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[Technical Paper]

Low-Temperature Wafer Bonding for MEMS Hermetic Packaging Using Sub-micron Au Particles


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Abstract

A study of wafer-level hermetic bonding using sub-micron gold particles with a mean diameter of 0.3 μm was conducted at bonding temperatures of 150–200°C with varying bonding pressures in the range of 50–100 MPa. 4.5 mm-square, 10 μm–100 μm-wide sealing line patterns of sub-micron Au particles were formed on glass wafers by means of wafer-level processing using photolithography and a slurry-filling technique. The tensile bond strength was measured with a stud-pull method using 5 mm × 5 mm chips and exhibited as > 20 MPa. A preliminary hermeticity test was performed by immersing the bonded wafer pairs into a low-viscosity liquid and it was confirmed that the sealing lines with widths as thin as 20 μm showed a good sealing property against the liquid. The result demonstrated the feasibility of this low-temperature wafer bonding process using sub-micron Au particles, which could achieve hermetic sealing with absorbing a micron-level surface roughness and/or topography.

Keywords: MEMS, Packaging, Low Temperature, Wafer Bonding, Hermetic Sealing, Au, Sub-micron Particle

1. Introduction

Metal-to-metal wafer bonding has recently been increasingly studied in the field of MEMS packaging since the technique could decrease the sealing line area which would result in the chip size reduction, realize hermetic sealing, and also enable electrical interconnections between the two bonded wafers.[1, 2] Low-temperature wafer bonding has also become important for various purposes such as reducing the post-bond residual stress at mechanical structures in MEMS devices, and preventing bowing or cracks when bonding materials with dissimilar coefficients of thermal expansion (CTE).

In order to lower the bonding temperature, sub-micron or nano-scale metal particles, such as gold, silver, and copper, have been tested since they are reactive at low temperatures due to their very active surfaces.[3–6] Wafer bonding with these metal particles has another advantage of being able to adapt to a certain level of surface roughness and/or topography at the bonding surfaces in contrast to bonding with thin metal films, which requires nanometer-order surface smoothness. It was observed in a previous study that micro-bumps formed of sintered sub-micron Au particles could be bonded at 230°C with a thermocompression method and exhibited a good bonding strength.[3]

In this paper, a wafer-level patterning and low-temperature wafer bonding with sub-micron Au particles were studied and the feasibility of hermetic sealing was investigated.

2. Experimental Procedure

2.1 Materials and samples

The 99.95wt% purity, spherical sub-micron Au particles were obtained through a wet chemical processing method by mixing chloroauric acid solution with a reducing agent. It was confirmed in the previous work that the obtained particles shown in Figure 1 consisted of individual gold particles without agglomeration and their diameters were in the range of 0.1 μm–0.5 μm.[3] Figure 2 shows the gold slurry which was prepared by mixing the water-rinsed sub-
micron Au particles with an organic solvent and surface active agents.

For the wafer bonding experiment, 100 mm-diameter double-side-polished glass wafers (TEMPAX Float®, Schott AG, 500 μm-thick, CTE: $3.3 \times 10^{-6}$ K$^{-1}$ at 20°C–300°C) were used to prepare two kinds of test wafers, one having only a patterned metallization layer and the other with the sealing-line patterns of sub-micron Au particles on the metallization layer. As the metallization layer, a 50 nm-thick Ti and a 200 nm-thick Au layer were sequentially deposited by sputtering. A photoresist thin film was deposited by spin coating using the Delta 80RC spin coating system (SUSS MicroTec AG) and patterned using a photolithography technique employing the MA8 mask aligner (SUSS MicroTec AG) to form the mask layer for wet-etching the metallization layer into rectangular patterns. Then, the sealing lines of sub-micron Au particles were formed by filling the Au slurry into the thick photoresist mold patterned with a negative photoresist THB-126N (JSR Corp.) according to the process flow shown in Figure 3. The widths of the sealing lines for the bonding tests were set at 10 μm, 20 μm, 50 μm, and 100 μm. The average thickness of the photoresist mold layer was 20.8 μm and the uniformity across the wafer (with 5 mm edge exclusion) was 3.68% on a 150 mm-diameter Si wafer, calculated by (max.–min.) / (max. + min). The details of the entire process flow of the patterning is described elsewhere.[3]

