Low Warpage Liquid Compression Molded Underfill for Wafer Level Packaging

Yijia Ma, Jimmy Nguyen, Rose Ha, Mark Hoshiyama, Tim Champagne, Kail Shim, Raj Peddi
Henkel Corporation
14000 Jamboree Road, Irvine, CA 92606
Irvine, CA 92606 USA
Email: yijia.y.ma@henkel.com

Abstract

As semiconductor chip design transforms to meet the increased functionality, performance, and miniaturization needs of applications such as 5G, high-performance computing (HPC) and autonomous vehicles, advances in packaging materials and technologies have become crucial to enable tighter pitches, higher interconnect density, and increased complexity of the new architectures.

Liquid compression molded underfill (L-MUF) has drawn attention as a new wafer level packaging material for its capability to gap fill and over mold simultaneously under low pressure. This material capability has improved efficiency and sustainability of the process and enabled higher reliability of the final package. L-MUF material development challenges include achieving void free gap filling in fine pitch applications and maintaining low warpage during the packaging process.

This paper presents analysis of L-MUF encapsulant materials that feature lower warpage compared to typical encapsulants, a high glass transition temperature, void free gap filling, and high reliability. The novel L-MUF materials are formulated with proprietary resin systems and ultra-fine fillers as key enablers for their unique material properties and application performance. The results demonstrate that L-MUF materials have the combination of good flowability and low warpage and have the potential to meet the growing demands of various wafer level packing applications.

Key words

Encapsulant, gap filling, liquid compression molding, molded underfill, wafer level packaging, warpage

I. Introduction

The proliferation of emerging technologies, such as artificial intelligence and autonomous vehicles, is dictating the use of advanced semiconductor packaging solutions to enable smaller form factors, higher performance, and higher integration. As semiconductor encapsulants become increasingly integrated into advanced packaging technologies, such as fan-out wafer level packaging, heterogeneous integration, and 2.5D/3D packaging, advances in encapsulant materials are critical in ensuring compatibility, performance, and long-term reliability of semiconductor devices.

The encapsulation of chips with narrow gaps and fine pitches is traditionally achieved through a two-step process in wafer level packaging. First, underfill materials are applied to reinforce the gaps and pitches underneath the chip to provide protection for solder joints and Cu pillars. Depending on the packaging type, underfill materials of various formats may be used, including capillary underfill (CUF) and non-conductive paste and film (NCP and NCF) [1]. Second, epoxy molding compounds (EMC) are applied to over mold (OM) the entire chip to provide protection against mechanical and chemical impacts. Typical EMC materials include liquid, granular, powder and sheet formats [2]. The underfill and over mold approach is a proven, robust, and mature process in the industry. However, there are factors inherent to this process that make it less suitable for more complex packaging designs. For example, CUF materials are typically dispensed along the chip unit-by-unit and use capillary forces to fill the gaps. As chip size becomes larger and more chips are integrated into one package, trapped voids and scalability become issues [3].

Consequently, compression molded underfill (MUF) was developed as an alternative approach. MUF combines the two encapsulant materials into one material and simplifies the process by achieving gap filling and over molding simultaneously under compression molding. It eliminates the need for separate underfill and curing steps, streamlining the encapsulation process, and reducing cycle times. Furthermore, it improves the sustainability of the process and the reliability of the package. Both liquid and solid forms (granular and sheet) MUF materials have been developed and investigated [3]-[6]. Typically, solid type MUF materials require higher molding pressure due to the higher filler content and higher viscosity nature. As chips miniaturize and get more complex, low molding pressure is preferred to reduce the possibility of damage. In this paper, the authors focus on the development of a liquid type molded underfill (L-MUF). Fig. 1 shows the sideview of a device with narrow gaps and tight pitches that was encapsulated with Fig. 1 (a) L-MUF approach and Fig. 1 (b) NCF/CUF + OM approach.

