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Low-Temperature Silicon Wafer-Scale Thermocompression Bonding Using Electroplated Gold Layers in Hermetic Packaging

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We describe a low-temperature wafer-scale thermocompression bonding using electroplated gold layers. Silicon wafers were completely bonded at 320°C at a pressure of 2.5 MPa. The interconnection between the packaged devices and external terminal did not need metal filling and was made by gold films deposited on the sidewall of the via-hole. Helium leak rate was measured for application of thermocompression bonding to hermetic packaging and was $2.74 \pm 0.61 \times 10^{-11}$ Pa m^3/s. Therefore, Au thermocompression bonding can be applied to high quality hermetic wafer level packaging of radio-frequency microelectromechanical system devices.
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The crucial parts of microelectromechanical system (MEMS) devices require hermetic wafer bonding to protect against the atmosphere, dirt, moisture, and other contamination, as well as against mechanical and radiation loads, which could destroy the (fragile) devices or affect their performance. Hermetic bonding techniques include silicon direct bonding (SDB),[1] anodic bonding,[2] intermediate layer bonding,[3] and so on. SDB requires high temperature and anodic bonding requires high electric field.

Intermediate layer bonding techniques include eutectic bonding,[4] adhesive bonding,[5] and glass frit bonding.[6] The materials for such intermediate layer bonding have included silicon dioxide and soft metals such as gold, indium, copper, and aluminum. Traditionally, they have been bonded using electrical, thermal, and compression techniques. Thermocompression bonding is a form of solid-state welding, in which pressure and heat are simultaneously applied to form a bond between two otherwise separate surfaces. At room temperature, tremendous pressure is needed for interatomic attraction to overcome surface asperities.[7,8] The oxides that naturally occur on the surface of solders prevent the formation of a strong bond. For complete bonding, these oxides must be removed either chemically or mechanically. As a noble metal, gold is an ideal bonding material. A good example of thermocompression bonding is gold wire bonding. The low yield point of pure gold aids the thermocompression process, and its corrosion resistance and electrical conductivity are desirable properties for packaging. In addition, gold does not attract inorganic substances such as slurry particles.[9] Therefore, as a metal, gold is expected to be effective as a hermetic sealing material.[10] The minimum bonding temperature for eutectic bonding of Si and Au is 370°C.[11] Using thermocompression bonding of Au to Au, the bonding temperature can be further reduced.

In the electrical contacts between packaged devices and external terminal, the via-hole interconnections can reduce the size of MEMS devices. To form the via-hole interconnections in Si substrates, a three-step process, via-hole forming, insulator forming, and conductive material filling, is carried out. The electroplating of copper (Cu) or nickel (Ni) is commonly applied to metal filling.[12,13] However, sometimes no electroplating has occurred in the holes because of the formation of air bubbles within via-holes.[14] In addition, one disadvantage of electroplating is the long process time. Therefore, we fabricated the via-hole interconnections, excluding the electroplating process, to save time and cost and to reduce noncontact by voids within the via-holes.

In this study, we investigate the thermocompression bonding of electroplated Au seal ring and bonding pads at a temperature of 300-350°C and a pressure of 0.65-2.5 MPa. We present a method that uses conductive materials deposited on the sidewall of via-hole for forming electrical contacts between the devices and external terminal.

