

High-strength Si wafer bonding by self-regulated eutectic reaction with pure Zn

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A method for bonding Si wafers has been developed using pure Zn as a solder. This process can be carried out under atmospheric pressure without metallization. The resulting shear strength of the bonding exceeds 50 MPa, significantly higher than the typical strength of conventional Au–20Sn solders. The superior results are ascribed to a uniform and void-free interface created by a self-regulated Si–Zn eutectic reaction. Our cost-efficient wafer bonding method may have a wide range of applications in Si-based devices.

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Si wafer-to-wafer bonding is recognized as a key technology for three-dimensional system integrations, such as multi-tip large-scale integration devices, stacked memories and microelectromechanical systems (MEMS) [1–3]. A considerable number of Si wafer bonding methods have been proposed in the literature [4–8], and these are generally classified into two categories: direct fusion and intermediate layer bonding [6]. The former process requires heat treatment at high temperatures, ~1000 °C, to create a fusion layer between directly contacted Si wafers [1,2]. The latter, in contrast, can be processed at considerably lower temperatures by adopting an intermediate bonding layer of polymeric [4] or metallic [5–8] material inserted between Si wafers under certain pressure. In this category, Au–Si eutectic bonding has been used for integrated circuits packaging and MEMS applications [5–7]. Typical drawbacks of this method, however, are the formation of air voids and facet pits caused by uncontrolled Si dissolution into the Au layer in the Au–Si eutectic reaction [5–7,9]. A sound bonding interface with high strength, i.e. uniform interface without any void/defect formation, is rarely achieved by the Au–Si eutectic method, and usually requires more metallization layers on the Si wafer, such as Ni, Pt or Cr. Nevertheless, the high cost of Au is

another drawback to using Au–Si bonding in commercial products. The high demand for establishing an effective but cost-efficient wafer-to-wafer bonding technique in the vast field of Si technologies has motivated us to develop an ideal bonding process based on our recent achievements, particularly on lead-free solder materials [10–12]. In this paper, we therefore propose a novel bonding process of Si wafers by utilizing a self-regulated Si–Zn eutectic reaction. Using pure Zn as intermediate solder material, our bonding method is processed in air, at atmospheric pressure, without surface metallization of Si wafers. The self-regulated Si–Zn eutectic reaction provides a thin and uniform bonding layer, resulting in a higher bonding strength than that achieved by other competing techniques. As well as the low cost of the process, the present method demonstrates promising interconnection features of bonded Si wafers.

Pure Zn (>99.99%), cold-rolled into 100 µm thick sheet, and mirror-polished 525 µm thick Si(100) wafer were prepared for the present study. The Zn sheet was cut into 10 mm × 10 mm specimens. Each surface of the specimens was then mechanically polished, and finished using 0.1 µm Al₂O₃ abrasive powder. The final dimensions of the Zn sheets were 10 mm × 10 mm × 0.05 mm. Two sizes of Si specimens, 10 mm × 10 mm and 15 mm × 15 mm, were cut from the prepared Si(100) wafer. Before bonding, these Si and Zn specimens were degreased in acetone and 20 vol.% aqueous HCl solution, and then rinsed with ethanol and deionized water, and

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finally dried under high-pressure air. The prepared Zn sheet was inserted between two Si wafers (the larger one, 15 mm × 15 mm, at the bottom), and held under a slight pressure (~ 2 kPa) of a 20 g Ni block, as schematically shown in Figure 1a. The prepared specimens were heated in an oven for 20 min at 450 °C, which is 30 °C higher than the melting point of pure Zn ($T_m = 419.58$ °C). For comparison, Si wafer bonding tests with using commercial Au–20Sn solder were carried out under similar processing conditions, but at a lower bonding temperature of 310 °C, which is also 30 °C higher than the liquidus temperature (280 °C) of the eutectic solder.

The quality of a wafer bonding can generally be evaluated by its mechanical properties since high bond strength is the fundamental issue for device packaging. Hence we first evaluate the mechanical properties of the bonded specimens by shear tests using a Dage 4000 where the head speed is set to $5 \mu\text{m s}^{-1}$ and the fly height to 50 μm from the base tip surface. As displayed in Figure 1b, the typical shear strength of pure Zn bonding exceeds 50 MPa, significantly higher than other methods reported in the literature: conventional Au–20Sn eutectic solder has a shear strength of <8 MPa, and Au–Si ~ 20 MPa [7]. These measurements may even underestimate the bonding strength of pure Zn because Si wafer always exhibits fractures around 50 MPa during the tests (see the picture presented in the inset of Fig. 1b). The breakage of Si wafer implies that pure Zn bonding exhibits sufficient mechanical strength as a soldering material for Si wafer. It is noteworthy that the process using pure Zn as an intermediate material does not require any metallization layer on Si surface to achieve this high bonding strength.

