Degradation of the Au_4Al compound in gold ballbonds during isothermal aging in air at 175 °C

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During molding of wire-bonded packages and soldering of packages at the board level, gold ballbonds are exposed to prolonged (2–3 hr during postmold cure) and high-temperature excursions in the range 180–250 °C that cause intermetallic compound growth. Gold ballbonding relies on the formation of a thin layer of such intermetallics during wirebonding to ensure a mechanically robust joint, but the manner in which they grow at high temperatures can affect mechanical reliability. If the joint weakens as intermetallics grow, due to void formation for example, the working life time of a package may be reduced. In the microelectronics packaging industry, a common screening test of the mechanical reliability of bare-bonded devices is isothermal aging at temperatures of 150–200 °C followed by pull testing. Several studies have reported extreme loss of mechanical strength (pull and shear) due to the formation of voids [1–4], while others report good bonds after extended isothermal aging at 175 °C for 1000 hr [5]. Void formation is usually attributed to the ‘Kirkendall’ effect, but contamination-induced corrosion may also reduce bond strength [1]. Recently renewed interest in the effects of intermetallic growth on the reliability of ultra-fine pitch packages has grown, for which reason ball lifts at short bake times are often observed [6].

A degradation mechanism which appears to depend on bonded ball squash height was observed during a study of gold ballbond mechanical reliability. A 20 μm diameter 4 N Au wire was bonded on a 50 μm pitch device with 10000 Å thick Al-1 wt% Si-0.5 wt% Cu pad metallization attached to a BGA substrate. A K&S 8028 120 kHz wire bonder was used to bond 208 wires with a ball diameter of 40 ± 2 μm and squash height of 6 μm or 7 μm. Devices were baked at 175 ± 5 °C in air in a fan-assisted oven up to 1000 hr. Forty wires were pulled and shear tested using a Dage 4000 series tester with pull velocity of 300 μm/s, shear velocity of 100 μm/s and tool height of 5 μm.

Pull and shear test results in Fig. 1a show that mechanically robust bonds are obtained with the 7 μm squash height. In every pull test, the wire showed the standard neck break mode at all times up to 1000 hr. However, Fig. 1b shows how the 6 μm squash height displays a drastic decrease in the pull and shear strength of the bonds after 200 hr, and after 500 hr of baking and shows widely varying pull strengths that consist of the usual neck breaks mixed with low strength and high strength ball lifts (referred to as LSBLs and HSBLs, respectively). At 1000 hr the 6 μm squash height shows only LSBL failures. The appearance of typical low strength (LSBL) and high strength ball lifts (HSBL) at the pad side after 500 hr of baking is shown in Fig. 2. The LSBL surface looks like a brittle fracture surface but the very low strength shows that fracture did not occur. The surface of the HSBL failure shows an annulus that grows from the outside edge of the ball inwards, with a similar surface texture as the LSBL, but what differentiates the HSBL is the presence of a well-adhered layer of gold at the pad center that was plastically deformed during pull testing, resulting in high strength even though the failure mode is technically a ball lift. At 1000 hr only low strength ball lifts (Fig. 2a) are observed, which leads to the conclusion that the annulus seen in the HSBL grows further inward until there is insufficient gold to support the extensive plastic deformation, and low strengths are observed. Thus the HSBLs transform to LSBLs by the growth of the annulus.

Cross-sections of the balls (Fig. 3) show that the annulus grows from the outside of the bonded ball. From Fig. 3 it appears that the Au_4Al compound disappears while the Au_5Al_2 compound is unaffected during baking, which suggests some type of chemical reaction. Such a reaction may also be enhanced by the presence of surface contamination (F, C, O) and the presence of Cu and Si in the bondpad, which may either be part of the intermetallic compound structure and may also affect the chemical stability of the compounds. Currently, the effects of such contamination are not well understood. It is possible for intermetallic compounds to oxidize. Oxidation of various types of binary aluminides has been widely studied [7] and while there are subtle and important differences, depending on the binary systems, the oxidation mechanism appears similar, with Al diffusing out of a solid solution to form Al_2O_3 at the alloy surface, leaving behind an enriched phase beneath the oxide. The oxidation of Au-Al intermetallics in thin films was recently studied by Piao and McIntyre [8] and Cong *et al.* [9]. This shows that bulk Au-Al aluminides, especially Au_4Al, appear to rapidly and easily oxidise, although bulk and thin/thick film chemical degradation mechanisms are not necessarily identical. It is likely that a more complex multi-component

