

Highly Reworkable Board-Level Underfill for Large PoP Devices

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Abstract

The primary objective for using board level underfill for CSP and BGA devices has been to increase the resistance to drop impact. However, the trend toward finer pitched devices, coupled with new designs such as package-on-package (PoP), has brought to light the importance of other measures of reliability. Large PoP devices, with dimensions greater than 14 x 14 mm, require the underfill to provide increased thermal cycling reliability and bending resistance. But, improving reliability is counter to the material characteristics required to improve reworkability. While the latter has typically been accomplished through the formulation of lightly crosslinked thermosets that lose strength rapidly at elevated temperatures, higher thermal cycling reliability requires the use of highly crosslinked, high glass transition (T_g) materials. Therefore, a new approach is required to achieve the combination of reworkability with high thermal cycling reliability. This paper will discuss the development of a new reworkable underfill that provides the high T_g and high adhesion necessary to improve thermal cycling reliability. Thermal cycle, drop impact, and bend test results on 14x14 mm PoP packages will be discussed. In addition, physical property characterization will be reported with an emphasis on aspects of high-throughput assembly.

Keywords: Underfill, Package-on-Package, PoP, Reworkable

Introduction

Today's Package-on-Package (PoP) 3D architecture is driving the need for high reliability, highly reworkable underfill. PoP technology is useful for handheld / mobile devices, as it enables the miniaturization of devices by providing increased functionality, memory and logic, but uses significantly less printed circuit board (PCB) area than single package configurations. [1-4] However, with this change in packaging technology, new reliability challenges have arisen for underfill adhesives.



Figure 1: Package-on-Package Architecture
Image courtesy of Amkor Technology

Thermal Cycling Reliability - Amkor reports that some second level underfills reduce the thermal cycling reliability. The company report early

thermal cycle failures of 300 cycles as compared to PoPs without underfill passing 1000 cycles.[4]

Drop Impact Performance - Because handheld devices are shrinking in size, there is an increase in the number of accidental drops. These drops crack the solder joints and lead to malfunction. For this reason, underfill with excellent drop impact resistance is required to extend the use life of mobile devices.[1]

Package Specifications and Geometry – Today's PoPs are 14 x 14 mm in size, and the solder ball pitch is 0.5 mm. The next generation of PoPs will be even larger and the pitch will be smaller. The result of this technology change will be higher package stress[4, 5], which may result in warpage and early failure during life testing.[2]

Reworkability – Assembly firms require underfill reworkability to improve yield and maintain profit levels. However, reworkability is more difficult to achieve when formulating underfills to meet 'high' reliability requirements.

Reversible Chemistry and Reworkability

This paper will describe a 'next generation' underfill ('NGen') technology that meets the requirements of high reliability *and* high reworkability for PoP technology.

Formulating a highly reworkable underfill adhesive for a high reliability application is a challenging proposition. Traditional Level 1 underfills offer high reliability by virtue of high modulus and high glass transition temperature. Level 1 type underfills are not considered reworkable, because they will damage the traces and pads during the rework process. Traditional board level underfills, or Level 2 underfills, are reworkable by virtue of their low modulus at elevated temperature. Unfortunately, Level 2 underfills generally have a high coefficient of thermal expansion that results in poor thermal cycling reliability performance.

Various approaches -- both physical and chemical -- towards high reliability underfills with reworkability have been published over the past ten years. A *physical* approach taken by C.P. Wong et al. included an additive enhanced epoxy underfill that resulted in micro-explosions upon exposure to the appropriate rework temperature. [6] These additives do not interfere with the chemical reaction; they vaporize and produce a large amount of gas during the rework process. At loadings up to approximately 5 wt %, authors note that the decomposition temperature of the underfill adhesive is about 50°C lower with these volatile additives as compared to cured epoxy without additives. Depending on the chemistry of the volatiles, this approach may be less desirable from a safety, health, and environmental perspective.

The *chemical* approach towards reworkability includes a thermoset adhesive with 'degradable' linkages in the backbone. The degradable or reversible linkages are denoted as squares in Figure 2. Upon exposing the thermoset polymer to the appropriate degradation temperature, the three dimensional network breaks, reduces the thermoset cross-link density, and thereby lowers the modulus at elevated temperature. This will promote reworkability.