To reveal the origin of the high bonding strength of the Si/Zn interface, we have observed the cross-section microstructure of the bonding interface by field-emission scanning electron microscopy (FE-SEM). The SEM images in Figure 2a–d present a typical interface microstructure of Si and pure Zn bonding, and that of Au–20Sn soldering. The interface morphology resulting from the two bonding methods is different each other: pure Zn appears to wet well on the wafer surfaces of both sides,

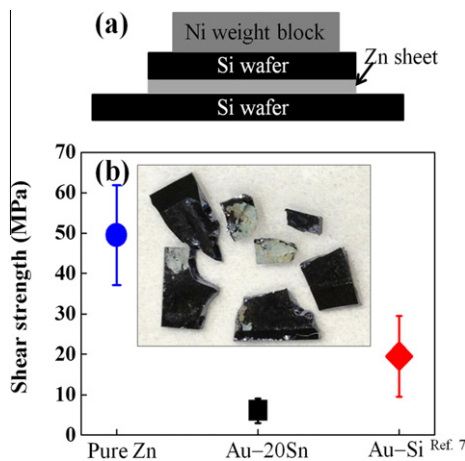


Figure 1. (a) Schematic of the present bonding structure. (b) Shear strengths of wafer bonding by pure Zn, Au–Si [7] and Au–20Sn. The inset image shows a typically broken specimen of pure Zn by fracture during the shear tests.

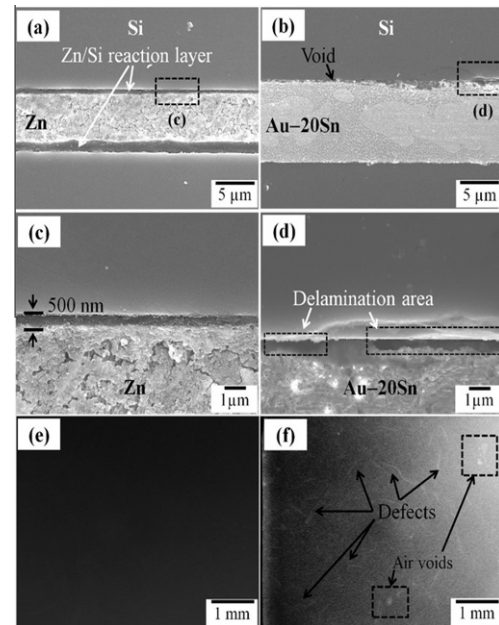


Figure 2. Cross-section images of bonding interface (a) with pure Zn and (b) with Au–20Sn. (c) and (d) are magnified images of (a) and (b), respectively. (e) Transmission X-ray images with no air void in pure Zn bonding; (f) images showing many defects in Au–20Sn soldering.

and creates uniform and void-free reaction layers with Si (see Fig. 1a). In contrast, no reaction layer is found at the Au–20Sn/Si interface as shown in Figure 2b; instead, a massive air void and an area of delamination area are observed. Higher-magnification images in Figure 2c and d confirm that the reaction layer at the Zn/Si interface is ~ 500 nm thick, but no reaction layer formed at the Au–20Sn/Si interface. In the literature, similar air void formation at the bonding interface between Si and intermediate materials have been reported, and those air voids are considered to be due to excessive Si dissolution into the Au layer, particularly when a Au–Si eutectic reaction occurs [9,13]. The differences of interface morphologies observed in the SEM images may explain the variation in joining strength registered in the shear tests. The uniform reaction layer between pure Zn and Si causes the high shear strength, while the absence of such a reaction layer in Au–20Sn solder results in poor mechanical bonding. The FE-SEM cross-section observations in Figure 2d thus confirm that the presence of an intact reaction layer is essential to achieving high joining strength in wafer bonding processes.

Transmission X-ray imaging was utilized to observe air void formation at the Si and intermediate material interfaces of the bonding test specimens in the present study. However, no detectable void or defect could be observed in the pure Zn bonded wafer specimens (see Fig. 2e). In contrast, the specimens of Au–20Sn bonding typically display many defects as shown in Figure 2f, supporting the observation of poorly connected areas of the bonding interface in the FE-SEM image of Figure 2d. The void-free interface recorded by X-ray transmission imaging again demonstrates the superior feature of our Si wafer bonding with pure Zn.

The formation process of the uniform reaction layer can be explained from the Si–Zn binary phase diagram

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