Flip-Chip Process Improvements for Low Warpage

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Abstract

Mechanical stress in flip-chip (FC) assemblies continues to be a significant problem both for the reliability of the component and for the assembly of a flat component to the next board-level assembly. This work describes the combination of unique low-temperature multi-step curing profiles with the use of Variable Frequency Microwaves (VFM) to produce lower warpage components both on the die side of the package as well as on the board carrier side. This lower warpage compared to standard convection cure is maintained even after three sequential lead-free solder reflow conditions. Statistical data supports this increased co-planarity by Shadow Moiré measurements at various stages of processing from as-received parts through prebake, cure, and three reflow cycles. Typical co-planarity improvement in the 12 to 65 percent range is observed and verified by confirmation sample sizes used for microwave cured parts and conventional box oven cured parts. Thinned and larger die, and reduced thickness substrate boards showed the most warpage improvement with VFM. Two under-fill chemistries show the same effect despite lower cure temperatures and faster cure cycle times. A reduction of the elastic modulus above Tg was found in the VFM step-cured samples which may account for the some of the reduction in stress of the under-filled packages.

Key words: Flip-chip, under-fill, warpage, microwave

Introduction

Flip-chip die attachment has gained significant use in production over the years because of its electrical performance and small form factor. Recent economic events have made flip-chip more cost competitive with gold wire bonding. As the size of the die increases beyond 20 mm on a side, the role of the under-fill adhesive becomes more critical to avoid the stress-induced cracking at the solder ball interfaces farthest from the center of the die (neutral point). Additional stresses have been created with the increased use of low-k dielectric layers on the die surface. Under-fill materials must now meet the higher temperature requirements of no-lead solder reflow as well. The substrates are also becoming thinner with the use of core-less constructions. All of these factors challenge the formulation of adhesives to provide the thermo-mechanical properties necessary to minimize stress at the solder balls; at the dielectric layer; in the thinner substrates; and during high temperature reflow cycles after the under-fill cure. An unfortunate example is the contradiction of needing a low Tg under-fill to protect the low-k dielectric layer but a high Tg under-fill to protect the solder balls [1,2]. The two stress concerns for flip-chip in production are the co-planarity of the substrate and reliability of the die attach. Warpage in both areas needs to be minimized to reduce the initial induced strain that can affect co-planarity as well as long term package reliability.

There have been several attempts to reduce stress in polymer materials used in microelectronics. They have focused primarily on low temperature cure and very long ramp rates to high final soak temperatures. The former sacrifices complete cure and the latter requires very long processing cycles [3]. Curing a thermoset material at less than the Tg could promise an increase in elasticity if the gradual increase in Tg could result in vitrification and finally, complete conversion. Any cure method that might result in a lower cross-link density and a decrease in elastic modulus (E') above Tg would decrease the stress.

Standard convection heat curing is a sequence of heat transfer from either coils or infra-red emitters to air, and then from air to the target parts, the oven walls and the fixtures. Even though microwave heating is a thermal process, the fundamental mechanism is based on the excitement of electronic dipoles in the adhesive and their subsequent dielectric loss to molecular rotations [4]. This direct increase in the entropy of the atoms at each dipole site causes more rapid collisions of reacting molecules and more often at the proper reaction orientation. The energy absorbed selectively at dipole sites results in higher "local" energy while leaving the bulk of the material at an effectively lower temperature until large chain molecular rotations begin.

Microwave curing also has a material-selective nature. Only materials that have available, polarizable electrons and some flexibility of molecular rotation, will be heated. Un-cured polar polymers and doped silicon are good examples of susceptible materials. Glasses, metals, and fully cured polymers do not directly absorb much radiation. In the case of a flip-chip assembly, only the under-fill and the silicon die are heated. The substrate, other components, the oven, the air and the fixtures are not directly heated. A variable frequency microwave (VFM) technology was developed to prevent the arcing of metals and to provide a uniform energy field particularly for use in microelectronics production processes. Many studies by semiconductor fabricators have shown no effect of VFM on the electrical or structural characteristics of semiconductor devices. Microwave curing of polymers has been in production use now for more than a decade with advantages of much faster cure cycles, lower temperature cure profiles and substantially lower energy expenditures. Encapsulants, glob-tops, wafer dielectric films, and flex tape bonding have taken advantage of VFM processing but there hasn't been much interest in under-fill curing until recently [5].