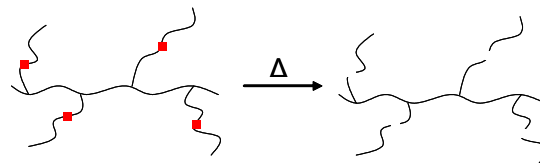


Figure 2: High temperature chemical degradation to promote reworkable adhesives

Early references to the idea of reversible chemistry for electronic applications were published by Tesoro and Sastri (1990), who developed epoxy resins containing disulfide linkages which decomposed upon treatment with triphenylphosphine. [7, 8]

Next, Ober et al. (1999) explored secondary and tertiary oxycarbonyl containing moieties as thermosets for repair, recovery, and recycling of electronic components. Within the body of the US Patent 5,948,922, a variety of structures are presented as possible 2° and 3° esters for degradation. [9]

Subsequent synthesis and formulation work was performed by C.P. Wong on carbonate containing cycloaliphatic epoxies. [10] Reworkable or degradation temperatures between 220 - 350°C were achieved. Wong presented empirical data demonstrating the network breakdown and T_g reduction following high temperature exposure. [6] In addition to the carbonate containing epoxy resins, C.P. Wong has also added to the field of reversible thermosets with research on the synthesis of epoxy functional resins containing secondary and tertiary esters possessing degradation temperatures less than 300°C. [11]

More recently, Hanley et al. submitted a patent application describing adhesive compositions containing thermally-labile groups for decreasing the degradation temperature of the adhesive for reworkability of electronic components in surface mounting applications. [12] The epoxy-based formulations contain a thermally labile group or reworkable link within the epoxy and/or curing agent. The preferred labile linkages on the resin side are ester, carbonate, and carbamate linkages; the preferred labile linkages on the curative contain N=N, N-N, and NCO₂ chemistry.

Lastly, Zhang et al describe acetal ester linkages incorporated into maleimide functional resins to provide degradable molecules at around 225°C.

Based on the published data, this approach may be the most compatible with the industry-wide rework process.[13]

While there are many approaches to reworkable thermosets, not all are suitable for an underfill application. The kinetics of the decomposition needs to align with the typical underfill process parameters for it to find utility in the underfill market (Figure 3). Some of these approaches are not ideal because the reversible or degradable link decomposes above the temperature range required to melt solder. Also, there are additional considerations when formulating adhesives for high-volume electronic applications. These chemistries need to be safe for the environment and must offer the traditional high reliability benefits associated with high adhesion epoxy chemistry. Chemistries containing these linkages should be hydrolytically stable to pass the accelerated damp heat testing required during underfill qualification. Additionally, the material needs to maintain a minimum of three days of work life at 25 – 33°C. These additional restrictions prohibit the use of some of the reversible chemistries described above.

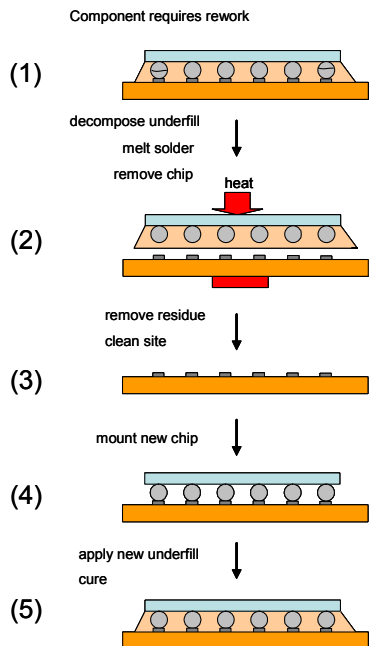


Figure 3: Schematic of Reworkability Process

Evaluation of the Degradation Mechanism

Analytical techniques used to confirm the degradation temperature and understand the kinetics of the decomposition mechanism

include a hot stage FTIR (Fourier Transform Infrared Spectroscopy), measurement of the change in the glass transition temperature, and/or an application specific assessment. These techniques will be discussed and available data will be presented based on the high reliability, highly reworkable next generation (NGen) underfill.

