

Study of stress to Solder Joint by Underfill filling

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Abstract

To investigate how the underfill of a device produced by flip chip bonding affects the chip's reliability, the Young's modulus distribution in the underfill's in-plane and thickness directions was measured at many micro regions throughout the material using a nanoindentation measuring method. The results showed that the underfill's nonhomogeneity can occur depending on the filling location and/or dispensing direction. The causes of this nonhomogeneity and stress distribution on the solder bump was analyzed using a finite difference method, finite element method and Piezoresistance test chips, and the effect of the underfill on the solder bump was studied.

Key Words: underfill, packaging, filler, solder, bump, nanoindentation, Young's modulus, FEM

1. Introduction

Mobile electronics use a variety of innovative mounting technologies such as 3D high-density mounting, Low-k materials, and lead-free soldering toward thinner, lighter, and environment-friendly products, which leads to enhancing their competitiveness in the market^{1),2)}.

Especially, flip chip bonding permits the mount area to have the same mounting density as a semiconductor device, so that it has been widely used for applications requiring higher density mounting within the limited dimension. Meanwhile, higher reliability is also a customers' demand, which requires a lot of time and resources for developing, designing and checking reliable products. In this regard, time is an important factor, since an optimum design, material and process should be achieved within a shortest lead time. One example is a simulation-based analysis that can produce accurate solutions in a short period of time.

As shown in Figure 1, a normally used stress relaxation process applicable for the flip chip bonding technology is one which inserts an underfill between the bare chip and substrate in order to reduce stresses from the solder bump^{3),4)}.

A typical underfill contains fillers, such as silica, to adjust the linear thermal expansion coefficient and flowability. Up to the present, the underfill is considered homogeneous, and thus the values of its linear thermal expansion coefficient

and Young's modulus is considered uniform throughout the body, so that reliability designs e.g. using an FEM analysis has been based on an assumption that these properties are constant throughout the underfill body (bulk properties were used for calculation). However, underfills become nonhomogeneous depending on the sedimentation of the filler and on the pouring conditions. This underfill's nonhomogeneity may affect the bonding reliability since the chip becomes smaller in physical dimension and more complicated in time⁵⁾. Unfortunately, however, the conventional methods for measuring the linear thermal expansion coefficient and Young's modulus, such as thermomechanical analysis (TMA) and dynamic viscoelastic analysis (DMA), are unavailable because the amount of the underfill in the micro region between the bare chip and substrate is too small to be used as a testing sample for these measuring technologies.

In our previous report, it was shown that through measurement using infrared microspectrometry (μ -IR), thermomechanical analysis (TMA) and nanoindentation for a set of samples (cut out by a special trimming technology), which represent different micro regions in the underfill, the linear thermal expansion coefficient, Young's modulus, and composition as well, are not uniformly distributed throughout the underfill body⁶⁾.

This paper reports in detail the in-plane

mechanical properties in the micro regions of two different underfills measured by using the nanoindentation method⁷⁾. Moreover, with regards to the factors influencing the condition of the underfill filler, the effects of flow analysis and filler conditions on the solder bump was analyzed through stress analysis.

To validate these analyses results, a Piezoresistance test chip based on Piezoresistance Effect, was used and the stresses that can occur in the test chip as a result of filling an underfill material were measured⁸⁾. Further, the effect of underfill's nonhomogeneity was investigated. The results will be discussed later.

2. Method of Experiment

2.1 Nanoindentation Method

The nanoindentation method measures the Young's modulus and hardness within a micro region of a material using an indenting point of 100 nm in tip diameter called Berkovich tip^{9),10),11),12)}.