2.2 Wafer bonding
Prior to wafer bonding, precise optical alignment was conducted on the BA8 bond aligner (SUSS MicroTec AG) to align the sub-micron Au sealing lines on one wafer to the corresponding metallization patterns on the other wafer. The wafer bonding was performed in vacuum on the SB8e wafer bonder (SUSS MicroTec AG), as shown in Figure 4, at bond temperatures ranging from 150°C to 200°C and applied pressures of 50 MPa or 100 MPa, with 10 minutes duration at each defined condition. The wafer bonder is equipped with top and bottom heaters that can be controlled independently and are capable of heating up

1. Photoresist patterning
   - photoresist
   - Ti/Au metallization
   - Si wafer

2. Filling of Au particles
   - Au slurry
   - -90 kPa

3. Drying (Solvent removal)
   - -90 kPa

4. Au particle removal from resist surface
   - blade

5. Sintering of Au particles
   - 70–100°C
   - In air

6. Photoresist removal
   - Au particle pattern

Fig. 1 FE–SEM image of the sub-micron Au particles.

Fig. 2 Photo of the Au slurry, the mixture of sub-micron Au particles and an organic solvent with addition of surface active agents.

Fig. 3 Process flow to form sub-micron Au sealing line patterns.
to 500°C with uniformity better than +/− 1.5% across a 200 mm-diameter area. A contact force of up to 20 kN can be applied with a controlled ramp time.

2.3 Measurement

The thickness and surface roughness (average roughness, Ra) of the sub-micron Au particle sealing lines before bonding were measured with a laser microscope, VK-9710 (Keyence Corp.), at 28 points across the wafers.

The bonding strength was evaluated using 5 mm × 5 mm chips that were diced from the bonded wafers using the Stealth Dicing method. Tensile strength was measured using the stud-pull method on a universal mechanical-strength tester, Romulus (Phototechnica Corp.), and the average values were calculated using three chips for each bonding condition. The bonding strength was calculated from the tensile force divided by the area of the sub-micron Au particle sealing line.

In order to check the sealing capability of the sub-micron Au bonding, the bonded wafer pairs were immersed into a low-viscosity hydrofluoroether liquid, Novec® (Sumitomo 3M Ltd.), in a vacuum container evacuated down to 1 × 10⁴ Pa. Gross leak can be easily checked by seeing whether the liquid flows into sealed areas or not.

3. Results and Discussion

3.1 Patterning of sub-micron Au particles

Figure 5 shows the result of the patterning of sub-micron Au particles using a photoresist mold layer. Photo (a) shows the photoresist patterns after the process step 1 described in Figure 3 and (b) exhibits the sub-micron Au sealing line patterns formed on the underlayer metallization after the process step 6. It can be seen in photo (b) that the shape of the sub-micron Au particle sealing lines was well defined by the photoresist mold layer with no critical defects like an open path which directly causes a leakage. The average height of the sealing line formed on a 100 mm-diameter wafer was calculated to be 18.0 μm with maximum and minimum heights of 19.1 μm and 17.3 μm, respectively, for a uniformity of 4.9%. The height uniformity of the sealing lines is in the same range as that of the photoresist mold layer and this means that the shape of the sub-micron Au particle patterns can be properly controlled by the preceding lithography of the photoresist mold layer.

The cross-section view and the surface topography of a 50 μm-wide sealing line are shown in Figures 6 (a) and (b), respectively. The measurement results indicate that the sealing lines have a surface topography with peak-to-valley distance of about 2 μm and an average roughness, Ra, of 0.56 μm.

3.2 Bonding strength

Figure 7 shows a cross-section SEM image of a sealing line bonded at 200°C and 100 MPa. The photo demonstrates that the sub-micron Au particles were densified into a bulk solid when they were pressed at the elevated temperature. It has been observed in a previous work[3] that sub-micron Au particles start to be joined at their surfaces at temperatures as low as 70°C and grow to larger grains...
with increasing temperatures, and that they could be compressed into bulk Au with eliminating voids by applying pressure.

Table 1 summarizes the result of the tensile strength measurements for three different bonding conditions for 5 mm × 5 mm chip samples with a sealing line width of 50 μm. It was demonstrated that sample #1, bonded at 200°C and 100 MPa, exhibited the maximum average strength of 45.8 MPa. Furthermore, the bonding strength was greater than 20 MPa for all conditions, even at a temperature as low as 150°C. These bonding strength values are high compared with those of other hermetic bonding methods such as 18 MPa for Au–Si eutectic bonding[7] and 10.1–10.7 MPa for Au–Au diffusion bonding.[8] The relatively large deviations of the values for each sample are considered to be due to the local non-uniformity of sealing line patterns that were confirmed at inspections prior to bonding.

