The role of Ni buffer layer on high yield low temperature hermetic wafer bonding using In/Sn/Cu metallization

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Low temperature hermetic wafer bonding using In/Sn interlayer and Au/Ni/Cu metallization as the high-melting-point (HMP) components was reported, wherein the thin Ni layer was introduced as a buffer layer to prevent solder consumption after their deposition. 8 in. wafer to wafer bonding was achieved at 180 °C for 20 min under 5.5 Mpa. Voids free seal joints composed of high temperature intermetallic compounds were obtained with good hermeticity. Present results show that the buffer layer is the key to ensure high yield hermetic wafer bonding when the low-melting-point solder was deposited directly on the HMP component. © *2009 American Institute of Physics*.
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Wafer bonding has been used as an essential process step for integrating electronics, photonics, and microelectromechanical system (MEMS) devices.[1,2] Recently low temperature wafer bonding process was driven by the MEMS manufacturing because dissimilar materials will result in a mechanical stress proportional with annealing temperature. Further, in many applications such as image sensor module and radio frequency devices, low processing temperature process below 200 °C is necessary for system integration.[3] Various low temperature wafer bonding technologies have been investigated, and they are categorized as two main approaches, i.e., direct bonding using special surface treatment techniques[4,5] and intermediate layer bonding using polymers[6] or low temperature solders.[7]

Eutectic bonding is a special technique used to produce bonded joints composed of intermetallic compounds (IMCs) at a low temperature.[8] Therefore eutectic bonding ensures devices withstand higher temperatures during operation without failing. Hermetic sealing can also be realized by fluxless eutectic bonding approach that comprises a low-melting-point (LMP) solder component such as In or Sn and a high-melting-point (HMP) component such as Au, Ag, and Cu.[7] Considering the bonding temperatures, formation of voids free joints and reliable IMCs, Sn/Au and In/Au systems have been studied extensively.[7–9] Comparing with Sn and In solders, In–Sn alloy is very attractive because of its low eutectic temperature and good wettability with various common substrates.[10] Since Cu is widely used in packaging technology and much cheaper compared with Au, in this paper Cu was chosen to bond with InSn solder.

One challenge for wafer level hermetic bonding is the large total thickness variation caused by wafer warpage. Therefore, sufficient solder is required to reduce the effect of the nonplanarity issue. Since the devices become much smaller and the deposition of thick metal layer is very costly, normally the thickness of solder material is several microns.[3,7] Because the diffusion rates between low temperature solder and Cu and Au are very high, a portion of the thin solder deposited directly on these components would be consumed before bonding. We have studied the interface microstructure of Sn/In/Au/Cu metallization after solder deposition. As shown in Fig. 1, it is clear that extensive diffusion between solder and Au/Cu occurred. Upon the Cu substrate, $Cu_6(Sn,In)_5$ ternary phase was formed due to the interdiffusion between Sn, In, and Cu. In addition, Au diffused toward solder side to form AuIn phase, which was found inside the $Cu_6(Sn,In)_5$ phase. The residual low temperature SnIn phase was located at the top of the interface, as circled by dash line. According to our preliminary 8 in. wafer bonding results, the consumption of solders would lead to the low yield of good dies. Large voids and cracks were found inside the joint, and the hermeticity was quite poor. We screened the bonded dies after dicing by using cross-section scanning acoustic microscopy (C-SAM). A die was defined as a "good die" if there

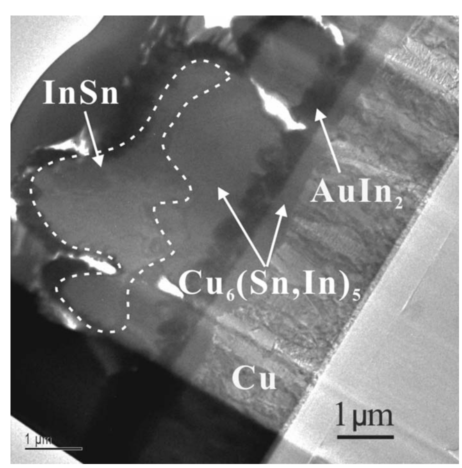

FIG. 1. TEM analysis for thin Cu2/Au0.03/(SnIn)3/Au0.03 metallization after deposition (thickness in micron). In order to obtain InSn alloy before bonding, ten thin alternatives In/Sn solder layers with each layer 0.3 μm were deposited by e-beam evaporation. The Au layers were deposited to protect the Cu and solder from getting oxidized.

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TABLE I. A view of preliminary bonding results without buffer layer.