Chips cured with 2 types of underfill (Sample A and Sample B) were prepared. The characteristics of each sample is shown in Table 1. The Young's modulus of each underfill was measured using nanoindentation method. Parallel to the cross-section line shown in Fig. 2, 10 lines were defined. On each of the sections determined by the 10 lines, 10 nanoindentation measurement positions were selected (total 100 measurement points). During measurement, locations which contain silica particles with diameter 10 μ m and above were not used as a measurement point. For any indentation test, including the nanoindentation, considerations must be made during the determination of the points of analysis since the test result can be affected by the surrounding material within the area ten times as large as the area of indentation. This experiment was done using NanoIndenter XP manufactured by MTS; measurement mode: Continuous Stiffness Measurement (CSM); excitation vibration frequency: 45Hz; strain rate: 0.05s⁻¹; and displacement into surface: 500 nm (standard for fused silica).

Table.1 Sample

	Underfill	
	Mean Silica size	T _g (°C)
SampleA	4.0 μ m	137°C (TMA)
SampleB	1.2 μ m	85°C (TMA)

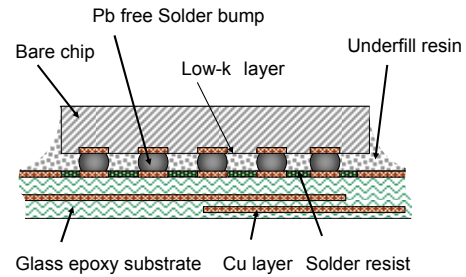


Fig.1 Schematic cross-sectional view of the flip chip interconnection with the underfill

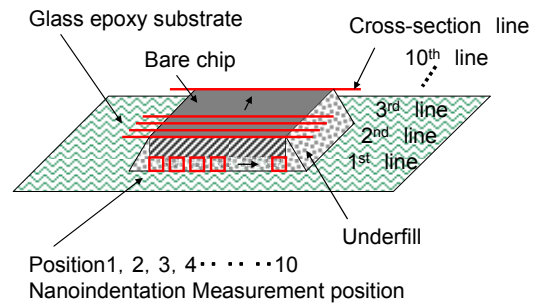


Fig. 2 Nanoindentation Measurement Points and Cross-Section Line

2.2 TEG Chip Stress Measurement

This experiment used a Piezoresistance test chip (TEG chip) to measure the relationship between the underfill filling process and post-cured residual stresses. Equation (1) shows that the change in resistance is proportional to the stress acting on the TEG chip¹³⁾. In equation (1), σ and S denote stress and stress sensitivity respectively.

$$(R-R_0)/(R_0)=S \times \sigma \quad (1)$$

Using these relationships, it is possible to determine how the stress acting on the TEG chip surface differ depending on the presence of underfill and on temperature rise by measuring the resistance R before dispensing the underfill and after it is cured. The TEG chip used for this test is JTEG PHASE5LF manufactured by Hitachi ULSI Systems; solder: Sn-3.5Ag, dimension: 3mm x 3mm, thickness: 0.6 mm. Figure 3 shows the layout of the Piezoresistance gauges. Prior to the experiment, the TEG chip mounted on the test substrate was connected to the multimeter and thermometer as shown in Figure 4.

The test substrate without underfill, defined as the initial test condition, was subjected to test at R.T., 50°C, 100°C and 150°C. Resistances in the X and Y directions at the center and at the corner positions on the TEG chip were measured. For Samples A and B, underfill was dispensed using two different methods shown in Figure 5, and was

heated for curing. After the underfill was cured, the TEG chip resistance values were again measured at R.T., 50°C, 100°C, and 150°C. Then, using equations (2) and (3) below, the stress was calculated.