Figure 8 shows microscope photos of the corresponding bonding surfaces after the tensile test. It can be observed that the sub-micron Au particle pattern was removed at the interface between the Au and the Ti underlayer metallization or between the Ti and the glass wafer. This indicates that the adhesion between the sub-micron Au particles and the Au metallization layer was stronger than the measured bonding strength.

It can be read from Table 1 that bonding strength improves with increasing bonding temperature or bonding pressure. Since sub-micron Au particles were well-densified, becoming bulk solid, bonding strength is considered to be determined by the bonding area where the Au particles are actually in contact with the Au metallization. The bonding area can be increased by elevating the bond temperature, which promotes surface diffusion to bond the Au particles with the Au metallization, or by increasing the bonding pressure, which can flatten the pattern surface to enable tighter contact. It appears that the latter effect contributed more in the bonding temperature region as low as 150°C–200°C.

### 3.3 Hermetic property

Figure 9 shows a photograph of a bonded wafer after immersion in the low-viscosity liquid used to check the

![Cross-section profile](image)

**Fig. 6** Measurement of the topography of a sub-micron Au sealing lines. (a) cross-section view and (b) surface roughness in longitudinal direction of a 50 μm-wide line.

![Cross-section SEM image](image)

**Fig. 7** Cross-section SEM image of a sub-micron Au pattern after bonding at 200°C, 100 MPa for 10 min. The black areas correspond to glass wafers and the bright part shows a densified Au particle sealing line. Ti/Au metallization layer was deposited on each glass wafer.

![Microscope photos](image)

**Fig. 8** Microscope photos of sealing lines after tensile measurement test.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Bonding Condition</th>
<th>Tensile Strength [MPa]</th>
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<tr>
<td></td>
<td>Temperature [°C]</td>
<td>Pressure [MPa]</td>
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<td>200</td>
<td>100</td>
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<td>#2</td>
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<td>#3</td>
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gross leak of the sealing lines. As you can see in Figure 9, the sealing quality can be easily checked by seeing whether any liquid leaks into the chip. The yield of good sealing was calculated for each sealing line width by dividing the number of “Good” chips by the total number of chips. This is plotted in the Figure 10 as a function of sealing line width. The figure indicates that the yield reached a maximum value of 91.2% with a line width of 20 μm. It should be mentioned that a yield of > 50% was obtained for a sealing line width of as narrow as 10 μm. It is considered that the yield was strongly influenced by the quality of the sealing line patterns. For thinner lines, leak paths (or open voids) might be generated more easily due to insufficient filling of Au particles into the resist mold. On the other hand, for wider lines, it was confirmed that a few amount of Au particles were accidentally removed from some pattern surfaces during the patterning step 4 in Figure 3, which created relatively large recesses on the pattern surfaces. This topography could degrade the yield. In order to improve the yield of good sealing and also bonding strength, it seems important to improve the quality of the sealing line patterns; in other words, to realize well-filled and smoother surface Au particle patterns.

### 4. Conclusion

Wafer-level patterning of sub-micron Au particles was carried out employing a photoresist mold and gold slurry. Sealing line patterns with widths of 10 μm–100 μm and a pre-bonding height around 20 μm were formed with a height uniformity of 4.9% across the 100 mm-diameter wafer. The surface roughness of the sealing lines was measured as the average roughness, Ra, of 0.56 μm.

Low-temperature wafer bonding using sub-micron Au particles was performed at temperatures as low as 150°C. Tensile strength measurements using 5 mm × 5 mm chips revealed that the average bond strength of the samples bonded at 200°C and 100 MPa was 45.8 MPa and the fractures occurred at the interface of the Ti/Au underlayer metallization or between the Ti and the glass wafer but not at the sealing line layer.

The feasibility of hermeticity by bonding using sub-micron Au particles was demonstrated by confirming no leakage of a low-viscosity liquid through the sealing lines. The yield of good sealing showed a maximum value of 91.2% with the sealing line width of 20 μm.

In order to improve the bonding quality, or bonding strength and sealing yield, it is important to realize well-filled and smoother surface Au particle patterns.

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to dice the wafers into individual chips for bond strength measurement.

**References**


