Interactions between Variable Frequency Microwave Underfill Processing and High Performance Packaging Materials

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Abstract

Variable frequency microwave (VFM) has been recently proposed as an alternative underfill curing method that provides flip chip package warpage improvement as well as potential underfill cure time reductions. The current paper outlines how such advantages in VFM processing of underfill can be compromised when applied to high performance organic packages. VFM recipes for three underfill materials were developed by performing several VFM curing runs followed by curing rate measurements using the differential scanning calorimetry method. The VFM curing rate was seen to strongly dependent upon the underfill chemistry. By testing flip chip parts that comprised large and high-end substrates, we showed that the underfill material has negligible impact on VFM warpage with the major cause attributed to the coefficient of thermal expansion mismatch between the die and the substrate. Comparison between the convection and the VFM methods indicated two warpage tendencies that depended upon the VFM curing temperature. First, when both curing methods used comparably high temperatures, warpage increases up to about + 20% were found with VFM. This unexpected result was explained by the high-density Cu loading of the substrate which systematically carried heat generated by VFM energy from the die/underfill system to the substrate. Since this high-end substrate consists of sequential dielectric/Cu layers with asymmetric distribution of Cu, additional stresses due to local CTE mismatches between the Cu and the dielectric layers were induced within the substrate processed with VFM. Second, warpage reductions down to about – 22% were obtained at the VFM curing temperature of 110°C with a curing time similar to that of convection cure. This suggests that the negative effect of the local CTE mismatches were no longer at play at the lower VFM temperatures and that the significantly lower final cure temperatures produced lower total shrinkage of the die and the substrate. Finally, due to lower elastic moduli, the cured VFM parts showed better mechanical reliability with no fails up to 1500 cycles.

Key words

Convection cure, flip chip, VFM cure, underfill, warpage.

I. Introduction

Warpage in flip chip assembly occurs mainly due to the global coefficient of thermal expansion (CTE) mismatch between the die and the organic substrate. Being indicative of package stress, excessive warpage can lead to significant reliability issues such as solder joint failure, die and interlayer dielectric cracking and delamination at the underfill to die or underfill to substrate interfaces [1]-[4]. It can also affect the assembly process at the board level as well as in 2.5D and 3D packaging due to non-planarity at the various joining surfaces [5]-[7].

High performance flip chip plastic ball grid array (FCPBGA) packages continue to push the envelope with respect to mechanical behaviour. Trends such as larger die and substrate size, finer pitch solder interconnects and reductions in substrate core thicknesses, while enabling major technological breakthroughs, all lead to increases in package warpage. Coupled with the environmentally motivated transition to Pb-free solder and its inherently lower ductility and higher reflow temperature, the aforementioned assembly and reliability issues become exacerbated for such packages and therefore warrant an increased focus on minimizing warpage.

A number of solutions for reducing warpage and thermo-mechanical stresses have been explored, addressing such areas as the geometric parameters of flip chip components [2], [8], [9], the material properties [8]- [11] and the process conditions [9], [11]. However, these solutions are not free from real concerns. For example, changing the package geometry can result in additional design complexity and cost. In another example, the use of a lower temperature underfill cure in a convection oven did not substantially decrease the package warpage, especially when processing continued with three reflow steps [12]. More recently, for coreless product development, large warpage has been minimized by attaching or clamping the substrate prior to die attach [11], [13] but this introduces compatibility issues for high volume and low cost assembly.

The present work focuses on an alternative underfill curing method that employs a variable frequency microwave (VFM) concept to minimize warpage. The VFM curing method has been recently extended to underfill material processing of FCPBGA [12], [14] after process validation for many microelectronics applications such as encapsulants, glob-tops, wafer dielectric layers, and flex tape bonding [15], [16]. It has been reported that VFM characteristics such as selectivity, uniform bulk heating and curing at lower temperature than convection method are the main causes of warpage reduction [12], [14], with improvements of 50% and 65% before subsequent reflow steps being cited for the die and substrate respectively [12]. Despite these promising results, the VFM studies on FCPBGA processing are not extensive enough to consider adoption in a production environment across a large spectrum of designs and assembly complexity. Moreover, the fundamental relationships between VFM parameters and these complexities are not fully understood. This paper therefore studies warpage after VFM curing of an advanced flip chip package that employs a high performance substrate. We subsequently explore the warpage difference between the VFM and convection curing methods. Finally, reliability results are reviewed as a preliminary assessment of the VFM concept for flip chip production.

