

# Novel Thermally Reworkable Underfill Encapsulants For Flip-Chip Applications

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**Abstract**—The flip-chip technique of integrated circuit (IC) chip interconnection is the emerging technology for high performance, high input/output (I/O) IC devices. Due to the coefficient of thermal expansion mismatch between the silicon IC (CTE = 2.5 ppm/°C) and the low cost organic substrate such as FR-4 printed wiring board (CTE = 18–22 ppm/°C), the flip-chip solder joints experience high shear stresses during temperature cycling. Underfill encapsulant is used to couple the bilayer structure and is critical to the reliability of the flip-chip solder interconnects. Current underfill encapsulants are filled epoxy-based materials that are normally not reworkable after curing. This places an obstacle in flip-chip on board (FCOB) technology development, where unknown bad dies (UBD) are still a concern. Approaches have been taken to develop the thermally reworkable underfill materials in order to address the nonreworkability problem of the commercial underfill encapsulants. These approaches include introduction of thermally cleavable blocks into epoxides and addition of additives to the epoxies. In the first approach, five diepoxides containing thermally cleavable blocks were synthesized and characterized. These diepoxides were mixed with hardener and catalyst. Then the mixture properties of Tg, onset decomposition temperature, storage modulus, CTE, and viscosity were studied and compared with those of the standard formulation based on the commercial epoxy resin ERL-4221E. These mixtures all decomposed at lower temperature than the standard formulation. Moreover, one mixture, Epoxy5, showed acceptable Tg, low viscosity, and fairly good adhesion. In the second approach, two additives were discovered that provide die removal capability to the epoxy formulation without interfering with the epoxy cure or properties of the cured epoxy system. Furthermore, the combination of the two approaches showed positive results.

**Index Terms**—Chip removal, degradable epoxy, flip chip, flip chip rework, removable underfill, repairable underfill, reworkable underfill, thermally reworkable.

## I. INTRODUCTION

THE flip-chip technique of integrated circuit (IC) chip interconnection has been a hot topic in the electronic packaging area due to its good features of high input/output (I/O) capability and short interconnects [1], [2]. While the flip-chip technique becomes more and more popular, the problem with coefficient of thermal expansion (CTE) mismatch between the IC chip and the organic substrate becomes critical, particularly with the large IC chips and fine pitch,

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TABLE I  
REQUIREMENTS OF UNDERFILLS [4]

Solids Content	100%
Form	Single component, pre-mixed
Coefficient of Thermal Expansion ( $\alpha_1$ )	22 – 27 ppm/°C
Tg	> 125 °C
Cure Temperature	< 150 °C
Cure Time	< 30 min.
Working Life (@ 25°C, visc. double)	> 16 hrs.
Viscosity (@ 25°C)	< 20 kcps
Filler Size	95% < 15 $\mu$ m
Filler Content	< 70 wt %
Alpha Particle Emission	< 0.005 counts/cm <sup>2</sup> /hr.
Hardness (Shore D)	> 85
Modulus	8–10 GPa
Fracture Toughness	> 1.3 Mpa-m <sup>1/2</sup>
Volume Resistivity (@ 25°C)	> 10 <sup>13</sup> ohm-cm
Dielectric Constant (@ 25°C)	< 4.0
Dissipation Factor (@ 25°C, 1kHz)	< 0.005
Extractable Ions (e.g. Cl, Na, K, Fe, etc.)	< 20 ppm total
Moisture Absorption (8 hrs. boiling water)	< 0.25%

low profile solder joints. Due to the CTE mismatch between the silicon IC (2.5 ppm/°C) and low cost organic substrates such as FR-4 printed wiring board (18–24 ppm/°C), the temperature cycle excursions generate tremendous thermo-mechanical stresses at the solder joints and subsequently result in performance degradation of the packaged system. The underfill is an adhesive that serves to reinforce the physical and mechanical properties of the solder joints between the chip and the substrate. The encapsulant does not only provide drastic fatigue life enhancement, but also provides corrosion protection to the IC, resulting in a ten- to over a hundred-fold improvement in fatigue life as compared to an unencapsulated package [3]. Due to these attractive traits, this new technique of underfill encapsulation has been gaining acceptance in the chip to substrate attachment process.

Cycloaliphatic epoxies, combined with organic acid anhydrides as the hardener, have been widely used in flip-chip assemblies as the underfill encapsulants. This is largely due to their low viscosity prior to curing combined with good adhesion properties after curing. Silica has been widely used as the filler in the underfill encapsulant formulations to lower the CTE of the epoxy resin. Up to 70% (by weight) of filler loading has been used in commercial products. Table I shows the material requirements for underfills [4].

However, due to their intractability after curing, it is extremely difficult to rework the epoxy underfilled device to remove the chip from the substrate. This is a severe limitation to FCOB technology development. An effective way to address

TABLE II  
EEW'S OF THE FIVE SYNTHESIZED DIEPOXIDES

Sample	Epoxide Equivalent Weight (EEW)	
	Theoretical	Measured
Epoxide1	133.5	142
Epoxide2	142	157
Epoxide3	147.5	176.5
Epoxide4	147.5	186
Epoxide5	155	162.5

this problem is to make underfills reworkable, i.e., to make the underfill removable under certain conditions. Presently, the materials that are undergoing development for reworkable underfills can be classified into two categories: chemically reworkable underfills and thermally reworkable underfills.

