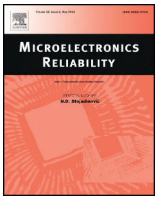
Microelectronics Reliability 73 (2017) 136–145

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel



Mechanism of warpage orientation rotation due to viscoelastic polymer substrates during thermal processing

Cheolgyu Kim [a], Tae-Ik Lee [a], Min Sung Kim [b],*, Taek-Soo Kim [a],*

[a] Department of Mechanical Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea
[b] SIMMTECH Co., Ltd., 73 Sandan-ro, Heungdeok-gu, Cheongju, Chungcheongbuk-do 28466, Republic of Korea

ARTICLE INFO

Article history:
Received 28 September 2016
Received in revised form 14 April 2017
Accepted 15 April 2017
Available online xxxx

Keywords:
Warpage orientation
Viscoelasticity
Flexible fiber-reinforced polymer substrate

ABSTRACT

The warpage orientation, which refers to the direction of maximum and minimum curvatures in a cylindrical warpage, was observed to have changed by flipping from a concave to a convex shape during thermal processing. In this paper, the mechanism of the warpage orientation rotation is demonstrated through analyzing the stress state and curvatures of the specimens using finite element method (FEM) simulations and experiments. It is revealed that the warpage transition temperature, where the curvature changes to other shapes, corresponds to the stationary point of the stress-temperature curve and the curvature change of the minimum direction precedes the curvature change of the maximum direction during the warpage orientation rotation. This precedence results from the stress relaxation of the fiber reinforced polymer (FRP) substrate. Because the curvature of minimum direction flips backward in advance of maximum direction, the cylindrical warpage shape converts to a saddle shape and it induces the rotation of the warpage orientation. The simulation without the viscoelastic properties of the FRP substrate is conducted and used for comparison in order to verify the stress relaxation effect of the warpage orientation rotation phenomenon. In conclusion, it is demonstrated that the viscoelastic properties of the FRP substrate are a critical factor in analyzing the warpage orientation rotation and its behavior.

1. Introduction

The warpage of electric components is a critical issue in electronics industries because electronic products tend to be thin, light, and portable [1,2]. In particular, the warpage affects the performance of the final products in their electrical and mechanical properties, reliability, etc. Furthermore, the warpage of the substrate results in low product yield rates during the manufacturing step and the assembly process of the integrated circuit (IC) packaging [3,4]. Numerous studies have been performed in order to understand the warpage behavior. It was determined that a critical factor for warpage is the coefficient of thermal expansion (CTE) and the residual stress of the layer [5]. In particular, high temperature warpage is dependent on the misfit of the CTE between layers [6–8] and room temperature warpage is determined by the non-mechanical stresses originating from the plating, curing, and layup operations [9,10]. The copper plating stress was measured in order to analyze the effect of chemical additives, seed materials, and plating conditions [11,12]. Research was conducted to investigate various warpage configurations such as spherical, cylindrical, and twist modes [13,14]. In addition, warpage begins initially in a spherical mode and develops into a cylindrical mode. This change is called curvature bifurcation [5,15–17]. The curvature bifurcation is phenomenon that the symmetric curvature shape changes its shape into asymmetrical curvature shape to release more strain energy when imposed load applied to the system exceed a critical value. Transforming into cylindrical curvature is more favorable than maintaining spherical shape to achieve it. Most warpage problems occur in cylindrical warpage shapes because the deflection of the spherical shape is not sufficiently large to be perceived, and this exacerbates the warpage issue. Cylindrical warpage can be described by its mode and orientation as depicted in Fig. 1. The warpage mode is defined by the direction in which the shape is curved from a cross-sectional view, and it can be either convex or concave. The warpage orientation is defined as the direction of the maximum curvature from the in-plane view. Therefore, the warpage orientation can be further classified into major and minor directions; the major and minor directions are the direction along the maximum curvature and the direction perpendicular to the major direction of warpage, respectively.

Semiconductor packaging is involved in thermal processes such as die attachment, wire bonding or flip chip bonding, mold cure, etc. In these thermal processes, the warpage orientation changes abruptly as the temperature varies and it affects the yield rate of the thermal

---

* Corresponding authors.
E-mail addresses: acumen00@gmail.com (M.S. Kim), tskim1@kaist.ac.kr (T.-S. Kim).

http://dx.doi.org/10.1016/j.microrel.2017.04.021
0026-2714/© 2017 Published by Elsevier Ltd.

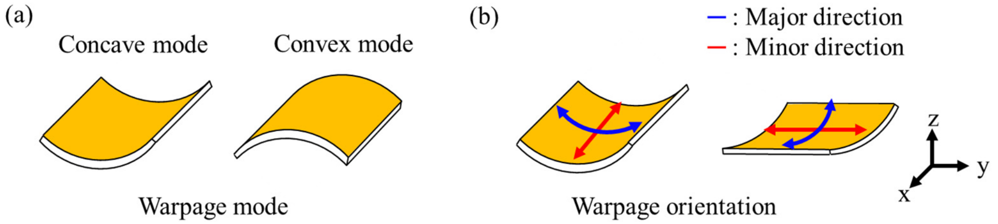


Fig. 1. (a) Two types of warpage mode: concave mode (positive curvature) and convex mode (negative curvature); and (b) warpage orientation described by the major direction (blue arrow) and the minor direction (red arrow). The film layer is on the top. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