II. Experimental

Experiments were performed using a representative package design for the IBM POWER7^{TM} server series used in high performance computing applications and based on IBM's 45 nm SOI CMOS technology. The package uses a large (22 mm x 27 mm x 0.8 mm) silicon die (hereinafter called the P7 die) that integrates, among other features, 8 high-performance processor cores, a 32-Mbyte embedded DRAM (eDRAM), and multiple I/O and memory controllers [17]. The organic substrate is 50 mm x 50 mm x 1.2 mm in size and designed with a 6-4-6 build up structure and 600 μm epoxy core thickness to meet the routing requirement of this powerful die. As seen in the cross-sectional view in Fig. 1, a build up substrate is typically made of sequential and alternate layers of metallization and polymer dielectric on both sides of a core. Metal layers are complex structures with a significant load of Cu and are interconnected together through multiple vertical micro-vias. The Cu loading density and building layer asymmetry of the substrate will affect the effective thermal conductivity within the substrate and are key parameters in warpage behavior. Three underfill chemistries UF#A, UF#B and UF#C from three main epoxy encapsulant manufacturers were tested. Some principal characteristics as provided by the manufacturers are presented in Table I.

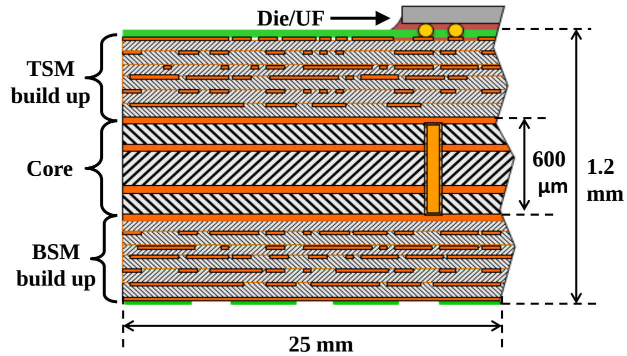

Fig. 1: Illustration of the organic substrate cross-section.

For the warpage study, parts were subjected to a typical advanced flip chip assembly process flow that comprises fluxing, parts placement, die attach by reflowing, dispensing underfill to fill the die/substrate gap and finally, an underfill cure. Here, the traditional convection method of curing was compared with the VFM approach. An additional step of lid attach for deep thermal cycling (DTC) tests was carried out on selected parts in order to estimate package reliability. VFM cure was conducted in a Microcure® 3100 system from Lambda Technologies whose fast frequency sweeping is intended to avert processing issues such as hot spots and metal arcing [14]. The VFM oven also provides two temperature sensors - an IR pyrometer to control the curing temperature through a closed-loop system and a fiber optic to monitor the temperature underneath the substrate. The tests were performed with a fixed ramp up rate of 15 °C/min. Warpage was characterized prior to and following the underfill curing stage. Warpage measurements were conducted at room temperature using a quick response laser-surface-scan that was calibrated on a sample basis using a Shadow Moiré system. Underfill behavior was additionally characterized by using differential scanning calorimetry (DSC) to measure the curing rate of the underfills during VFM recipe development and dynamic mechanical analysis (DMA) to determine the elastic modulus (E') after curing.

III. Results and Discussion

A. VFM recipe development

To effectively study package warpage behavior, it is

Table I
Underfills characteristics.

