

Mechanical properties characterization of CuSn intermetallics for advanced flip-chip bonding

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Abstract

In this paper, we investigate the mechanical properties of CuSn intermetallics formed in the Cu/Sn system in three different ways. First, we characterize CuSn intermetallic films by nano-indentation. Here the CuSn intermetallics are formed by interdiffusion of Cu/Sn bi-layer films. Second, we do Cu/Sn flip-chip bonding to form CuSn intermetallic joints and then characterize the intermetallics on small bumps also by nano-indentation. Third, unlike the afore-mentioned two approaches, we fabricate a free-standing CuSn intermetallic beam for micro-tensile test, from which we can extract the Young's modulus, yield strength, and fracture strength. Combining all these experiments, we find the Young's modulus of CuSn intermetallic is between 75 to 150 GPa, the yield strength is ~810 MPa, and the fracture strength is ~980 MPa.

Keywords: Intermetallic compounds, Mechanical property, Nano-indentation, Micro-tensile test

Introduction

Continuous shrinking in device dimensions in the integrated circuits requires fine pitch interconnects. In case of a solder bump connection, the height of solder medium has to decrease with the bump size. However, the intermetallic joint that is formed between the solder bump and the under bump metallization (UBM) is not scaled. Therefore, the intermetallic compounds comprise a large volume fraction in the small bumps, and will strongly influence the overall mechanical behavior of interconnect. An extreme case is the Transient Liquid Phase (TLP) flip-chip bonding, during which all solder is transformed into intermetallic compounds that have much higher melting points than the solder itself. TLP bumping recently drew much attention in 3D chip stacking technology because it enables repeated stacking of additional layers without remelting the bumps at lower levels of the stack [1,2]. Therefore, detailed study of intermetallic compounds is of great importance for the most advanced interconnect technology.

In this paper, we investigate the mechanical properties of CuSn intermetallics formed in the Cu/Sn system. This is because first the Sn-based solders are the most leading Pb-free solder candidate and Cu is one of the common UBM materials, and second there are no consensus on the Young's modulus (E) of CuSn intermetallics (see Table 1) [3-13]. For the yield strength (σ_y), the experimental data has not been reported yet to the authors' best knowledge. Instead, it is often estimated by the classical plasticity relationship, i.e., $\sigma_y = H/3$, where H is the hardness [9]. Apart from this, a few σ_y values were reported that were based on the finite element (FE) analysis and nano-indentation test (also see Table 1).

Table I: E and σ_y of CuSn intermetallics from literature.

	E (GPa)	σ_y (MPa)	Remark	Reference
Cu ₆ Sn ₅	85.56		Fine grain bulk	Fields
	96.06		Bulk	Cabarat
	85		Coarse grain bulk	Subrahmanyam
	102		Thick film many defects	Ostrovskay
	97.2		Solder joint flat X-section	Xu
	134		X-section of a thick film	Chromic
	119		Bulk	Chromic
	112	2009	FE simulation	Deng
	59-101		Solder joint	Rhee
	120		VRH calculation	Lee
Cu ₃ Sn	108.3		Fine grain bulk	Fields
	106		Bulk	Cabarat
	80		Coarse grain bulk	Subrahmanyam
	153		Thick film many defects	Ostrovskay
	114.8		Solder joint flat X-section	Xu
	160		X-section of a thick film	Chromic
	143		Bulk	Chromic
	134	1787	FE simulation	Deng
	100	480	FE simulation	Ramm
	127-171		VRH calculation	An

In order to accurately evaluate these parameters, we apply three different approaches as follows:

First, we characterize CuSn intermetallic films by nano-indentation. Here Cu and Sn are deposited sequentially by electroplating, and then are annealed at 200°C for ~100 hours to form Cu₃Sn dominated films. These films are investigated by nano-indentation to achieve the Young's modulus and hardness.

Second, we bond Cu/Sn bumps by flip-chip bonding to form CuSn intermetallic joints and then characterize them also by nano-indentation. After flip-chip bonding, we first create a series of planar surfaces with a bump size of Ø40 µm by shear test. Then we study the exposed intermetallics on each bump.