Buchwalter *et al.* [5]–[7] developed epoxy compositions that are soluble in organic acid after curing, which fits into the chemically reworkable category. But the use of chemicals makes localized repair difficult. Furthermore, it could be time consuming for the chemicals to penetrate into and dissolve the underfills between the chip and the substrate [8]. On the other hand, thermally reworkable materials offer the possibility of a fast, clean, and localized rework process.

Gutierrez and Yu [9] reported development of a reworkable flip-chip type of circuit module using a nonstick release coating (pyralene) on all surfaces intermediate of the chip and the substrate. Although the use of release coating enables the chips to be removed from the underfill, the exposed underfill as well as pyralene require expensive cleaning processes by depotting solvents [8].

The purpose of our work is to develop thermally reworkable underfills that can provide good reliability to the flip-chip package while allowing the chip to be easily removed at elevated temperatures. The two approaches we took include development of thermally-cleavable-block-containing epoxies and additive-modified epoxies. The first approach involved synthesizing diepoxides with blocks that were stable during the epoxy curing, but decomposed at certain temperatures (200–250 °C). These diepoxides were then characterized and compared with a commercially available epoxy resin. Another approach focused on two additives that decomposed at around 200 °C and emitted large amount of gases during the decomposition. These additives were mixed with the epoxy formulation and the mixtures were studied [10].

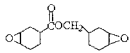
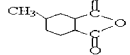
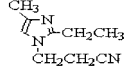
## II. EXPERIMENTAL

### A. Chemical Ingredients of the Reworkable Underfills

1) *Syntheses of Diepoxides*: Five cleavable-block-containing diepoxides, Epoxide1–Epoxide5 were synthesized. They are all cycloaliphatic type diepoxides. The cleavable blocks inside these diepoxides are either carbamate group or carbonate group. The epoxide equivalent weights (EEW's) of these five diepoxides were measured according to ASTM D1652-90. Table II shows their theoretical and measured EEW values.

2) *Other Chemical Ingredients*: Table III lists the chemical structures of the commercial epoxy resin, hardener, and catalyst used in the experiments. The commercial epoxy

TABLE III  
INGREDIENTS OF UNDERFILL FORMULATION

Name of chemicals	Structure of Chemicals
ERL-4221E	
HMPA	
2E4MZ-CN	

resin was 3,4-epoxy cyclohexyl methyl-3,4-epoxy cyclohexyl carboxylate provided by Union Carbide under the trade name ERL-4221E and used as received. Its EEW value is 133. The hardener was hexahydro-4-methylphthalic anhydride (HMPA) purchased from Aldrich Chemical Company, Inc. and used as received. The catalyst used was 1-cyanoethyl-2-ethyl-4-methylimidazole (2E4MZ-CN) provided by Shikoku Company and used as received.

Two additives were obtained from a commercial source. These are fine powders and dried at 100 °C in vacuum before use.

### B. Preparations of Reworkable Underfill Formulations

1) *Cleavable-Block-Containing Epoxies*: As mentioned before, the five synthesized diepoxides were named Epoxide1–Epoxide5. ERL-4221E (also a diepoxide) was used for the comparison and named Epoxide0. Six epoxy underfill formulations were then made based on these six diepoxides mixed with the hardener and the catalyst. In all these six formulations, the mole ratio of diepoxide to hardener was kept at 1 : 0.8. The catalyst level was 4% by weight. These six formulations were named Epoxy0–Epoxy5, which correlates to Epoxide0–Epoxide5, respectively.

2) *Additive-Modified Epoxies*: The formulations were based on the epoxy formulations described above plus 5% of the additives by weight. Two additives were studied at this time and named Additive1 and Additive2.

### C. Characterization

1) *Differential Scanning Calorimetry (DSC)*: A modulated DSC (by TA Instruments, model 2920) was used to study the curing profile and Tg of the underfill formulations. Approximately 10 mg of sample was used each time. The curing profile was obtained by heating the sample at 5 °C/min to a temperature that the sample was completely cured, but prior to the decomposition temperature. To obtain the Tg of the cured sample, the sample was left in the DSC cell and cooled down to room temperature at 30 °C/min. Then the sample was reheated at 5 °C/min to a temperature at which its Tg can be clearly identified.

2) *Dynamic Mechanical Analyzer (DMA)*: A DMA (by TA Instruments, model 2980) was used to measure the dynamic moduli of the underfill formulations. The specimens for the DMA testing were prepared by placing the degassed liquid formulations into 1.5-in-diameter aluminum pans, putting the

pan into a room temperature convection oven, heating to the desired temperature, and holding for the prescribed time. After curing, the sample was removed from the oven and cooled to room temperature. A diamond saw was then used to cut the cured sample into strips (approximately  $32 \times 11 \times 3$  mm). The DMA measurement was performed in single cantilever mode under 1 HZ sinusoidal strain loading while the specimen was heated from room temperature to 250 °C at a rate of 3 °C/min. Storage modulus  $G'$ , loss modulus  $G''$ , and loss angle and were obtained.