Experimental

The bonding process is illustrated in Fig. 1. First, high-resistivity silicon (HRS, >15000 Ω) wafer was used to reduce the substrate losses. An n-type 4 in. 500 μm thick silicon wafer was cleaned in buffered HF solution to remove any native oxide. Holes were formed in a silicon wafer using deep reactive ion etching (DRIE). To define a hole diameter suitable for via-hole interconnection, the holes were formed with different diameters of 30, 40, 50, and 60 μm. The DRIE conditions were as follows. The gas ratio used was SF_6:Ar = 3:2. Applied radio-frequency (rf) power was 900 W. The working vacuum had a pressure of 2 Pa. The etching rate was 2.7 μm/min, and the depth of hole was ~70 μm (Fig. 1a). A seed layer of Cr/Au (50/150 nm) was deposited successively on the surface and on the sidewall of via-hole by the dc sputter system (Fig. 1b). A thick (12 μm) negative photoresist (PMER) was coated on the Cr/Au film by a spinner and patterned by photolithography as a mold. The Au pattern was selectively electroplated on the exposed parts of the Cr/Au film. In electroplating, the current density control is one of the most important factors that influence the formation speed and the configuration of the seal ring and bonding pads. The current density of 3 A/cm^2 was adopted in this experiment. The width and thickness of Au seal ring were 100 and 4 μm, respectively. Also, the size of the cavity fabricated was $1.2 \times 1 \times 0.004$ mm. After plating, the photoresist and seed layers were removed (Fig. 1c). The O_2 plasma treatment was applied to form a clean surface and to remove organic contaminations before the bonding process. Cr/Au (50/1500 nm) film was deposited onto base wafer by an e-beam evaporator. The base wafer was processed by photolithography to produce the bonding pads. The seal ring and bonding pads on the cap wafer were aligned with the base wafer. The cap and base wafers were sent into the bonder (TPS-1000A, BNP Science, Korea) for heating in N_2 atmosphere. Also, pressure was applied to the samples during heating (Fig. 1d). Bonding temperature ranged from 300 to 350°C, pressure ranged from 0.65 to 2.5 MPa, and hold time ranged from 20 to 60 min. After the bonding

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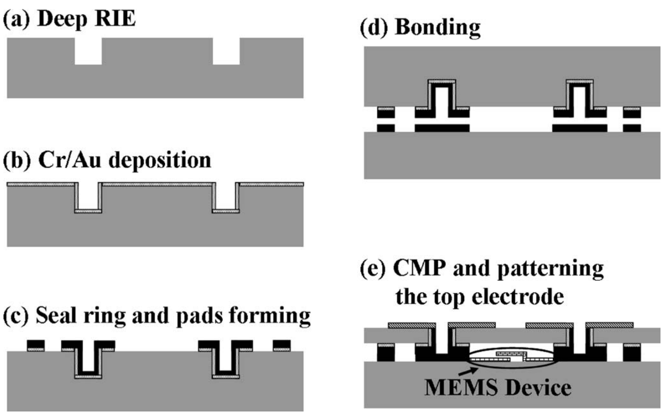

Figure 1. Schematic of process flow in the thermocompression bonding using electroplated gold layers.

process, chemical mechanical polishing was performed over the cap wafer until the holes opened. A Cr/Au(50/500 nm) metal layer was sputtered over the cap wafer. Photolithography and etching were applied to form the external terminal bonding pads (Fig. 1e). Electrical contacts could be made to the external terminal bonding pads, which were outside the hermetically sealed volume on the cap wafer. The razor blade and helium leak tests were performed to measure the bonding quality and hermeticity. Bonded interface was observed by cross-sectional scanning electron microscopy (SEM). The insertion loss was measured to evaluate the electrical and rf characteristics of the package.

Results and Discussion

To define a hole diameter suitable for via-hole interconnection, the holes were formed with different diameters of 30, 40, 50, and 60 μm. In the 30 and 60 μm diam holes, the electrical resistance appeared unstable, ranging from 2 Ω to 1.1 MΩ. In the 30 μm diam hole, the sputtered Cr particle could not be deposited completely on the sidewall of the via-hole because of the small quantities of the particles that enter inside the hole. Also, in the 60 μm diam hole, the deposition of the seed layer was discontinued because the area of the sidewall is wide. However, in the 40 and 50 μm diam holes, the resistance appeared stable from 0.019 to 0.2 Ω. Figure 2 shows the cross-sectional SEM image of the 40 μm diam hole deposited by sputtering with Cr/Au layer. Therefore, we defined the range of the hole diameter suitable for interconnect via-hole to be 40-50 μm. Figure 3 shows the cap wafer fabricated.

Various bonding conditions are listed in Table I. The bond strength was qualitatively determined with the razor blade test. A strong bond is formed when the razor blade cannot penetrate the bonding interface.[15] In Table I, the bond quality is described as follows. A good bond is formed when a razor blade cannot penetrate the bonding interface and the wafers become inseparable. Also, in these cases, the bonded wafers do not fracture at the interface. Next, a partial bond is formed when the wafers are separated from the bonding interface upon considerable force to the razor blade. Finally, a poor bond is formed when the razor blade can separate the two wafers with relative ease or the wafers do not bond at all.

