Thermal Shock Test of IC Packages Sealed with Epoxy Molding Compounds Filled with Irregular-Shaped Silica Particles

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SYNOPSIS

The effect of the filler silica particle size on the properties of integrated circuits (IC) packages sealed with an epoxy molding compound was studied. For this purpose, two kinds of epoxy molding compounds filled with irregular-shaped silica particles having mean sizes of (A) 16 μm and (B) 5 μm were prepared. The fracture toughness (Kc) of cured A was higher than that of cured B, but the flexural strength of cured A was lower than that of cured B, i.e., cured A and B had opposite physical properties. The thermal shock test was carried out in which IC packages were repeatedly dipped alternately in −65 and 150°C liquids and package cracking was observed. The thermal shock property of the IC package sealed with A was superior to that sealed with B. There was a good relationship between the thermal shock test property and Kc value. © 1993 John Wiley & Sons, Inc.

INTRODUCTION

Recently, in the integrated circuits (IC) sealed with epoxy molding compounds, the chip size has been rapidly increasing while the package dimensions have become smaller and thinner.[1] These trends increase thermal stress in the device package system and this stress often causes the package cracking during thermal shock testing as accelerating ambient conditions.[1-4] Therefore, it has become an important issue in the designing of a device package to reduce the thermal stress[4] and to increase the strength and toughness of the cured epoxy molding compounds.[2]

In a series of our investigations,[5-12] effects of the particle shape and size on the fracture toughness,[5,9,10,12] mechanical strength,[6,9,11,12] and impact properties[8,11] of the cured epoxy resin filled with silica have been studied. In these studies, irregular-shaped or spherical silica particles ranging from 2 to about 50 μm in diameter were dispersed in the liquid-type epoxy resin[5-11] (bisphenol A type epoxy resin and dicarboxylic anhydride hardener) and in the solid-type epoxy resin[12] (*o*-cresol novolac-type epoxy resin and phenol novolac-type resin as a hardener). The former was developed as "model system" and the latter was an actual cured molding compound of encapsulating material for IC. In these studies, as the particle size increased, the fracture toughness increased but the flexural strength decreased, i.e., the particle size has an opposite effect on the fracture toughness and the flexural strength. Therefore, the relationship between these values of the cured epoxy molding compound and the actual properties of the IC package sealed with the epoxy molding compound must be clarified.

In this article, the IC packages sealed with the epoxy molding compounds filled with irregular-shaped silica particles having two different particle sizes were prepared and the relationships between the flexural strength and fracture toughness of the cured molding compounds and the thermal shock test results of IC packages will be discussed.

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EXPERIMENTAL

Materials

The irregular-shaped silica particles were prepared by the crushing of amorphous silica made by fusing natural raw quartz at 1900°C (RD-8, mean size: 16 μm, and ZA-30, mean size: 5 μm, Tatsumori Ltd.). Figure 1 shows the size-distribution curves obtained using a laser beam size distribution analyzer (Granulométre 715 type, Cilas Alcatel). As described in previous articles,[5,10] the particle sizes at which the cumulative distribution values reached 50% were defined as the mean particle sizes.

The epoxy resin used was *o*-cresol formaldehyde novolac-type epoxy resin (ESCN-195XL, Sumitomo Chemical Co.; equivalent weight per epoxy group: 195; softing point: 85°C). Phenol formaldehyde novolac resin (P-180, Arakawa Chemical Industries; equivalent weight per hydroxyl group: 104; softing point: 80°C) and 1,8-diazabicyclo(5,4,0)-7-undecene (DBU) were used as a hardener and an accelerator for curing of the epoxy resin, respectively.

Sample Preparation

Table I shows the formulation of an epoxy molding compound. To prepare the molding compounds, these materials were mixed in a mixing roll at 110°C for 5 min, then cooled and crushed. The test specimens were prepared by transfer molding at 175°C for 2 min and cured in an oven at 175°C for 5 h.