operation. For example, because a guide apparatus supports the substrate along its longitudinal side only, it cannot keep the electric package substrate flat because the warpage orientation changes from a longitudinal direction to a transversal direction during the thermal operation. Then, the distance between the substrate and camera becomes different with their initial location and it is impossible to simultaneously focus the fiducial marks of the center and the edge unit on the substrate. This could lead to failure in aligning the semiconductor with each corresponding unit area of the substrate. Furthermore, the orientation of the substrate and the silicon die in the warpage orientation during the die attach process should be the same at the reflow temperature to reduce the non-wet risk of the bump. Therefore, the warpage orientation rotation is a critical issue in influencing the quality of packaging. The warpage orientation rotation phenomenon is essential in understanding the thermal behavior of the substrate and in solving the quality issue in the IC packaging. However, this has not yet been quantitatively discussed in the existing warpage research. Even the terms “warpage orientation” and “warpage mode” were not clearly defined, and many researchers defined them independently [18–22].

There are some related previous researches about warpage orientation rotation which is called snap-through buckling [23–26]. The warpage orientation rotation can be treat as a type of snap-through bucking. The snap-through buckling phenomenon is that the composite laminates has bistable or multiple stable state and be snapped from one stable shape to the other at a specific mechanical load. The most of previous researches deals with unidirectional laminate with unsymmetric structure such as [90°/0°], [90°/0°/90°/0°], or [90°/90°/0°/0°] to make initial curvature. Unlike the general snap-through bucking, the substrate used in this paper is cross-woven fiber reinforced substrate, which is symmetric structure with respect to the thickness direction. Furthermore, specimen has only one stable state at specific temperature and cannot be changed its state by mechanical loading. Therefore, the warpage orientation rotation cannot be explained using the conventional approach. It should be emphasized that the viscoelasticity of the material could be crucial in studying the phenomena of warpage orientation rotation [27,28].

In this research, two types of flexible fiber reinforced polymer (FRP) substrate-based specimens were tested in order to analyze the warpage orientation changes during thermal experiments. The warpage behavior of the specimens was measured throughout the thermal process with a temperature range from 30 °C to 180 °C. An optical 3D scanner (ATOS, GOM mbH, Germany) captured the warpage behavior of the specimens at each temperature. The moduli of the two FRP substrates were measured using a three-point bending test and the viscoelastic properties were measured using a dynamic mechanical analyzer (Q800, TA Instruments Inc., USA). The specimens were prepared as two different FRP substrates with copper film. The experiment results were compared via a finite element method (FEM) simulation. The simulation was conducted with and without the viscoelastic properties of the FRP substrates (only the elastic properties were applied in the latter case). The mechanism of the warpage orientation rotation was verified through analyzing the experiment results and the differences between the two simulations.

2. Experimental section

2.1. Specimen preparation & warpage measurement

The specimens for experimental verification were prepared in simple bilayer structures. Fig. 2 presents the preparation sequence of the specimens; the seed copper layers on both sides were laminated on a bare FRP substrate with heat and pressure at 230 °C (Fig. 2(a)). After cooling to room temperature, the flexible FRP substrate with the copper layers became copper clad laminate (CCL), which is used commercially for manufacturing printed circuit boards (Fig. 2(b)). Then, the copper layer was electroplated on the laminated seed copper layers. The copper layer thickness was 5 μm to 20 μm depending on the type of packaging board. In this paper, the electroplated copper thickness was 9 and 17 μm for experimental convenience (Fig. 2(c)). In the final step, one side of the copper layer was etched out. The warpage was observed immediately after the etching step due to the stress imbalance (Fig. 2(d)). All specimens were cut from a panel sized (405×510 mm^2) into 64 pieces with size of 44×56 mm^2 after the etching process.

An optical 3D scanner was used to measure the warpage of the specimens during the thermal process. The blue light source spread a fringe pattern on the specimens. Two charge-coupled device (CCD) cameras captured the deformed fringe pattern of the warped specimen. The advantage of this warpage measurement method is that it can measure all specimens in the field of view at once. Moreover, the warpage can be measured regardless of the state of the specimen's surface, while the conventional moiré method requires an additional surface treatment. In order to measure the warpage orientation rotation phenomena during the thermal process, the specimens were placed in a heat chamber. Due to the limited space of the heat chamber, three specimens were randomly selected from the 64 pieces. These three specimens were positioned at the center, upper left, and lower right of the panel.

2.2. Material property measurement

In order to obtain the flexural modulus of the flexible FRP substrates, three-point bending tests were performed at room temperature based on ASTM D790 and ASTM D7264. Two types of FRP substrates (type A and type B) were used in this experiment. Type A and type B FRP substrates were single-ply glass fabric laminates with bismaleimide triazine (BT) and cyanate ester (CE) based epoxy resins, respectively. The type of glass fabric for type A and type B FRP substrates were #2116 T glass and #1501-imp T glass, respectively, according to the standard code of the Institute for Printed Circuits (IPC). The detailed properties of both FRP substrates are listed in Table S1 in the supporting material. The specimen thicknesses of 100 μm and 150 μm were not sufficient to measure the modulus using a conventional tensile test. Thus, for the tensile tests, an additional substrate was stacked in order to obtain a sufficient thickness. However, it was not easy to measure the accurate modulus due to the effect of the adhesive layer between the FRP substrate and the effect caused by the fiber positioning in the substrate. In contrast, the three-point bending method could measure thin substrates and did not have a slippage problem. In addition, the specimen for the testing could be