Finally, unlike the afore-mentioned two approaches, we fabricate a free-standing CuSn intermetallic beam for micro-tensile test, from which we can extract the Young's modulus, yield strength, and fracture strength.

Experimental

Eight inch Si(001) wafers were used as base material for all experiments. First a 30 nm-thick Ti and 150 nm-thick Cu were sputtered on SiO₂ as the seed layer. Then, a 3.3 µm-thick Cu and 1.5 µm-thick Sn layer were deposited sequentially by electroplating, followed by an annealing at 200°C for a certain time to form the intermetallics. Here the thickness of Cu and Sn was designed to mainly form Cu₃Sn. In order to fabricate the free standing intermetallic beams, the front side of the wafer needed to be patterned prior to plating and annealing. Once the intermetallics were formed, the front side will be protected by a carrier wafer. After that, the back side of the device wafer also needed to be patterned, and the intermetallic beams were released by deep dry etching. Finally, the carrier wafer was removed by acetone. Cu/Sn to Cu/Sn flip-chip bonding was carried out at the FC-6 bonder. The bonding temperature was 250°C and the pressure was 5 MPa. Shear test was done after bonding in order to break the intermetallic joints and hence a planar surface was created.

The formation of CuSn intermetallic compounds was studied by XRD. The nano-indentation tests were carried out at a MTS nano-indenter. A three-sided Berkovich indenter tip was used, and a fused quartz standard was used for calibration before testing. The Load-displacement data was analyzed using the Oliver and Pharr technique, as described elsewhere [8].

The tensile test was done at a four-point-bending tool. The test sample, which was symmetric and connected by an intermetallic beam and two supporting Si frames, was first mounted on the sample holder. Then the two supporting frames were cut by a high speed drill so that the sample was only connected by a free standing intermetallic beam. During the measurement, the stress-strain curve was recorded.

Results

Fig. 1 shows the XRD spectra of a Cu/Sn film after anneal at 200°C for more than 30 h, which indicate the intermetallic formation in the Cu/Sn bi-layer. Here Cu₃Sn (ε) is the dominant phase, while Cu₆Sn₅ (η) can still be found. If the initial thickness of Sn is slightly reduced, the amount of Cu₆Sn₅ is almost negligible after 100 h anneal (XRD not shown). Since there is sufficient Cu in the bi-layer, Cu is always there.

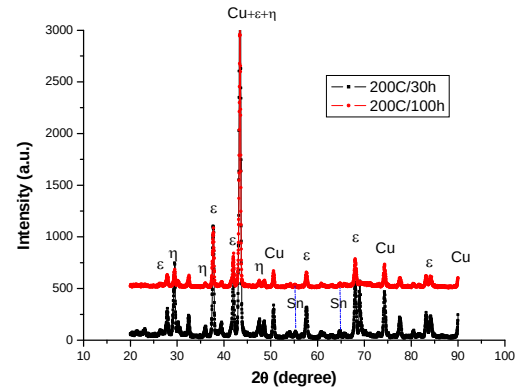


Fig. 1. XRD spectra of Cu/Sn film after long time anneal at 200°C.

Fig. 2 shows the load-displacement curves obtained from nano-indentation tests on Cu₃Sn, Cu, and Sn. As expected, Sn is soft. If we look at the indentation data closely, we can find some pop-in phenomena even in Cu₃Sn (Fig. 3). This indicates the existence of grain yielding due to dislocation motion. The E values of Cu and Sn are 130 and 54 GPa, respectively, which fit the literature values well.[8] For Cu₃Sn, it is 148 GPa (Fig. 4), which seems to be a little high but still in the range reported in literature. The hardness of Cu₃Sn is 5 GPa (Fig. 5), and hence σ_y is estimated to be 1667 MPa.

