Effects of External Bending Stress on Characteristic Change of Embedded Device

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Abstract

The displacement and stress-strain distribution of a device-embedded substrate under bending stress was simulated using the finite element method (FEM). In addition, the capacitance change of embedded devices was measured experimentally using an actual TEG substrate under bending stress. The results of the FEM analysis indicated that tensile stress at the surface of an embedded device may be a cause of electrical property changes. They may be affected by the substrate construction, especially the existence of a surface-mounted device. From the results of measuring the capacitance of an embedded chip capacitor with applied bending stress, the capacitance value increased relative to the stress. It was presumed that the distance between the electrodes of a laminated ceramic capacitor was narrowed slightly by the bending stress, which caused the capacitance increase.

Keywords: Device-embedded Substrate, Passive Devices, Bending Stress, FEM

1. Introduction

Device embedding is a promising technique for the downsizing and performance improvement of PWB, such as high wiring density and low transmission loss for high-frequency applications. Recently, fabrication techniques have been established for both active and passive devices owing to the development efforts of PWB-related companies and organizations.[1–4] However, in order to extend the market for device embedding substrates, some specific quality assurance issues related to embedded devices should be discussed. Although the resin-filled structure of device embedding brings high interconnect reliability, it may have some specific behavior differences from surface mount devices. One of the critical issues is electrical performance changes before and after the device embedding process caused by external mechanical stress. We previously reported on the displacement behavior of embedded bare die using an FEM analysis and actual experiments for some PWB constructions.[5] The stress-strain distribution of an embedded passive device has been investigated by several groups.[6, 7] In this paper, we focused on the characteristic change in behavior of passive devices and the stress-strain distribution at the embedded part.[8]

2. Experimental Procedure

2.1 TEG substrate

The layer construction of a TEG substrate is illustrated in Fig. 1. The substrate had a four-layer construction and a total board thickness of 0.32 mm. The insulating layer consisted of three types of materials. The core material (Resin C) was an FR-5-equivalent high-Tg FR-4 material, and Resins A and B were insulation materials for the build-up. An embedded device was placed in a cavity that was formed by cutting the core layer before the lamination process. After the lamination process and resin curing, laser via-holes were formed from the outer layer toward the external electrodes of the embedded device in order to...
produce an electrical connection. The via-holes were then filled with electrolytic copper plating. The dimensions of each bending test specimen were 40 mm in length and 30 mm in width. One passive device (resistor or capacitor) was embedded into the center part of each substrate, and their electrical properties could be measured at the outer electrodes of the substrate during the bending test. A view of the specimen is shown in Fig. 2.

2.2 FEM simulation

An FEM analysis model was constructed based on the TEG substrate. Configuration and dimensions of an embedded device are indicated in Fig. 3. Although an external electrode consist of multi-metal layers in actual devices, the external electrode in this model was simplified as single metal layer of copper. Because each metal layer is very thin, so effect of small difference of mechanical properties of each layer would be negligible. Since the substrate had a symmetrical configuration, the model was quartered in order to reduce the calculation load, as indicated in Fig. 4. A simulation mesh was created from the 3D-CAD data of the TEG substrate using a preprocessor (HyperMesh12, Altair Engineering, Inc.). The simulation was carried out using a solver (Marc2013, MSC Software Corp.), and the calculated results were output using a postprocessor (HyperView12, Altair Engineering, Inc.).

2.3 Three-point bending test

The bending test was carried out using a bench-top bending tester (Ez-LX, SHIMADZU Corp.). The lower span was 28 mm, and a bending load was applied on the device-embedded part up to maximum displacement of 1.5 mm. The crosshead speed of the applied load was 0.2 mm/min. Property changes of the embedded chip capacitor were measured during the bending test using an LCR meter. The lead wires of the LCR meter were connected to the outer electrodes of the substrate with solder, as shown in Fig. 5.

3. Results and Discussion

3.1 Substrate deformation and strain distribution

Four cases of substrate constructions were simulated as follows:

Case I: Load applied from the via-hole side of a device-embedded substrate
Case II: Load applied from the flip side of a device-embedded substrate
Case III: Load applied from the via-hole side of a substrate with an embedded device and a surface-mounted device
Case IV: Load applied from the via-hole side of a substrate without an embedded device (only surface-mounted)

In the simulation, a bending load was applied from 5.1 to 11.1 N in increments of 0.5 N. This load corresponded to a bending stress of 70 to 150 MPa in the substrate. In case III and IV, the surface-mounted device was placed at the same position in X-Y direction as the embedded device and
adhered with Sn-Ag-Cu solder. Specifications of the surface-mounted device were same as the embedded device. The simulation results of the substrate deformation and strain distribution under the applied 11.1 N of load are depicted in Fig. 6. The calculated results of the substrate deformation values ranged from 1.51 to 1.53 mm. They showed good agreement with the actual bending test. While the deformation values of Case I and III were equal despite of existence or non-existence of the surface-mounted device, Case IV had smaller deformation value than the other cases. Because this case did not have a cavity for device embedding, the stiffness of the core layer seemed to be higher than the other cases. This indicates that mechanical properties of the resins at the cavity could be a dominant factor to substrate deformation.

