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Reliability analysis of 3D heterogeneous microsystem module by simplified finite element model

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ABSTRACT

Analyzing the structural reliability of 3D heterogeneous microsystem modules is an important step in their development. The finite element models of such modules are simplified by simulating the complicated structure of MEMS (microelectromechanical systems) devices integrated into a single interposer. In this study, thermal stress and cycling analyses for different finite element models of 3D heterogeneous microsystem modules are investigated. The results of the thermal stress analysis reveal the values of the maximum von Mises stress in the finite element models, at the interface between the interposer and the microgyroscope, and in the microgyroscope spring. They also illustrate the advantages and disadvantages of the different fabrication models. Module reliability assessments are also obtained through a thermal cycling analysis, the results of which show that properly simplified models designed to reduce computation time benefit the reliability analysis. This study provides useful suggestions for manufacturing and reliability assessments of 3D heterogeneous microsystem modules embedded using the through-silicon via technique.

1. Introduction

The process of integrating different devices into a single interposer has most recently been developed with specific requirements, namely, multi-functionality and a small size. These systems are called 3D heterogeneous microsystem modules. Experiments have been conducted to verify the packaging techniques used in microelectromechanical systems (MEMS) devices, including through-silicon vias (TSVs), anodic bonding, and the feasibility of 3D heterogeneous packaging devices [1]. The TSV technique, which has been used in interposers to reduce energy loss and signal transmission, is a key method for high-density packaging structures [2]. Therefore, the analysis of structural reliability is an important issue in interposer development. However, the structural complexity of modules that incorporate MEMS devices substantially increases computation times. A proper simplified model can reduce analysis costs and boost efficiency; thus, a reasonable computational model facilitates module structure reliability analysis. In this study, the reliability of 3D heterogeneous microsystem modules is investigated using a simplified computational model.

The TSV technique is one of the key processes driving 3D integrated circuits (ICs). However, the thermal stress between TSVs and silicon interposers (SIs) is a major concern, as it can lead to crack growth at the via/SI interface and fatigue failure [3]. In 2005, Ranganathan *et al.* [4] ran simulations of heated copper TSVs and silicon vias. They found that high stress at the interface can cause delamination at the tops of copper vias. Miranda and Moll [5] conducted a finite element analysis (FEA) and discussed the possibility of a failure mechanism caused by the stress distribution of TSVs due to a coefficient of thermal expansion (CTE) mismatch. Zhang *et al.* [6] examined the stress distribution of heated TSVs in a 3D chip. They used X-ray and an FEA to measure the thermal stress of copper vias and discovered that a maximum von Mises stress occurred at the ends of the TSVs. Jiang *et al.* [7] characterized the thermal stresses in the TSV structures by combining wafer curvature technique, micro-Raman spectroscopy, and FEA. They found that the TSV extrusion might be caused by the localized plastic deformation of Cu vias near the via/SI interface. As the abovementioned studies show, the interface condition of TSVs is a key element in interposer reliability analysis. Therefore, in this study, the thermal stress levels in different finite element models are investigated by comparing the thermal stress at the interface of TSVs and SIs.

The various processes used to fabricate MEMS devices in a 3D heterogeneous microsystem module may affect the devices' reliability. Choa [8] used experimentation and an FEA to study the reliability issues of packaged microgyroscopes under mechanical cycling loading, and found that a maximum stress occurred at the interface between the comb structure and the spring. Liu *et al.* [9] conducted an FEA of simulated microgyroscopes under different environmental conditions and found that thermal deformations resulted in operational errors.

The fatigue life predictions of different packaging structures have also been investigated. Pang *et al.* [10] looked into the predicted fatigue life of a flip-chip-on-board structure by modeling plastic and creep

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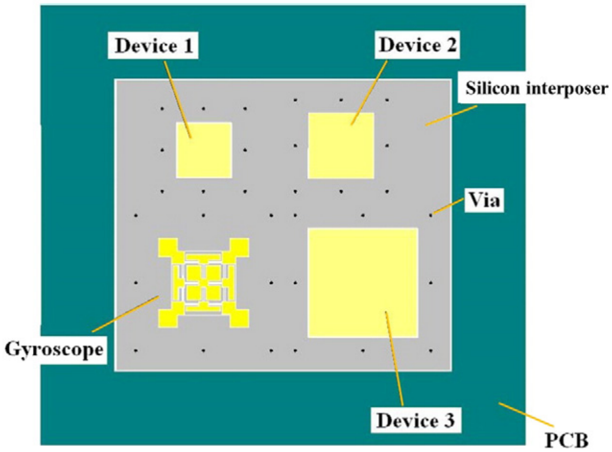

Fig. 1. Top view of 3D heterogeneous microsystem module.

deformations. Zhong and Yip [11] compared the fatigue life of a 3D stacked package with that of a single flip-chip package under thermal cycling using an FEA. They found that the interface between the solder ball and the chip at the outside corner failed first.