Wafer pair	Cap wafer (thickness in micron)		Bottom wafer (thickness in micron)		Bonding parameter			
	HMP component	Solder	HMP component	Solder	Pressure (MPa)	Temperature (°C)	Time (min)	Yield (%)
1	Cu2/Au0.03	(Sn/In)3[a]	Cu2/Au0.03	(Sn/In)4[b]	3.0	180	20	44
2	Cu2/Au0.03	(Sn/In)3[a]	Cu2/Au0.03	(Sn/In)4[b]	5.5	180	20	67

[a]Ten layers in turn, each layer was 0.3 μm.
[b]Ten layers in turn, each layer 0.4 μm.

were no detectable voids and/or cracks under C-SAM. The bonding yield was further defined as the percentage of good dies to the gross dies of a bonded wafer. As listed in Table I, the bonding yield was 44% and 67% with the pressure of 3 and 5.5 MPa under 180 °C for 20 min. Limited improvement was observed when the bonding pressure was increased.

To control the diffusion process, a thin buffer layer is introduced into the HMP components. As described in Fig. 2, the buffer layer has two main effects. First, it can prevent fast diffusion between the low temperature solder and Cu component during storage and the step of heating up in bonding process. Second, the thin buffer layer would dissolve into the solder quickly at the beginning of the soldering reaction. Then the diffusion between the solder materials and the Cu started and finally all solder was converted into IMCs. Since the buffer layer saved the low temperature materials for soldering, the yield of wafer bonding would be improved. Because Ni is well known as a barrier layer for Sn based solder and Cu substrate and it can easily diffuse into Cu based IMCs,[11] a thin Ni layer was used as a buffer layer in this present study.

Square rings with the width of 300 μm and length of 11 mm were fabricated on 8 in. wafers. At first, 300 Å thick SiO_2 and 1500 Å SiN were formed on silicon wafer in turn by the thermal oxidation and low pressure chemical vapor deposition process. They acted as hard mask for cavity etching. The patterning process was done by photolithography using dry film as a photoresist material. Cavity with area of 6×6 mm^2 and 250 μm in depth was formed using wet-etching process with KOH inside of each bonding ring on both the cap wafer and the bottom wafer. Ti–Cu–Ni–Au metallization was sputtered on $Si/SiO_2/SiN$ substrate as the HMP component for diffusion bonding. The thickness of Ti–Cu–Ni–Au metallization was designed as 0.05, 2, 0.05, and 0.03 μm, respectively. Here thin Ti layer acted as the adhesive layer, and Ni was the buffer layer. A thin Au layer was necessary for wetting and to prevent metals from oxidizing before solder deposition. Four alternatives Sn/In solder layers with the thickness of 1, 1, 0.8 and 07 μm were deposited in turn in an e-beam evaporation chamber. To protect solder surfaces from getting oxidized, a 0.03 μm thick Au layer was deposited on the top at last. After deposition and dry film stripping, O_2 plasma descum was conducted before the bonding process to remove the oxide layer and organic contaminants to obtain a clean surface. Two wafers with the same structure and materials systems were then bonded face to face using wafer bonder (EVG520) in controlled N_2 atmosphere. In the present case, bonding pressure was 5.50 MPa and bonding temperatures was 180 °C. The bonding time was 20 min at peak temperature.

After bonding, the bonded wafers were diced into dies with size of 13×13 mm^2 with a dicing speed of 2 mm/s. All dies from bonded wafers were checked with C-SAM to evaluate the bonding quality of the seal rings. There were no detectable voids in any single seal ring. That meant a 100% yield after bonding was achieved by present bonding method. One typical C-SAM graph of dies was shown in Fig. 3. Each bonding ring was in a uniform gray color indicating the bonded joints have intimate contact.

Five dies were mounted and cross sectioned for scanning electron microscopy inspection. Energy dispersive x-ray (EDX) analysis was used to check the compositions of the bonded ring joints. The interfacial microstructure showed that voids free joints were obtained after bonding. As shown in Fig. 4(a), thick remaining Cu and thin IMC layers were found in the joint, and two kinds of IMCs were detected by EDX. The composition of the main phase in gray color corresponded to the $(Cu,Ni)_6(Sn,In)_5$ η phase.[12] Another particle compounds embedded in η phase with white color belonged to $Au(In,Sn)_2$ phase. According to the present materials design, the thickness of seal joint should be around 10 μm. However, the achieved thickness value was about 7 μm. The reason is that under present bonding temperature, solder materials melt fast and had a good flowability. When

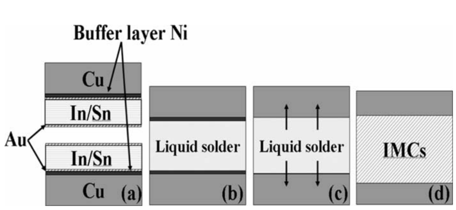

FIG. 2. Schematic drawing of the role of buffer layer during bonding: (a) before bonding, (b) liquid solder formed at the beginning of wafer bonding, (c) buffer layer dissolved into solder, and (d) high temperature IMC joint formed finally during bonding.

