Uniaxial tensile and shear deformation tests of gold–tin eutectic solder film

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Abstract

This paper describes a novel experimental technique for measuring mechanical properties of gold–tin (Au–Sn) eutectic solder film used for soldering package in microelectromechanical systems (MEMS). Dual-source DC magnetron sputtering was employed to deposit Au-20 weight % (wt%) Sn film. The tensile test with in situ X-ray diffraction (XRD) measurement evaluates the Young’s modulus and Poisson’s ratio at intermediate temperatures. The Young’s modulus and Poisson’s ratio at room temperature were found to be 51.3 GPa and 0.288, lower than bulk values. The Young’s modulus decreased with increasing temperature, whereas the Poisson’s ratio did not depend on temperature. The XRD tensile test also showed creep deformation behavior of Au–Sn film. We have developed a shear deformation test technique, which is performed by using Au–Sn film sandwiched by two single crystal silicon (Si) cantilever structures, to characterize the shear properties of the film. The shear moduli obtained from the shear deformation tests ranged from 11.5 to 13.3 GPa, about 38% lower than those from the XRD tensile tests. The measured shear strength from 12 to 17 MPa exhibited a temperature dependency. Information about the tensile and shear characteristics would likely to be of great use in designing Au–Sn soldering packages for MEMS.

Keywords: XRD tensile test; Shear deformation; Young’s modulus; Poisson’s ratio; Shear modulus; Shear strength; Au–Sn film; Sputtering

1. Introduction

Solder joints play a key role as important electrical and mechanical interconnections in packaging technologies, such as flip-chip package, chip-scale package, and direct chip attach. In the microelectromechanical systems (MEMS) package fields, several kinds of solder films deposited by sputtering are employed to bond microelements made of silicon (Si) or glass. The reliability of the package assemblies largely depends on that of the solder film joints because the film joints have relatively low structure compliance as compared with the jointed elements. Therefore, the precise evaluation of solder film’s mechanical behavior is one of the most important issues in terms of the development of reliable MEMS soldering packages.

To date a lot of efforts to investigate mechanical properties of solder materials have been made [1–4]. Uniaxial tensile test, which is a common method for mechanical characterization of materials, is often employed to study elastic–plastic properties, creep behaviors, and bond strength of solder materials having milliscale dimensions. But, few mechanical testing of solder films has been carried out in view of difficulties in preparing thin film specimen, in applying a tensile force to the specimen, and in detecting very small physical response from the film during testing. In addition to tensile characteristics, the shear properties of solder films should be measured if the films are used as adhesion bond material. This is because solder films used as a joint for hermetic package suffer from a shear deformation damage originating from the difference between inner and external pressures. However, the shear test technique for a film specimen is hardly found due to technical difficulty in applying shear force to such small specimen.
The objective of this research is to investigate tensile and shear properties of sputtered Au–Sn eutectic solder film at intermediate temperatures. Young’s modulus and Poisson’s ratio were obtained by uniaxial tensile testing with in situ X-ray diffraction (XRD) measurement. We develop a new shear testing technique for estimation of shear modulus and shear strength of the solder film.

2. Experimental procedure

2.1. Deposition of Au–Sn solder film

Au–Sn eutectic solder films were deposited by an in-house multi-source DC magnetron sputtering apparatus. The film composition was set to be 80 weight % (wt%) and 20 wt% for Au and Sn, respectively, by controlling electric power for each sputtering gun. During deposition, a fixed distance between the target and substrate was maintained to be 95 mm, and pure argon, maintained at a constant pressure of 0.2 Pa, was employed as a working gas. The substrate temperature was not controlled. All the Au–Sn films were deposited onto the diced single crystal Si chip covered with a silicon oxide (SiO₂) thin layer originating from a thermal oxidation process. Before deposition, the Si chip was rinsed with a mixed solution of sulfuric acid and hydrogen peroxide in order to remove an organic matter on the chip.

2.2. XRD tensile test

A uniaxial tensile test technique with direct strain measurement function using XRD was employed to measure Young’s modulus and Poisson’s ratio of Au–Sn solder film. Fig. 1 shows a photograph of tensile test specimen along with longitudinal elastic strain distribution derived from finite element analysis (FEA). The specimen fabricated through conventional MEMS fabrication processes consists of a specimen gauge section, hooking holes on Si grip ends, and frame [5]. The gauge section has a fillet to reduce stress concentration during testing. By applying the compulsory displacement of 1% gauge length to the entire specimen model, longitudinal elastic strain at the straight part was calculated to be 0.683%. Thus, elongation at the gauge section of the specimen was estimated by multiplying a factor of 0.683 by the relative displacement of specimen holders.