□Correction of measured resistance:

$$R_c = R_m / (1 + (\beta_1 \times (T_m - T_c) + (\beta_2 \times (T_m - T_c)^2))) \quad (2)$$

R_c : resistance corrected by temperature

R_m : resistance as measured

T_c : temperature for corrected resistance

T_m : temperature at measurement

β_1 : Temperature dependency of Piezoresistance (1st)

β_2 : Temperature dependency of Piezoresistance (2nd)

□Stress calculation:

$$\sigma = ((R - R_0) / R_0) / S \quad (3)$$

σ : stress

R_0 : Piezoresistance without underfill (initial value as corrected by temperature)

R : Piezoresistance with underfill cured (final value as corrected by temperature)

S : stress sensitivity

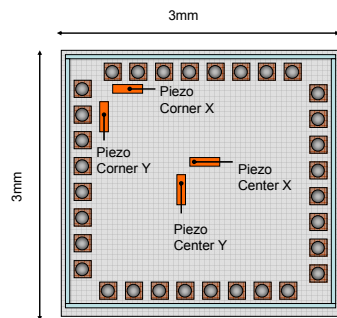


Fig.3 TEG Chip Layout(bottom view)

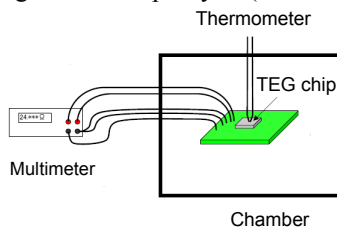


Fig.4 Layout of residual stress measurement

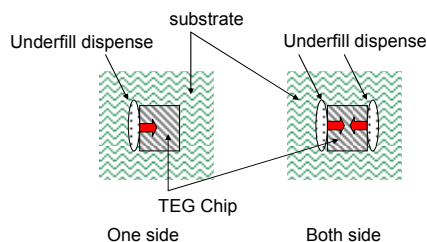


Fig. 5 Two Different Filling Models Representing Underfill's nonhomogeneity (Top Views)

3. Results and Discussions

3.1 Nanoindentation Test Result

Photo 1 shows the cross section of Sample A. Figure 6 shows one sample nanoindentation test result for Sample A.

When the indentation is shallow, surface unevenness, contaminants and water absorption may affect the measurements. Therefore, an indentation depth of 500 nm was chosen so that stable and correct measurements could be obtained with the minimum surface effects.

Figures 7 and 8 show the mapping effect of Young's modulus at the middle part of Sample A and Sample B respectively

The underfill on the test substrate was produced by a 2-minute dispensing operation of a homogeneous underfill material. However, Sample A showed a large difference in Young's modulus distributed over the measurement points (10 lines x 10 points/line) having the smallest value of 4.2 MPa and largest value of 17.7 MPa (four times larger than which the smallest value). For the 2nd to 5th lines, which are located near the dispensing point, where there are a lot of organic components, the Young's modulus measured was around 4 GPa which is comparable to that of the organic components. By contrast, for the 6th to 10th lines, where the silica content is larger, a larger Young's modulus was measured. Sample B, on the other hand, showed a larger Young's modulus value of 21 GPa at positions 3 to 8 on the 1st line, while its value of around 14 GPa was obtained at all other points. Moreover, Sample B showed a more stable distribution of Young's modulus as it approaches the 10th line. For the distribution of Young's modulus in the thickness direction, Samples A and B showed the same trend with the largest value at the middle part followed by the upper part and then by the lower part. It is therefore concluded that even if a homogeneous material is dispensed, nonhomogeneity (e.g. in terms of Young's modulus) may occur both in the in-plane and depth directions depending on the type of the underfill material used.

On the surface of the bare chip and substrate, there are various factors affecting the flow of underfill material such as flow restrictions caused by unevenness of circuit patterns and solder bumps, wettability depending on the type of material, and gravitational force. These lead to the nonhomogeneity of the cured underfill material, as

indicated by the nanoindentation test described above. Some numerical analyses indicated the same results. For example, a numerical analysis based on a lattice Boltzmann simulation showed that an underfill that become nonhomogeneous due to wettability and capillary action after being dispensed^{14),15)}. From the results above, the underfill's physical properties, even though it has been conditioned to a homogeneous state in liquid before it is dispensed onto the substrate, may not be uniform in the cured state due to various factors. Thus, temperature rise may cause the whole chip to be subjected to unbalanced stress and local strain.