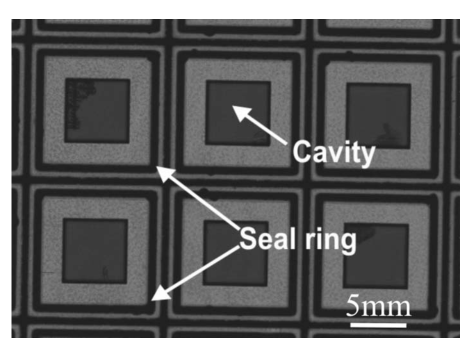

FIG. 3. C-SAM graph of bonded dies.

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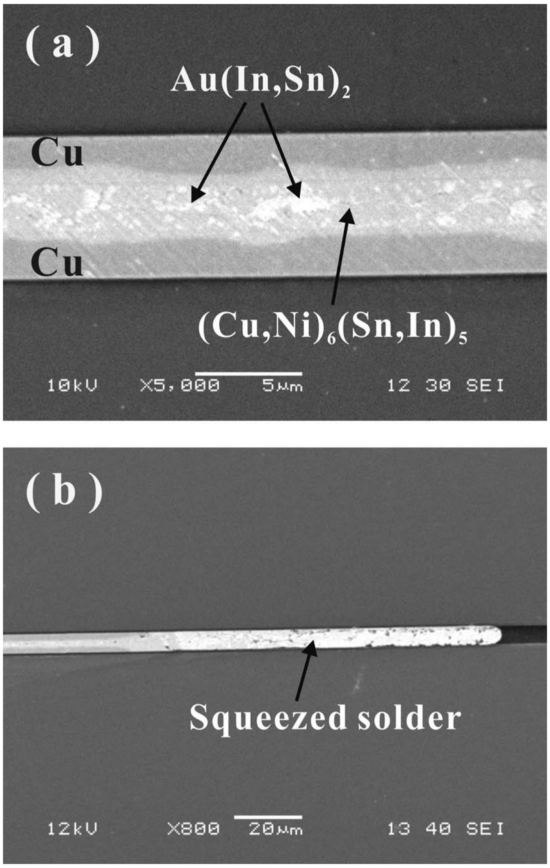

FIG. 4. Interfacial microstructure of the joint bonding at 180 °C: (a) high temperature IMC joint and (b) squeezed solder out of the seal ring.

bonding pressure was applied, a portion of liquid alloy was squeezed out. As shown in Fig. 4(b), the length of the squeezed solders was about 80 μm.

In order to know the kinetics of the bonding process involving Ni buffer layer, transmission electron microscopy (TEM) and EDX analysis were performed upon seal joint. It was found between Cu and $(Cu,Ni)_6(Sn,In)_5$ phase that a thin layer of $Cu_6(Sn,In)_5$ (~200 nm thick) existed. Island shape $Au(In,Sn)_2$ particles embedded in the $(Cu,Ni)_6(Sn,In)_5$ phase were also determined. These results confirmed that after bonding, Ni buffer layer has been dissolved into $(Cu,Ni)_6(Sn,In)_5$ phase. The whole bonding process involving buffer layer can be explained as follows. First, due to the slow reaction between solder and Ni, liquid solder alloy formed at the bonding temperature. Then liquid solder started to wet and react with thin Ni buffer layer. Ni dissolved into solder as Ni_3Sn_4 (Ref. 13) or NiInSn (Ref. 14) ternary phase. Since Ni buffer layer is very thin, after a short time, InSn solder would start to react with Cu to form $Cu_6(Sn,In)_5$ compounds. Since Ni has a large solubility in the $Cu_6(Sn,In)_5$ compounds, chemical potential gradient would generate, which led the dissolution of the Ni containing compounds. Finally, All Ni atoms went into $Cu_6(Sn,In)_5$ solution to form $(Cu,Ni)_6(Sn,In)_5$ phase.

The hermeticity of the ring seals for patterned dies was evaluated by helium leak rate tests based on MIL-STD-883.[15] According to the internal cavity volume of the bonded dies ($\sim 0.02\ cm^3$), the pressure of helium gas in bombing chamber was set as 75 Psia and exposure time was 2 h. After bombing, the dies were put into helium leak detector to measure the leak rates. 20 bonded dies were tested. The testing results showed that the leak rates of all the samples bonded at 180 °C were smaller than 5×10^{-8} atm cc/s, which indicated that the dies obtained acceptable hermeticity according to the criterion of MIL-STD-883. To evaluate the mechanical properties of the seal ring joints, five samples were used for shear tests. The shear test was conducted with a shear tester (BT4000 Dage) using a speed of 50 μm/s. The average shear strength of the joints was 32 Mpa, which meant robust bonding strength was achieved for these patterned dies.

In summary, 8 in. wafer level hermetic bonding using In/Sn solder as the interlayer and Cu as the main HMP component was investigated. By introducing Ni buffer layer into the HMP components, 100% bonding yield was achieved at 180 °C with a bonding pressure of 5.5 MPa for 20 min. The thin Ni buffer layer played a key role for wafer bonding by controlling the diffusion bonding process. After bonding, voids free seal joints composed of high temperature IMCs were formed with a small part of squeezed solder at the edges. In addition, the seal rings had good hermeticity and robust shear strength.

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