3) *Thermo-Mechanical Analyzer (TMA)*: A TMA (by TA Instruments, model 2940) was used to measure the CTE's of the underfill formulations. The specimen preparation was the same as for the DMA testing, except that the sample was cut into  $5 \times 5 \times 3$  mm pieces. After the sample was mounted in the TMA, it was heated from room temperature to 250 °C at a rate of 5 °C/min.

4) *Thermo-Gravimetric Analyzer (TGA)*: A TGA (by TA Instruments, model 2940) was used to study the thermal decomposition of the underfill formulations. Approximately 20 mg of material was used for each sample. The heating was from room temperature to 350 °C at a rate of 20 °C/min. The purge gas was air.

5) *Rheometer*: A rheometer (by TA Instruments, model AR1000N) was used to measure the viscosity of the underfill formulations. The viscosity measurement was performed on a cone and plate geometry at 25 °C. The shear rate range used was from 1 to 1000  $S^{-1}$ .

6) *Bond Tester*: The adhesion strengths of the underfill formulations to alumina substrate and silicon die were measured in shear mode using a bond tester (by Royce Instruments, model 550-100 K). The die was  $80 \times 80$  mil passivated with silicon nitride. Both the die and the alumina substrate were cleaned prior to testing. The cleaning procedure and adhesion test procedure followed those found in literature [11].

7) *Particle Size Analyzer*: Particle size analysis was performed by a laser diffraction particle analyzer (Malvern MasterSizer Micro Plus).

8) *Die Removal Test*: Die removal test on the underfills was performed according to the following procedure:

#### A) Preparation

- 1) Cut substrate into approximately  $2 \times 2$  cm pieces.
- 2) Cut silicon wafer into  $1 \times 1$  cm pieces.
- 3) Clean silicon dies and substrates.
- 4) Mix and degas underfill samples.

#### B) Mounting

- 1) Put a drop of underfill on top of the substrate.
- 2) Place the die over the underfill on the substrate and press down so that the underfill fills the gap.
- 3) Cure underfill.

#### C) Testing (these steps videotaped)

- 1) Preheat the hot plate to desired temperature.
- 2) Place the test vehicle on the hot plate for a specified period of time.
- 3) Remove the die from the substrate using tweezers.

9) *Scanning Electron Microscope (SEM)*: SEM study of the interfaces was performed by using a SEM (by Hitachi,

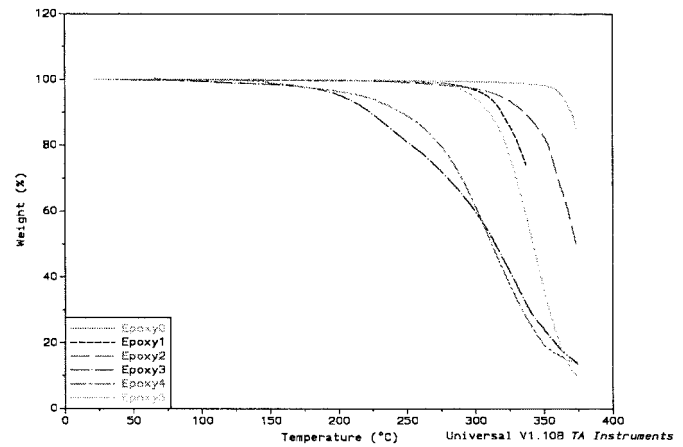


Fig. 1. TGA curves of samples Epoxy0-Epoxy5.

model S-800). The samples for SEM study were prepared the same way as the samples for the die removal test. Then they were cut into small strips using a diamond saw and then mounted on SEM sample stubs using superglue. They were then polished, cleaned, and gold sputtered before observed by SEM. After the observation, the sample with the sample stub was placed in a preheated oven for a specified time and then observed under SEM again.

### III. RESULTS AND DISCUSSION

#### A. Cleavable-Block-Containing Epoxies

The first approach taken was to introduce the thermally cleavable groups into the epoxy structure. The cleavable groups were selected to meet the following two criteria:

- 1) cleavable group should be inert to the curing reaction of the epoxy network and be stable during thermal cycling of the flip-chip package;
- 2) cleavable group should decompose quickly at the temperature range between 200–250 °C so that it breaks down the structure of the epoxy network, leading to easier rework.

This temperature range was selected because the melting point of eutectic solder was 186 °C, and the peak temperature used to reflow the eutectic solder was typically around 220 °C.

1) *Thermal Analysis*: Fig. 1 shows the TGA curves of the six formulations. It can be seen that Epoxy0, which was based on ERL-4221E, did not start decomposition until the temperature reached 350°C. The other five formulations, which were based on the cleavable-block-containing diepoxides, started to decompose at lower temperatures, which was expected. Also, it can be seen that some formulations decomposed at lower temperatures than others.