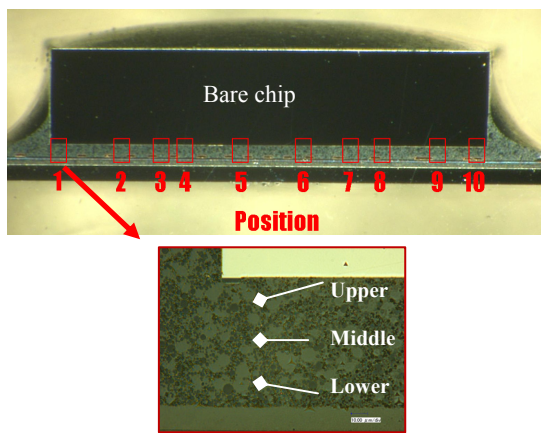


Photo1 Cross-section of SampleA 1st line and the positions “□” of the Nanoindentation measurement(e.g.)

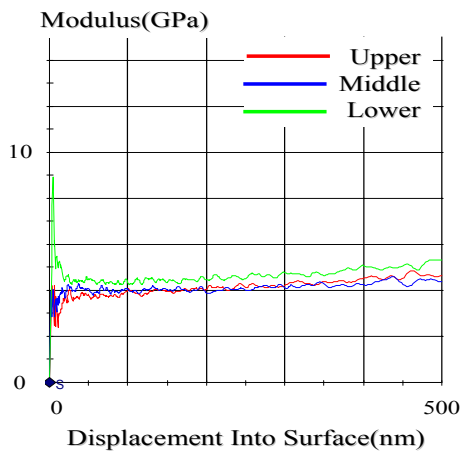


Fig.6 Nanoindentation result of the SampleA
Cross-section 1st line-position1 of the Flip-Chip
Device Assembled

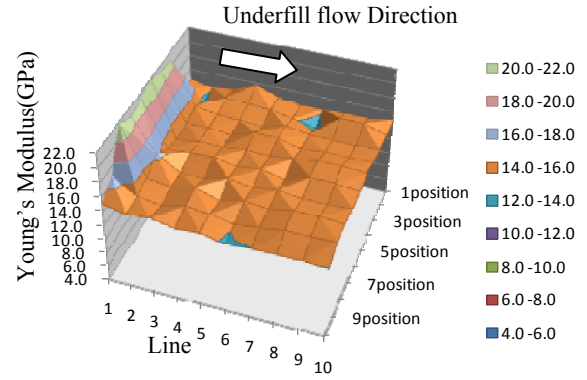


Fig.7 Nanoindentation Mapping of SampleA

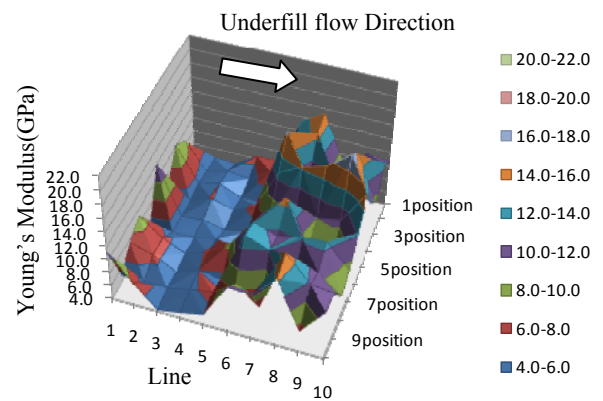


Fig.8 Nanoindentation Mapping of SampleB

3.2 Finite Difference Method (FDM) Analysis

3.2.1 Underfill Flow Analysis

Noting the result of the nanoindentation test showing nonhomogeneous distribution of silica particles in the underfill after curing, we performed FDM analysis to determine the behavior of the underfill material before it is cured. For Sample A and Sample B, whose particle size differ from each other, we created a 2D flow analysis model (Figure 9) which can investigate the behavior of flow and distribution of silica particles on the substrate, during and after flow, and then we performed a comparison study. This flow analysis used the continuity equation (5) representing the law of conservation of mass, the Navier-Stokes equation (6) representing the law of conservation of momentum, the VOF transport equation (7) as a fluid rate transport equation, and the equation of particle motion (8).