Hot-Stage FTIR

Zhang et al. describe the use of hot-stage FTIR (HS-IR) to monitor the disappearance of the pertinent degradable chemistry. The authors report the FTIR spectra plotted as a function of temperature ranging from 25 to 275°C. At ~250°C, the decoupling of cross-linked segments can be seen via the decrease in their respective absorbance.[13]

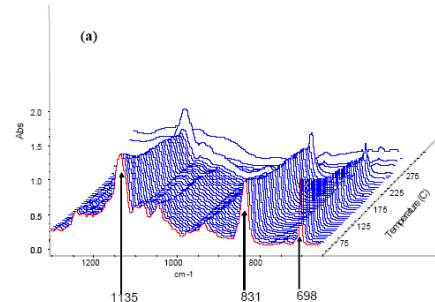


Figure 4: Hot Stage FTIR for Disappearance of Chemical Functionality

Zhang notes the change in intensity of the acetal C-O peak (~1135 cm⁻¹), indicating that the decomposition occurred at this linkage. The decomposition not only led to an intensity decline, but also to a frequency shift of the breaking bond in the IR spectra. The HS-IR data for the NGen underfill is not published based on its proprietary nature.

Glass Transition Measurement

Measuring the glass transition temperature of an adhesive formulation can be analyzed in one of many ways. Figure 5 illustrates the change in T_g as a function of exposure time at 240°C for a next generation (NGen) highly reworkable underfill as measured by DSC. During this experiment, the T_g was measured during a temperature ramp of 10°C/min.

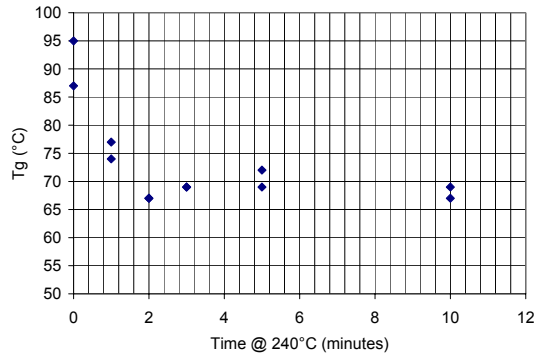


Figure 5: Degradation of T_g vs. time at 240°C

During a typical rework process, a component is removed from the PCB after exposure to 240°C for two minutes. Figure 5 illustrates a change in the glass transition temperature of approximately 20°C after two minutes of exposure at elevated temperature. The glass transition temperature does not appear to decrease further after additional exposure to the elevated temperature. This data suggests that the chemical decomposition kinetics of the NGen underfill is compatible with the standard rework profile.

Application-Specific Assessment

Application-specific testing is necessary to understand if the chemical degradation enables the desired reworkability performance. The reality of application-specific testing is that it can be difficult to distinguish marginal improvements from one material to the next. A significant performance benefit is desired to gain confidence that the novel, chemical approach is significant. Unfortunately, reworkability is a difficult property to assess as it is highly dependent on operator skills, method, substrate, and component. In the authors' application laboratory, reworkability of an adhesive is quantified by assessing the ease of removal for an underfill, residual underfill following removal, ultimate pad damage after cleaning, ultimate PCB damage after cleaning, solder mask damage after cleaning, and time to clean. Quantifying a material's reworkability is based on a weighted sum calculation; parameters such as ease of removal and pad / trace damage are the greatest factors in the calculation.

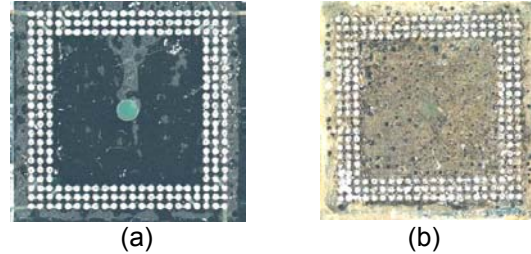


Figure 6: Reworkability Assessment of Underfill (a) with and (b) without Degradable Linkage

Figure 6 illustrates the difference the reversible or degradable linkage makes when attempting to rework the high reliability underfill adhesive. Two formulations were prepared that contained the same chemistry. The best effort was made to maintain the Mw, Mw distribution, hardener chemistry, and associated stoichiometry. The only difference between the two formulations associated with (a) and (b) is that one of the primary resins in formulation NGen -- or image (a) -- contained the reversible linkage. It is clear that the reversible linkage has some merit. Following the rework and cleaning process, a component can be placed on site (a); however, site (b) was unable to be reworked as a result of the board damage during the rework process.

Performance

After achieving reworkability, the underfill must be evaluated against the basic reliability tests for which it is considered. In this evaluation, the NGen underfill has been evaluated in thermal cycling and drop testing using 14 mm PoP components with 0.65 mm and 0.5 mm pitch on the top and bottom packages, respectively. The perimeter array configuration uses alloys SAC305. For the bend test evaluation, the NGen was tested in combination with a 12 mm, 0.5 mm pitch CTBGA-228 perimeter array with alloy SAC305.