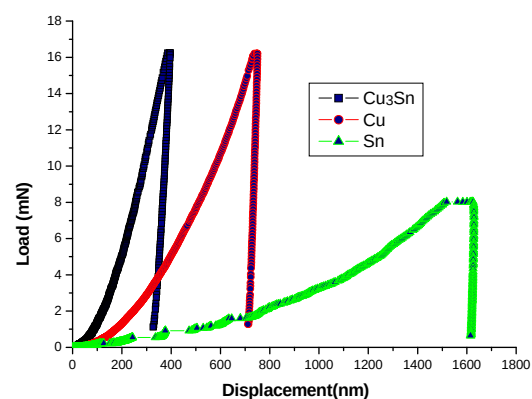


Fig. 2. Nano-indentation data of load versus displacement for CuSn intermetallics, Cu and Sn. The thickness of each,

$\sim 4, 5, 6 \mu\text{m}$, is much thicker than the displacement so that the substrate effect is negligible.

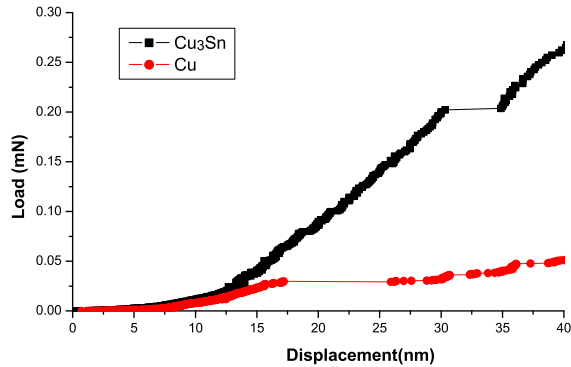


Fig. 3. Zoom in of Fig. 2 to show the pop-in phenomena in Cu_3Sn and Cu.

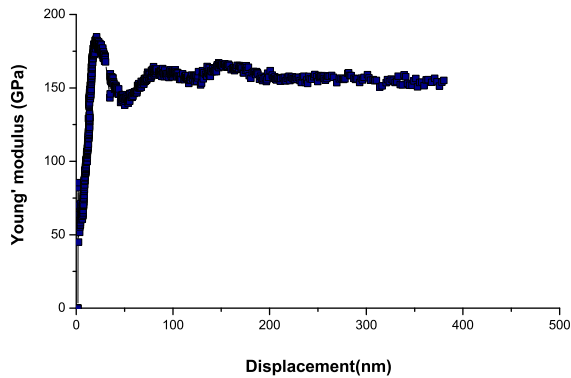


Fig. 4. Young's' modulus versus displacement for CuSn intermetallics.

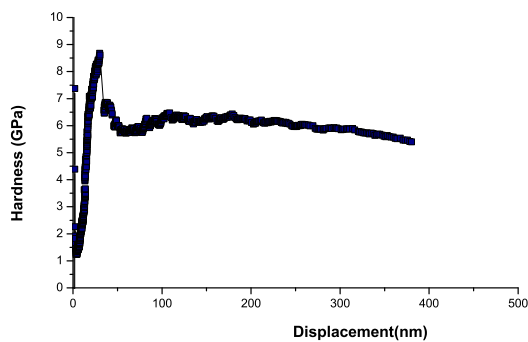


Fig. 5. Hardness versus displacement of CuSn intermetallics.

In microbumps the situation is found to be different, as shown in Fig. 6. Here both the E and H values are much lower than that of CuSn intermetallics formed in

the Cu/Sn film. The low E and H values were also found by Rhee in the solder joint, where the CuSn intermetallic compounds and Sn co-exist. Indeed, after the 250°C bonding for ~ 2.5 min, there is still a small amount of Sn in our micro-bumps, which is confirmed by XRD (not shown).

