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Full intermetallic joints for chip stacking by using thermal gradient bonding

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ABSTRACT

Solid-liquid interdiffusion bonding is a promising process for three dimensional chip stacking, but nevertheless is plagued with low throughput. A new solid-liquid interdiffusion bonding process, with much higher bonding speed, is proposed in this study. Instead of using a homogeneous bonding temperature, a temperature gradient is superimposed across the joint in the new process, which possesses many advantages. Firstly, the new process is 3–10 times faster, depending on the bonding parameters. Secondly, columnary Cu_6Sn_5 grains grow from the cold-end to the hot-end, with the crystallographic orientation of Cu_6Sn_5 preferentially aligned along the (0001) pole. Lastly, the new process consumes very little Cu substrate at the cold-end due to the fact that most of the Cu atoms are from the hot-end. The mechanism for the new process is proposed and experimentally verified in this study.

1. Introduction

Solid-liquid interdiffusion (SLID) bonding is a very promising technology for chip bonding and chip stacking in three-dimensional integrated circuits (3D ICs) process [1]. This bonding process, also known as isothermal solidification or transient liquid-phase bonding, has been used very successfully for joining high temperature alloys for many years [2]. It has the advantage of not requiring high pressures needed in typical solid state diffusion bonding processes. It utilizes an interlayer with a relatively low melting point that melts and solidifies as a result of interdiffusion with the substrates. The major limitation of the SLID process is that the latter stages of SLID bonding involve solid-state diffusion and therefore the process is relatively slow, usually requiring several hours.

Investigations on adapting the SLID process for semiconductor bonding started very early. Bernstein [3] proposed in 1966 using Ag-In, Au-In, and Cu-In systems to bond two individual chips. The key concept of Bernstein's idea for semiconductor bonding is summarized in Fig. 1. First, a layer of a high melting point (T_m) metal, *e.g.* Ag, Au, or Cu, is deposited onto each of the surfaces of the two chips to be joined. Additional adhesion layer(s) between each chip and the high T_m metal may exist, but these adhesion layer(s) do not participate in the bonding reaction and are omitted here for simplicity. Subsequently, a layer of low T_m metal, *e.g.* In or Sn, is deposited onto each of the surfaces of the high T_m metal, as illustrated in Fig. 1(a). Secondly, the two chips are then brought into contact and kept at a temperature between the high T_m and low T_m to melt the low T_m metal, as illustrated in Fig. 1(b). Interdiffusion occurs and the molten metal reacts with the high T_m metal, forming intermetallic compounds (IMCs). During bonding, the joint undergoes isothermal solidification process until the last molten metal is completely consumed by the formation of IMCs, as illustrated in Fig. 1(c). As IMCs usually have much higher melting temperatures, the joint is able to withstand a high service temperature. In short, SLID has the distinctive advantage of being able to be bonded at a low temperature for service at a higher temperature. Nevertheless, SLID being a relatively slow process is the major roadblock that prevents SLID from finding widespread applications in semiconductor industry.

To speed up SLID processes, the amount of molten metal has to be as small as possible. Typical micro solder joints in 3D ICs have diameters of about 5–15 μm [1,4], one order of magnitude smaller than the next smallest type of solder joints in electronics. Such a characteristic makes 3D ICs micro joints particularly suitable for SLID implementation [1,5]. However, recent experimental studies

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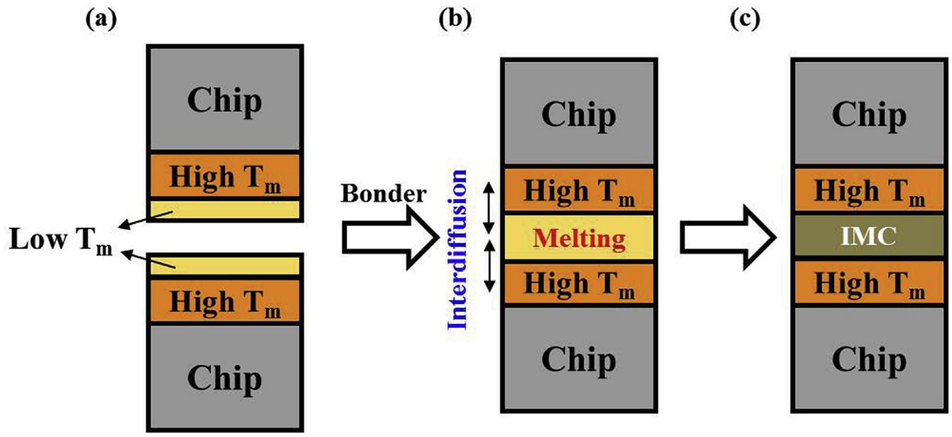

Fig. 1. Illustrations showing the SLID bonding process. SLID does not require too much pressure due to the formation of a liquid layer. The combination of low bonding pressure and temperature makes SLID ideal for bonding delicate devices such as 3D ICs.

by several research groups [6–12] consistently showed that the time required to produce full IMC joints was longer than 10 min even for micro joints as small as 10 μm. To make the bonding process economically viable for mass production, the bonding time has to be well within 10 min.