There are three reasons to believe a VFM cured under-fill material might produce lower stress and warpage:

1. The uniform bulk heating of VFM should be expected to cure the material in all directions equally. This should reduce the radial stress difference between the edges of the die and the center as found with conventional heating [5]. The uniform heating at both surfaces (die and board) also promotes improved adhesion from the onset of cure.

2. The difference in expansion (and especially contraction) of the silicon die and organic substrate during cure is known to produce significant warpage (Figure 1). Since the substrate is not directly heated by VFM, that differential shrinkage is less than half that normally found [6].

3. It is well known that a lower final cure temperature will produce a lower total shrinkage during cooling of epoxy materials [6]. Since the adhesive can be cured at lower temperatures with VFM (to the same extent of cure and Tg), the expected shrinkage should be lower and the expected induced strain lower as well.

Figure 1: Package CTE mis-match

A fourth potential contributor to lowered stress has been suggested in a study of the curing of polyamide amine/epoxy mixtures [7]. It was found that at a lower temperature only, the VFM cured material showed higher elongation and lowered modulus. There was an indication of structural modification (by FTIR) with VFM that was not found at the same low temperature with convection heating. The suggestion was that lower cross-link density was the cause of lowered stress.

A study using a commercial under-fill (Henkel FP4527) found that VFM curing at lower temperatures and faster times doubled the die radius of curvature (lower stress) and increased the shear strength by 50% compared to standard convection oven curing [8, 9].

It is important to note that any further thermal processing of parts that had been cured at lower temperatures should reset the shrinkage to correspond with the expected shrinkage at the highest temperature. The use of multiple solder reflows at 260°C for BGA parts would be a common example of this. The low temperature advantage of VFM cure might be nullified for this reason.

The objective of this work is to determine whether the lower warpage of under-fills can be maintained even after succeeding solder reflows and whether this effect is found in more than one under-fill chemistry. An additional objective is to determine whether a chemical and morphological advantage of VFM cure contributes to the lower stress and warpage.

Experimental

VFM curing was done on a Lambda Technologies Microcure 2100-700 system. Ambient gas control or vacuum was not required. Four-thousand ninety-six frequencies were cycled between 5.8 and 7.0 GHz every 0.1 seconds for a residence time of 25 s at each frequency. Part temperature was controlled in a closed-loop feedback system by measurement with a calibrated non-contact IR sensor. A fiber-optic contact probe on the bottom of the substrate was also monitored. A ramp rate of 30ºC/min brought the part to soak temperature with a control of +/- 1 ºC for the programmed time. The cool time was usually about 2-3 minutes since the chamber air was at room temperature during the tests. Power was automatically adjusted to maintain the programmed temperature profile as measured through the back of the die.

The test parts include a variety of dice and substrates as described in each section below. The convection oven was a Despatch LAC model. Shadow Moire' (Akrometrix) measurements were made by spraying white paint on the die and substrate sides and using the interference patterns to determine co-planarity from center to corners. All of the BT laminate substrates were treated to a preliminary prebake of 165°C for three hours to complete the cure of any epoxy material within the substrate.

Tg measurements were made by DSC, TMA, and DMA depending on the samples. DOE analyses were done with MiniTAB and Stat-Ease software.

Results

The first phase was to reproduce the results described above for a commercial under-fill (Henkel FP4527) and to determine whether the improved warpage remained after three high-lead (260°C) solder reflow steps.

In these tests, 20mm x 20mm silicon dice with solder ball arrays were combined with 40mm x 40mm BT substrates (Tg = 155°C) of 0.59mm thickness including solder mask. A dispense of 105-110 mg of FP4527 was dispensed in a star pattern and the dice were pressed into the underfill until the gap was closed. The standard cure profile for this material is a 3°C/min ramp to 165°C followed by a soak at 165°C for 30 minutes.

A series of convection oven cure profiles were undertaken to determine whether a lower temperature cure with standard convection heating would decrease the final warpage after reflow cycles. Table 1 shows the adjustments in time that were made when the cure soak temperature was reduced. Half of the runs were intentionally under-cured somewhat to replicate the unintentional under-curing sometimes found in practice [10]. Run 8 is the standard cure profile with the standard 3°C/min ramp rate.