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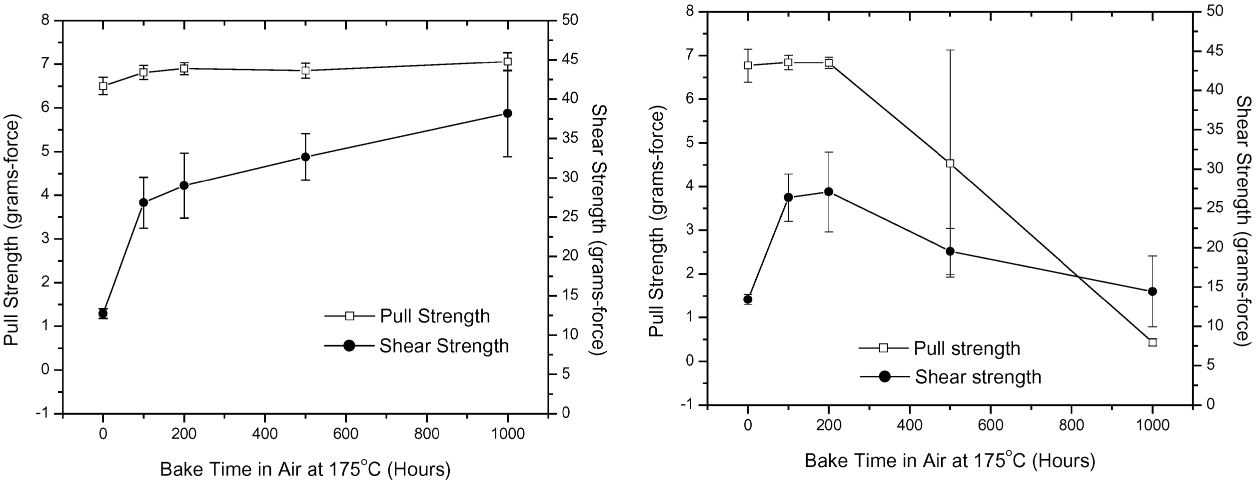
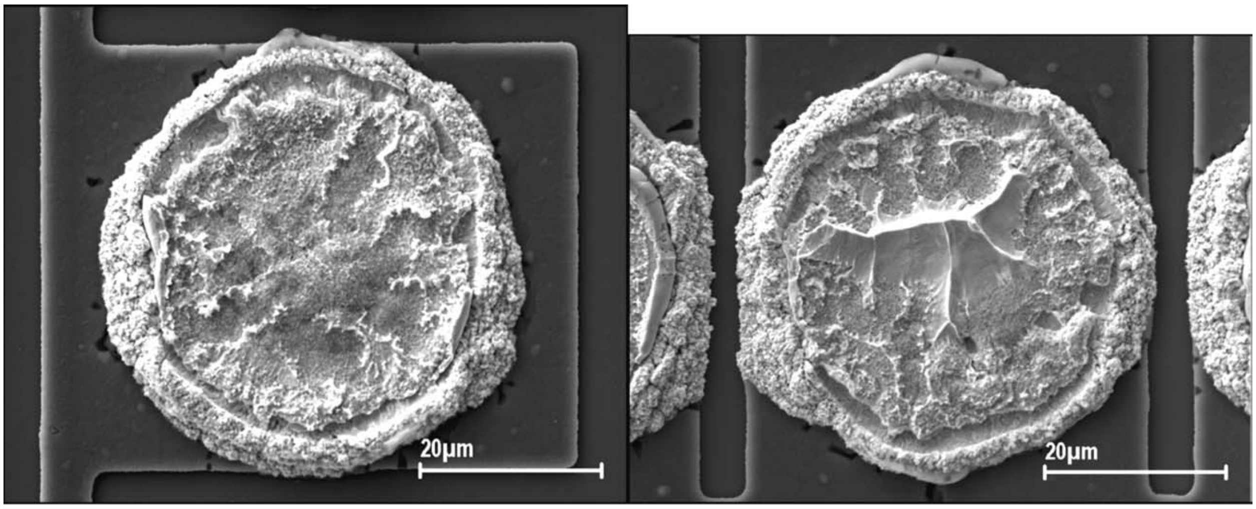


(a) (b)

Figure 1 Pull strength and shear strength of ballbonds with (a) 7 μm mean squash height and (b) 6 μm mean squash height after isothermal aging at 175 °C in air.