The following review focuses on 3D stacked die packaging with embedded TSVs under thermal cycling loading. Tanaka *et al.* [12] pointed out that TSVs limit the plastic deformation of the gold bump under thermal cycling loading, which reinforced the interposer connection. Yoon *et al.* [13] investigated the reliability of solder balls in the stacked module using a thermal cycling test and found that the stacked module embedded TSVs could survive after 1,000 temperature cycles. Yoon *et al.* [14] indicated that the stress concentrated on the solder ball between the printed circuit board (PCB) and the SI was obvious, based on the fatigue model of the 3D stacked die packaging. Moreover, the underfill played an important role in the fatigue life of the solder joints. Selvanayagam *et al.* [15] used a non-linear stress analysis to examine the local and global CTE mismatch issue for a package under temperature loading. They investigated the effects of various TSVs and the geometry of and underfill surrounding the solder balls and found that adding underfill affected the likelihood of a CTE mismatch. Yeh and Lu [16] proposed an alternative simplified finite element model with a microgyroscope to predict the fatigue life of a solder ball through thermal stress and cycling analyses.

In fabricating 3D heterogeneous microsystem modules for this study, a laser drilling technique was first used for TSV formation in SIs. Then the TSVs were filled by electroplating, and the MEMS device was created using wet etching. The interposer was attached to the PCB by the solder ball on its backside. The PCB with the SI was cooled from the reflow temperature of the solder ball (250 °C) to room temperature (25 °C). In this study, a 3D heterogeneous microsystem module with embedded TSVs under thermal loading and thermal cycling loading is studied using commercial ANSYS software [17]. The feasibility of simplified models with various fabricating processes is investigated through an FEA.

Table 1
The material properties of module [18–21]

	E (GPa)	ν	α (ppm/°C)
Silicon	165	0.22	2.5
Copper TSV	128	0.36	16.8
Solder ball (Sn63/Pb37)	43.25	0.4	25
Underfill	10	0.4	26
FR4-PCB	22.38	0.143	16

2. Finite element analysis

The reliability of a 3D heterogeneous microsystem module was evaluated using finite element software developed by ANSYS, including thermal stress and thermal cycling analyses. Initially, the thermal stress in the different models of the 3D heterogeneous microsystem module with a microgyroscope was analyzed. Regarding the thermal stress analysis, the feasibility of simplified models with various interposer fabricating processes was discussed. Moreover, a second MEMS device, the micromirror, was built into models and subjected to thermal cycling loading.

2.1. Thermal stress analysis

The thermal stress of a 3D heterogeneous microsystem module, as shown in Fig. 1, was evaluated. There were four MEMS devices on the top of the interposer: a microgyroscope at the lower left and three other devices that were assumed to be silicon cubes in this simulation. The sizes of the microgyroscope and the micromirror were $4\times4\times0.6$ and $5\times5\times0.525$ mm^3, respectively. The second layer was an SI with embedded TSVs that was $15.3\times13.3\times0.45$ mm^3 in size. The copper TSVs (diameter 0.1 mm; depth 0.45 mm) were distributed around the interposer. The solder balls were bonded between the TSVs and the PCB in the third layer, and surrounded by underfill. The height of each solder ball was 0.12 mm with a diameter of 0.26 mm. The size of the PCB was $20\times20\times1.6$ mm^3. Fig. 2 provides a cross-sectional view of the 3D heterogeneous microsystem module.

The finite element models were built by element Solid 45, which has 8 nodes and 3 degrees of freedom per node. The material properties

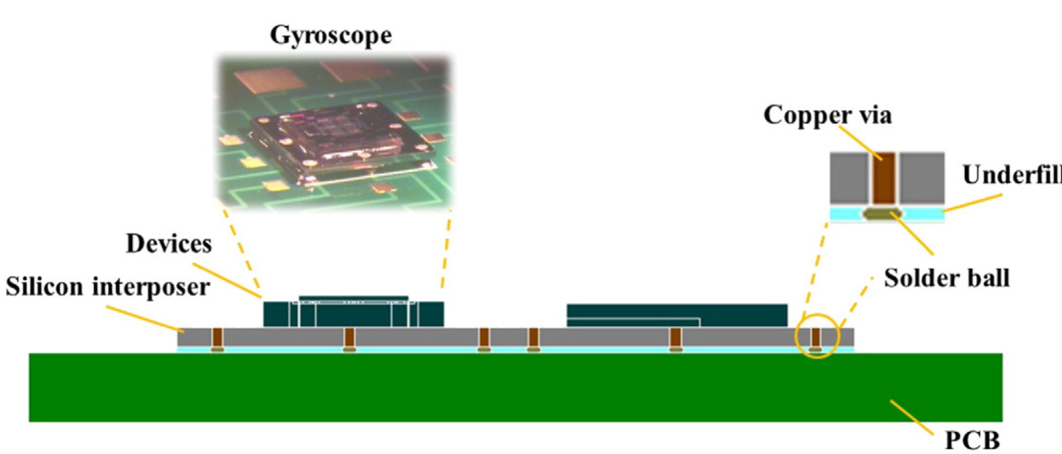

Fig. 2. Cross-sectional view of 3D heterogeneous microsystem module.