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Reliability of Cu wire bonds in microelectronic packages

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ABSTRACT

In this study the thermo-mechanical response of 25 μm Cu wire bonds in an LQFP-EPad (Low Profile Quad Flat-Exposed Pad) package was investigated by numerical and experimental means. The aim was to develop a methodology for fast evaluation of the packages, with focus on wire bond fatigue, by combining finite element analysis (FEA) and mechanical fatigue testing. The investigations included the following steps: *(i)* simulation of the warpage induced displacements in the encapsulated LQFP-176-Epad package due to temperature changes, *(ii)* reproducing the thermally induced stresses in the wire bond loops in an unmolded (non-encapsulated) LQFP package using an accelerated multiaxial mechanical fatigue testing set-up under the displacement amplitudes determined in case (*i*) and determination of the loading cycles to failure (N_f), *(iii)* FEA of the experiments performed in *(ii)* based on the boundary conditions determined in *(i)* to calculate the states of stress and strain in the wire bonds subjected to multiaxial mechanical cyclic loading. Our investigations confirm that thermal and mechanical cyclic loading results in occurrence of high plastic strains at the heat affected zone (HAZ) above the nail-head, which may lead to fatigue failure of the wire bonds in the packages. The lifetime of wire bonds show a proportional relation between the location and angle of the wire bond to the direction of loading. The calculated accumulated plastic strain in the HAZ was correlated to the experimentally determined N_f values based on the volume weighted averaging (VWA) approached and presented in a lifetime diagram (Δd - N_f) for reliability assessment of Cu wire bonds. The described accelerated test method could be used as a rapid qualification test for the determination of the lifetimes of wire bonds at different positions on the chip as well as for related improvements of package design.

1. Introduction

About 90% of all wire bonded interconnects in semiconductor packages consist of thermosonically bonded wires with diameters in the range of 15 to 75 μm. Recently Cu and Pd coated Cu wires on Al, Ni—Au and bare Cu bond pads are used in fine-pitch packages allowing higher lead counts and smaller pad sizes. The standard methods for evaluation of the quality and robustness of the wire bonds are pull or shear tests. These types of tests provide only information about the robustness of the wire bonds being exposed to static loads. In the practice the packages are exposed to high thermal and mechanical alternating stresses. The component level reliability tests for evaluation of the plastic packages subjected to thermo-mechanical loads include, among others, thermal cycling (TC) with temperature swings (ΔT) in the ranges of about −40 °C to 150 °C depending on the application type [1]. The thermomechanically induced cyclic shear and tensile stresses may lead to fatigue failure of the wire bonds.

The heat affected area above the nailhead has been recognized as one of the vulnerable sites of the package resulting in failure due to necking of the wire bond. Recently mechanical fatigue testing at higher frequencies has been proposed as a promising method for rapid evaluation of different types of interconnects as an alternative to thermal and power cycling tests. The basic idea is replacement of thermally induced stresses by mechanical means in order to decrease the testing time and to study the effect of thermal and mechanical stress factors on the lifetime of components separately [2].

In this study lifetime and fatigue properties of 25 μm Cu wire bonds in LQFP-EPad packages were investigated by numerical and experimental methods. A displacement controlled vibrational based experimental set-up was used to determine the number of cycles to failure of the wire bonds under multiaxial loading conditions. The displacements which were applied to the wire bonds during the mechanical loading were determined from thermomechanical simulation of the package, looking at its warpage when exposed to a temperature difference of −40 °C to 150

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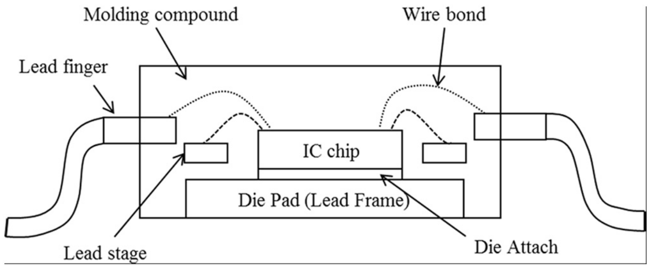

Fig. 1. Schematic model of LQFP-EPad package.

°C. The integrated wire bonds in the non-encapsulated package were simulated with multiaxial vibrations in order to reproduce the thermomechanically induced displacements. The inhomogeneous microstructure of the wire bond above the nail head and the loop was modeled by using two different material parameters extracted from the experimentally determined stress-strain curves. A lifetime model for Cu wire bonds in the package is proposed based on the experimental fatigue curves and the strain values calculated by FEA.

2. Warpage and displacement range of LQFP-176-EPAD package established by thermomechanical FEA

Finite-Element-Analysis (FEA) was performed using ANSYS software to assess thermomechanical stresses and warpage of an LQFP-176-Epad package during temperature swings between −55 °C to 150 °C. The finite element model was constructed using SOLID186 with three-Dimensional 20 node structural solid elements that exhibit quadratic displacement behavior [3]. Only a quarter of the LQFP-176-Epad was modeled due to the symmetric nature of the geometry. The model consists of lead finger, lead paddle (die pad), silicon chip and die attached adhesive as shown in the Fig. 1. The FEA model was constrained at the x and y axes with symmetry boundary conditions, and a zero degree of freedom constraint was applied at the origin of the model. The simulated temperature was a cooling down process which represents the same heating up temperature with inverse displacement warpage. The package was assumed to be in a stress-free state at 175 °C.