Table IV shows some thermal analysis data of these six materials. It shows in general that the formulations based on the synthesized diepoxides tended to have similar CTE values and storage moduli as compared with Epoxy0. The onset decomposition temperature data was obtained from analyzing the curves in Fig. 1. It shows that the decomposition temperatures of Epoxy 2 and Epoxy3 were in the desired

TABLE IV  
THERMAL ANALYSIS RESULTS OF CLEAVABLE-BLOCK-CONTAINING EPOXIES

Sample	Parameters			
	Onset decomposition temperature (°C)	T <sub>g</sub> (°C)	$\alpha_1$ -unfilled (ppm/°C)	G'-unfilled (GPa)
Epoxy0	350	170	86	2.6
Epoxy1	280	166	73	2.9
Epoxy2	280	105	91	2.8
Epoxy3	200	86	80	-
Epoxy4	250	57	90	-
Epoxy5	275	153	85	2.8

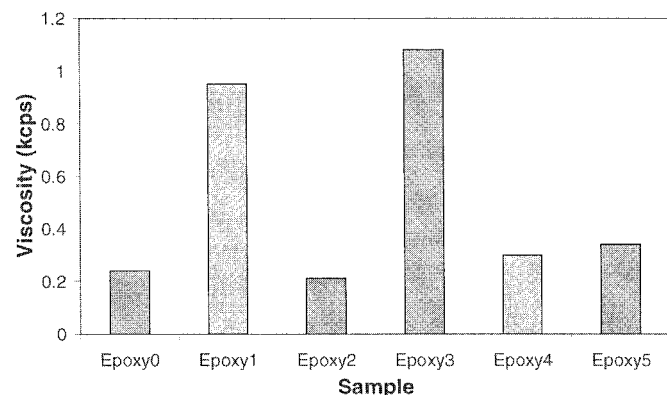


Fig. 2. Viscosities of Epoxy0–Epoxy5.

region, while those of Epoxy1, Epoxy2, and Epoxy5 were a little high.

The T<sub>g</sub> of a material is very important in determining whether the material can be used as underfill. A material should have a T<sub>g</sub> higher than 125 °C before it can be considered a suitable underfill. The T<sub>g</sub> of Epoxy0 was 170 °C (fairly high), while Epoxy1 and Epoxy5 showed acceptable T<sub>g</sub>'s (166 and 153 °C). But the T<sub>g</sub>'s of Epoxy2, Epoxy3, and Epoxy4 were lower than acceptable. Therefore, among the five formulations with synthesized diepoxides, only Epoxy1 and Epoxy5 met the T<sub>g</sub> requirement of the underfills.

2) *Viscosity*: Viscosity is another important issue for the underfill. Basically, the lower the viscosity, the better. These six formulations were all Newtonian fluids; that is, their viscosities were independent with the shear rate. Fig. 2 shows the viscosity values of these formulations at room temperature. It shows that the viscosity of Epoxy0 was fairly low. This is one of the reasons why ERL-4221E and HMPA have been widely used in the commercial underfill formulations. Among the five new formulations, Epoxy2, Epoxy4, and Epoxy5 had viscosity values comparable or slightly higher than that of Epoxy0. Epoxy1 and Epoxy3 deviated considerably from Epoxy0. So based on viscosity, Epoxy2, Epoxy4, and Epoxy5 were better formulations.

3) *Adhesion*: The adhesion of the underfill to both the die and the substrate is another important parameter. Since underfill acts as the reinforcement material to the flip-chip package, better adhesion brings about a stronger package.

Fig. 3 shows the die-shear test results. It clearly shows that Epoxy0 had the best adhesion. Among the five formulations studied, only Epoxy2 and Epoxy5 had adhesion strengths close to that of Epoxy0. The other three formulations provided poor adhesion.

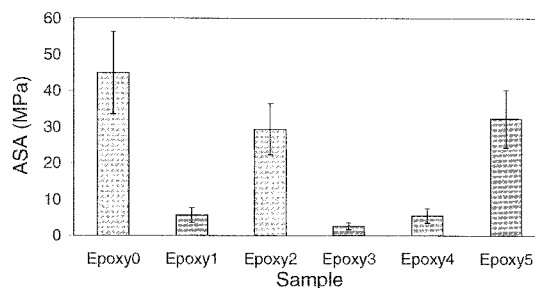


Fig. 3. Adhesion of Epoxy0–Epoxy5.

TABLE V  
LIST OF THE TWO ADDITIVES

Sample	Average particle size (μm)	Decomposition temperature range (°C)
Additive 1	6.1	205–215
Additive 2	8.4	228–235

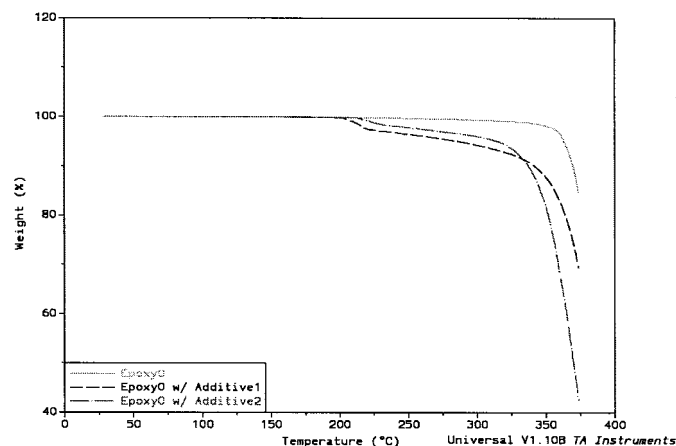


Fig. 4. TGA curves of Epoxy0, and Epoxy0 with additives1 and 2.