Thermal Reliability Data

To assess the thermal reliability of 14 mm x 14 mm PoPs underfilled with the NGen reworkable thermoset adhesive, assemblies were exposed to thermal profiles of -40°C to 85°C with 15 minutes dwell times until failure (Figure 7). For this evaluation, the electrical resistance of these assemblies must not increase by more than 10% to receive a 'pass' assessment.

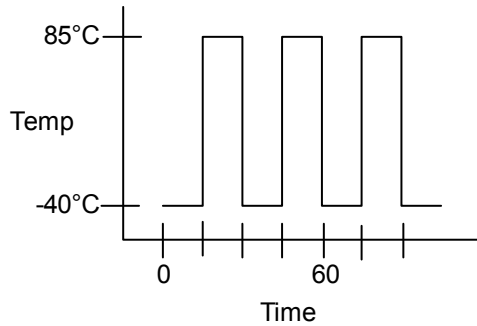


Figure 7: Thermal Reliability Profile

Components without underfill have survived through 1400 cycles without any failures. One out of sixteen components underfilled with the reworkable thermoset NGen failed at 1300 cycles. However, the other fifteen components passed the electrical requirement through 1400 cycles. This exceeds the typical standard of 1000 cycles without electrical failure.

Two physical property requirements that are critical to passing the thermal reliability test are T_g and modulus. Previous data published by Amkor suggests that underfills with a high modulus and high glass transition temperature are more likely to pass the test.[1] This conclusion is intuitive when one considers the mechanical changes in the assembly during the temperature cycling test. When a material's T_g is above the upper limit of the thermal cycle parameters, the adhesive's coefficient of thermal expansion remains low throughout the testing. This is illustrated in the DMA/TMA overlay in Figure 7. The glass modulus remains between 2–4 GPa from -40 – 80°C, because the T_g is around 80°C. Below 80°C, the CTE of the NGen underfill remains low 56 ppm/°C; above the T_g rises to 192 ppm/°C. Although Amkor presented insight into the thermal reliability – physical property correlation, the paper did not discuss the reworkability aspect of high reliability underfills.

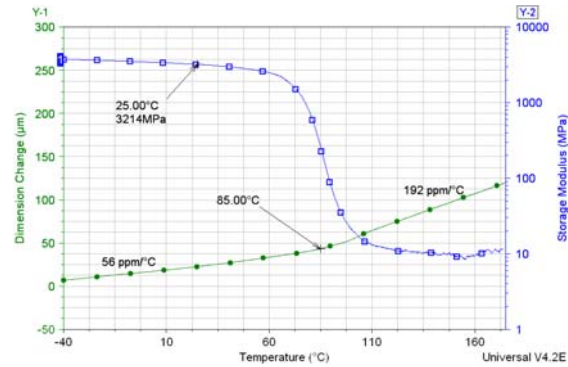


Figure 7: DMA/TMA Overlay of Underfill NGen

Based on the thermomechanical response, it is highly probable that the adhesive will survive the thermal cycle reliability testing.

Drop Impact Performance

14 x 14 mm PoP components underfilled with the novel reworkable chemistry, NGen, were exposed to 1500 g pulse acceleration and 1.0 ms pulse duration as described in Figure 8, which shows results from an automated drop tower analysis.

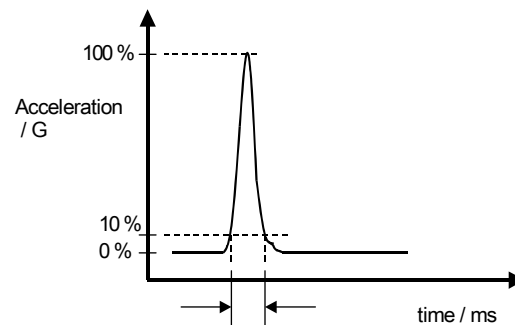


Figure 8: Drop Impact Profile

Boards were placed in the drop tower such that the components faced downward. Failed components exhibited an electrical resistance increase of > 10% relative to the initial resistance during the pulse or static measurement following the drop. This technique will capture failure in the solder ball during the highest strain point and failure in the ball at its zero strain point. Results of the drop performance are illustrated in Figure 9.