	Temp (°C)	Time (min)	Cure
1	105	45	Under
2	105	90	Full
3	125	30	Under
4	125	60	Full
5	145	22	Under
6	145	45	Full
7	165	15	Under
8	165	30	Full

Table 1: Convection cure of FP4527

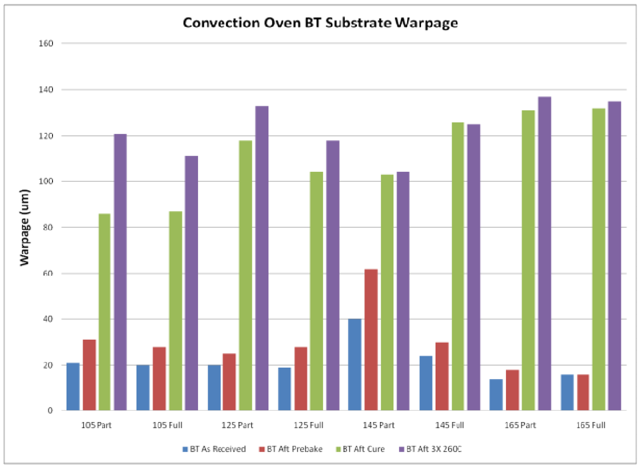

Figure 2: BT Substrate warpage with convection cure

It can be seen in Figure 2 that for FP4527 the lower temperature convection cures resulted in lower initial BT warpage but after three reflows the warpage increased to about the same level as the high temperature cures. The partial cures were fully cured after the three reflows but did not have significantly different BT warpage than the full cures before reflows. The practical use of a partial under-fill cure is limited to parts that would all see a subsequent high temperature process.

The die warpage for the FP4527 under-filled packages is shown in Figure 3. Once again there is lower die warpage initially at lower temperatures but after three reflows the advantage is lost. An improved convection profile for this material was a slow ramp to 145°C and soak for 22 minutes.

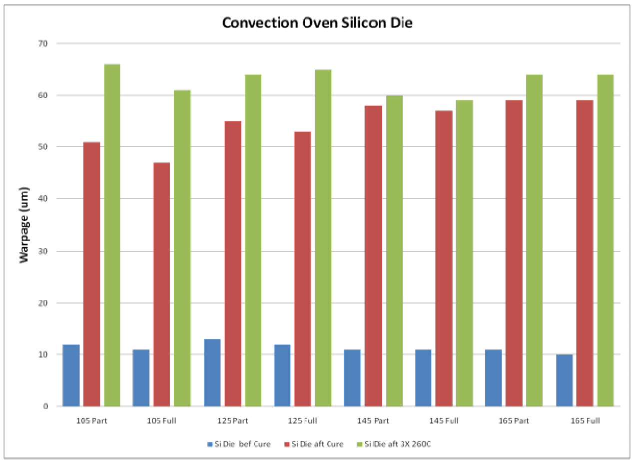

Figure 3: Silicon Die Warpage with Convection Cure

The VFM trials were performed as a sequence of four cure temperatures, twenty degrees apart with varying soak times (Figure 4). The designed experiment used the four soak times as the primary variables. Earlier experiments have shown that modest changes in ramp times before and between soaks were not significant in either the extent of cure or in warpage. A more thorough evaluation of ramp rates is under study. The ramp rates were set to 30°C/min which is known to avoid any generated voids from being trapped in the matrix with a faster ramp rate. This is still ten times faster than the convection ramp rates. The cooling period consisted of the 2-3 minute time it took for the materials to passively return to room temperature (oven ambient) after the last soak. The times chosen for each soak was developed by evaluating the extent of cure with VFM at each of the individual temperatures and decreased to allow for the cure times at other temperatures and times.

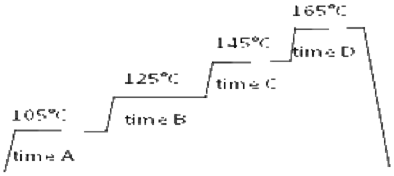

Figure 4: VFM cure DOE variables

The most significant substrate warpage reduction was related to the highest cure temperature (165°C) although all the other step times were statistically significant (Figure 5). Note that the highest soak time is above the Tg of the BT. The range of temperatures may have been chosen too high.