Table I Formulation of Epoxy Molding Compound[a]

Epoxy resin[b]	27.03
Hardener[c]	17.83
Accelerator[d]	0.14
Silica particles[e]	70.00

[a] Unit: wt %.
[b] *o*-Cresol formaldehyde novolac resin.
[c] Phenol formaldehyde novolac resin.
[d] 1,8-Diazabicyclo(5,4,0)-7-undecene (DBU).
[e] Irregular-shaped silica particles.

Fracture Toughness Test

The critical stress intensity factor (fracture toughness, *Kc*) and critical strain energy release rate (fracture energy, *Gc*) were measured by a *S*ingle *E*dge *N*otched *B*eam loaded in a three-point bending (SENB) test according to ASTM.[13] The specimen size was 10 × 4 × 44 mm with a support span of 40 mm, having a slot at the center part. An acute incision was introduced at the base of the slot by pressing with a fresh razor blade. The displacement rate was 10 mm/min. The detailed conditions were explained in our previous article.[5]

Flexural Test

The specimen size was 10 × 4 × 80 with a support span of 64 mm. The displacement rate was 5 mm/min (ASTM D790). The detail conditions were explained in our previous article.[6]

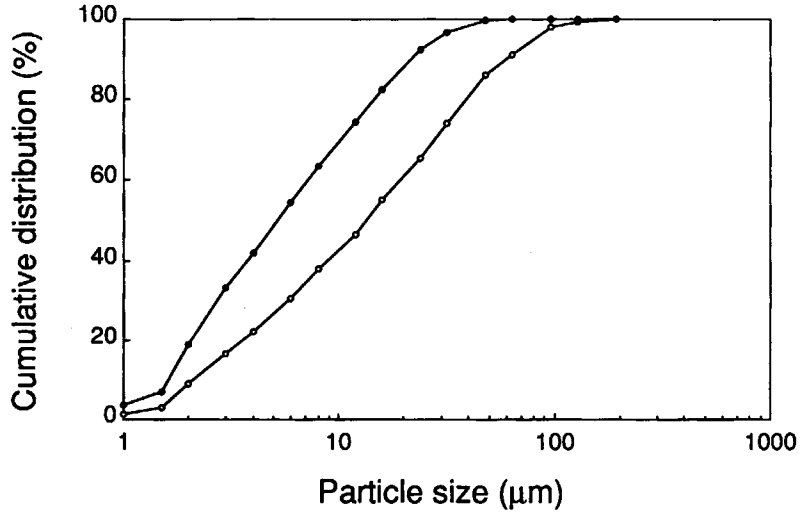

Figure 1 Cumulative size-distribution curves for irregular-shaped silica particles. Mean particle size: (○) 16 μm; (●) 5 μm.

Thermal Mechanical Analysis

Thermal expansion coefficients below and above glass transition temperature (T_g) of the cured epoxy molding compounds and T_g were measured by a thermal mechanical analyzer (TMA/SS-100, Seiko Instruments Inc.). The detailed conditions were explained in our previous article.[14]

Thermal Shock Test

The package used in this study was 80 pin Quad Flat Package (QFP, 20 × 14 × 2 mm) with Alloy 42 (Alloy of Fe and Ni [Ni: 42 atom %]) lead frame. The chip and the chip pad sizes were 7.5 × 7.5 and 8 × 8 mm, respectively. The thermal shock test (TST) was carried out using a liquid bath thermal shock chamber (TSB-1L, Tabai Espec Corp.) in which test packages were repeatedly dipped alternately in −65 and 150°C liquids for 5 min each and for 30 s in transition. The number of test packages for each epoxy molding compound was 20.

RESULTS AND DISCUSSION

Figure 2 shows scanning electron microscopic (SEM) photographs for the polished surfaces of cured epoxy resins filled with irregular-shaped silica particles. In both (a) large- and (b) small-particle-filled systems, particles were well dispersed in the cured epoxy matrix.

Table II shows some thermal and mechanical properties of cured epoxy molding compounds. The fracture toughness (Kc and Gc) values for the large-particle-filled system were higher than those for the small-particle-filled system, while the flexural strength value for the large-particle-filled system was lower than that for small-particle-filled system, i.e., the particle size had an opposite effect on the fracture toughness and the flexural strength in the same way as it did in our previous articles[5,6,12] in which the reason for it was already clarified.

