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# Investigation of interfacial behavior in miniaturized solder interconnects

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ABSTRACT

In the present study the influence of intermetallic compound growth on mechanical and thermal response of miniaturized lead free solder joints was investigated. The focus of the study was the relationship between the solder gap size and thickness of the intermetallic compound (IMC) on tensile behavior of Cu/Sn3.5Ag0.75Cu/Cu solder joints with different ratios of IMC to the gap size and temperature boundary conditions. Independent of the IMC to solder gap thickness ratio a steady increase of tensile strength with decreasing gap size was observed. The reason for this behavior is the so called constraint effect which is well explained by plasticity models. The variation of the IMC size was realized by different reflow times or heat treatments. An increasing ratio of IMC thickness to the gap size results in a transition of the fracture mode from ductile to brittle and affects the strength of the solder joint. Thereby, embrittlement of the material seems to be a consequence of short diffusion paths introduced by defects and failures as confirmed by finite element analysis. Furthermore, thermal experiments revealed that the overall coefficient of thermal expansion of the joints decreased with increasing the IMC proportion of the joints. This study shows that the mechanical response and failure modes of thin solder joints are strongly dependent on the interaction between the proportional thickness, inherent defects and morphology of the IMC layer in addition to the constraint effect.


## 1. Introduction

In recent years Sn-Ag-Cu (SAC) alloys have emerged as one of the mostly accepted solders among the lead-free solder compositions in microelectronic applications [1]. The knowledge of the complex thermo-mechanical response of miniaturized solder joints is of high significance for a prediction of the reliability of the devices. Thermal and mechanical behavior of the solder joints are primarily affected by the dimensional constraint and microstructural factors. Several experimental and theoretical investigations have shown that decreasing the solder gap size results in an increase in the tensile strength of the solder joints by the build-up of a triaxial state of stress in thin joints [2–4]. Extensive investigations have shown that during the processing and the subsequent operational life the lead free solder joints in microelectronic devices are subjected to continuous microstructural modifications which consequently affect their deformation behavior [5]. The thermally induced grain growth and intermetallic diffusion processes significantly alter the composition and the thermo-mechanical performance of the solder joints. Recently numerical methods in combination advanced analytical techniques have been applied for modeling and prediction of the temperature dependent evolution of the microstructure of the solders and the corresponding mechanical properties [6–8]. On the other hand, the strong dependency of the mechanical properties of lead-free solder joint systems to long-term thermal exposure or higher temperatures has been found to be primarily related to the growth of the interfacial IMC layers. Studies show that increasing the thickness of the interfacial IMCs which is congruent with morphological changes and decreasing the roughness of these layers inversely affects the strength of the joints [9–12]. This effect was mainly related to a transition of the failure mode from ductile fracture of the solder to brittle interfacial fracture along the intermetallic interfaces [9,10]. The relationship between the solder size/volume and the microstructure has also been the subject of a number of investigations [4,13,14]. Concerning the dependency of the tensile and shear properties of the solder joints, to their microstructure and the stand-off height (ratio of the interfacial IMC layer to the solder gap thickness) controversial results have been found [4]. Systematic studies on the influence of size and

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microstructure of the intermetallic compound (IMC) layers between the solder and the substrate and their aspect ratio on the mechanical and thermal response of miniaturized solder joint are scarce.

In the present work the influence of the IMC layer thickness on mechanical and thermal properties of Cu/Sn3.5Ag0.75Cu/Cu solder joints was investigated. Stress-strain curves of samples with solder gap sizes in the range of 50 μm to 800 μm and different ratios of the IMC layer thickness to the solder gap size were obtained. Furthermore the effect of IMC layer thickness on the thermal response of thin Sn-Ag-Cu solder joints was studied. The results showed a clear dependence of tensile strength, fracture strain, failure mode and the value of coefficient of thermal expansion (CTE) on the proportions of $Cu_3Sn$ and $Cu_6Sn_5$ IMC layers of the solder joints.

## 2. Materials and methods

Model solder joints of Cu/Sn3.5Ag0.75Cu/Cu with gap sizes of 800 μm, 400 μm, 100 μm and 50 μm were prepared using a commercial solder paste and copper strips with a purity of 99.9% as substrate. The end faces of the copper strips were ground carefully with 600#, 1200# and 2500# SiC paper and were cleaned to prepare the soldering. A specially prepared sample holder allowed adjusting the gap size in the desired range. The samples were soldered in a reflow furnace by using a near-industrial reflow temperature profile as shown in Fig. 1. The melting temperature of the used Sn3.5Ag0.75Cu solder is 218 °C. The resulting reflow temperature was chosen 25 °C above the melting temperature of the used solder alloy to achieve an optimal soldering. The reflow temperature was 270 °C with a total time of ~15 min to obtain a resulting peak temperature of 243 °C of the sample. After the soldering and some preparation steps, the dog bone shaped tensile samples with a soldered area of $3 \times 2\ mm^2$ were mechanically polished to reveal their microstructure (Fig. 2). The samples were then subjected to three different heat treatments to modify the microstructure of the joints: (1) stress relieving at 80 °C for 3 h, (2) aging at 150 °C/500 h and (3) aging at 150 °C/1000 h. The soldering process and the subsequent aging of the samples resulted in the formation of different ratios of IMC to joint thickness in samples with different gap sizes. The aging temperature at 150 °C was selected with respect to the maximum temperature occurring during the operation of the real devices. This aging step simulates the occurring aging of real devices in a natural accelerated way. It makes it possible to study the microstructural effects on mechanical properties.