Fig. 2 illustrates the XRD tensile test setup. The handmade tensile tester is composed of a piezoelectric actuator, load cell, linear variable displacement transducer (LVDT), specimen holders, and heater. These components are put in the actuator case with the dimensions of 130 mm × 80 mm × 30 mm. The actuator case has a lever for amplification of the actuator’s displacement by a factor of five in the tensile direction. The compact tensile tester is settled onto a sample stage in an XRD apparatus in order to directly measure a change of the lattice spacing in the out-of-plane direction of specimen during tensile loading. Based on the Bragg’s law, a decrease in the lattice spacing can be calculated from the shift of XRD peak position towards a higher angle. Consequently, we can derive out-of-plane strain, leading to the Poisson’s ratio determination [5].

2.3. Shear deformation test

Fig. 3 schematically represents a concept of shear deformation test for a solder film, along with a photograph of the fabricated shear test specimens. The shear test specimen consists of Au–Sn film section and two Si cantilever structures with a grip end. The Au–Sn film is sandwiched between the Si structures at these free ends. Once a tension is applied to the cantilever structures, shear deformation happens into the film. The Si cantilever has a V-shaped notch, which serves for reducing the generation of nonuniform shear strain in the film [6]. The Si cantilever...
Fig. 2. Schematic of uniaxial tensile testing with in situ XRD measurement for film specimen. A compact tensile tester is settled on a sample stage in an XRD apparatus, in order to measure out-of-plane strain with increasing tensile loading. Based on the Bragg’s law, the out-of-plane strain can be determined by a change in XRD peak angle.

Fig. 3. A schematic of the concept of shear deformation test for Au–Sn solder film, along with a photograph of the produced shear test specimen. The Au–Sn film is sandwiched by two Si cantilever structures. Shear deformation in Au–Sn film can be produced by applying tensile loading to the Si structures.
structures are firstly fabricated from an SOI (0 0 1) wafer with the thicknesses of 150 μm in both the device and handle layers. After deposition of Au–Sn film on the free end of the cantilevers, the cantilevers are jointed at the Au–Sn film section by means of the annealing treatment at 673 K for 30 min under a constant pressure of 1 MPa in an electric furnace.

For derivation of Au–Sn film shear properties, shear strain of the film must be determined. But, shear strain is for sure very small so that direct measurement of the strain in testing is thought to be quite difficult. So, we determine the shear strain of Au–Sn film by means of FEA. Fig. 4 depicts FEA results showing (a) longitudinal elongation distribution in specimen and (b) variation in the ratio of Au–Sn film’s shear displacement, β, to the entire specimen’s displacement, z, against the applied Young’s modulus, E, of the film. In Fig. 4(a), elastic deformation is produced in not only a film section but also a cantilever section, despite of the film’s low compliance. As shown in Fig. 4(b), the displacement ratio, β/z, decreases with increasing the applied Young’s modulus and the width of cantilever, whereas the ratio is proportional to film

![Diagram](image)

Fig. 4. Typical FEA results of shear deformation test. Longitudinal elongation has occurred in the Si cantilever section as well as the Au–Sn film section. The displacement ratio of β to z depends on the film’s Young’s modulus, thickness, and the width of the specimen section. If the entire displacement, z, is measured, shear displacement, β, can be estimated from the relations in the figure. (a) Longitudinal elongation distribution in specimen for shear deformation test and (b) the ratio of shear displacement, β, to entire displacement, z vs. applied Young’s modulus of Au–Sn.)
thickness. The relation can be fitted by the following equation:

$$\beta = A(w, t)E^{B(w, t)}$$  \hspace{1cm} (1)

where \( w \) is the cantilever width, \( t \) is the film thickness. \( A \) and \( B \) indicate the functions of \( w \) and \( t \). If \( \beta \) is much smaller than \( t \), shear strain, \( \gamma \), of the film is given by

$$\gamma = \beta / t.$$  \hspace{1cm} (2)

From the above equations, \( \gamma \) can be roughly estimated if \( \alpha \) and \( E \) are measured through the shear and tensile tests, respectively.