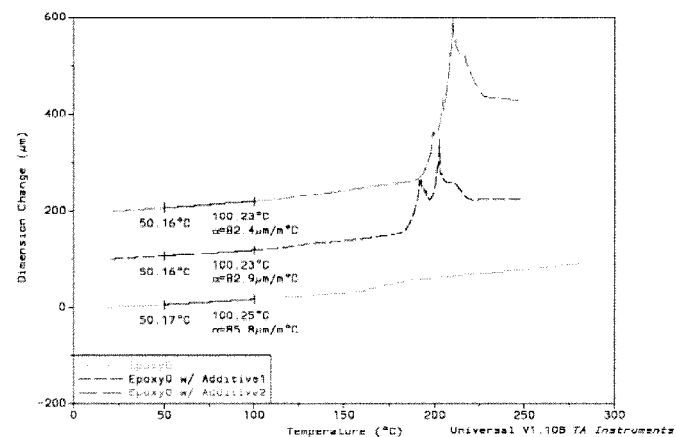


Fig. 5. TMA curves of Epoxy0, and Epoxy0 with additives1 and 2.

Based on T<sub>g</sub>, onset decomposition temperature, viscosity, and adhesion, Epoxy5 was the only formulation that was acceptable.

## B. Additive-Modified Epoxies

An alternative to develop reworkable underfill encapsulants was by adding specific additives to the nonreworkable epox-

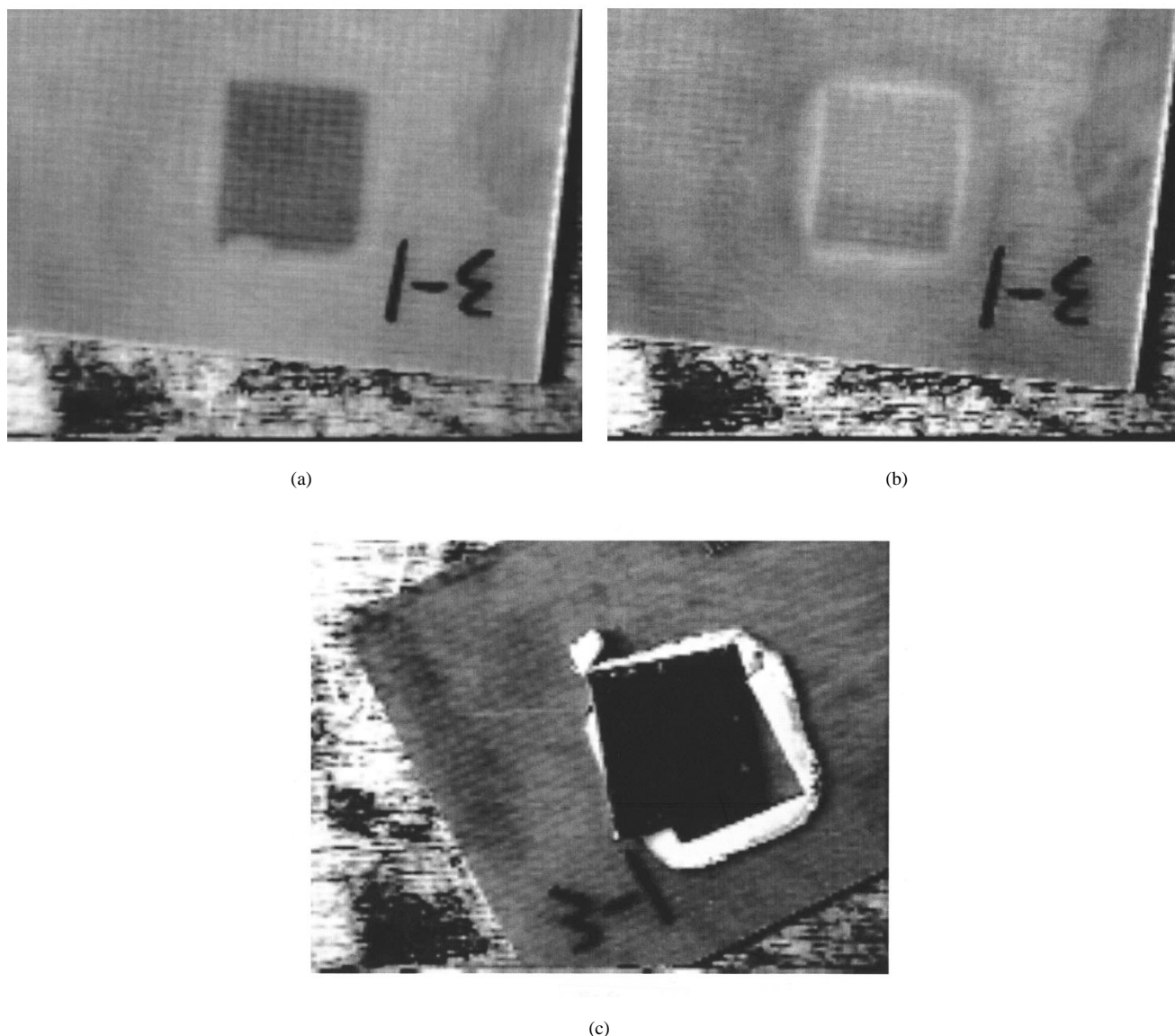


Fig. 6. Pictures of silicon on FR-4 underfilled with Epoxy0 with additive1 in the die removal test: (a) before exposed to heat, (b) after exposure to 200 °C/3 min, and (c) after silicon removed from FR-4.