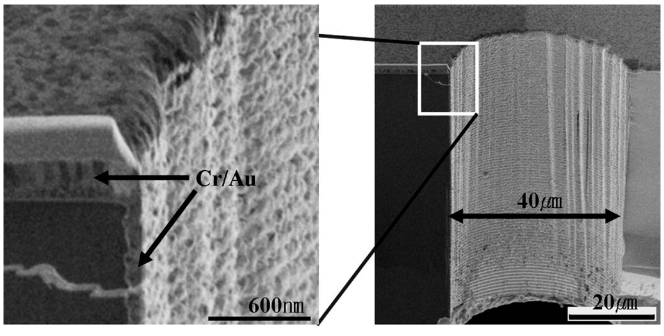

Figure 2. Cross-sectional SEM images of the 40 μm diam hole deposited by sputtering Cr/Au layer on the surface and sidewall of the via-hole.

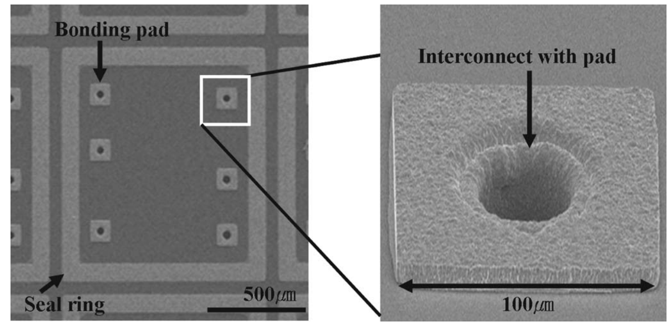

Figure 3. SEM images of the seal ring and pads fabricated by electroplating method.

Samples A, B, C were easily separated into the two wafers at 0.65 MPa and below 320°C. The hold time did not seem to have an effect on the bonding strength at 320°C. Only wafer pair E in samples B, D, E was successfully bonded at 2.5 MPa and 320°C; the wafer passed the razor blade test. The partial bonding was achieved at 1.3 MPa. The wafers in G and H had good bonding strength at high bonding temperature of 350°C. In the thermocompression bonding, atom diffusion is increased greatly under a high-temperature environment when atoms overcome the diffusion barrier to form the Au bond. As temperature is increased, the bonding time can be reduced to 20 min. without significant changes to the bonding strength. Therefore, the bonding strength of Au-Au not only depends on the bonding temperature but also on the pressure. Figure 4a shows a cross-sectional SEM image of the bonded Au-Au pads of wafer E. Figure 4b shows the base wafer forcefully removed from the cap wafer in wafer E. Fig. 4a suggests that the bond is achieved completely by diffusion of Au atoms. In Fig. 4b, the bonded wafer does not fracture at the interface of Au-Au, but at the interface of Si-Cr deposited by e-beam evaporator. Also, we found small bonded fragments of the base wafer.

Hermeticity plays an important role in the reliability and the long-term drift characteristics of the device. To evaluate the quality of hermetic packaging, helium leak rate is tested by Heliot 700 series (ULVAC). The MIL-STD-883[16] specifies a reject limit of 5.07×10^{-9} Pa m^3/s for volumes smaller than 0.40 cm^3. In the hermeticity test, wafers E, G, and H had the leak rate of $2.74 \pm 0.61 \times 10^{-11}$ Pa m^3/s. Compared to the hermetic seal requirements of MIL-STD-883, the specimens of the above wafers satisfy the hermetic sealing criterion.

For measurement of electrical and rf characteristics of the package, the co-planar waveguide (CPW) line was fabricated on the HRS

Table I. Bonding conditions in this study.