Underfills	**Cure recipes**	***Tg***
UF #A	**150°C/120min**	**109°C**
UF #B	**165°C/120min**	**98°C**
UF #C	**165°C/90min**	**110°C**

essential to ensure adequate and comparable cure of the underfills. As such, VFM curing recipes were established by evaluating various curing time-temperature combinations followed by DSC validation. By convention, a curing level of 95 % was chosen as the minimum value at which the underfill could be considered sufficiently cured, either by convection or VFM, in order to avert any reliability issues across the typical range of subsequent processing (in particular solder reflow) and product operation. For convection curing, complete cure recipes are provided by the underfill suppliers as presented in Table I. VFM recipe development for each underfill was premised upon using its recommended convection temperature across a range of curing times beginning with 10 % of the suggested convection cure completion time. Cure rates achieved by this protocol are presented in Fig. 2. As expected, all underfills achieved complete cure more rapidly with VFM than with the convection method. This is explained by the ability of microwave to allow higher energetic molecular motions at the underfill dipolar groups (O-H, N-H, C=O, ...) [14]. However, VFM curing rate comparison showed that the UF #A exhibited a lower curing rate (42 % reduction in curing time versus convection) than UF #B and UF #C (90 % reduction). Clearly, the efficiency of the VFM curing seems strongly dependent upon underfill chemistry. While not covered in this work, future efforts dedicated to discriminating the effects of the individual underfill constituents on curing rate would be pertinent for optimal development of new underfills specifically directed towards VFM cure.

These baseline results were then used to investigate VFM curing recipes at temperatures lower than the convection recommendation insofar as complete cure could still be obtained within (and ideally lower than) the known convection curing time for the particular underfill, that is 120 minutes for UF#A and UF#B and 90 minutes for UF#C. Curing recipes thus obtained are summarized in Table II, where all data reflected curing between 95% and 97% complete. For UF #A, such complete cure within 120 minutes could only be obtained at temperatures exceeding 140 C. Consistent with the low VFM curing rate observed in Fig. 2, this suggests limited opportunities to lower the

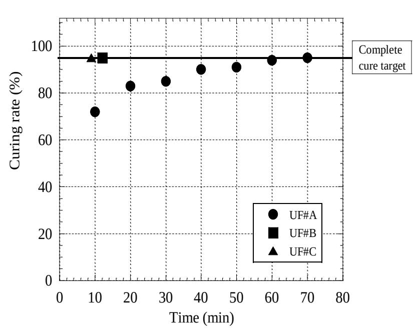

Fig. 2: Curing rate of the UF#A, UF#B and UF#C after VFM curing at the convection temperature.

Table II
VFM curing recipes of the three underfill chemistries.

VFM curing temperature	Curing time (min)		
	UF#A	UF#B	UF#C
150 °C	60	NA	NA
140 °C	120		
165 °C	NA	12	9
145 °C		45	25
130 °C		52	40
125 °C		60	45
120 °C		80	60
115 °C		100	72
110 °C		120	90

curing temperature of UF #A for warpage improvement. In contrast, UF #B and UF #C exhibit high potential for warpage improvement due to their high VFM curing rates that allow curing with seven temperatures ranging from 165 °C to as low as 110 °C, with the tradeoff being a longer time to reach complete cure as cure temperature is decreased.

B. *VFM and Convection warpage comparison*

The aforedescribed VFM curing recipes were used to assess warpage behavior of the P7 package across a range of time and temperature for VFM cure of each underfill. Control measurements were performed on the same package configuration using the convection cure recipes presented in Table I. Fig. 3 summarizes the results for both the P7 die and substrate where values represent % increase or decrease in warpage for VFM cure relative to the convection method. A first observation of note is the similarity in warpage behavior between UF#B and UF#C. From 165°C to 110°C, the relative P7 die warpage was seen to decrease by 32% and 33% after curing of the UF#B and UF#C, respectively. The substrate warpage also decreased by 34% and 33% for UF#B and UF#C, respectively. These results suggest that the faster curing time inherent to the UF#C chemistry had no significant effect on warpage at a given temperature and that warpage was more a function of the particular cure temperature. Accordingly, the main cause of the VFM warpage seen here needs to be determined. We further addressed this issue by directly studying P7 die and substrate warpages for the UF#A (low VFM curing rate) and UF#B (high VFM curing rate) when cured at identical VFM conditions then comparing their results as warpage ratios and curing rate values as shown in Table III. At a given VFM recipe, the warpage ratio was essentially equivalent to unity despite the difference in the underfill type and the curing rate. Results in Table III suggests that the die/substrate global CTE mismatch was the main cause of the warpage seen in the present work and that the underfills themselves, having smaller thicknesses and elastic moduli as compared to the P7 die and the substrate, were mainly subjected to shear stresses with negligible effect on warpage [8]. This seems consistent with other reports [11] where a decrease in substrate dimensional and mechanical parameters, such as with thinner core or coreless substrates demonstrated a more significant effect of underfill on package warpage. It is therefore postulated that warpage improvements garnered by VFM cure is related to its ability to achieve full cure at a lower temperature than convection cure, thereby reducing the total shrinkage of the P7 die as well as the substrate.