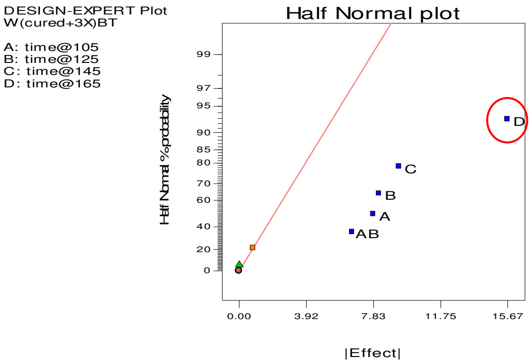

Figure 5: Effects of VFM cure on BT warpage

It was found that the most significant variable for the die warpage data was the time at 105°C with a smaller but significant effect of the time at 145°C (Figure 6). Once again there was no effect on warpage from the fast ramp rates. Room for further improvement in warpage appears to be in even longer times for the lowest temperature soak. The best VFM cure profile from this experiment was a 40 minute soak at 105°C followed by an 8 minute soak at 145°C. No further experiments were done to optimize this nor were there experiments to evaluate even lower temperature soak steps in the profile. In each trial the completion of cure after the four soak profile was confirmed by Tg.

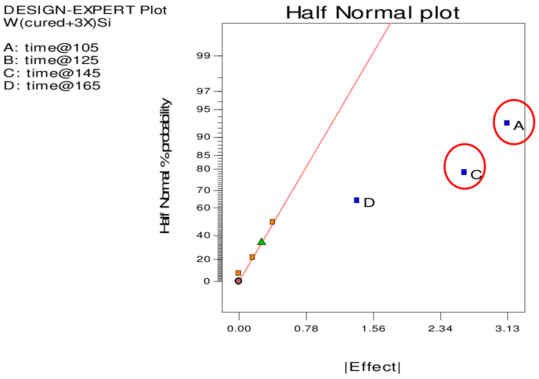

Figure 6: Effects of VFM cure on die warpage

Confirmation trials were performed using standard and optimized convection profiles and the VFM profile (not optimized) from the previous experiments. Twelve parts each were assembled with results shown in Table 2 including post-cure 3X reflow processes at 260°C.

	BT(cure)	BT(reflow)	Si(cure)	Si(reflow)
Conv.(std)	124um	114um	59um	61um
Conv.(opt)	124um	120um	58um	60um
VFM	95um	103um	45um	53um
Change	**-24%**	**-14%**	**-24%**	**-13%**

Table 2: Warpage confirmation for FP4527

A second phase of the work was to determine if the improved warpage with VFM was specific to one under-fill or more general. Direct modification of under-fill components was not possible for this study so a second under-fill material ("Epoxy B") of a different chemical class was evaluated using the same substrates and dice as before. The standard convection cure for this material is a 35 minute ramp to 150°C, hold at 150°C for 2 hours and let cool.

A multi-step profile DOE was run as shown in Figure 7 to determine the significant soak temperature effects on warpage.

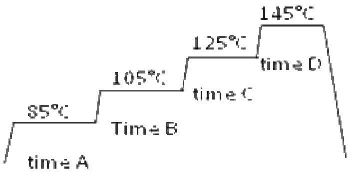

Figure 7: Multi-step DOE profile for Epoxy B

It is important to compare equivalently cured samples when making comparisons of thermo-mechanical properties. The heats of reaction of cured and un-cured Epoxy B resins (Figure 8) are shown Table 3. The lower Tg for the VFM sample is seen to be insignificant with respect to % cure.

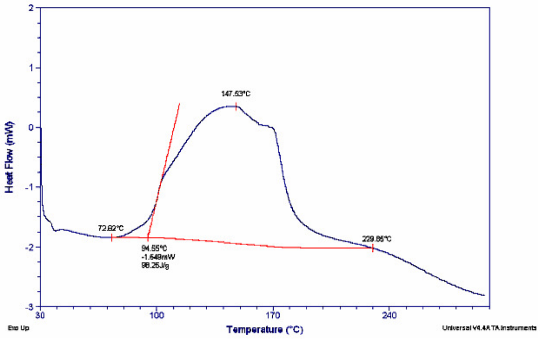

Figure 8: DSC of un-cured Epoxy B

	Tg (°C)	ΔH (J/g)	% cure
Un-cured		98.25	0
Convection	106	0.11	99.9
VFM	102	0.19	99.8

Table 3: DSC cure comparisons for Epoxy B

In the VFM multi-step cure profile experiment, there was a strong interaction between the 85°C and 145°C temperatures for both the BT substrate warpage and the silicon die warpage (Figures 9 and 10). Once again the lowest soak temperature is a common thread with respect to package warpage as well as higher temperature interactions.

