Thick photoresist at the bottom, of the cavity

**Figure 11C** 200 micrometer square photoresist opening at the bottom of the cavity
In both cases an acceptable resolution is achieved. The thinner photoresist was used to demonstrate the capability of printing photoresist lines down to 10 micrometers in the deep cavities and even along the sidewall. The thicker photoresist was used for the selective patterning of a 7 micrometer thick sputtering coating at the bottom of the cavity.

**DISCRETE vs WAFER LEVEL PACKAGING:**
For decades the standard method of manufacturing optical filters was to coat individual substrates wafers which would be diced into singulated discrete windows for assembly into sensors or camera systems, this is known as discrete manufacturing. Through recent photolithography and semiconductor trends the industry is experiencing a shift to wafer level packaging for thin film optics. In this process wafers are coated, bonded, and then diced. This allows for greater process automation, higher yields, and lower costs. In the results section we will discuss the pairing of semiconductor technology with thin film coatings that provides patterned thin film coatings with greater performance for several markets including cap wafers for micro-bolometers, rejection filters for sensing applications, as well as solderable coatings for seal rings.

**RESULTS:**
The selective patterns defined by the wafers construction and the photo mask determine where the thin film material will adhere. An example of the pattern used in this is seen in figure 12.

**LONG Wave (LW) ANTI-REFLECTION COATING (ARC):**
Anti-reflection coatings reduce the effect caused by the Fresnel losses. This effect can be dramatic especially on high index substrates such as silicon. As seen in figure 14 the average transmission was increased from 48.7% to 84.7% over the area of interest 8,000-13,000 nanometers. This 36% increase results in a higher signal to noise ratio which is beneficial when designing any optical system. As seen in figure 13, with spray coated photoresist we have the ability to pattern and deposit ARC on both the mesa surface as well as the bottom of the cavity.
**Figure 13** LW AR Coating a 100 micrometer Feature Size

**Figure 14** Transmission of AR coated Silicon
THERMAL EVAPORATION of SOLDERABLE COATING:
Thermal evaporation of metals for solderable seal rings is a key enabler of WLP technology. Coating stacks such as Cr: Ni: Au, Ti: Au and Au: Sn eutectics can all be performed with thermal evaporation. For WLP applications utilizing bonded wafers with getters being used, thermal evaporation is preferred to sputtering due to argon entrapment. Argon permeates the coating and can compromise the vacuum after wafer bonding. An example of a solderable coating is shown in figure 15 the composition of the stack is Cr: Ni: Au. This pattern has 15 micrometer line width and 3.8 micrometer spaces. Through modification of the coating geometry we are able to achieve very conformal coatings on substrates with pronounced topographical features. Figure 16 shows the interactions between the Cr: Ni: Au coating with the 4 micrometer targeted thickness of nLOF 2070 photoresist. The seal ring coating conforms to the etched slope of the silicon as well as the transition to the flat mesa of the substrate. This allows adhesion and clean liftoff of the photoresist.

Figure 15  Cr: Ni: Au Coating 15 micrometer Line Width

Figure 16  Cr: Ni: Au Coating on Etched Slope
SPUTTERING of VISIBLE SHORT PASS COATING:
Sputtering coating processes offer extremely consistent repeatability and the ability to coat a wide variety of materials. Various oxide materials can be used to produce custom spectral responses from the UV to near infrared (200 - 2,000 nanometer). The short wave pass coating in figure 18 represents a coating that passes the lower wavelengths of light and reflects the longer wavelengths. These wavelength rejection filters can be coated directly on CMOS, CCD or MEMS wafers which offer better performance and a form factor that is drastically reduced as seen in figure 17.

**Figure 17 Sputtering Coating 100 micrometer Feature Size**

![Sputtering Coating 100 micrometer Feature Size](image)

**Sputtering Short Pass Spectral Results**

![Sputtering Short Pass Spectral Results](image)

**Figure 18 Sputtering Coating Spectral Response**

CONCLUSION:
The constant trend with consumer electronics is for higher performance, smaller form factors, all at a lower cost [5]. To keep up with these trends the semiconductor and thin film industries are enabling sensor manufacturers with technology solutions such as spray coating for challenging topographies and custom designed thin film optical filters. These optical thin films can be optimized for various wavelengths ranging from the ultra violet to the long wave infrared. These processing solutions offer advances that enable sensor manufactures to push the envelope of performance and form factor.
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