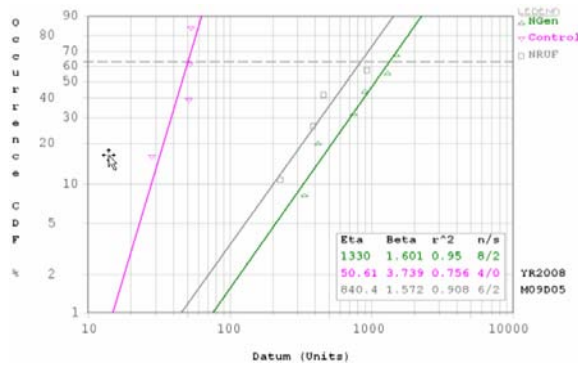


Figure 9: Weibull Plot for Drop Testing

As is evident from the data, the novel reworkable chemistry provides a significant improvement in drop impact performance. Based on the N63 value, the underfill increases the drop impact performance by nearly a factor of 20 as compared to a non-underfilled PoP. Also, the NGen underfill provides equivalent or better drop performance as compared to a high T_g , *non-reworkable*, high reliability underfill ('NRUF'). The drop performance is expected based on the high modulus and die shear adhesion. Die shear adhesion testing resulted in a very good failure mode (board damage) and a high ultimate adhesion value (90 Kg/ 10.9 mm²) with FR4 board damage (substrate tear).

Bend Resistance

Bending resistance is relevant to portable or handheld electronics as it estimates the short, frequent compressions associated with typing. The test method used to assess continuous bend resistance includes a 5 mm deflection at 10 mm/s for 12 mm CTBGA-228 with 0.5 mm pitch and SAC solder bumps. Per JEDEC specifications, the bend test failure criteria include a resistance of 1000 ohms or 5x the initial resistance. The initial resistance of the test boards is approximately 1 Ω ; 1000 Ω and is used as the failure criterion.

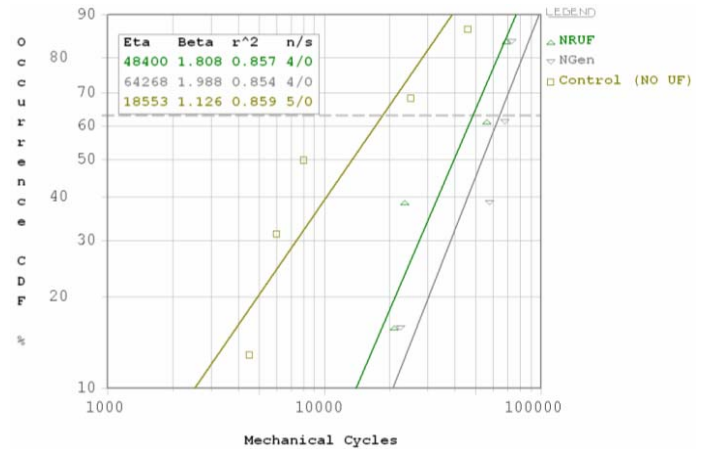


Figure 10: Weibull Distribution for Bend Testing

The NGen highly reworkable adhesive improves the bend resistance of the assembly by 3.5 times the assembly without underfill (Figure 10). Also plotted in Figure 10 is the bend resistance for the high reliability, non-reworkable underfill ('NRUF'). The bend resistance of the reworkable NGen is at least as good as the high reliability, non-reworkable E-1216 based on the preliminary data.

Moisture Resistance

Creating a thermally reversible or degradable link in a thermoset system requires that it decomposes at the correct time, and that it doesn't introduce other unwanted properties into the thermoset. Although some of the reversible chemistry decomposes or reverses in the correct temperature range, it is also known to be hydrolytically unstable. Moderate heat and moisture will cause the degradable link to cleave and this may result in early device failure. Moisture uptake testing is one way to demonstrate the stability of the material upon exposure to moisture. At various time intervals, bulk property measurements such as permittivity or weight change can be used to assess a material's resistance to moisture.[14]

The NGen underfill gains 4-5 wt/wt% at 85°C / 85% RH for 6 weeks (Figure 11). This is a reasonable expectation, as the soak temperature is at the material's T_g . When the temperature exceeds or is in close proximity to the T_g of the adhesive, there is more free volume for moisture to ingress into the adhesive. Most importantly, the weight uptake does stabilize. Some chemistry containing a high percentage of reworkable linkages will lose weight rapidly

after the initial moisture uptake. Continual weight loss is a sign of hydrolytic instability. The NGen material appears to be sufficiently stable in this aggressive test condition.