Oizumi et al.[15] reported the failure phenomena during the TST. Before the TST, the chip pad and the encapsulating material (cured epoxy molding compound) were completely adhered. As the number of the dipping cycles in the TST was increased, the delamination between the chip pad and the encapsulating material progressed from edge to center of the interface. Since the curvature radii of the edge tips are usually on the order of 1 μm,[2] after complete delamination of the interface, the crack originated from the edges of the chip pad and propagated to

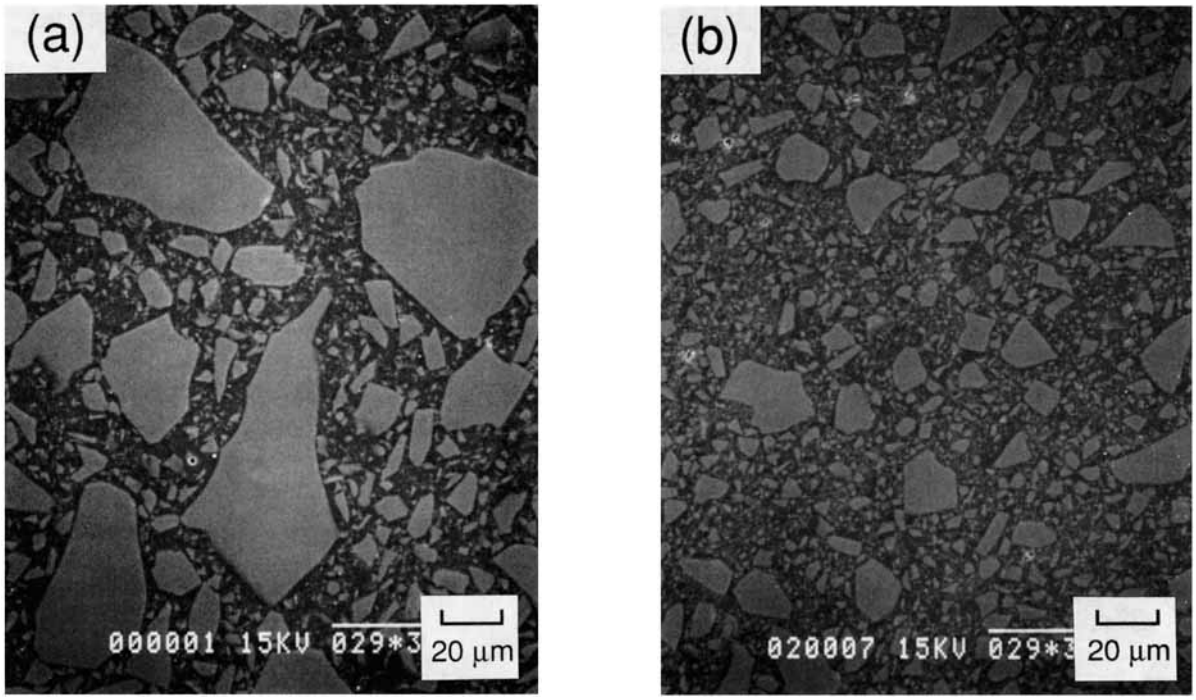

Figure 2 SEM photographs of polished surfaces of cured epoxy molding compounds filled with irregular-shaped silica particles at a particle content of 70 wt %. Mean particle size of the filled silica: (a) 16 μm; (b) 5 μm.

the bottom surface of the package. In this study, to neglect the influence of the interfacial adhesion between the chip pad and the encapsulating material, the bottom surface of the chip pad was coated with silicone grease (from the toluene solution and dried in an oven). The interface was completely delaminated before the test.

Figure 3 shows the result of the TST. The degree of package cracking indicates the percentage of the packages that had cracked visibly on the package surface, whereas the cracks in the package's interior were not counted. Before the TST, the initial crack with a 10–30 μm length was observed at the lower edges of both sides of the chip pad in the packages sealed with the small- and large-particle-filled resins. These cracks propagated to the bottom surface of the package during the TST. In the small-particle-filled system (●), most of the packages cracked within 30 cycles, whereas in the large-particle-filled system (○), about half the packages did not crack over 30 cycles, i.e., the TST result of the large-particle-filled system was superior to that of small-particle-filled system.