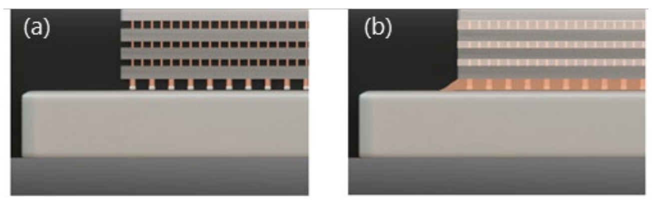


Fig. 1. Encapsulation of a device with narrow gaps and tight pitches: (a) L-MUF approach and (b) NCF/CUF + OM approach.

The development of a L-MUF presents several challenges because of the combined requirements from two types of encapsulant materials that vary significantly in filler loading, viscosity and curing profiles. Among them, low warpage and void-free gap filling are the two challenging requirements for fine pitch applications. L-MUF materials need to meet both requirements to achieve the desired performance.

Low warpage is crucial for ensuring robust handling during process steps and low stress build at the interfaces between materials to prevent reliability failures, especially when the molded area gets larger, such as panel level packaging. The warpage of molding compounds has been extensively studied to understand the underlying mechanism and to develop reduction strategies. Previous studies reported that the warpage of molding compound materials was affected by several material properties, including glass transition temperature (Tg) [7], coefficient of thermal expansion (CTE) [7], modulus [7]-[8], thermal and chemical shrinkage [8], and stress relaxation [4],[10]-[11]. Studies also found that varying molding parameters led to different warpage levels [12], indicating that warpage management was possible through process optimization.

Voiding has been the primary concern for adopting L-MUF as a new encapsulation option. The presence of voids creates discontinuities in the underfill material and can cause electrical and reliability failures. Root causes and mitigation strategies have been investigated [4]-[5],[13]-[14]. Experimental results showed that voiding was greatly affected by the dispensing pattern [4]-[5], [13]. Center dispensing typically resulted in voiding due to initial air trapped in the central area. Spiral and serpentine and dispensing patterns, as well as their combination, were effective in reducing voids [4]. However, there was no single dispensing pattern that worked for all materials because different L-MUF materials had vastly different rheological behaviors [5]. Material properties and process conditions needed to be studied together to achieve zero voiding. Simulation studies on voiding formation were carried out to further understand the gap filling mechanism [13]-[15]. Results showed that voids were typically located at the center of the chip and the size of the voids was dependent on the molding conditions, such as dispensing patterns, compression force, and vacuum levels.

Due to the demanding material requirements for L-MUF materials, limited products exist in the current market. In this paper, a novel liquid molded underfill (L-MUF) material that can achieve low warpage (<1mm) on 12-inch wafers and void-free gap filling for test vehicles (TV) with 20 µm gaps and pass MSL3 level reliability is introduced. Five L-MUF formulations (M1 to M5) that were designed with variations in their resin system to achieve varied materials properties are discussed. The goal was to understand the correlations between formulations and their warpage and gap filling performance, and to use the knowledge to design formulations that could achieve both low warpage and void-free gap filling. The effect of molding parameters on gap filling performance was also investigated.

II. Experiments

A. Formulation designs

L-MUF formulations contain various components, each serving a unique purpose in achieving the desired overall material performance. Commonly used components include epoxy resins, hardeners, catalysts, silica fillers, tougheners, and additives such as adhesion promoters, dispersing agents, and pigments. In this paper, five L-MUF formulations (M1 to M5) that differed in their resin systems to achieve various material properties are evaluated, as summarized in Table 1. Their viscosities were measured by a rheometer with parallel plates. Cure speeds were determined by reaction onsets and offsets from differential scanning calorimeter (DSC) with a 10 °C/min. constant ramp rate. CTE and storage modulus were measured by thermomechanical analysis (TMA) and dynamic mechanical analysis (DMA) at a 5 °C/min. constant ramp rate, respectively. Tg by TMA was obtained from the inflection point of the dimension change signal during the ramp cycle.