TABLE VI  
THERMAL ANALYSIS RESULTS OF ADDITIVE-MODIFIED EPOXIES

Sample	Parameters		
	Epoxy0	Epoxy0 w/ Additive1	Epoxy0 w/ Additive2
T <sub>g</sub> DSC (°C)	170	172	161
G'-unfilled (GPa)	2.6	2.1	2.5
$\alpha_1$ -unfilled (ppm/°C)	86	83	82
Onset decomposition temperature (°C)	350	200	210

TABLE VII  
VISCOSITIES OF EPOXY 0 AND EPOXY 0 WITH ADDITIVES1 AND 2

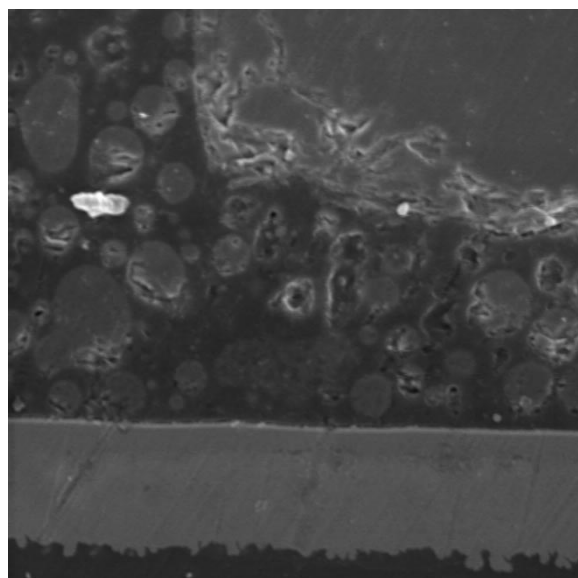
Sample	Viscosity (@ 25°C, cps)
Epoxy0	0.24
Epoxy0 w/ additive 1	0.55
Epoxy0 w/ additive 2	0.55

ies. These specific additives should be inert to the curing reaction of the epoxy network and be stable in the thermal cycling of the flip-chip package. Furthermore, these additives

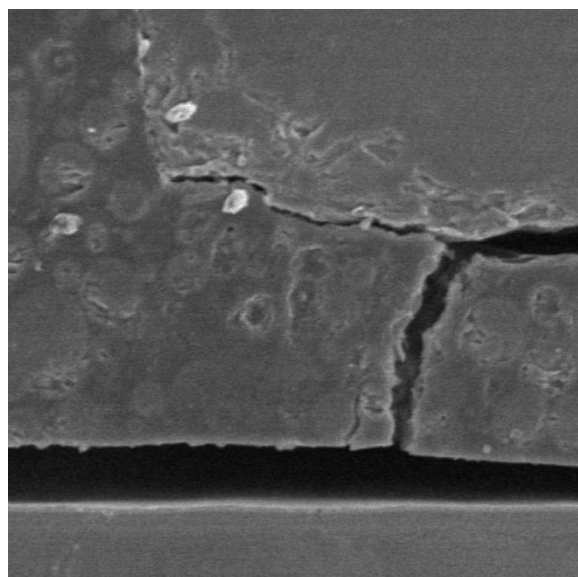
should readily cause dramatic changes on the properties of the epoxy network under specific temperature to provide an easily reworked network.

*1) Characteristics of Two Additives:* Two additives were selected which met the above criteria. They both were commercially available in the form of fine powder. Both additives started to decompose between 200–250°C. Once decomposed, they emitted a huge amount of gases. Table V shows their average particle size and decomposition temperature ranges.

Besides their decomposition feature, both additives easily mixed with the underfill into a uniform mixture. Furthermore, these two additives were fairly stable during the underfill cure. After curing, the additives remained dispersed in the solid underfill matrix. When this solid underfill was heated to the decomposition temperature of the additive, the additive that remained inside the matrix started to decompose and release gas that caused a dramatic increase in the CTE of the underfill.



(a)



(b)

Fig. 7. SEM photos of interfaces of silicon on Epoxy0 with additive1 on polyimide with Ni-Au metal pad (a) before and (b) after exposure to 200 °C/5 min.

As will be shown later, this dramatic CTE increase provided the underfill with die-removal capability.

2) *Thermal Analysis*: Fig. 4 shows the TGA curves of Epoxy0, and Epoxy0 with two additives (5wt% loading), respectively. The TGA curves clearly show the weight loss caused by the decomposition of the additives. Both additives within the underfill matrix started to decompose at around 200 °C, which is close to the solder reflow temperature.

Fig. 5 shows the TMA curves of the above three materials. The two curves for the two formulations with the additives show the dramatic increase of the material CTE at the additive decomposition temperature region.

