LOW-TEMPERATURE HERMETIC SEAL BONDING FOR WAFER-LEVEL MEMS PACKAGING USING SUB-MICRON GOLD PARTICLES WITH STENCIL PRINTING PATTERNING

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INTRODUCTION

Wafer-level hermetic packaging with electrical interconnection is necessary for the integration of MEMS and LSI devices, and low-temperature metal bonding such as AuIn, AuSn, Cu-Cu and Au-Au has been increasingly attractive [1]. Among those bonding methods, Au-Au thermo-compression bonding is a promising candidate, which has advantages of no concern of surface oxidation and simple process control [2]. In order to compensate the surface roughness after MEMS processing which could degrade the hermetic properties, surface compliant Au-Au bonding using sub-micron Au particles has been developed combined with the patterning method using photolithography process [3]. In this study, a rim structure was adopted to define a narrow bond line width for reducing the bonding force within the range of commercial wafer bonders (e.g. the maximum force of 100 kN for 200 mm wafers) and conventional stencil printing was employed to lower the patterning process cost.

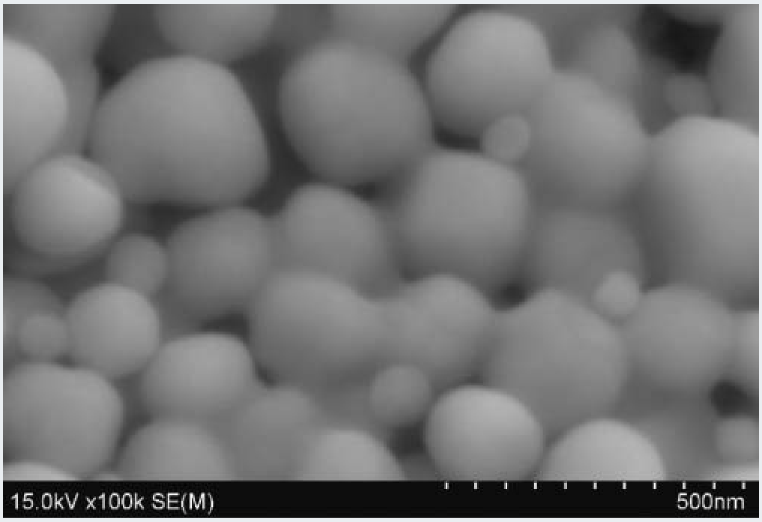


Figure 1 *SEM image of sub-micron Au particles after heating at 200 °C for 30 minutes in air*

EXPERIMENTAL PROCEDURE

Materials preparation

99.95 wt% purity, spherical sub-micron-size Au particles were prepared by a wet chemical processing method by mixing chloroauric acid solution with a reducing agent. The particle size distribution was in the range of 0.2 - 0.5 µm in diameter (the mean diameter of 0.3 µm), which could exhibit a fine size effect to activate the Au-Au interdiffusion. Figure 1 shows the sintering behavior of sub-micron Au particles being connected each other at 200 °C for 5 minutes in air without any compression force.

Sample preparation and wafer bonding

The wafer-level hermetic sealing process using a rim structure covered with sub-micron Au particles is shown in Figure 2. A diaphragm wafer was prepared to evaluate the hermetic properties, formed by anisotropic wet etching using a TMAH (tetramethylammonium hydroxide) solution. On the other hand, to fabricate a rim wafer, 10 µm-tall/10 µm-wide rim structures were formed on a ϕ100 mm oxidized Si wafer by Si deep-RIE (PEGASUS, SPP Co., Ltd.), and Au/Pt/Cr (0.2/0.03/0.03 µm-thick, respectively) metal layer were deposited by sputtering (Figure 2(a)). A customized Au paste (AuRoFUSE™, Tanaka Kikinzoku Kogyo K.K.) was deposited to cover rims (Figure 2(b)) by conventional stencil printing method using a high-precision screen printer (LS-25TVA, Newlong Seimitsu Kogyo Co., Ltd., Figure 3) together with a suspended Ni-metal mask (Taiyo Yuden Chemical Technology Co., Ltd). After aligning the rim wafer and the metal mask on the screen printer, printing was completed within 10 seconds per wafer. As shown in Figure 4, successful wafer-level printing on 200 mm wafers has already been demonstrated.