The objective of this paper is to report a novel bonding process that is based on the SLID process but is much faster. The underlying mechanism responsible for this faster process is also discussed. In conventional SLID bonding, the entire sample is subjected to a uniform temperature environment. In this study, we show that the bonding can be accelerated if a proper temperature gradient is superimposed across the two chips.

2. Experimental

A layer of Cr (300 Å) as the adhesion layer and then a layer of Cu (3000 Å) as the seed-layer were sputter-deposited on each of the silicon wafers (500 μm thick) used in this study. A 30 μm Cu layer was then electroplated over the seed layer. The electroplated Cu layer served as the high T_m layer illustrated in Fig. 1(a). The wafers were then sectioned into 3 mm × 3 mm chips. Two such Si chips were aligned head-to-head separated by a Sn layer, which served as the low T_m layer, as illustrated in Fig. 2.

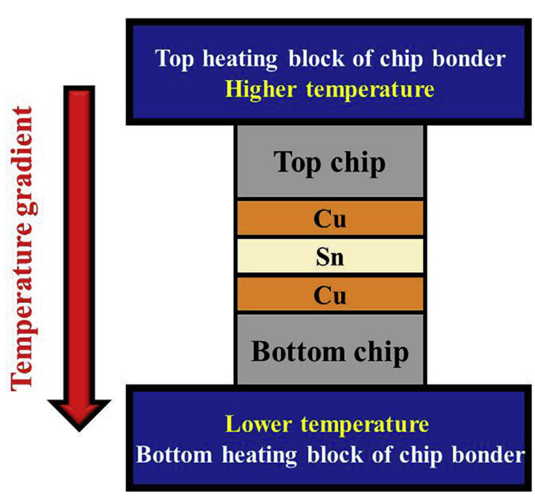

Fig. 2. Illustrations showing the thermal gradient bonding (TGB) process used in this study. A temperature gradient is obtained by setting different temperatures to the top and bottom heating blocks.

The bonding process was carried out by using a flip-chip bonder. The distance between the top and the bottom chips was maintained by a spacer, as described in a previous work [11]. The heating of the chips was through thermal conduction from the top and the bottom ceramic heating blocks. Isothermal heating could be established by keeping the two heating blocks at the same constant temperature. Alternatively, a temperature gradient could be introduced by keeping the two heating blocks at different temperatures.

After bonding, the joints were cross-sectioned and polished for further observation. Scanning electron microscopy (SEM) and energy dispersive X-ray spectrometry (EDX) were utilized to examine the microstructure and identify the chemical compositions of the IMCs. Electron backscattered diffraction analysis (EBSD) was used to establish the crystallographic orientation of IMCs.

3. Results

3.1. Thermal gradient bonding (TGB) versus conventional SLID

Fig. 3(a)–(d) shows the cross-sectional micrographs of Cu/Sn (10 μm)/Cu sandwiches after TGB for 1, 2, 3, and 5 min, respectively. The top heating block was kept at 300 °C, and the bottom heating block at 200 °C. After 1 min, highly asymmetry growth of IMCs was observed, with thicker Cu_6Sn_5 at the cold-end and thinner Cu_6Sn_5 at the hot-end, as shown in Fig. 3(a). The Cu_6Sn_5 grains exhibited the classical scallop morphology. The asymmetric growth of Cu_6Sn_5 became more obvious as the bonding time increased to 2 and 3 min, as shown in Fig. 3(b) and (c), respectively. When the bonding time reached 5 min, as shown in Fig. 3(d), the Cu_6Sn_5 grains growing from the cold-end had impinged on the hot-end. The larger Cu_6Sn_5 grains from the cold-end merged with the smaller ones at the hot-end, becoming many single grains that spanned across the sandwich. The morphology of the grains had changed from the initial scallop-type to columnary. It is believed that at this state the joint is sturdy enough to withstand subsequent chip-stacking without collapse because a solid phase spans across the entire joint.

The most important advantage of TGB is that the growth of Cu_6Sn_5 grains is much faster and the necessary time for vertical grain impingement is shorten substantially. Fig. 4(a)–(b) shows the cross-sectional micrograph of Cu/Sn (10 μm)/Cu sandwiches after conventional SLID bonding at a homogeneous temperature of 250 °C for 15 and 20 min, respectively. The temperature of 250 °C corresponded to the average temperature of top heating block (300 °C) and the bottom heating block (200 °C). Scallop-type