Table 1. Basic material properties of L-MUF candidates

	M1	M2	M3	M4	M5
Filler loading [wt%]	A	A	A	A	A
Filler size top cut [μm]	5	5	5	5	5
Viscosity at 25°C [Pa.s]	221	287	109	161	156
Tg by TMA [°C]	123	124	127	114	142
CTE 1 [ppm/°C]	10	10	10	9	12
CTE 2[ppm/°C]	39	31	27	24	27
Storage modulus at 25 °C [GPa]	13	16	13	13	11

B. Warpage measurements

To measure the warpage of the above formulations, the target amount of paste was dispensed onto the center of the wafer manually (Fig. 2 (a)) to mold a layer of 400 μm thick material onto a 770 μm thick 12-inch bare silicon (Si) wafer (Fig. 2 (b)). The molding was performed by a Yamada molding machine and the in-mold-cure (IMC) condition was either 110 °C for 600s or 120 °C for 600s for the formulations in this study. After IMC, the materials were typically 60%-80% cured and needed to be post-mold-cured (PMC) in a heat oven at 150 °C for one hour to achieve 100% cure. The wafer warpage was characterized by a Nikon NEXIV video measuring system at one-hour and 24-hour intervals post PMC. High warpage and low warpage examples are shown in Fig. 2 (c) and (d). Blue and red colors in the warpage images indicate low and high elevations, respectively. In this paper, positive values are used to refer to a concave/smiling shape of warpage and negative values are used to refer to a convex/crying shape of warpage.

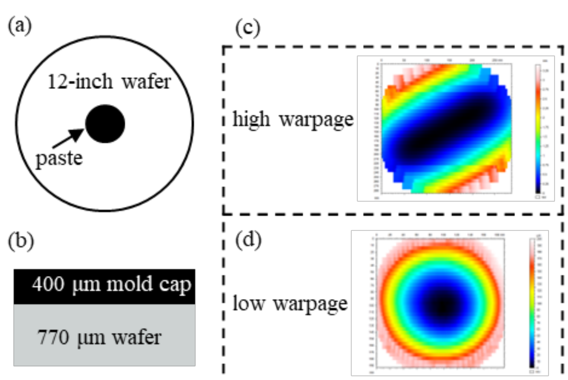


Fig. 2. Warpage measurements on 12-inch wafers: (a) paste dispensing location, (b) mold cap and wafer thicknesses, (c) high and (d) low warpage examples

C. Gap-filling measurements

One-layer high bandwidth memory-2 (HBM2E) test vehicles were used in this study to evaluate the gap filling performance of the L-MUF formulations. The HBM2E TV had a dimension of 7mm×11mm×0.15mm and contained 27,190 bumps in total. It had a gap height of 20 μm and pitch sizes ranging from 30 μm to 66 μm. Due to the 20 μm gap of the TV, 5 μm cut silica filler was used for all five L-MUF formulations. For each test, two HBM TVs were attached to the edge of an 8-inch bare Si wafer to have the furthest flow distance, as shown in Fig. 3 (a). During molding, L-MUF paste was dispended manually in the center of the wafer with a target mold thickness of 400 μm. The effects of molding parameters on the gap-filling performance, including clamping speed and molding temperatures, were also investigated in this study.

After IMC and PMC, the TVs were diced into individual units for void examination. Scanning acoustic microscopy (C-SAM) with a 230 MHz transducer was used to map the voids across the whole TV. During C-SAM, voids inside the TV could be detected by monitoring the ultrasonic echoes reflected from the voids. Void-free and voiding examples in HBM2E TV are shown in Fig. 3 (b) and (c). Fig. 3 (b) also shows an example of severe flow marks. It was discovered that such flow marks typically sat on top of the HBM2E TV and could be greatly reduced by mechanically grinding off the L-MUF layer above the TV. The shape of the flow mark also indicates that L-MUF filled the area surrounding the TV first due to low flow resistance and then filled the narrow gaps underneath the TV. To investigate reliability performance of the material, molded TVs were subjected to accelerated moisture sensitivity level 3 (MSL3a: soaking at 60 °C/60% relative humidity for 40 hours), reflowed three times at 260 °C, and scanned again to check voiding development.