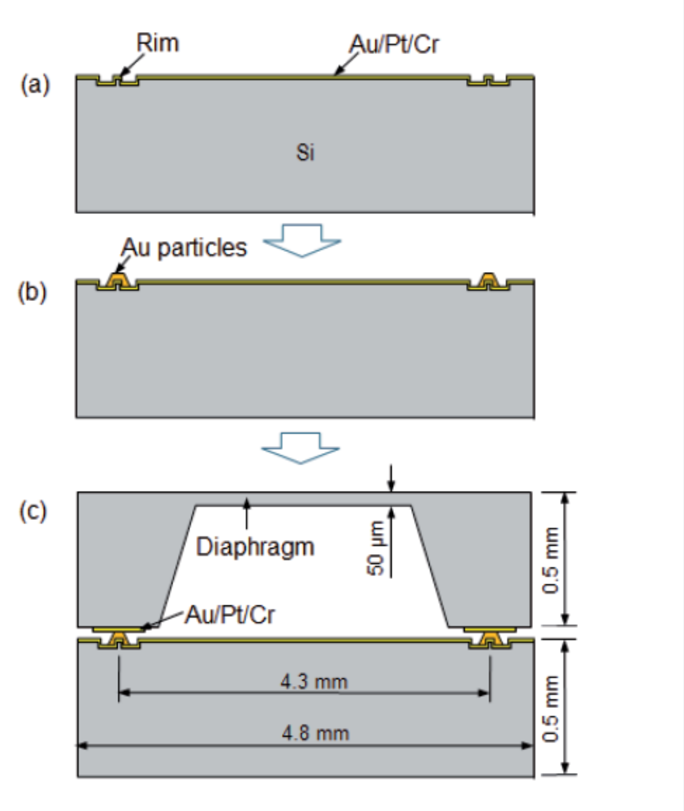


Figure 2 *Wafer-level fabrication process using sub-micron Au particles. (a) Formation of a rim structure by dry etching process and deposition of metal layers, (b) stencil printing with sub-micron Au particles (AuRoFUSE™) sintered at 200 °C, and (c) thermo-compression bonding at 200 °C*

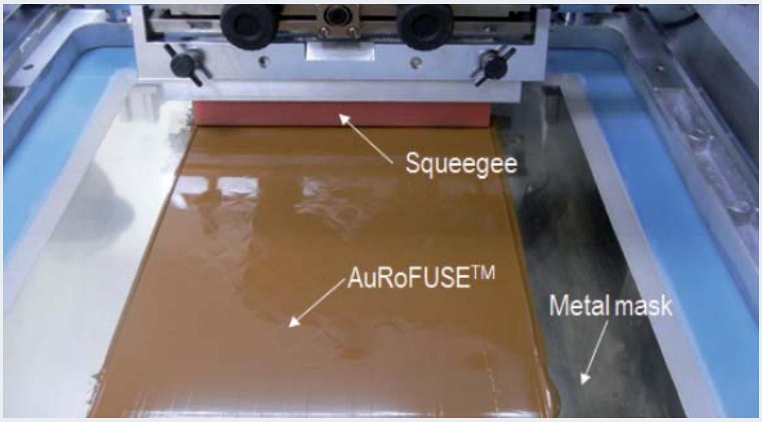


Figure 3 *Wafer-level stencil printing on a precision screen printer with AuroFUSE™*