Table VI shows the thermal analysis data of Epoxy0, and Epoxy0 with two additives (5wt% loading), respectively. It can be seen that the additives did not greatly affect the properties

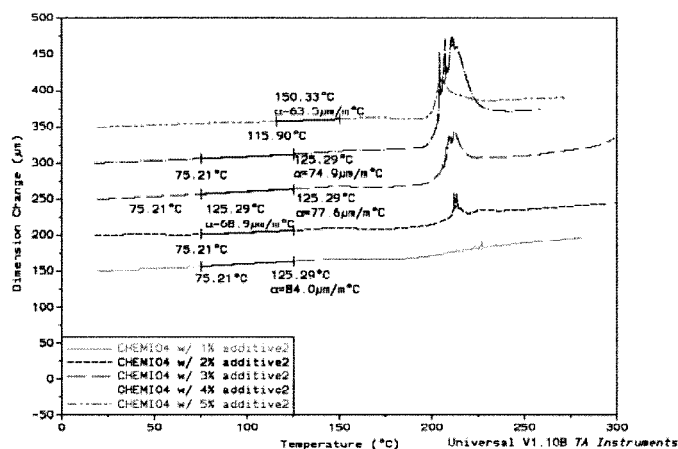


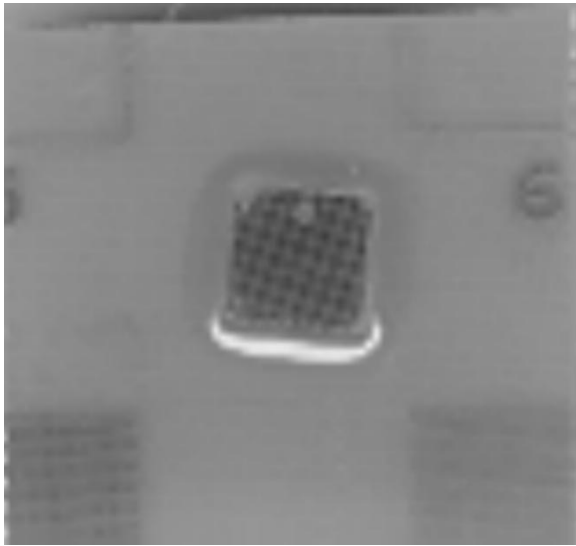
Fig. 8. TMA curves of underfill Epoxy0 containing additive2 with different additive levels.

of the underfill such as T<sub>g</sub>, α<sub>1</sub>, and modulus. But by mixing the additives with underfill, the decomposition temperatures of the underfill were greatly decreased and the CTE's were greatly increased by the decomposition of the additives during the temperature range of 200–250 °C.

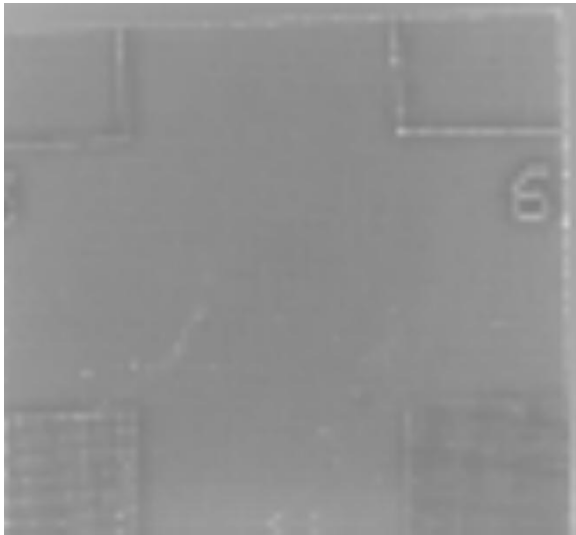
3) *Viscosity*: Table VII shows the viscosity data of Epoxy0, and Epoxy0 with two additives (5wt% loading), respectively. It indicates that the addition of the additives into the underfill increased the viscosity of the underfill. But even at 5% additive level, the viscosity of the underfill was still fairly low.

4) *Die Removal Test*: Fig. 6 shows pictures of a silicon piece on a FR-4 board underfilled with Epoxy0 with additive1 (5wt%) during the die removal test. Pictures A and B were taken from the backside of the board. Since FR-4 board is translucent, the delamination between the silicon and the board was visually detected by direct visual inspection through the backside of the board. The area covered by the silicon was dark when there was no delamination. The white portion in this area indicated some delamination occurred. Picture A indicates that there was no delamination between the board and the silicon, while picture B indicates that delamination occurred. It was found that this delamination between the board and silicon occurred shortly after exposure to 200 °C. This delamination may be due to the dramatic CTE increase of the underfill caused by the decomposition of the additives. By using a pair of tweezers, the silicon was easily removed from the board (picture C).

5) *SEM*: Fig. 7 shows the SEM cross section of silicon-Epoxy0 with additive1–polyimide with Ni-Au pad before and after the sample was exposed to 200 °C/5 min. The reason polyimide board was used instead of FR-4 board was that polyimide board was much stiffer than FR-4. In SEM sample preparation, there was one step in which the board-underfill-silicon test vehicle was cut into small strips to expose the cross-section. This required a stiff board so that there would be minimum warpage of the board during the cutting without causing any interface delamination. Photo B clearly shows failure at both of the interfaces and cohesive failure in the underfill after the underfill was exposed to 200 °C for 5 min. This clearly supports the die-removal test results.