As shown in a previous article,[4] the thermal stress caused during the TST at the edge of chip pad is calculated according to the following equation:

$$\sigma = \int_{-65}^{150} E(\alpha_1 - \alpha_L)dT \qquad (1)$$

where σ is the thermal stress caused during TST; α_1 and E, the thermal expansion coefficient below T_g and the flexural modulus of cured epoxy molding compound, respectively; and α_L, the thermal expansion coefficient of the lead frame (chip pad = 0.5 $\times$ 10^{-5}/°C was used[3]). It was also clarified that as the thermal stress was decreased the occurrence of

Table II Some Thermal and Mechanical Properties of Cured Epoxy Molding Compounds Filled with Irregular-Shaped Silica Particles

	Mean Particle Size of Filled Silica	
	16 μm	5 μm
Thermal mechanical analysis		
α_1[a] ($\times 10^{-5}$/°C)	2.1	2.0
α_2[b] ($\times 10^{-5}$/°C)	6.8	6.6
T_g (°C)	170.0	169.0
Flexural test[c]		
Flexural modulus (GPa)	14.5	14.7
Flexural strength (MPa)	128.0	163.0
Displacement at break (mm)	1.6	2.1
Fracture toughness test[d]		
K_c (MPa $\sqrt{m}$)	2.6	1.8
G_c ($\times 10^{-1}$ kJ/m^2)	3.3	1.8
Thermal stress[e]		
σ (MPa)	49.9	47.4

[a] Thermal expansion coefficient below T_g.
[b] Thermal expansion coefficient above T_g.
[c] Three-point bending flexural test. Displacement rate: 5 mm/min.
[d] Single-edge notched beam-loaded in three-point bending (SENB) test. Displacement rate: 10 mm/min.
[e] Calculated from $\sigma = \int_{-65}^{150} E \cdot (\alpha_1 - \alpha_L)\, dT$, where σ is the thermal stress caused during the TST; α_L, the thermal expansion coefficient of the lead frame (chip pad = 0.5 $\times$ 10^{-5}/°C), and E, the flexural modulus of the cured epoxy molding compound.

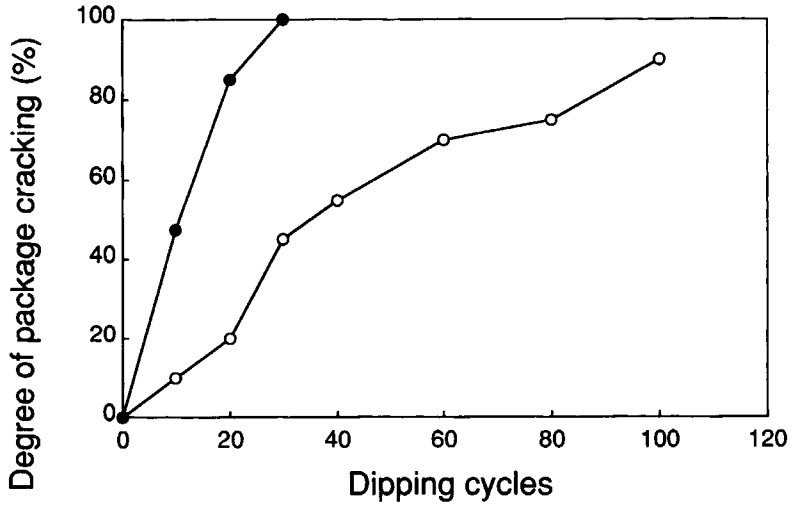

Figure 3 Package cracks caused during the TST of IC packages sealed with epoxy molding compounds filled with irregular-shaped silica particles with a particle content of 70 wt %. Mean particle size of the filled silica: (○) 16 μm; (●) 5 μm.