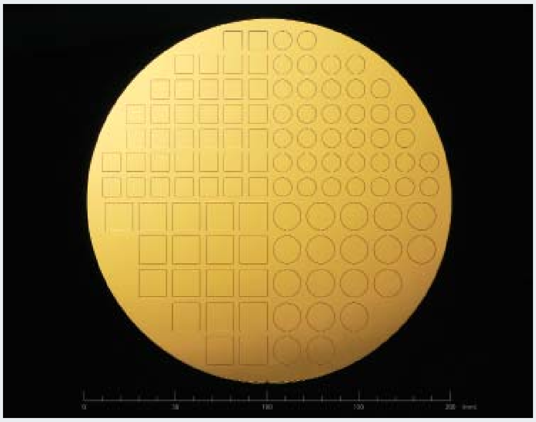


Figure 4 *An example of a 200 mm wafer with test patterns of sub-micron Au particles formed by stencil printing*

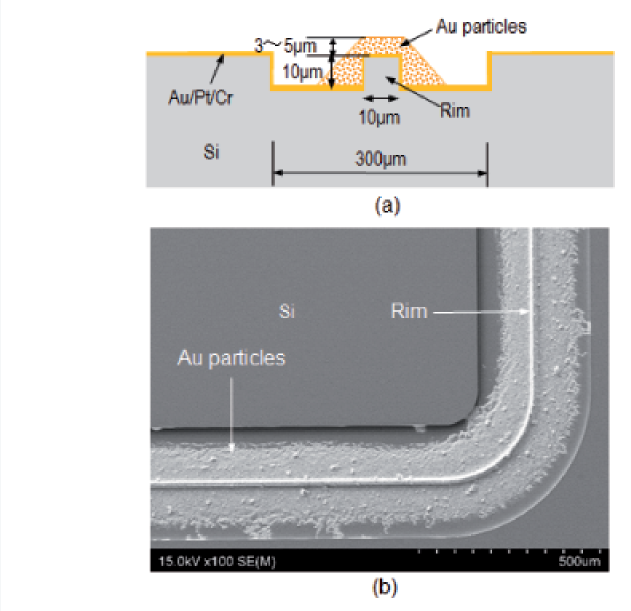


Figure 5 *(a) Schematic drawing of the cross-sectional view of the rim structure covered with sintered Au particles, and (b) SEM image of the rim on a Si wafer*

Figure 5 shows (a) a schematic illustration of the cross-section rim structure and (b) a SEM image of the rim covered with sintered sub-micron Au particles. The thickness of sintered Au particles on top of the rim was in a range of 3-5 μm over the entire surface of 100 mm wafers. Following the annealing of the rim wafer at 200 °C for 2 hours in 4 % H_2-Ar gas flow, precise alignment was performed between the rim wafer and the diaphragm wafer on the bond aligner (SUSS BA8). Then, the aligned wafer pair was bonded on the wafer bonder (SUSS SB8e) at a temperature of 200 °C for 30 minutes with an applied pressure of 200 MPa to fabricate the structure as shown in Figure 2(c). The vacuum level of the bond chamber was maintained at 10^{-3} Pa during the thermo-compression bonding. The bonded wafer pair was diced into single chips for evaluation of the bond strength and hermetic properties.

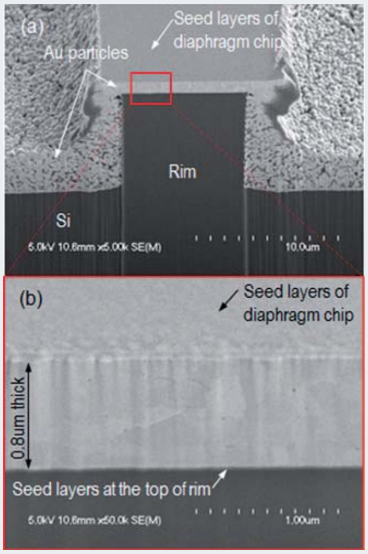


Figure 6
Cross-sectional FIB-SEM images of the rim joint after tearing off the chip.
(a) A complete picture of the rim joint, and (b) a higher magnification of the recrystallized structure of sintered Au particles and metal layers