$$\nabla \cdot \rho U = 0 \quad (5)$$

$$\partial U / \partial t + (U \cdot \nabla)U = -1/\rho \nabla P + G + S \quad (6)$$

$$\partial F / \partial t + \nabla \cdot FU = 0 \quad (7)$$

$$dU_p/dt = -1/\rho_p \nabla P + g \quad (8)$$

ρ = fluid density, t = time, U = velocity vector, P = pressure, G = acceleration of body force, S = acceleration of viscous force, F = VOF function, ρ_p = particle density, U_p = particle velocity, g = gravitational force on particle, and body force

Figure 10 shows the silica particle diameter models. FLOW-3D was used as a solver.

One restriction of using this particle model is that it defines a particle as a point of mass, not as a volume. Another presumption is that the fluid flow resistance between the fluid and particle is taken into consideration, while collision between particles can be disregarded.

Flow of underfill material through the channel was simulated. The silica particle distribution, 60 seconds after the flow was started, is shown in Figure 11.

Part of the flow channel, a length from 0 (start end) to 3 mm, was divided into 30 sections with 0.1 mm interval. The average height of the silica particles in each section was plotted. This was done by substituting the particle diameter (d) to the weighted formula (9) shown below.

$$\text{Mean height} = \frac{\sum(hXd)}{\sum d} \quad (9)$$

This study shows that Sample A, containing larger particles, has a greater tendency to subside and has a higher degree of nonhomogeneity.

Figures 12 and 13 show the ratio of silica particles in the vertical direction (upper, middle and lower parts), for Samples A and B respectively. Sample A shows that the distribution of the number of particles in the vertical (thickness) direction varies significantly throughout the length of the channel (as can be seen in the unstable high and low values), and that the large particles subside due to gravitational force, as evidenced by the smaller number of particles at the upper part. Also, it can be seen that the ratio of particles at the middle and lower parts at the same section of the channel both have radical high and low values, making the sample nonhomogenous as a whole. On the other hand, Sample B shows that the distribution of particles by its number in the vertical direction is almost constant, though the number at the middle part becomes larger around the 3mm flow distance.

Figure 14 shows the plot of the proportion of particle diameter to the gap between the bare chip and substrate (gap ratio %) for each of silica particle size. The degree of nonhomogeneity in the underfill is higher with a larger gap ratio or larger

difference in the particle size of silica contained.

Therefore, for underfill materials containing silica, in order to reduce nonhomogeneity, the slope of the line shown in Figure 14 as well as the gap ratio should be reduced.