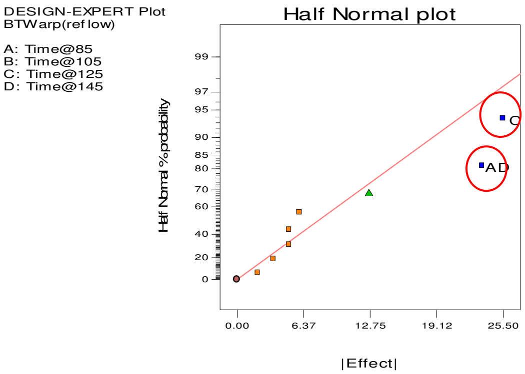

Figure 9: Effects of VFM cure on BT substrate

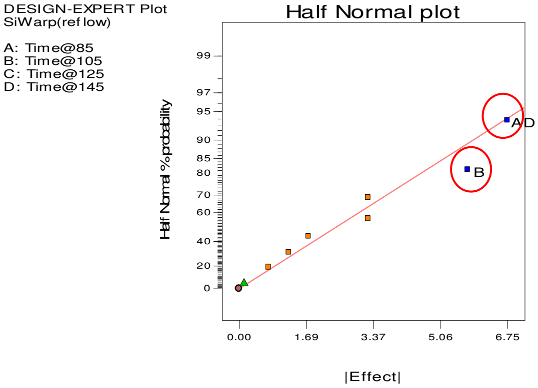

Figure 10: Effects of VFM cure on silicon dice

In this case there is an interaction that favors either long or short times at both extreme temperatures (Figure 10). Since it is unlikely that 5 minute soaks at 85°C and 145°C would thoroughly cure the under-fill, the best conditions would combine 35 minutes @ 85°C and 25 minutes @ 145°C. In fact the best warpage results for the BT and silicon dice were at these settings (with 5 minutes at the other two temperatures – highlighted with arrow). The intermediate temperatures are significant but smaller.

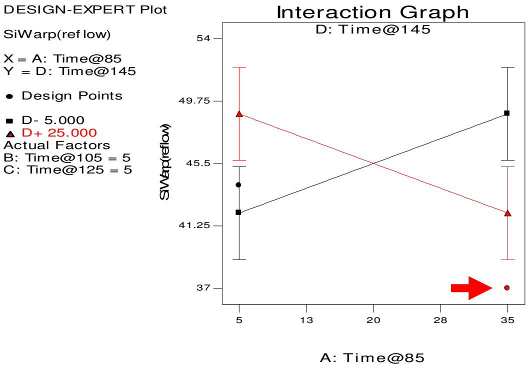

Figure 11: Optimum profiles for VFM

Confirmation runs were made with the standard convection cure of 35min. ramp to 150°C + 120min 150°C soak and the best results VFM run of 35min@85°C + 5min@105°C + 5min@125°C + 25min@145°C as discussed above. The extent of cure of the convection cured and VFM cured materials were both determined to be 100% (within measurement error) by Tg from DSC, TMA, and DMA.

There were 10 parts for each cure process using the same 59 mil thick BT substrates but with only 15 mm square dice available (Table 4). Since the smaller dice would not represent the same warpage improvement, the actual results of VFM are listed for comparison to the 20mm dice used in the previous experiments. Note that the BT standard deviations are significantly higher than the die which was generally the case. Finding substrates with consistently low variation in bow was difficult.

	BT(cure)	BT(reflow)	Si (cure)	Si (reflow)
Conv.(std)	105um	122um	49um	60um
S.D.	13.5um	18.4um	3.2um	2.8um
VFM	68um	109um	29um	50um
S.D.	14.6um	18.0um	3.0um	3.6um
Change	**-35%**	**-12%**	**-39%**	**-16%**
VFM #2	38um	75um	18um	37um
Change	**-64%**	**-39%**	**-63%**	**-38%**

Table 4: Confirmation results for Epoxy B

Additional experiments were performed with Epoxy B to determine the reduction of warpage with VFM on parts that were more representative of modern BGA packages. The silicon dice were 20 mm square but thinned to 75 µm and the BT substrates were 47 mm x 30 mm but only 200 µm thick. The die had a large array of solder bumps. There was an additional wait step of two days inserted between the cure of the under-fill and the 3X lead-free reflow steps. This wait step was meant to determine whether there could be a relaxation of the cure stress with time between processes. Four assemblies each were made with standard convection and VFM multi-step curing profiles as described above. A significant stress relaxation after cure can be seen in Tables 5 and 6 but the stress has increased beyond the original level after solder reflow. There was significantly less stress for the VFM cured parts even after reflows.