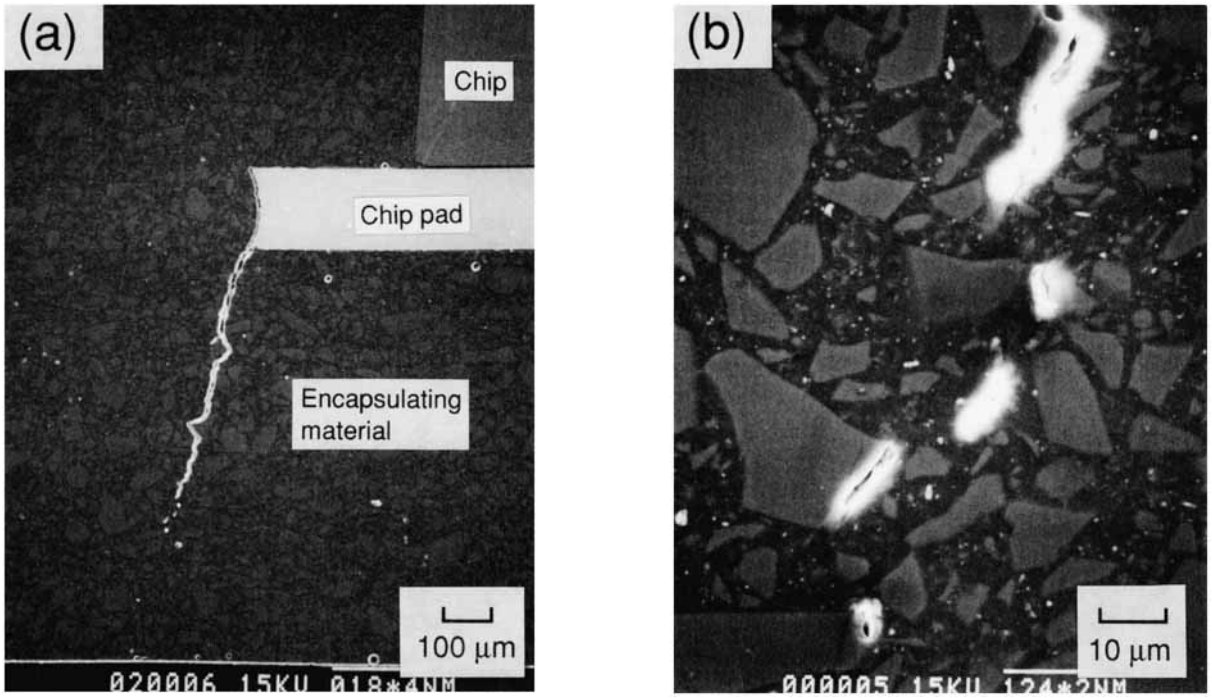

Figure 4 Polished-appearing surfaces for cross sections of IC packages during the TST observed by SEM sealed with epoxy molding compounds filled with irregular-shaped silica particles with a particle content of 70 wt %. Mean particle size of the filled silica: (a, b) 16 μm; (c) 5 μm. Dipping cycles until observation: (a, b) 30; (c) 10.

package cracking decreased.[4] The thermal stress values evaluated from eq. (1) are shown in Table II. Since the values were almost the same level, the TST result seems to be caused by the difference of the mechanical properties of cured epoxy molding compounds, i.e., the TST result showed the same tendencies as those of the fracture toughness values (K_c and G_c) of the cured epoxy molding compound, whereas it was independent of the flexural strength values.

Next, the crack propagation during the TST was observed with an SEM. For this purpose, the dipping was stopped before the crack reached the bottom surface of the package and the IC package was cut into vertically and the exposed surface was polished.

Figure 4 shows the cross sections of the test packages. In the large-particle-filled system (a), the crack propagation was deflected by the large particles. Figure 4(b) is the magnified crack tip region of Figure 4(a). At the crack tip region (b), debonding of the particle/epoxy matrix interfaces was observed. Such a microfracturing seems to release partially the stored strain energy at the crack tip and to obstruct the crack propagation. This region in which microfracturing occurred is called the "damage zone."[16,17] On the other hand, in the small-particle-filled system (c), the crack propagation was linear and no damage zone was observed at the crack tip region.