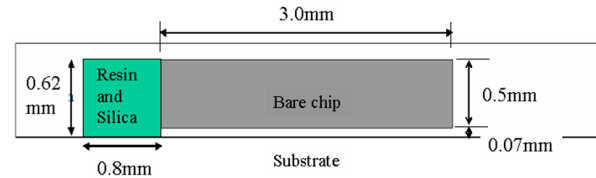


Fig. 9 Underfill 2D Flow Analysis Model

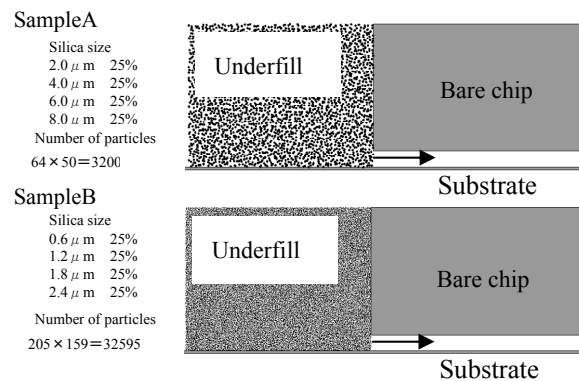


Fig. 10 Underfill 2D Flow Analysis Conditions

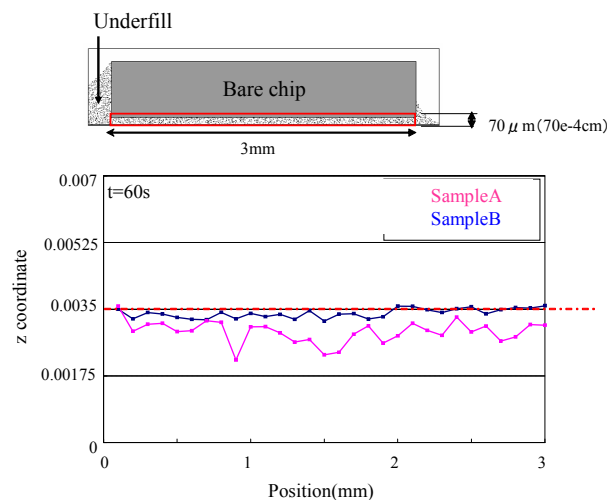


Fig. 11 Underfill 2D Flow Analysis Result – Silica Particle Distribution

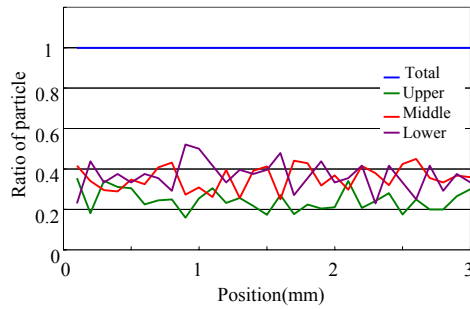


Fig. 12 2D Flow Analysis Result – Particle Number Distribution for Sample A

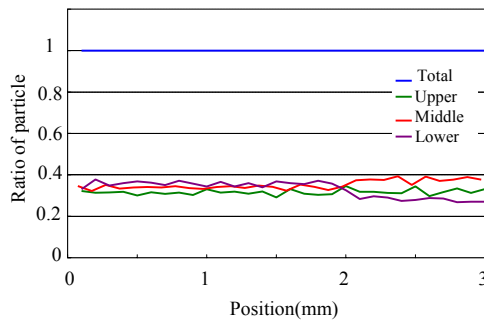


Fig. 13 2D Flow Analysis Result – Particle Number Distribution for Sample B

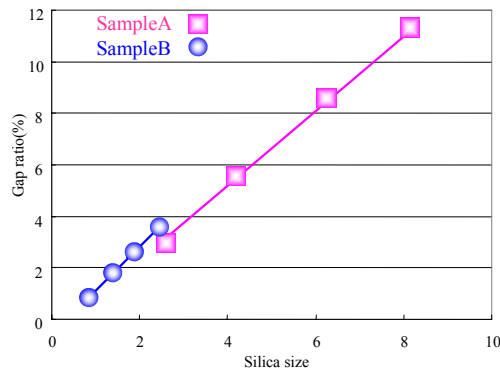


Fig. 14 Ratio of Silica Size to Gap

3.2.2 Analysis of the Solder Bump Stress

To investigate the effect of silica particles and that of the nonhomogeneity of underfill around the solder bump, we defined Models A and B. Figure 15 shows the 3D stress analysis models.