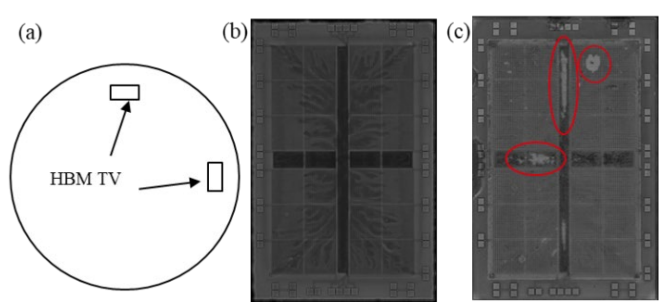


Fig. 3. Gap filling measurements: (a) TV locations on a wafer, (b) void-free gap filling, (c) whitening indicates voiding

III. Results and Discussion

A. Warpage performance

Warpage control of L-MUF formulations is commonly achieved through both filler and resin adjustments. Due to the low CTE of silica fillers (~3 ppm/°C), increasing silica filler loading is effective for reducing the CTE of the material, thus reducing warpage. However, increasing silica loading also significantly increases the viscosity of the material. As gaps get narrower and pitches get tighter in future devices, ultra-fine fillers are required for void-free gap filling, posing challenges in increasing filler loading. Therefore, this study focused on investigating the correlation between warpage and resin systems. All five formulations were developed from the same base resin system so the results could be clearly interpreted. Minor resin adjustments were made in each formulation to achieve distinct levels of CTE, Tg and modulus. The same 5 µm upper cut filler package was used in all the formulations with the same filler loading. Their 12-inch warpage performance is summarized in Table 2.

M1 and M2 showed high warpage after PMC + one hour. M1 used a fast-curing resin that led to high cure shrinkage and high CTE, resulting in high warpage. M2 adjusted the cure speed by introducing a slower curing resin, however, such change increased the modulus significantly and also led to high warpage. Though M1 and M2 both had high warpage one hour post PMC, their 24-hour warpage behaved quite differently. The warpage of M1 was able to relax over time and reduced 41% after 24 hours, while the warpage of M4 only showed only 3% change after 24 hours, indicating its lack of ability to relax due to its high modulus. M3 had a more balanced combination of CTE and modulus. It showed a lower CTE than M1 and a lower modulus than M4. As a result, it was able to relax significantly and achieve 79% warpage reduction after 24 hours. The observations indicated that low CTE and low modulus were both critical in achieving low initial warpage and warpage relaxation over time.

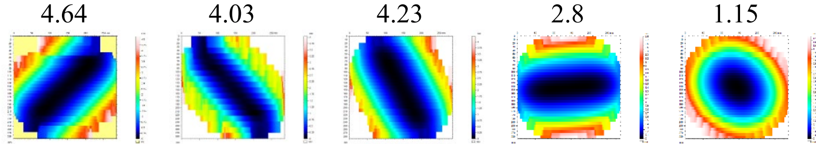
Though M3 was able to achieve <1 mm 24 hours post PMC, its one-hour post PMC warpage level was still considered high for wafer level package applications that require the wafer warpage to be at <1.5 mm on a 12-inch wafer during all processing steps. Consequently, M4 and M5 were developed by using stress release tougheners to further reduce CTE and modulus. M4 showed 34% reduction in the one-hour post PMC warpage compared to M3 and the warpage was able to relax to < 1mm after 24 hours. M5 showed the lowest warpage among all candidates. It achieved ~1mm warpage one hour post PMC and the warpage continued to reduce over time to close to zero.