	BT(cure)	2 days	BT(3X reflow)
Conv.(std)	756um	669um	890um
VFM	263um	287um	330um
Difference	**-65%**	**-57%**	**-62%**

Table 5: BT Warpage of thin assemblies

	Si (cure)	2 days	Si (reflow)
Conv.(std)	407um	355um	509um
VFM	204um	159um	357um
Difference	**-50%**	**-55%**	**-30%**

Table 6: Die warpage of thin assemblies

The improvement in warpage reduction was also found to be related to the die size (Figure 12). There is also an indication that thinner dice will exhibit more warpage improvement with VFM curing.

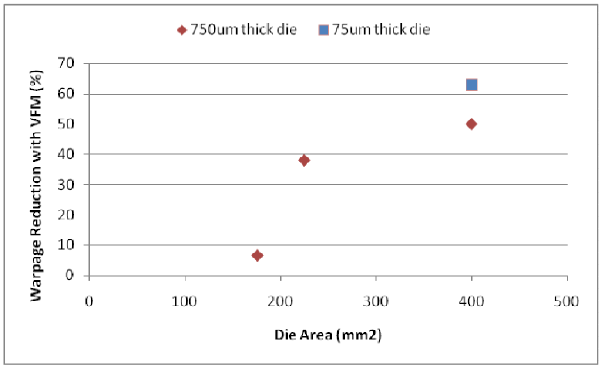

Figure 12: VFM warpage reduction vs. die size

The next question was whether there was a contribution to warpage reduction due to a morphological or chemical change when VFM curing was used. One method of reducing stress in a thermoset is to increase the elasticity by lowering the network cross-link density [6]. Lowered cross-link density can be identified by lowered elastic (storage) modulus (E’) above the Tg (the rubber state). The moduli (storage, loss, tan δ) of Epoxy B are shown in Figure 13 after standard 150°C cure in a convection oven for two hours.

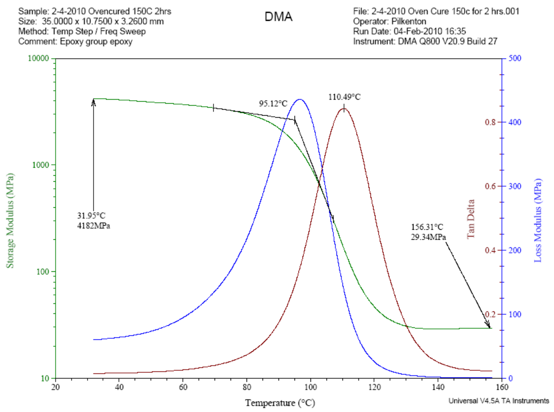

Figure 13: DMA of Epoxy B – convection cured

The moduli of Epoxy B after VFM cure at 35min@85°C + 5min@105°C + 5min@125°C + 25min@145°C are shown in Figure 14 and the data for the two samples are summarized in Table 7. The much lower E' (above Tg) with the VFM cure indicates a lowered cross-link density is created with a lower temperature multi-step microwave cure. The Tg values of the two samples are within measurement error.