Focusing now on the actual relative warpage values of Fig. 3 that serves to compare the two curing methods, we note that the most important observation which differs from previous research [12], [14] was that no systematic warpage improvement was obtained with VFM curing. More specifically, two distinctive trends can be noted depending on the VFM curing temperature. VFM cure warpage was higher than that of convection cure at the higher end of temperatures investigated (150°C/70min and 140°C/120min for UF#A, 165°C/12min and 145°C/45min for UF#B and 165°C/9min and 145°C/25min for UF#C) despite shorter VFM curing times and, in some cases, lower curing temperatures. However, where significantly lower temperatures could achieve full cure, as was the case with UF#B and UF#C, gradual warpage reduction was seen with VFM compared to convection. For the P7 die and the substrate, reductions as much as about - 22% were reached with the lowest curing temperature of 110°C. It should be noted that at this temperature, no time reduction was obtained compared to convection curing. Comparable warpage values between both curing methods were found at a VFM curing temperature of 130°C, suggesting an inflection point at this temperature. To further understand this phenomenon, we examined heating rate of the substrate by monitoring the temperature on the bottom side center of the substrate during VFM curing. For example, substrate and curing temperatures of the UF#B with the recipe 165°C/12min are presented in Fig. 4. It is interesting to note that the temperature of the backside center of the substrate systematically tracked the curing temperature. In that preliminary fundamental tests on the individual

Table III
UF#B and UF#C curing rate effect on VFM warpage.

Under-fill	Tempera-ture (°C)	Time (min)	Curing rate (%)	Warpage ratios	
				Die	Substrate
UF#A	110	120	83	1.01	0.96
UF#B			96		
UF#A	130	60	84	0.99	1.04
UF#B			98		
UF#A	145	45	84	1.02	1.01
UF#B			97		