3. Results and discussion

3.1. Uniaxial tensile test results

Fig. 5(a) shows typical XRD curves of Au–Sn solder film specimen in tensile tests at room temperature (RT) and 373 K. The Gauss function was used to determine diffraction angle at the peak position. At RT, when tensile stress of 0.011 GPa is applied, the diffraction angle at the peak position of XRD curve is approximately 78°, which corresponds to a typical XRD angle of Au5Sn (2 2 3). As tensile stress increases, the peak position shifts toward a higher angle. This indicates that the lattice spacing of the Au5Sn (2 2 3) planes, which lie parallel to the specimen surface, gradually decreases with increasing stress. The shift rate of the peak angle per tensile stress is almost constant. From the changes in lattice spacing, out-of-plane strain of the Au–Sn film specimen can be determined. A similar trend is observed also at 373 K. Although the different XRD peaks corresponding to other orientations were appeared, these peak intensities were very weak as compared with the intensity of Au5Sn (2 2 3). Considering the Bragg’s law, higher angle peaks give better resolution on strain calculation, but in view of the peak intensity, only the Au5Sn (2 2 3) peaks were used for strain calculation. Furthermore, if the grain size is comparable to the specimen size, different peaks may provide different elastic response. But, in fact, the Au–Sn specimen size would be surely much larger than the grain size that is thought to be sub-micron scales, though the grain size has not been measured. Therefore, we assumed that the influence of the different XRD peak on elastic response of micron specimen could be ignored.

Fig. 5(b) shows typical tensile stress–strain relations at RT and 373 K. The solid line is plotted by reference to the
3.2. Shear deformation test results

Fig. 6 shows typical shear stress–strain curves of Au–Sn solder film. Shear stress, \( \tau \), was calculated by dividing the film’s bonded area by tensile force. Shear strain, \( \gamma \), was obtained from the LVDT elongation measurement result and Eqs. (1) and (2) based on FEA, as explained in the previous section. The shear stress–strain relations at RT and 323 K are almost linear though in the case at RT a nonlinear region is seen before failure. The relation at 373 K is mostly dominated by a linear region, but a stress drop is observed just before the specimen has failed. The nonlinear region suggests that yielding phenomenon in Au–Sn would have occurred. The shear modulus estimated from the slope in the linear region at RT is found to be 13.3 GPa, which decreases to 11.5 GPa with increasing temperature to 373 K. The shear stress ranges from 12 to 18 MPa, and also decreases with temperature elevation. Although the photograph of the failed specimen is omitted in this paper, all the specimens tested have fractured at the Au–Sn film bonded section, and no specimen failed at the Si section has obtained. This indicates that the obtained values of strength can probably regard as the shear strengths of the Au–Sn films at each temperature. In addition, the adhesion strength between Si and Au–Sn film would be higher than the shear strength of the film.

Assuming that the produced Au–Sn solder film follows the linear elastic theory for isotropic material, shear modulus, \( G \), is calculated by the following equation:

\[
G = \frac{E}{2(1 + \nu)}. 
\]  

(3)

Fig. 7 shows a relationship between shear modulus and temperature. The open circle plots are derived from shear deformation tests, the closed square plots represent the moduli obtained by substituting \( E \) and \( \nu \) from XRD tensile tests into Eq. (3), and the diamond plots represent the bulk values [4]. The shear modulus obtained from XRD tensile tests at RT is found to be 20.8 GPa, which decreases with increasing temperature, as does the modulus from shear deformation tests. The values measured from tensile tests at respective temperatures are approximately 9% lower than the bulk values. This would be caused by lower film density as compared with bulk. Moreover, the values from shear deformation tests are indicative of 62% of those from tensile tests, and are 53% of bulk values. The difference in the obtained shear modulus between shear deformation and XRD tensile tests might have been caused by nonuniform shear deformation in shear tests or by the difference in the out-of-plane Poisson's ratio, which was clearly observed in the shear tests or by the difference in the out-of-plane Poisson's ratio.
in a creep deformation effect between the shear and tensile tests. Also, in this study, the tensile test specimens were as-deposited films, whereas the shear test specimens were annealed at 673 K. In the case of shear test specimen, by virtue of annealing, atomic diffusion and densification would have occurred. This difference in sample preparation condition between the shear and tensile tests might have affected the deformation of Au–Sn film. However, the cause of the difference in the shear modulus should not be concluded until further experiments and analyses have been carried out.

4. Conclusions

In this study, XRD tensile and shear deformation tests were performed to measure mechanical properties of sputtered Au–Sn solder films. In XRD tensile tests, the XRD peak shift to a higher angle with increasing tensile stress was clearly observed, and enabled us to estimate the Poisson’s ratio of the film. Tensile stress-longitudinal strain relation showed a step shape originating from creep deformation in the film. The measured values of Young’s modulus and Poisson’s ratio at RT were 51.3 GPa and 0.288. The Young’s modulus decreased with increasing temperature, but the Poisson’s ratio did not show a temperature dependency.

We proposed a shear deformation test method that employed a lapped specimen consisting of Au–Sn solder film and two Si cantilever structures. The shear test enabled the shear modulus and strength of the film to be experimentally determined. However, the measured shear modulus was 38% lower value than the modulus calculated from XRD tensile test results. The difference is under investigation, and further experiments are required for investigation of the cause that the low shear modulus has been obtained.

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