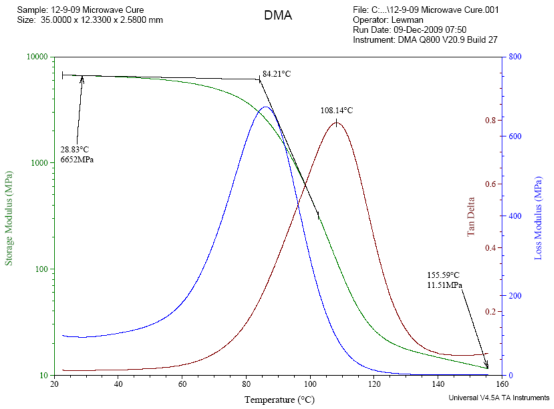

Figure 14: DMA of Epoxy B – VFM cured

	Tg (°C)	E' (>150°C)
Convection	110	29 MPa
VFM	108	11 MPa

Table 7: Epoxy B elastic modulus comparisons

Discussion

The use of a lower temperature under-fill cure in a convection oven did not substantially decrease either the warpage of the substrates or the silicon die in flip-chip packages especially when package processing continued with three reflow steps. In contrast, the use of multi-step low temperature VFM cure of the same under-fills was very effective in improving substrate co-planarity and reducing silicon die warpage in flip-chip packages. The improvements with VFM cure were found with two different under-fill chemistries and reached levels as high as 62% less warpage even after 3X reflows. Variation in substrate co-planarity was higher than that with silicon dice but the improvements were more dramatic as well. Silicon die warpage was reduced with VFM curing by as much as 30% after 3X reflows. For packages such as pin grid arrays that do not see additional thermal excursions, the BT and die warpage reductions can be as high as 65% and 50% respectively. As the substrates and dice became thinner the warpage improvements became more dramatic. The stress decreases rapidly for dice with areas larger than 200 mm^2. These improvements become more useful as die are thinned and core-less substrates become more common. There was an initial relaxation of the warpage after cure but additional thermal processing increased the final warpage in all cases with VFM cured parts retaining most of the stress reduction.

As a practical matter, the total multi-step cure cycle times with VFM were still shorter than the standard convection times as shown in Figure 15. Further improvements in warpage were indicated as possible for both of these materials by the models derived from the designed experiments without changes to the formulations.

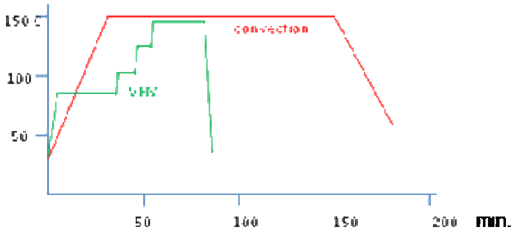

Figure 15: Total cure-cycle time

The reasons for this warpage improvement can be attributed to the well known characteristics of microwave heating (uniformity, selectivity, low temperature cure) but there appears to be a contributing factor of increased cross-link density with the VFM cure profiles. Additional work is being done to determine the exact chemical nature of this enhancement in stress reduction during low temperature VFM cure of model compounds [11]. These investigations may help explain the previously documented component reliability improvements found from the use of VFM cure profiles. An understanding of the relationship between time-at-temperature and cross-link morphology could produce general rules for microwave thermoset cure. A better understanding of microwave curing mechanisms could also lead to further improvements in the design of low stress thermoset materials as they have with thermoplastic materials [12].

References

1. L. Li *et.al.*, "Materials Effects on Reliability of FC-PBGA Packages for Cu/low-k Chips", 2006 ECTC (IEEE).
2. M. Paquet *et.al.,* "Underfill Selection Strategy for Pb-Free, Low-K and Fine Pitch Organic Flip Chip Applications", 2006 ECTC (IEEE).
3. P.H. Townsend, *et.al.,* "Cure Technology For Controlled Stress in Thin Benzocyclobutene Coatings", Mat. Res. Soc. Symp. Proc., Vol.264 (1992).

4. A.C. Metaxas, R.J. Meredith, "Industrial Microwave Heating", 1983, Peter Peregrinus Ltd., London.
5. R. Hubbard *et.al.,* "Low Temperature Curing of Epoxies with Microwaves", Proceedings of the International Microelectronics and Packaging Conference, October, 2006.
6. H. Lee, K. Neville, "Handbook of Epoxy Resins", 1967, McGraw-Hill, New York.
7. K. Tanaka *et.al*., "Variable Frequency Microwave curing of Amide-Epoxy Based Polymers", IEEE Transactions on Components and Packaging Technologies, Vol. 30, No. 3, September 2007.
8. Z. Fathi *et.al.,* " Innovative Curing of High-Reliability Advanced Polymeric Encapsulants", Proceedings of Electronic Packaging Materials Science, IX Symposium, Boston Material Research Society, p125, 1997.
9. B. Anderson, *et.al.,* "Rapid Processing and Properties Evaluation of Flip-Chip Underfills", NEPCON WEST, 1998.
10. C. Lin, *et.al.*, "Effects of Environmental Exposures on Underfill Material Behavior", Proceedings of the International Microelectronics and Packaging Conference, October 2006.
11. D. Tyler et.al., "Unusual Cure Mechanisms of Thermoset Epoxy Resins in Microwave Fields", SMTA International, October, 2009.
12. R. Hubbard, *et.al.*, "Low Temperature Cure of PBO Films on Wafers", Proceedings of the Twelfth International Symposium on Polymers, May 2006.

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