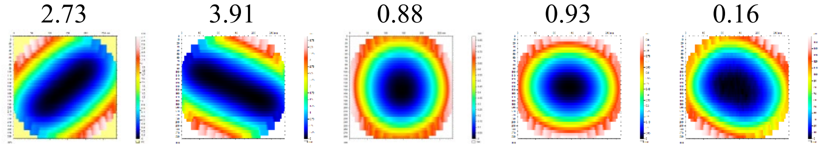
B. Gap-filling performance

Based on the warpage performance of the above formulations, M3, M4 and M5 were molded onto wafers with HBM2E TVs to evaluate their gap filling performance. The results are summarized in Fig. 4. Though M5 showed the lowest warpage among all materials, it had trouble gap filling the TV (Fig. 4 (a)). C-SAM detected large patches of whitening area across the whole image, indicating severe voiding inside the TV. Both TVs on the wafer (Fig. 3 (a)) showed similar voiding results and confirmed the data was valid. For comparison, M3 was molded with the same molding condition and showed much less voiding from C-SAM (Fig. 4 (b)). The poor gap filling capability of M5 was likely related to its rheological behavior. Fig. 5 shows the isothermal viscosity comparison of M3 and M5. M5 showed higher viscosity and shorter gel time than M3, resulting in higher flow resistance and shorter flow time, and thus inferior gap filling.

Table 2. Correlations between L-MUF material properties and their warpage on 12-inch wafers

	M1	M2	M3	M4	M5
Modulus	Medium	High	Medium	Medium	Low
TMA Tg	Medium	Medium	Medium	Medium	High
CTE	High	Medium	Medium	Low	Medium
12-inch Warpage after PMC					
PMC+1 hour [mm]	4.64	4.03	4.23	2.8	1.15
PMC+24 hour [mm]	2.73	3.91	0.88	0.93	0.16





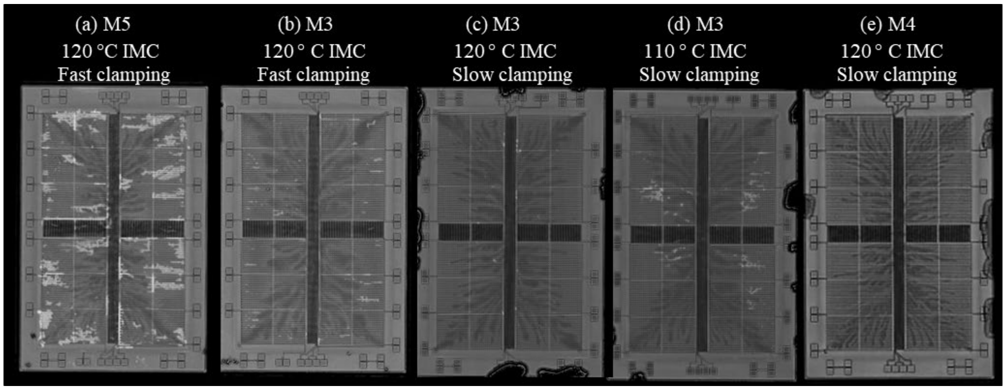


Fig. 4. Gap filling performance of M3, M4 and M5

Molding process modifications were applied to M3 to further reduce the voiding, including a lower clamping speed (Fig. 4 (c)) and a lower IMC temperature (Fig. 4 (d). Results showed that a slower clamping speed was effective in reducing voiding, potentially due to the more even flow front and longer material warm up time. Lower molding temperature resulted in more voiding, likely due to the higher viscosity at a lower molding temperature. Based on the above results, 120 °C IMC temperature and a slow clamping speed were the preferred process parameters for the current L-MUF platform. Other process parameters could also affect the gap filling performance significantly and should be optimized for achieving the best results, including vacuum level, clamping force, dispensing patterns, etc. Due to the limited length of this paper, those parameters are not discussed here.