(a)



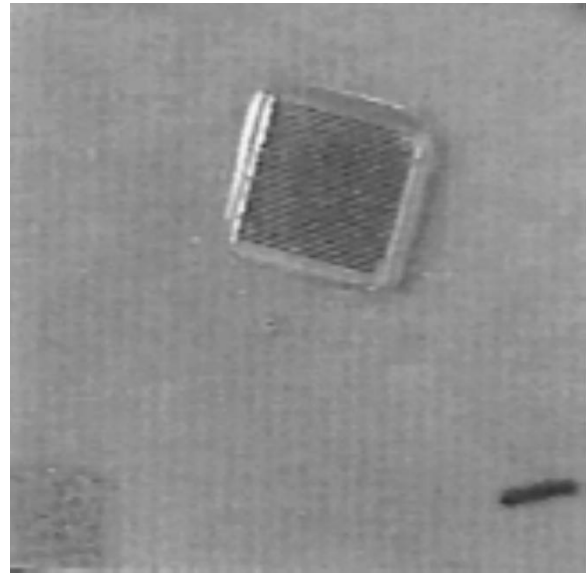
(b)

Fig. 9. Pictures of quartz chip on FR-4 underfilled with Epoxy5 with additive2 (3%) in the die-removal test: (a) before exposure to heat and (b) after exposure to 200 °C/5 min, chip removal and solvent cleaning using hot DMSO.

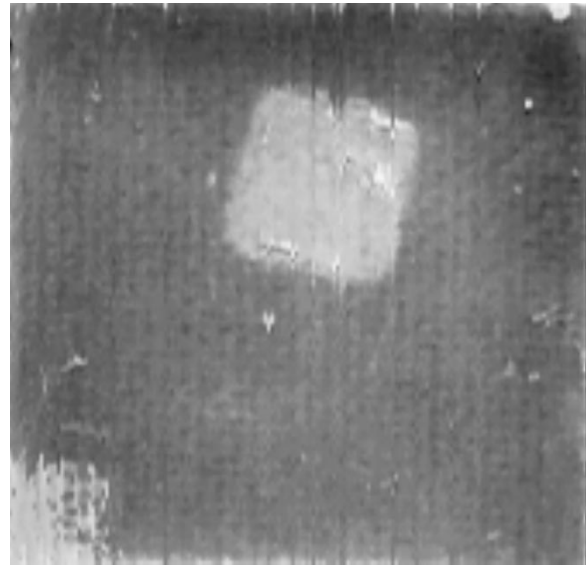
6) *TMA Test for Optimal Additive Loading:* The above results show that the two additives provided the underfill die-removal capability at around 200 °C at 5% of additive loading. TMA test was performed again to determine the optimal additive loading in the underfill. Fig. 8 shows the TMA curves of Epoxy0–Additive2 mixtures with additive level from 1–5%. It can be seen that when the epoxy contained 3% Additive2, the dramatic CTE increase during the additive decomposition temperature region started to show up. This indicates that 3% of additive level may be good enough.

### C. Combination of the Two Approaches

A good reworkable underfill material should provide not only die removal but also residual underfill removal capability. This is because die removal is only the first step of reworking



(a)



(b)

Fig. 10. Pictures of quartz chip on FR-4 underfilled with Epoxy5: (a) before exposure to heat and (b) after exposure to 250 °C/5 min, chip removal and solvent cleaning using hot DMSO.

a flip-chip package. After that, the residual underfill left on the board has to be removed and the site to be prepared before another die could be assembled.

It was shown above that the additives provided the die removal capability to the underfill, and new epoxies were developed that decomposed at around solder reflow temperature. The combination of these two approaches could bring about an underfill with both die removal and underfill removal capability. Because once decomposed, the epoxy could be easily removed with organic solvents.

This idea was tried by using the combination of Epoxy5 and 3% of additive2 to do the die removal test again. This time quartz chips with solder bumps on and FR-4 boards were used. Fig. 9 shows the pictures of the die removal test using

Epoxy5 with 3% additive2. It was found that the chip was easily removed from the board after exposure to 200 °C for 5 min. The residual underfill on the board was then removed by hot dimethyl sulfone (DMSO) to give a board that was undamaged (pictures A and B). For the comparison, Fig. 10 shows the pictures of the die removal test using Epoxy5 without additives. In this case, the test vehicle was exposed to 250 °C before the chip could be removed from the board. It was also found that it took longer to remove the underfill residue with hot DMSO, and the solder mask layer of the board was found damaged (pictures A and B). This result once again shows the function of the additive during the die removal. It also indicates that by combining the thermally degradable epoxy and the additive together, both die removal and underfill removal were achieved.

#### IV. CONCLUSION

Five diepoxides containing thermally cleavable groups were synthesized. The cured samples using the five diepoxides initiated decomposition at lower temperatures than the sample using the commercially available epoxy resin, ERL-4221E. Among the epoxy samples based on the synthesized diepoxides, Epoxy5 had acceptable properties such as  $T_g$ ,  $\alpha_1$ , storage modulus, relatively good adhesion, and low viscosity. Two additives were discovered that provided die removal capability around 200 °C to the cycloaliphatic epoxy, and seemed not to adversely affect the epoxy's properties. Both die removal and underfill removal were achieved by the combination of the two approaches, cleavable-block-containing epoxies and additive-modified epoxies.

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