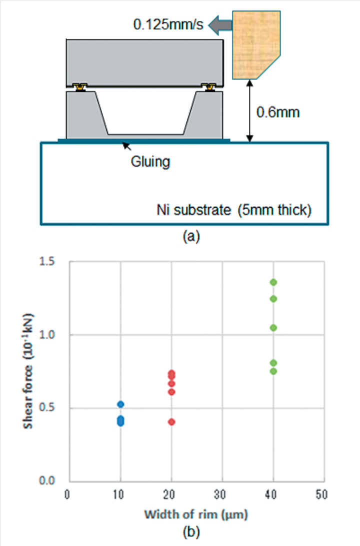


Figure 7
(a) Schematic illustration of die shear test to measure the die shear strength of the test chip, and (b) a relationship between the die shear strength and the rim width

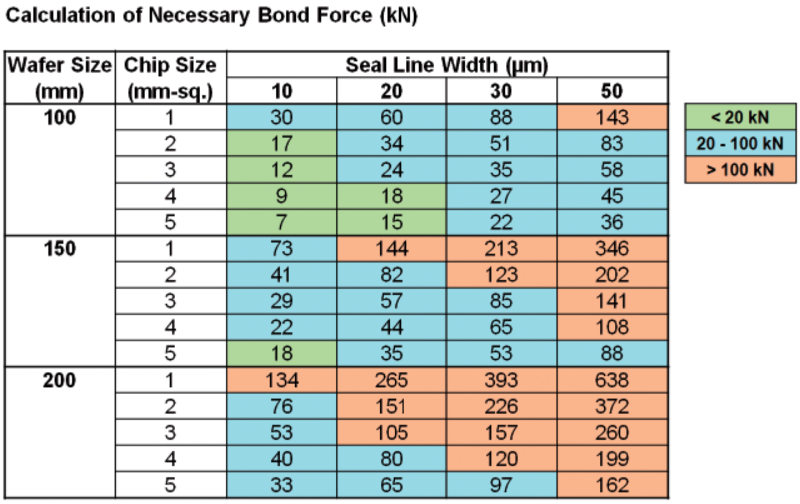
RESULTS AND DISCUSSIONS

Bonding performance

Figure 6 shows a cross-sectional FIB-SEM image of the rim joint after tearing off the bonded chip. The joint was separated at the boundary of silicon surface of the diaphragm wafer and its metal layer of Au/Pt/Cr. The metal layer of the diaphragm wafer attached closely to the densified structure of Au particles. The sintered sub-micron Au particles layer measured 3-5 μm-thick, which was compressed on the rim structure down to the thickness of 0.6 μm during the bonding. The sub-micron Au particles recrystallized and densified into bulk structure to realize hermetic interface.

As shown in Figure 7, the die share strength of a singulated test chip was measured by a bond-tester (series-4000, Dage) to be an average value of 44 N.

Assuming a bond pressure of 150 MPa for achieving hermetic sealing by sub-micron Au particles bonding, Table 1 summarizes the calculated necessary bond force for each wafer/chip size with varying the seal line width. In calculation, the following parameters were assumed: edge exclusion = 5 mm, dicing street width = 0.2 mm. The bond force values were classified into three categories such as "<20 kN", "20 - 100 kN" and ">100 kN", where 20 kN and 100 kN is the maximum force of SUSS SB8 Gen2 and XB8 wafer bonder, respectively. It is estimated from the table that hermetic bonding with sub-micron Au particles can be realized by commercially available wafer bonders even for 200 mm wafers with a small chip size of 2 mm x 2 mm.



Calculation of Necessary Bond Force (kN)

Wafer Size (mm)	Chip Size (mm-sq.)	Seal Line Width (µm)			
		10	20	30	50
100	1	30	60	88	143
	2	17	34	51	83
	3	12	24	35	58
	4	9	18	27	45
	5	7	15	22	36
150	1	73	144	213	346
	2	41	82	123	202
	3	29	57	85	141
	4	22	44	65	108
	5	18	35	53	88
200	1	134	265	393	638
	2	76	151	226	372
	3	53	105	157	260
	4	40	80	120	199
	5	33	65	97	162