Model A: silica particles even distribution but different volume concentration (30 vol%, 50 vol%, 70 vol%)

Model B: silica particles uneven distribution in the thickness direction (homogeneous, center, flottage, subsidence)

Series A models have an even distribution of silica particles throughout the underfill, but each of them has a different volume percent of 30, 50 and 70 respectively, as shown in Figure 16. On the

other hand, each of the series B models has a different distribution of silica particles with respect to the vertical (thickness) direction: homogeneous, center (concentrated at the middle part), flottage (concentrated at the upper part) and subsidence (concentrated at the lower part). For the series B models, the content of silica particles was assumed to be 50 vol% for the case of homogeneity, and 30 and 70 vol% at thinly and densely concentrated heights respectively. Consequently, seven models in total were defined to represent different silica particle distribution in the underfill layer. A single geometry of solder bump was defined and stress analysis using FEM model was done. ABAQUS v.6.6-2 was used as the solver and “8-noded linear brick solid element” was chosen as the element type. The element was subjected to an axial load acting against the bare chip.

Figure 16 shows analysis results for series A models. With a higher content of silica particles, the stiffness of the underfill is larger, which in turn reduces the stresses acting on the central part of the solder bump. However if the underfill has a higher stiffness value than that of the solder bump, an opposite result was obtained.

Figure 17, showing the analysis results for series B models, indicates that different types of nonhomogeneity in the underfill lead to different locations where stress concentration occurs. When the underfill is homogeneous, the stress in the solder bump is even. When the silica particles are concentrated at middle, upper or lower part, stress concentration occurs at the interface between the bare chip and substrate. There is a tendency that relatively higher stress will occur at regions where the concentration of the silica particles is lower. The stress concentration at the interface between the bare chip and substrate is caused mainly by the warping of the bare chip and substrate due to their expansion or shrinkage, and also caused by the shearing load acting on these plates. However, the underfill's nonhomogeneity can likely be an additional cause to the stress concentration.