In terms of strain distribution, the data showed some interesting results. Very small strain was found in the plated via-holes and around them whether the load application direction was on the via-hole side or flip side. Both the embedded device and via-holes were constrained by insulating resin; therefore, they seemed to be reinforced by the resin-molding. On the other hand, large strain was calculated at the soldering pads of the surface-mounted devices in Cases III and IV, particularly beneath the soldering pad at the outer-layer of the substrate. One of the critical issues of device embedding, which we expected, was the connection reliability of the electrodes of the embedded device and substrate. These results indicated an advantage of device embedding regarding improved connection reliability compared with surface-mounting.

### 3.2 Simulated stress distribution in the embedded device

In order to know the electrical performance change of an embedded device, the principal stress distribution was simulated. The simulated models were (a) an embedded device in Case I, (b) an embedded device in Case II, (c) an embedded device in Case III, and (d) a surface-mounted device in Case III. The stress distributions of the devices were extracted from the simulation results, as shown in Fig. 7. The applied load in this case was 5.1 N. As described previously, the model was quartered because of its symmetry. Therefore, the nearest corners in the figure correspond to the centers of the devices. The calculated value of principal stress at the center of the surface of each device is indicated in the figure. The colors do not correspond to absolute values because the contour figures were color mapped automatically.

As shown in Figs. 7a and 7b, a large tensile stress was...
calculated at the surface of the opposite side of applied load in the case of device embedding. The maximum value was about 230 MPa in both cases. This indicates that a large tensile stress may be the cause of changes in electrical properties, such as resistance or capacitance. Particularly, in the case of a chip resistor, a thin film resistor is located on one side of the ceramic substrate. Therefore, if bending stress is expected in the application, the direction and location of the device should be considered at the design phase. Meanwhile, in Case III (device embedding plus surface-mounting), the generated stress at the embedded device was smaller than in Cases I and II. The maximum value in this case was 10.4 MPa (see Fig. 7c).

There are two possible causes for this major difference despite the fact that the devices were embedded at the same location. The first seemed to be a stiffness increase of the substrate construction caused by the existence of the surface-mounted device. The second might be translation of the neutral axis of the bending stress also caused by the existence of the surface-mounted device. Because the embedded device was located at the center position in the through-thickness direction, the neutral axis passed through the device in Cases I and II, as shown in Fig. 8a. On the other hand, when a surface-mounted device existed, the neutral axis moved toward the surface-mounted device side, as depicted in Fig. 8b. This allowed the stress field of the device-embedded area to be slight compressive. Consequently, the stress at the embedded
device was considered to be smaller than in Cases I and II.

3.3 Electrical property change during bending test

In order to evaluate the electrical property changes of an embedded device, a 1005-size ceramic chip capacitor was embedded in a TEG substrate. Since the chip capacitor was designed for device embedding, its thickness was 0.15 mm and it had copper-plated external electrodes for copper via connections. The capacitance of the embedded device was measured using an LCR meter during the bending test. The capacitance value and bending stress were plotted as a function of bending displacement in Fig. 9. In this figure, the obtained capacitance was normalized as against nominal values and plotted against the left vertical axis. The capacitance value was increased by approximately 2% depending on the applied bending load and decreased accordingly during unloading (see data sets (a) and (b)). The capacitance of a parallel-plate capacitor is given by

\[ C = \varepsilon \cdot \frac{S}{d} \]  

(1)

where \( C \) is the capacitance, \( \varepsilon \) is the dielectric permittivity, \( S \) is the electrode area, and \( d \) is the distance between electrodes. Because the dielectric permittivity is constant, the capacitance is determined from the electrode area and distance. The previously-described tensile stress must expand the electrode area, and the applied load in the through-thickness direction must narrow the distance between the electrodes of the laminated ceramic capacitor microscopically. These changes cause the capacitance to increase according to Eq. (1). A laminated ceramic chip capacitor is an aggregate of parallel-plate capacitors. Accumulated small increases in the parallel-plate capacitor result from the increase in electrode area and decrease in electrode distance. These would cause the measured capacitance increase of 2%.

The bending stress plotted against the right vertical axis was calculated from the measured applied load based on the assumption that the specimen was a rigid body with a thickness of 0.32 mm. The stress change showed irreversible behavior, as indicated by data sets (c) and (d) in Fig. 6. The source of this behavior is not clear, but very small delaminations caused by bending stress might have occurred at the interface between the conducting and insulating resin materials during the load application.

4. Conclusion

The stress-strain distribution and electrical property changes during the bending test of a device-embedded substrate were evaluated through FEM analyses and an actual experiment. The results are summarized as follows:

(1) The results of the FEM analyses indicated that the tensile stress at the surface of an embedded device, which may be a cause of electrical property changes, was affected by the substrate construction, especially the existence of surface-mounted devices.

(2) In the case of an embedded chip resistor, the location of the resistor thin film should be considered in terms of stress distribution.

(3) Although the stress and strain were small at the external electrodes of the embedded device and plated via, a large strain was found at the soldering pad of the surface-mounted device.

(4) From the results of the bending test, capacitance increased relative to the bending stress. The bending stress seemed to affect the electrode area and distance of the embedded chip capacitor, which must have caused the capacitance value change.

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