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Wafer level hermetic packaging for RF-MEMS devices using electroplated gold layers

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Abstract. Thermocompression bonding of electroplated gold is a promising technique for achieving low temperature, wafer level hermetic bonding without the application of an electric field or high temperature. Silicon wafers were completely bonded at 320℃ at a pressure of 2.5㎫. 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. In the hermeticity test, packaged wafers had the leak rate of $2.74 \pm 0.61 \times 10^{-11}$ Pa m^3/s. In the result of application in packaging of FBAR filter, the insertion loss is increased from -0.75dB to -1.09dB at 1.9㎓.

1. Introduction

MEMS packages for high reliability applications may need to be hermetically sealed to avoid stiction problem [1], and low temperature is necessary as temperature sensitive component or structure is always contained. Hermetic bonding techniques include silicon direct bonding (SDB),[2] anodic bonding,[3] intermediate layer bonding,[4] and so on. Currently SDB always require a high temperature which can't be applied to MEMS component; anodic bonding is restricted to bond glass with silicon and high electric force isn't compatible for active devices. Also, 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.[5] However, sometimes no electroplating has occurred in the holes because of the formation of air bubbles within via-holes.[6] In addition, one disadvantage of electroplating is the long process time.

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. As a noble metal, gold is an ideal bonding material. The low yield point of pure gold aids the thermocompression process. The minimum bonding temperature for eutectic bonding of Si and Au is 370°C.[7] Using thermocompression bonding of Au to Au, the bonding temperature can be further reduced.

In this study, we investigate the thermocompression bonding of electroplated Au seal line 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.

2. Experimental

The bonding process is illustrated in Fig. 1. First, high resistivity silicon (HRS, > 15000 Ω) wafer was used to reduce the substrate losses. Holes were formed in a silicon wafer using deep reactive ion etching (DRIE). The depth of hole was approximately 70 μm (Fig. 1a). A seed layer of Cr/Au (50/150 ㎚) was deposited successively on the surface and on the sidewall of via-hole by the DC sputter system (Fig. 1b). The Au pattern was selectively electroplated on the exposed parts of the Cr/Au film. The width and thickness of Au seal line were 100 μm and 4 μm, respectively. Also, the size of the cavity fabricated was 1.2 × 1 × 0.004 mm^3. After plating, the photoresist and seed layers were removed (Fig. 1c). Cr/Au (50/1500 ㎚) film was deposited onto base wafer by an e-beam evaporator. The base wafer was processed by photolithography to produce the bonding pads. 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 process, chemical mechanical polishing was performed over the cap wafer until the holes opened. A Cr/Au (50/500 ㎚) metal layer was sputtered over the cap wafer. Photolithography and etching were applied to form the external terminal bonding pads (Fig. 1e). 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.

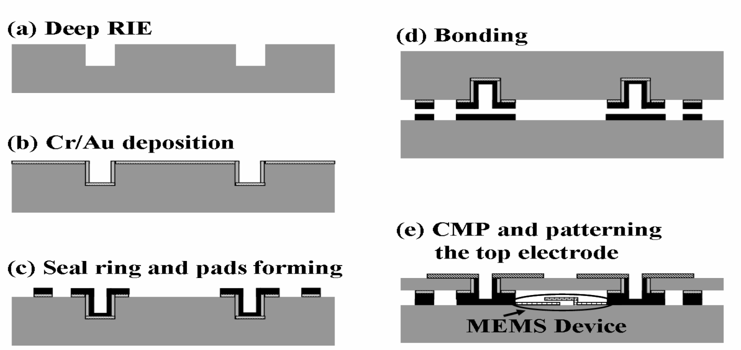

Figure 1 Schematic of process flow in the thermocompression bonding using electroplated gold layers.

3. Results and Discussion

Figure 1 shows the cap wafer fabricated by electroplating method. The conductive materials deposited on the sidewall of via-hole were well interconnected with pads.