Wafer no.	Temperature (°C)	Pressure (MPa)	Hold time (min)	Bond quality
A	300	0.65	30	Poor
B	320	0.65	30	Poor
C	320	0.65	60	Poor
D	320	1.3	30	Partial
E	320	2.5	30	Good
F	330	1.3	30	Partial
G	350	1.3	20	Good
H	350	2.5	20	Good

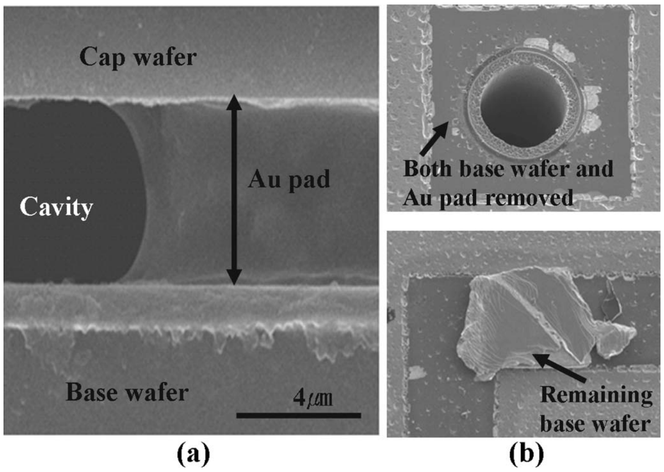

Figure 4. SEM images of (a) bonded Au-Au pad and (b) the base wafer forcefully removed from cap wafer.

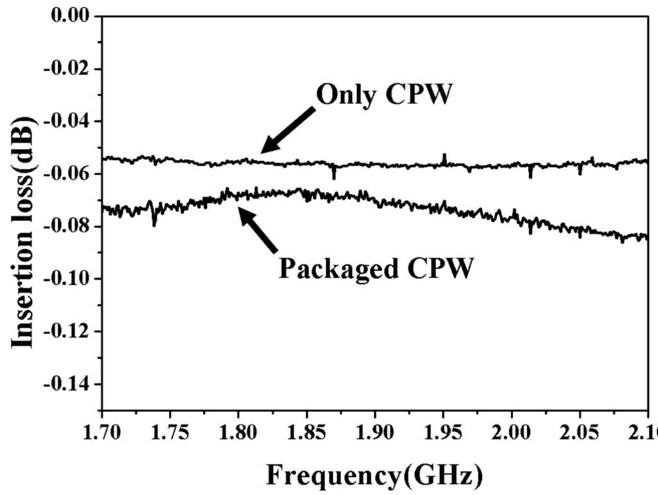

Figure 5. Plot of the insertion loss S_{21} of the CPW and the CPW packaged.

wafer. The CPW was made of gold material. The cap and base wafers having CPW were bonded. HP 8753D network analyzer was used to analyze the electrical and rf characteristics of the package. The insertion loss of the CPW line was first measured to obtain the reference of insertion loss before measuring insertion loss after the packaging. Insertion loss of the CPW is very important in the estimation of packaging characteristics. The insertion loss of the CPW was -0.054 to -0.057 dB at 1.7 ~ 2.1 GHz. Figure 5 shows the measured insertion loss of the bonded CPW throughout the 1.7-2.1 GHz band. The insertion loss of the CPW packaged was -0.069 to -0.085 dB. We obtained a very good rf characteristic after packaging the CPW line. We calculated the difference of the insertion loss between the unpackaged and packaged CPWs. The value was less than -0.03 dB. This result shows that rf-signal is well transmitted without losses after the packaging.

Conclusions

Complete thermocompression bonding using the electroplated Au solder ring and bonding pads was achieved at 320°C for 30 min at a bonding pressure of 2.5 MPa. At a relatively low pressure of 1.3 MPa, the complete bonding was achieved at a temperature of only 350°C. Therefore, we suggest that temperature and pressure are the two key factors in thermocompression bonding using the electroplated seal ring and the pads. In the process proposed, the via-hole interconnection between the packaged devices and external terminal did not need metal filling process and was made by gold films deposited on the sidewall of the via-hole. The helium leak rate was $2.74 \pm 0.61 \times 10^{-11}$ Pa m^3/s. In addition, the insertion loss of the CPW packaged was -0.069 to -0.085 dB. These values show very good rf characteristics of the packaging. We expect that the proposed themocompression bonding with Au can be applied to the hermetic wafer-level packaging of rf MEMS devices.

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