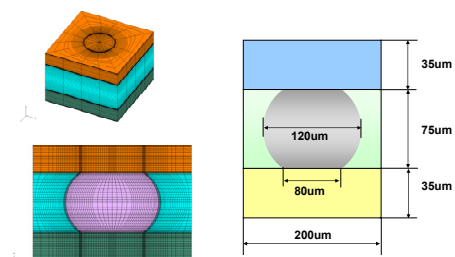


Fig. 15 3D Stress Analysis Model

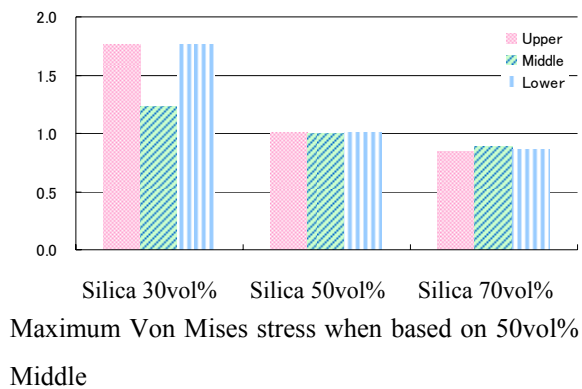


Fig.16 Model A FEM analysis for solder joint

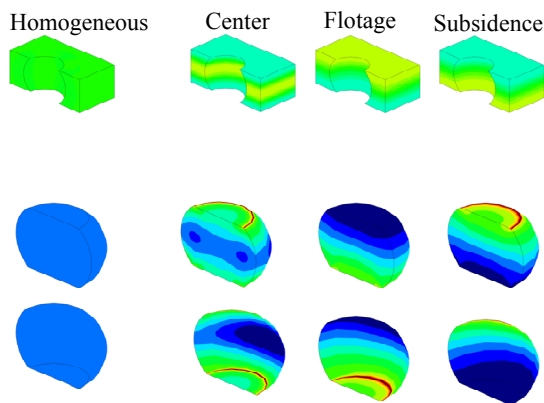


Fig.17 Model B FEM analysis for solder joint

3.3 TEG Chip Stress Measurement Result

Figure 18 shows the result of a test with a TEG chip mounted on a test substrate for investigating how the stress distribution in the X direction of the chip differs depending on temperature. This test used a symmetrical layout of underfill by filling at both sides of the TEG chip expecting that the symmetry leads to an even distribution of in-plane stress in the underfill after it is cured. Another type of underfill, one which is located at one side only, was also used for comparison. The underfill material used for this test was Sample B, which showed stable characteristics at the nanoindentation test. As a result of this TEG chip stress measurement, every sample showed a constant stress of -30 (MPa) at a temperature lower than the glass transition temperature (T_g). Later on, as the temperature rises toward the T_g boundary, lines moved toward the minus (tension) direction. For the sample with underfill at one side only, as the temperature rises, the stress reaches a value as low as -200 (MPa) at 150°C. A possible reason for this result is that the mechanical properties of the underfill such as Young's modulus and linear expansion coefficient changed due to the resultant

relaxation of the molecular chains caused by the glass transition, which resulted in the reduction of the underfill's restraining force acting on the internal stresses generated between the TEG chip and substrate.

Unlike the both-side symmetrical layout, the one-side underfill layout became nonhomogeneous after curing so that when the temperature rose over T_g , besides the internal stresses generated between the TEG chip and substrate, and the weakened restrictive stresses brought about by the underfill, an additional effect was brought about by the nonhomogeneity of the underfill itself. For example, when the underfill under the TEG chip is so nonhomogeneous that the silica particles concentration is higher at some regions while it is lower at other regions, the Young's modulus and linear expansion coefficient of the underfill change partly as the temperature rises, which results in the generation of stress concentration and strain in the underfill and then later on affect its surroundings.

The both-side symmetrical layout of underfill is likely capable of reducing the degree of nonhomogeneity, since it is symmetrical with respect to the TEG chip. So, the effect of nonhomogeneity at temperature above T_g was less than that with the underfill made by one-side filling, which led to different stress levels between the two underfill types.

It is thus suggested that when using a nonhomogeneous underfill, the residual stresses that could occur within the material can be reduced by improving the dispensing (filling) process.

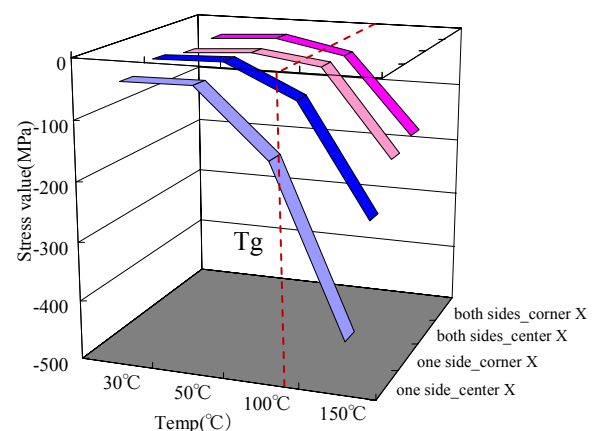


Fig. 18 TEG Chip Mounted Test Substrate – Stress vs. Temperature Measurement

4. Conclusion

This study demonstrated the internal states of two different types of underfill (Samples A and B) by measuring the Young's modulus using a nanoindentation method. Using the measured data, the effect of the underfill's flow and nonhomogeneity on the surroundings was evaluated by a finite difference method and finite element method. For a demonstration purpose, two different types of underfill layout – dispensing at both sides of the chip, and one side only – were evaluated using a TEG chip test sample. The obtained information is as follows:

- Even if the underfill material (liquid) has been conditioned to a homogeneous state, the filler can group together and/or subside during the dispensing and curing process due to some external factors, which results in an uneven distribution of Young's modulus in both the in-plane and thickness directions.
- As a result of evaluating different filling condition models through a silica particle flow analysis, a higher level of homogeneity was obtained with a smaller ratio of the silica particle diameter to the gap between the bare chip and substrate, and with a smaller difference in particle diameter.
- Based on measuring the temperature of a TEG chip mounted on a test substrate, the sample with a symmetrical layout of underfill strips at both sides of the chip, which was expected to reduce the level of nonhomogeneity, showed a reduction in the internal stress.

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