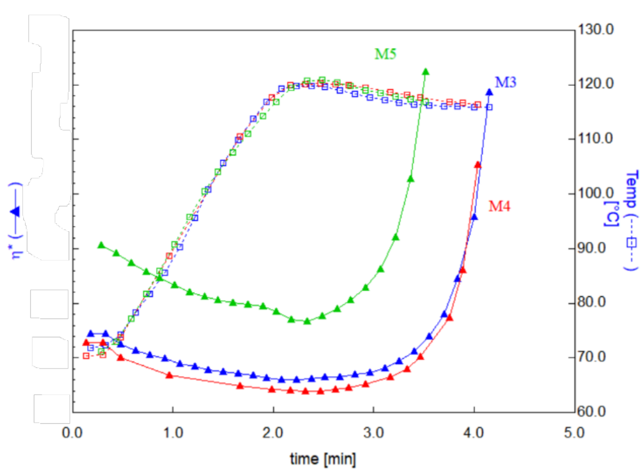


Fig. 5. Isothermal viscosities of M3, M4 and M5 at 120 °C

M4 was molded using the identified preferred combination of 120 °C IMC and slow clamping and showed void free C-SAM images. To better compare the gap filling performance of M3 and M4, they were molded side by side multiple times to eliminate test variations. Results showed that M4 had a higher void-free rate than M3. The two materials shared similar viscosity profiles as shown in Fig. 5. Their gap filling performance difference was likely caused by the toughener type difference in their formulations. The toughener in M4 was more compatible with the rest of the epoxy resins, enabling better flow at high temperatures.

To check the reliability performance, void-free TVs molded with M3 and M4 were subjected to quick kill conditions, including soaking at MSL3a and reflowing at 260 °C three times. After the quick kill, M3 showed severe whitening in the high-density cross areas of the TV (Fig. 6 (a)). SEM images of the cross sections of the TV revealed delamination at the high-density primary region (Fig. 6 (c)) and voiding near the neck of the Cu pillars (Fig. 6 (d)). M4 showed no whitening after the quick kill condition (Fig. 6 (b)), indicating its better reliability performance than M3, likely enabled by its lower warpage and CTE.

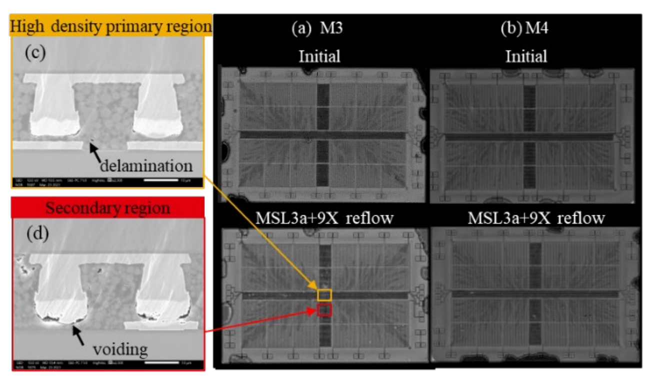


Fig. 6. C-SAM images of M3 and M4 before and after MSL3a + reflowing at 260 °C

IV. Conclusion

In this study, five L-MUF materials that varied in modulus and CTE were evaluated to understand the correlation between material properties and warpage/gap filling performance. It was revealed that 1) low CTE and low modulus are beneficial to reducing material warpage, 2) low viscosity, long gel time, better material compatibility and optimized molding parameters can improve gap filling, and 3) low warpage is critical to achieving good reliability performance. The viability of achieving void-free gap filling in HBM2E TVs afford opportunities to use an L-MUF material as a new encapsulating approach in chips with 20 µm gaps. However, as the gaps are getting narrower in future devices, finer than 5 µm cut filler are needed and should be studied in future works.

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