In case of bi-layer or multi-layer structures consisting of two or more materials, the Lagrangian approach can be used for each material with its CTE and initial strain due to displacement of origin [4]. Using Lagrangian coordinate systems, X^1, X^2, X^3 with the same coordinates before and after the expansion of the material, the distance between the

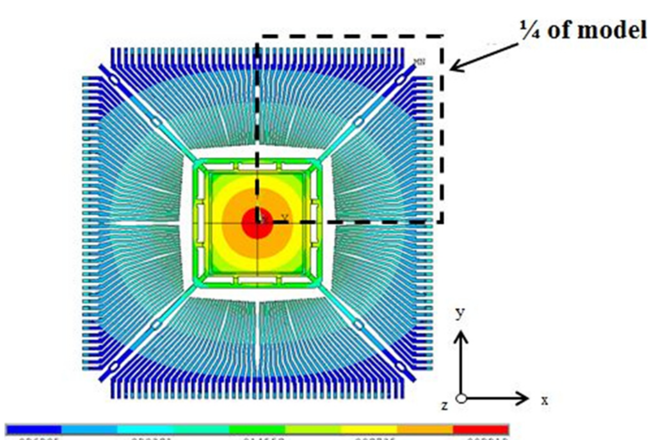

Fig. 2. Thermomechanical simulation of LQFP0176EPad package without wire bonds at −55 °C with T_{ref} = 175 °C (molding compound is not shown).

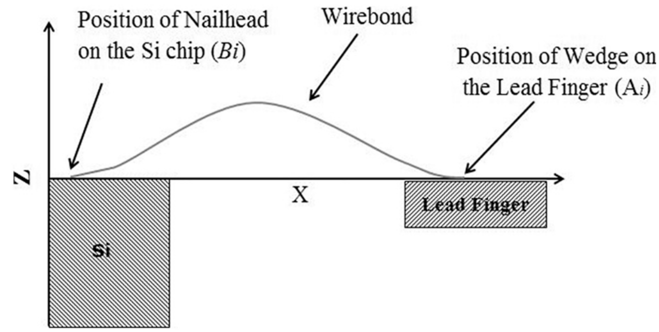

Fig. 3. Schematic demonstration of the positions of nail head and wedge in the package.

two points A and B is approximated in terms of a metric tensor G_{ij} as follows:

$$\delta l \approx \sqrt{G_{ij}\left(X_B^i - X_A^i\right)\left(X_B^j - X_A^j\right)} \tag{1}$$

where the components G_{ij} are evaluated at a point between X_A and X_B. The aim of FEA is to calculate the displacements between points B_i and A_i (Fig. 3) at different temperature steps. The Fig. 2 shows the displacement in z direction after cooling down from 150 °C to −55 °C. The simulation of the encapsulated package shows a warpage when being exposed to a ΔT of up to 205 K. From Fig. 2 it can be seen that after a temperature change the package will be shaped to a positive (convex) warpage or in other words it shows a crying effect in z direction. The positions of the nail head (marked with B_i) and wedge (marked with A_i) of a wire bond in the package are schematically shown in the Fig. 3. The Fig. 4 shows the position of the nail heads on the chip surface (points B_1 to B_{22}) and wedges on the lead fingers (points A_1 to A_{22}). The displacement differences between points B_i and A_i in x, y and z direction can be used to estimate the displacements of the wire bonds during TC loading. The results show different displacements in x, y and z directions depending on the positions of the wire bonds.

The objective of thermomechanical FEA simulation was to find the appropriate displacement amplitude for the multiaxial mechanical fatigue set up. Table 1 shows a summary of B_i -A_i displacement ranges for all selected wire bond positions. The calculated total displacement, normalized, between points B_i and A_i for three values of T_a is in the range between 5.8% and 28.5% to origin coordinate system at $T_{ref.}$ (reference temperature). Another conclusion is that the calculated total displacement is near to the (1,1,1) direction, which means 45° to the XY-plane and 45° to the YZ-plane.

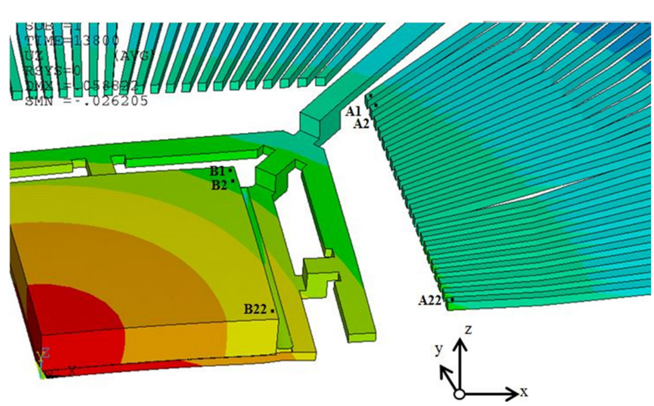

Fig. 4. Calculation of the displacements in z direction at −55 °C.