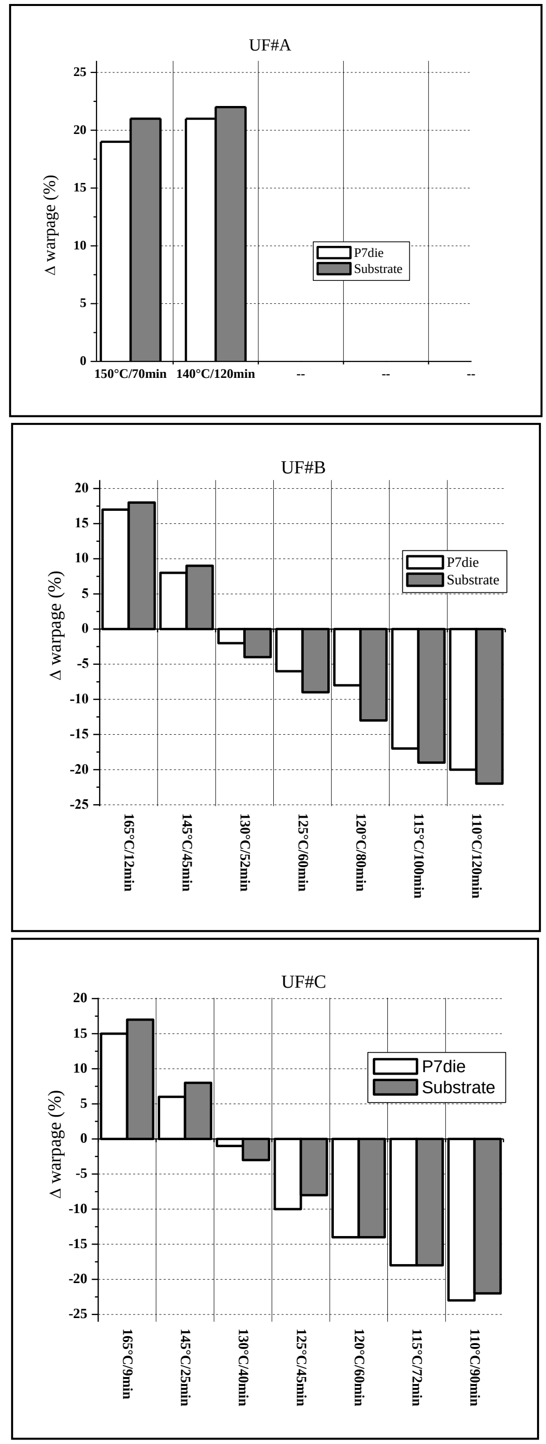

Fig. 3: P7 die and substrate warpage difference between VFM and convection methods of the UF#A, UF#B and UF#C at different curing recipes.

components, not presented here, determined that VFM energy heats the P7 die and the underfill but not the substrate, it can be derived that the heating induced by VFM in the P7 die/UF system was transferred to the substrate through the solder joints and underfill/substrate interface. For this particular package, heat transfer was most likely enhanced by the high-density Cu loading shown in Fig. 1. The sequencing of dielectric/Cu layers and the asymmetry of the Cu distribution within the substrate may induce, during cooling, a thermal gradient along both the in-plane and the out-of-plane axes of the substrate. So, it is proposed that the substrate under VFM heating may experience local CTE mismatches between the dielectric layers and the Cu structures whereas such mismatches are negligible with convection curing where all components are consistently at a uniform temperature. Given the distinctive variation in relative warpage behavior as a function of cure temperature, it would appear that the severity of the stresses induced by such local CTE mismatches depends greatly on the VFM processing temperature. Thus, at temperatures above 130°C for this package design, the negative impact on warpage caused by such locally induced stresses may be negligible leading to VFM warpage reductions. Again, as previously noted, this behavior should be considered valid under the particular conditions of this package configuration that is high Cu loading and negligible underfill effects. In fact, earlier studies have reported warpage improvement with VFM cure that was assumed to be related to changes in underfill properties relative to convection cure, in particular a lower cross-link density and decreased elastic modulus above *Tg* [12], suggesting that a package configuration that is more susceptible to underfill properties was used. This was not observed in the present results since higher VFM warpage was found compared to convection warpage even if the post VFM moduli after Tg taken at 200°C were lower with recipes at 165°C and 145°C for UF#B (see Table IV).

Table IV
Post cured UF#B properties comparison.

Cells	*E'*(@200°C)	Warpage: VFM vs. Convection
Convection 165°C/120min	129 MPa	
VFM 165°C/12min	98 MPa	Higher
VFM 145°C/45min	100 MPa	Higher
VFM 125°C/60min	95 MPa	Lower
VFM 115°C/100min	100 MPa	Lower

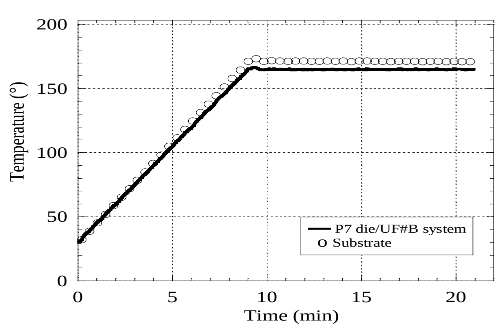

Fig. 4: Temperature profiles of the P7 die/UF#B system and the backside center of the substrate during VFM curing.