(a) (b)

Figure 2 SEM images of the surfaces of bondpads from 6 μm squash height ballbonds showing (a) low strength ball lift with brittle fracture, 0.5 gf lift and (b) high strength ball lift with brittle fracture and ductile failure within gold wire, 7 gf.

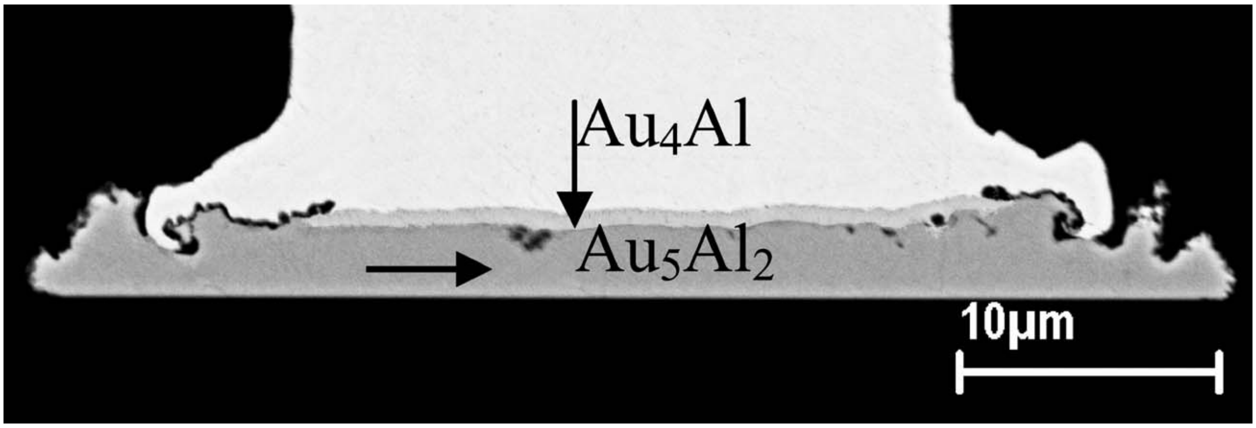


Figure 3 SEM, SE image of a cross-section of 6 μm squash height ballbonds on Al-1 wt% Si-0.5 wt% Cu pad, showing only two phases with a layered structure after annealing for 1000 hr at 175 °C in air.

oxidation process can take place in intermetallics formed between doped Au wires and alloyed Al pad metallization.

For the intermetallic compound in a ballbond to oxidize, there must be contact with air. From Fig. 1 there is no degradation in pull strength between 200 and 500 hr so there is an apparent incubation time. Breach and Wulff [10] demonstrated that within about 20 hr of aging in air at 175 °C, all of the Al pad metal is converted to intermetallics but the intermetallic does not grow