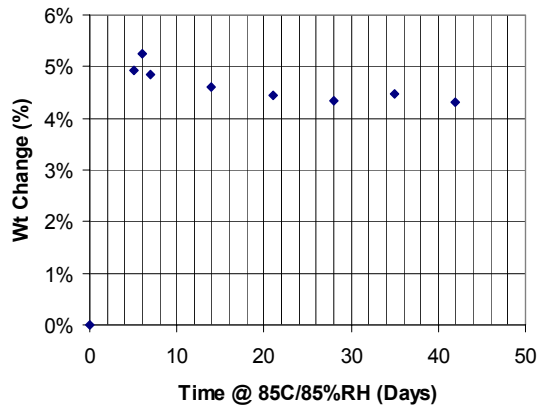


Figure 11: Moisture Resistance of Underfill NGen

Conclusions

The NGen adhesive is capable of offering a high reliability, highly reworkable underfill for assemblies that incorporate 14 x 14 mm Package-on-Package devices. The concept of highly cross-linked structures that are reversible opens a pathway to highly filled systems, which to date has not been possible with reworkable underfill. Additional work is necessary to understand the suitability for the next generation PoP geometry.

Works Cited

1. Lee, J.-Y.H., Tae-Kyung; Kim, Jin-Young; Yoo, Min; Sohn, Eun-Sook, Chung, Ji-Young; Dreiza, Moody. *Study on the Board Level Reliability Test of Package on Package (PoP) with 2nd Level Underfill*. in *Electronic Components and Technology Conference*. 2007.
2. Lin, W.L., Min Woo. *PoP/CSP Warpage Evaluation and Viscoelastic Modeling*. in *Electronic Components and Technology Conference*. 2008.
3. Sjoberg, J.C., Todd; Geiger, David; Shanguan, Donkkai. *Process Development and Reliability Evaluation for Inline Package on Package (PoP) Assembly*. in *Electronics Components and Technology*. 2008.
4. Lee, S.W.K., Hyon Chol; Lee, Chi Young; Kwon, Heung Kyu; Cho, Tae Je, Kange, Sa Yoon. *Board Level Drop Reliability of Package-on-Package*. in *International Microelectronics and Packaging Society*. 2007. San Jose.
5. Carson, F.L., Seong Min. *Controlling Top Package Warpage for PoP Applications*. in *Electronic Components and Technology Conference*. 2007.
6. Wang, L.W., C.P., *Study of Additive-Epoxy Interaction of Thermally Reworkable Underfills*. *Journal of Applied Polymer Science*, 2001. **81**: p. 1868-1880.
7. Sastri, V.J.T., G. C., *J Appl Polym*, 1990. **39**: p. 1439.
8. Tesero, G.C.S., V., *J Appl Polym*, 1990. **39**.
9. Ober, C.K., Hilmar, *Compounds with substituted cyclic hydrocarbon moieties linked by secondary or tertiary oxycarbonyl containing moiety providing reworkable cured thermosets*. 1999, Cornell Research Foundation, Inc.: USA.
10. Wang, L.W., C.P., *Syntheses and Characterizations of Thermally Reworkable Epoxy Resins II*. *Journal of Polymer Science Part A: Polymer Chemistry*, 2000. **38**: p. 3771-3782.
11. Li, H.W., Lejun; Jacob, Karl; Wong, C.P., *Syntheses and Characterizations of Thermally Degradable Epoxy Resins. III*. *Journal of Applied Polymer Science Part A: Polymer Chemistry*, 2002. **40**: p. 1796-1807.
12. Hanley, M.K., Joseph, *Reworkable Adhesives Containing Thermally Labile Groups*, in *USPTO*. 2006, International Business Machines Corporation: USA.
13. Zhang, X.C., Gang-Chi; Collins, Andrew; Jacobson, Solomon; Morganelli, Paul; Dar, Yadunandan; Musa, Osama, *Thermally Degradable Maleimides for Reworkable Adhesives*. *Journal of Polymer Science Part A: Polymer Chemistry*, 2008.
14. Collins, A.C., Ian. *Effect of Moisture on Dielectric Properties of CSP Board Level Underfill*. in *International Microelectronics and Packaging Society*. 2007. San Jose.