C. Reliability results

The reliability of the VFM was evaluated by subjecting parts used here to deep thermal cycling (DTC) tests where temperatures ranged from – 40°C to + 125°C. The UF#B was chosen for this evaluation by selecting two cells cured by VFM under different conditions (125°C/60min and 115°C/100min) along with one control cell cured by standard convection at 165°C/120min. The underfill choice was motivated by the fact that UF#B is an experimental material for which early fail data (at 1000 cycles DTC) already existed for convection cure and therefore presented a strong opportunity to discern reliability variations between VFM and convection cures. Each cell comprised nineteen parts that, as described in the experimental section, were subjected to post-underfill operations to more closely simulate actual package thermo-mechanical conditions. The DTC results are summarized in Table V. At 1000 cycles, readouts on the control cell confirmed previously obtained results in that mechanical failure initiated at the four corners of some P7 dies, whereas VFM parts exhibited no fails before 1500 cycles. Failure analysis on parts from the control cell at 1000 cycles revealed delaminations at the circuitry/polyimide interface and cracks in the underfill material (Fig. 5). The improvement in package integrity obtained by VFM is believed to be related to the lower

Table V
DTC results.

Cells	1000 cycles	1500 cycles	2000 cycles
Convection 165°C/120min	Fails initiation	Major Fails	Major Fails
VFM 125°C/60min	Passed	Fails initiation	Major Fails
VFM 115°C/100min	Passed	Fails initiation	Major Fails

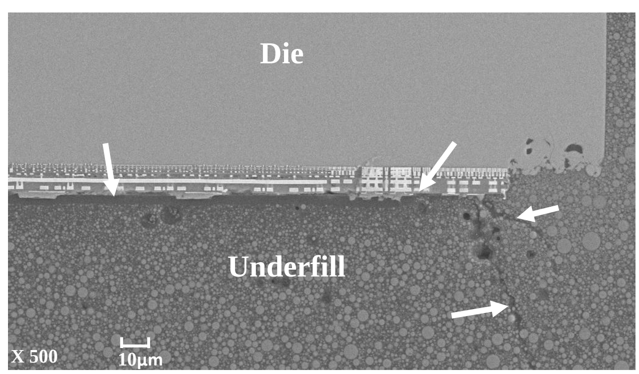

Fig. 5: A failed part of the control cell after 1000 cycles.

post-cure underfill moduli that this cure technique produces, as seen in Table IV. Therefore, VFM provides a more compliant system able to better absorb the high thermo-mechanical stresses caused by the die/substrate global CTE mismatch, thereby improving the package life time.

IV. Conclusion

The interactions between high performance FCPBGA components (substrate, die and underfill) and the use of VFM underfill cure were investigated with respect to process behavior and package integrity. The major conclusions can be summarized as follows:

(1) The VFM curing rate strongly depended upon the underfill chemistry resulting in materials with both high curing rates and low curing rates.

(2) The role of the underfill in VFM warpage improvement, within the constraints of the package configuration of this study, was limited to the determination of the curing temperature. Underfills with high curing rate were found to offer lower VFM curing temperature possibilities that led to warpage reduction.

(3) The VFM warpage reduction was significantly governed by the die/substrate global CTE mismatch regardless of underfill curing rates.

(4) The high-density Cu loading of the evaluated substrate was seen to cause systematic heating of the substrate by thermal conduction, thereby inducing additional stresses due to local CTE mismatch between Cu/dielectric layers.

(5) Depending upon curing temperature, the stresses induced by VFM can be higher or lower than those induced by convection, which in turn leads to higher or lower relative warpage. The lowest warpage obtained with VFM was about - 22% relative to convection and this was achieved at 110°C with no cure time reduction compared to convection processing.

(6) The VFM curing showed better mechanical reliability than the convection curing due to a lower post cure elastic modulus.

Finally, while this study has furthered the fundamental understanding of VFM underfill cure in advanced packaging applications, it is recognized and recommended that additional potential issues, such as coreless product warpage behavior and silicon device interaction with VFM technology at a wafer level, should be explored in future study.

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