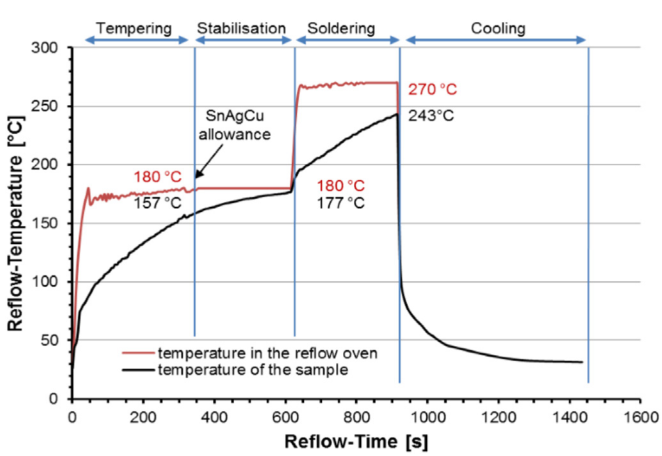


**Fig. 1.** Actual heating profile measured during the soldering process (Sn3.5Ag0.75Cu).

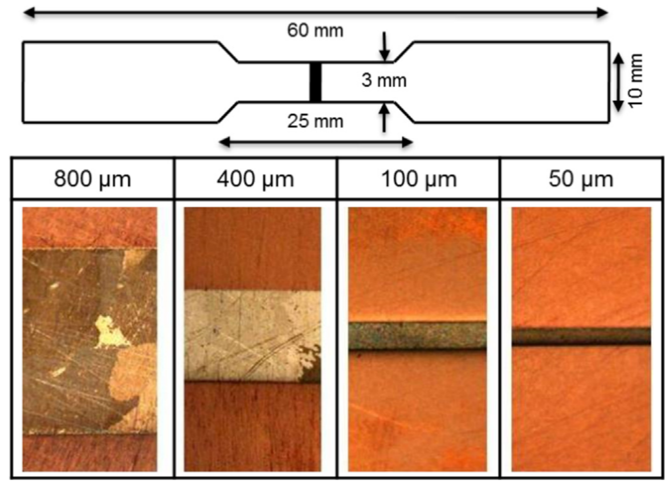


**Fig. 2.** Schematic picture of the specimen geometry (Cu/Sn3.5Ag0.75Cu/Cu) and illustration of the fabricated solder gap size.

Tensile experiments were performed using a μ-strain tensile machine with a crosshead stroke resolution of 0.04 μm and a minimum load resolution of 10 mN. The tests were conducted using a fixed cross head speed of 0.2 mm/min for all gap thicknesses. The strain of the first test series was measured by a non-contacting laser speckle extensometer with a gauge length of about 20 mm and a strain resolution of $10^{-5}$. The stress-strain curves were plotted by using the initial solder gap size of each sample assuming the Cu substrate as rigid in the measured region. In the second series of tests a VIC-3D Micro™ system by Correlated Solutions was used to measure displacement and strain under high magnification. The speckle patterns movement on the solder joint is measured by determining the first four components of the Lagrange finite strain tensor, in addition to providing a graphical representation of the strain concentration gradient at every point on the specimen surface.

A laser interferometer displacement sensor was used to measure the coefficient of thermal expansion of the solder joints. The system allows determination of local deformation between two Vickers microhardness indentations with a distance of max 200 μm with a displacement resolution of about 2 nm [15]. With the measured change of indentation distance d$L$, the coefficient of linear thermal expansion α can be calculated by using the Eq. (1).

$$\alpha = \frac{1}{L_0}\frac{dL}{dT} \tag{1}$$

where $L_0$ is the base length between the indentations and d$T$, the change in temperature. Thermal strain measurements were performed on samples with a solder gap size of 120 μm with three different IMC layer thicknesses to demonstrate the influence of the ratio of solder to IMC on local thermal expansion of the solder joints.

## 3. Results and discussion

### 3.1. Microstructural investigations

Mechanical properties of the solder joints depend on the microstructure of the solder alloy. The challenge is to make a solder joint model, which has a comparable microstructure to that of a real device. The microstructure of a solder joint is mainly influenced by the geometry, the used substrate and especially the cooling profile of the soldering process. The ternary eutectic