The initiation point of fracture at fractured surfaces of the flexural test specimen was observed by SEM in the same way as described in our previous articles.[6,11] In the small-particle-filled resin, the fracture was initiated from the defect that had existed on the specimen surface or edge, whereas in the large-particle-filled resin, the fracture was initiated from the particle fracture in all tested specimens. As mentioned in the previous articles,[5,6] as the particle size increased, the shape became more irregular and the number of microcracks within the individual particles seems to increase. Accordingly, such large particles seem to be cracked easily when the stress is concentrated. This was the same observation as that in the same irregular-shaped silica-filled systems shown in our previous articles.[6,12]

The crack tip regions of the fracture toughness test specimens before and after the test were observed in the same way as in our previous articles.[5,10] The observed phenomena were exactly the same as the above-mentioned effect of the particle size on the crack propagation during the TST and on the fracture toughness obtained in the same irregular-shaped silica-filled systems shown in our previous articles.[5,12]

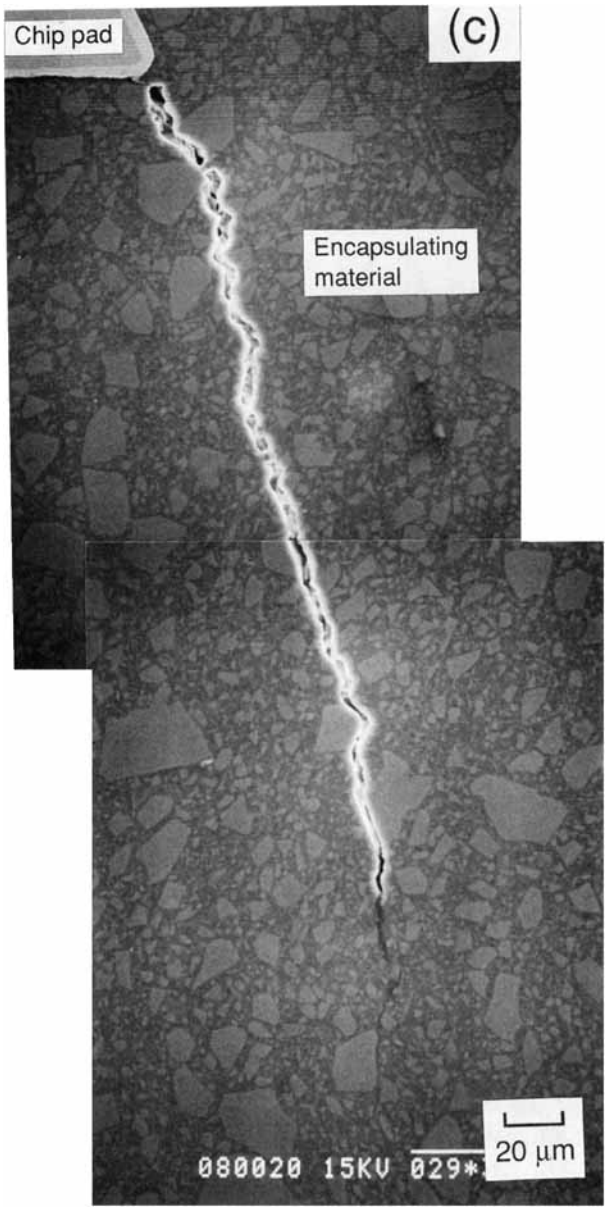

Figure 4 (*Continued from the previous page*)

The reason that the particle size has the opposite effect on the flexural strength and the fracture toughness, which was clarified in our previous articles,[5,6,12] was explained as follows: In the flexural test, the strength depends on the size of the inherent flaw in the specimen.[6] On the other hand, in the fracture toughness test, the toughness depends on the resistance to crack propagation from the constant-sized flaw (the starter crack) that was preliminary introduced in the all specimens by a fresh razor blade.[5] As described above, as the particle size increases, the inherent flaw of the particle increases, and the resistance increases because of the energy absorption by the crack deflection and the formation of the damage zone. Therefore, in our system, the particle size affects negatively the flexural strength but affects positively the fracture toughness.

From the above results, it is concluded that the package cracking during the TST of the IC packages sealed with the epoxy molding compounds filled with irregular-shaped silica particles is dependent on the fracture toughness values, while being independent of the flexural strength values.

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