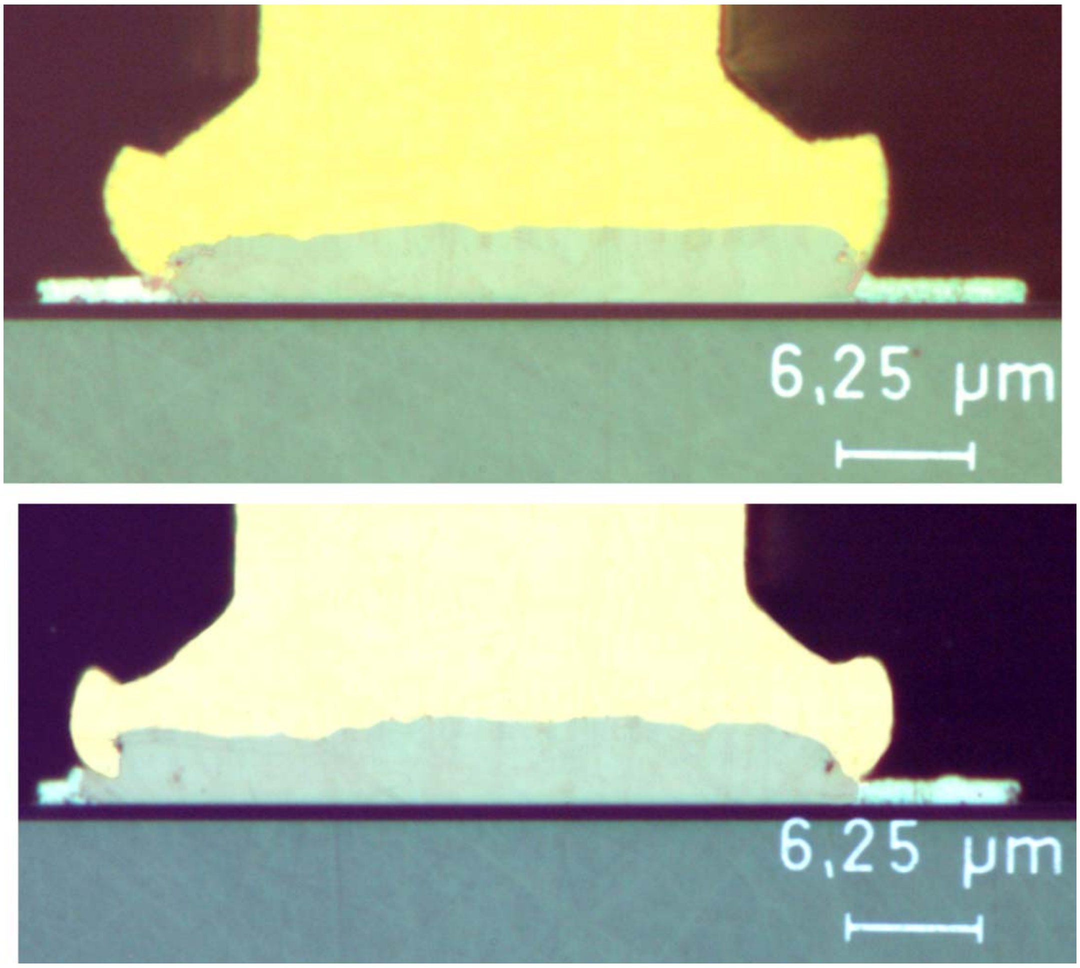


Figure 4 SEM images of unetched samples after 20 hr (top), and 50 hr (bottom) at 175 °C.

beyond the edge of the ball until 50–100 hr. Therefore contact between intermetallic and air cannot be established until approximately 50 hr have passed and from 50 to 200 hr the annulus must grow so slowly that the contact area at the ball-pad interface is still large enough to result in neck failures during pull tests. Cross-sections of the samples in Fig. 4 show that for the ballbonds in this study, the intermetallic does not make contact with the outer region of the ball until around 50 hr.

HSBLs should be encountered approximately when the contact area approaches the wire diameter. The annulus can effectively act as a notch, concentrating the stress and initiating a blunt crack that propagates into the gold wire, undergoing extensive plastic deformation. Assuming a linear growth velocity v for the annulus, and a bonded ball radius of r_b, a simple expression for the radius of the ball in contact with the pad as the annulus grows is $r(t) = r_\mathrm{b} - vt$. Assuming that the critical time at which HSBLs occur is 300 hr and the incubation time is 50 hr then with $r_\mathrm{b} = 20\ \mu\mathrm{m}$ and $r(t) = 10\ \mu\mathrm{m}$, the velocity v can be estimated as $\sim$11 pm/s. A crude estimate of the time taken to form HSBLs with a 40 μm bonded ball is $\sim$150–200 hr. However, using the same devices and wires but with a different mean squash height of 7 μm the result was zero defects of the type seen in Fig. 2, and bonding parameters as well as ballbond geometry appeared to be influential.

The results shown here suggest that chemical degradation of the $\mathrm{Au_4Al}$ compound occurs, which may be due to oxidative degradation. Bondpad contaminants which can act as catalysts may also play a role in the degradation process. The role of stress and squash height in connection with oxidation or corrosion of Au-Al intermetallics in gold ballbonds has not been studied in detail. Further investigations into these types of failures, particularly the role of bondpad surface cleanliness, wire and pad metal composition, and bonding parameters is important for the microelectronics industry, especially as wirebond pad pitches of 35 μm are approached. In ultra-fine pitch applications, more precise control of ballbond geometry and bonding conditions may become important in ensuring reliable wirebond processes.

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