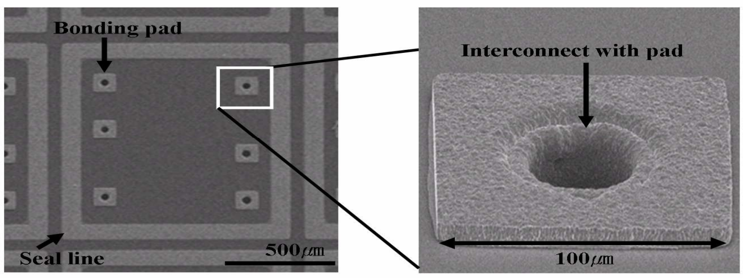

Figure 2 SEM images of the seal line and pads fabricated by electroplating method.

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.[8] 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 fracture not 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.

Table 1. Conditions and result of thermocompression bonding 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

Samples A, B, C were easily separated into the two wafers at 0.65 MPa and below 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 wafers in G and H had good bonding strength at high bonding temperature of 350°C. Therefore, the bonding strength of Au-Au not only depends on the bonding temperature but also on the pressure.

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[9] 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 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 ~ -0.057 dB at 1.7 ~ 2.1 GHz. Figure 3(a) 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 ~ -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. Also, the cap and the wafer having the band pass filter fabricated were bonded in wafer level. Insertion loss of the filter was -0.75dB at 1.9GHz. Figure 3(b) shows the result of S parameter of the bonded the filter. The insertion loss of the filter packaged was -1.09dB. A decline the characteristics in the MEMS devices frequently occur during dicing. The insertion loss of dicing was -1.31dB. This result shows that RF-signal is well transmitted without losses after the packaging and dicing.

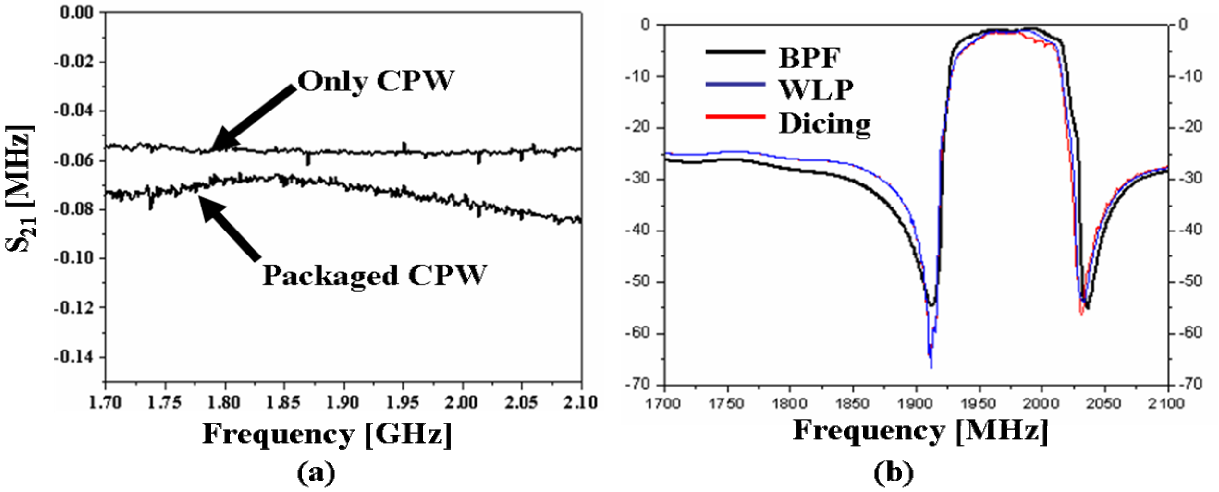

Figure 3 Plot of the insertion loss S_{21} of (a) the CPW packaged and (b) the band pass filter

4. Conclusion

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 can 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 ± 0.61 $\times 10^{-11}$ Pa m^3/s. Also, the insertion loss of the CPW packaged was -0.069 ~ -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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