🟩 < 20 kN
🟦 20 - 100 kN
🟧 > 100 kN

Table 1 *The calculated necessary bond force for various wafer and chip size with varying the seal line width, with assuming the bond pressure of 150 MPa. In calculation, edge exclusion and dicing street width was assumed as 5 mm and 0.2 mm, respectively*

Hermetic sealing performance

Figure 8(a) shows a picture of a test chip exhibiting a concave deflection of the 50 µm-thick diaphragm under the atmospheric pressure. The deflection measured 5 µm in the ambient, indicating a vacuum encapsulation inside the sealed cavity. In order to estimate the encapsulated pressure inside the cavity, the deflection of the diaphragm in vacuum was precisely measured by an optical surface profiler (MSA-500, Polytec) with controlling the chamber pressure. The concave/convex deflection of the diaphragm against the chamber pressure is shown in Figure 8(b). From the results, the encapsulated pressure in the sealed cavity is estimated at 100 Pa by seeing the chamber pressure when the diaphragm becomes flat. The hermetic performance of the sub-micron Au particles sealing was evaluated by helium fine leak test (MUH series, Fukuda Co., Ltd.). The maximum He leak rate of the test chip was estimated in the range of 10^{-14} Pa·m^3/s, which is sufficient for most of the MEMS applications.

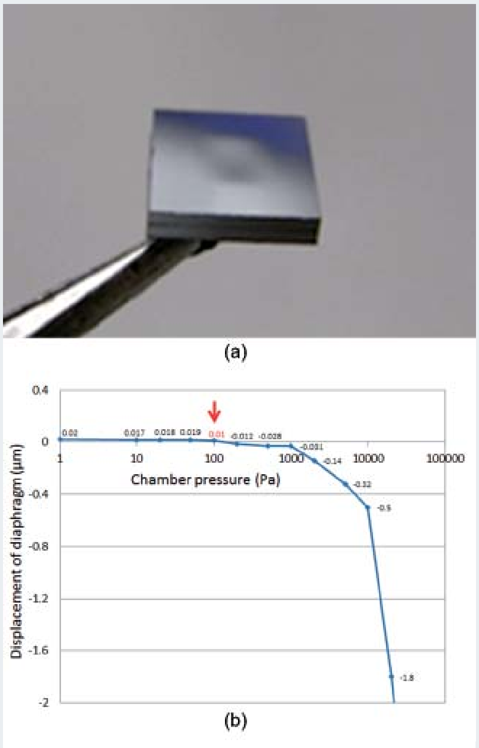


Figure 8
(a) A singulated test chip showing a diaphragm deflection due to vacuum sealing, and (b) the concave/convex deflection of the diaphragm measured by an optical surface profiler

CONCLUSION

Low-temperature Au-Au hermetic seal bonding has been successfully demonstrated employing a rim structure on a ϕ100 mm Si wafer covered with sub-micron Au particles. The sintered Au particles on the rim structure were densified by the thermo-compression bonding to realize the hermetic sealing. The summaries of this study are as follows:

1) The layer of sub-micron Au particles with the thickness of 3 - 5 µm was deposited on the 10 µm-tall / 10 µm-wide rim structure by a conventional stencil printing

2) The hermetic sealing by the sintered sub-micron Au particles on the rim structure was successfully achieved by the thermo-compression bonding with 200 MPa at 200 °C

3) An excellent vacuum hermetic sealing was confirmed; the encapsulation pressure was measured to be 100 Pa, and the maximum leak rate was estimated in a range of 10^{-14} Pa·m^3/s (He)

This bonding technique can be expected for further development towards production use for wafer-level hermetic sealing of MEMS packaging.

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Hiroyuki Ishida joined SUSS MicroTec KK in 2006 as a senior application engineer and then worked as a business development manager in Japan mainly focused on wafer bonding applications. He is now the manager of Bonder Division - Japan, being responsible in all activities related to permanent bonding and temporary bonding / debonding products. He is also taking care of the collaboration with Japanese material suppliers for temporary bonding applications. He received his B.E. and M.E. in Electronic Engineering from Tohoku University.