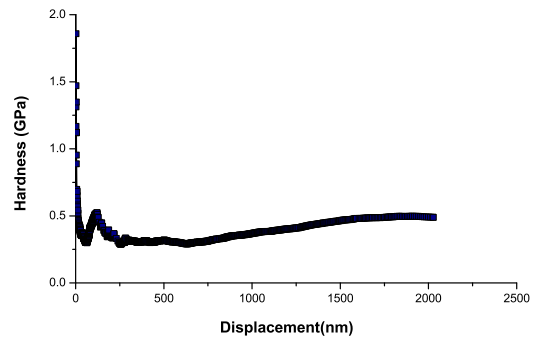
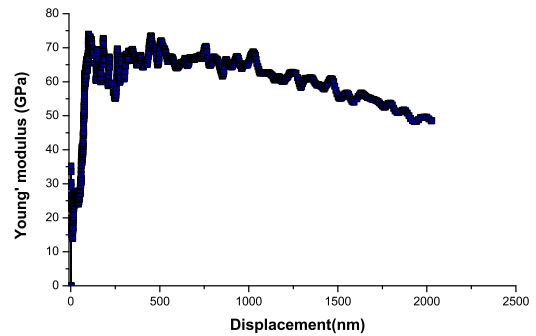
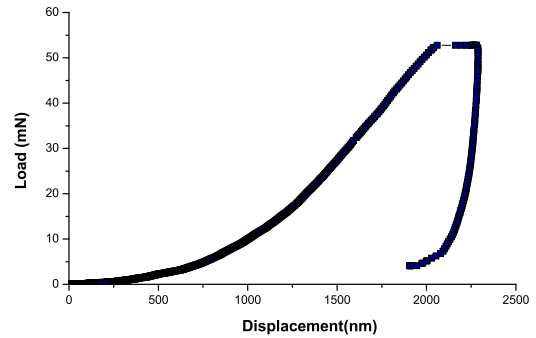


Fig. 6. Nano-indentation data of load (upper), Young's modulus (middle), and hardness (lower) versus displacement for CuSn intermetallics formed by flip-chip bonding at 250°C for ~ 2.5 min. The diameter of the bump is $40 \mu\text{m}$.

Finally, we use the micro-tensile test to study the free standing beam, which is shown in Fig. 7. This beam as mentioned before is composed of Cu_3Sn and Cu. Our preliminary test shows that the E value, the slope of the

linear part of the stress-strain curve, is 75 GPa. This value is somehow lower than the one obtained from the nano-indentation on blanket film, but it is quite close to Subrahmanyam's value, 80 GPa [5]. The fracture strength, 980 MPa, can also be obtained from this test. Interestingly, a very small plastic deformation is observed, from which the σ_y , 810 MPa, is obtained. Note that this value is only a half of the one estimated from the hardness which is obtained from our nano-indentation test, but it is higher than the one reported by Ramm, 480 MPa [13]. In fact, small plastic deformation prior to fracture has been observed by Kang et al. [14], although Cu_3Sn is believed to be brittle in nature. This plastic deformation may relate to the grain yielding as discussed in Fig. 3, where we find the pop-in phenomenon in Cu_3Sn in the nano-indentation test. A more detailed study is still on going in order to get a better understanding on the deformation behavior during tensile test.

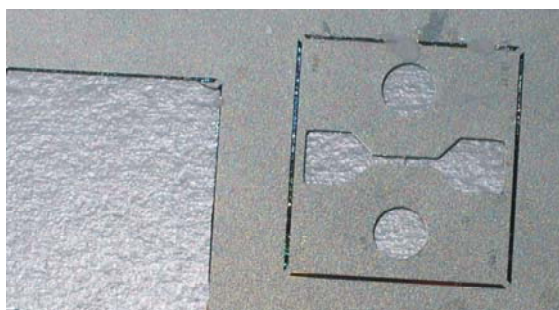


Fig. 7. Top-view of the micro-tensile test sample. Note that sample in the left side is not removed from the wafer matrix yet. The two columns are used to mount the sample on the sample holder, and the two Si frames near the squares will be cut before testing.

Conclusions

The mechanical properties of CuSn intermetallics are investigated by nano-indentation and micro-tensile test. It is found that the Young's modulus of CuSn intermetallic depends on the sample preparation and characterization technique. One can estimate the yield strength based on the hardness that is obtained from the nano-indentation test. However, the yield strength and also the fracture strength can be directly obtained from the micro-tensile test. In fact, we find the E value of CuSn intermetallic is between 75 to 150 GPa, σ_y is ~ 810 MPa, and the fracture strength is ~ 980 MPa.

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