# Wafer-Level Film Selection for Stacked-Die Chip Scale Packages

Daniel Shi, Xuejun Fan
Intel Corporation
Flash Manufacturing Group, Intel Technology Development (Shanghai) Ltd., Shanghai 200131, P. R. China
Tel: 86-3873-3114; Email: daniel.shi@intel.com

## Abstract

Wafer-level dicing tape format die-attach (DA) film and the corresponding lamination method provide a suitable solution for handling thin-wafers. However, such die-attach films typically have a Young's modulus less than 10MPa at soldering reflow temperature (e.g. 260°C). This introduces a new failure mode, i.e., cohesive failure in the DA film. Through extensive experimental DOE studies described in this paper, it has been observed that some CSP packages with such film are very sensitive to substrate thickness and reflow profiles. In this work, a fundamental understanding of failure mechanisms was obtained through comprehensive finite element simulation and material characterization. It was noted that there might be a risk of cohesive failure with low-modulus die-attach film during reflow. Further, several types of die-attach films were evaluated based on full stack and discrete packages. Experimental results showed that not all die-attach films with very low modulus are sensitive to reflow profiles with cohesive failures. A general methodology for selecting die-attach film for ultra-thin stacked-die packages was developed based on the advanced measurement techniques and finite element simulation. If the film is not sensitive to reflow profile, even though the die-attach film has very low modulus, the film modulus, moisture diffusivity, and saturated moisture concentration will not be critical the parameters for screening the DA films. In this case, interfacial adhesion and the film voids become the key modulators. Since the stress state in the film is hydrostatic in a confined constraint condition, the effective hydrostatic stress in the film is not as high as vapor pressure, the low-modulus die-attach film can be used without cohesive failure. On the other hand, when cohesive failures are present, the integrated modeling approach with material characterization can be applied to design a package without failure.

## 1. Introduction

The development of three-dimensional (3D) electronic packaging with multi-die stacking technology has become essential to increasing functionality with higher memory capacity in more complex and efficient architectures in smaller form factor packages. Wafer thinning is typically required to accommodate multiple dies to meet form factor requirements. Consequently, the traditionally-used die-attach paste materials and the assembly method are not capable to handle such thin chips due to various issues such as paste material bleed-out and die cracking. Instead, wafer-level dicing tape format DA film and the corresponding lamination method provide a suitable solution. However, a key challenge for developing ultra-thin stacked-die chip scale packages (CSP) is to meet the package performance requirements without delamination/cracking in the package during moisture sensitivity test. The higher reflow temperature required for lead-free packaging results in increased reliability concerns for these plastic packages.

Cohesive delamination and cracking has been observed in the first layer die-attach film (film 1), as seen in Figure 1 [1]. Failures were detected by TSAM after moisture sensitivity Level 3 pre-conditioning stressing. The pre-conditioning stress test involves soaking at a constant temperature/humidity condition, followed by a reflow process. The failure rate depended on the reflow profiles even with the same peak temperature. Figure 2 illustrates different reflow profiles, both satisfying JEDEC standard. The delamination rate was dramatically less in the TYPE II case than the TYPE I case.

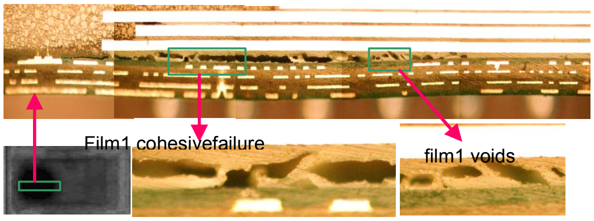


**Figure 1** After L3 preconditioning, massive cohesive delamination was seen in the first layer die attach film (film 1). The cohesive delamination is a consequence of void growth and coalescence induced by vapor pressure during the reflow process.

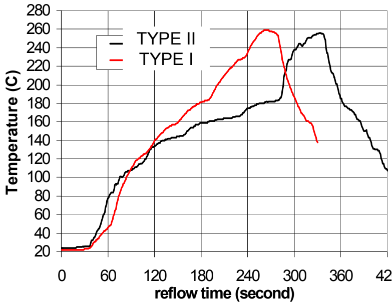


**Figure 2** Two reflow profiles both meet the JEDEC standard. The main difference is that TYPE II ramps much slower up to the temperature peak than the TYPE I.

In this study, we demonstrated that moisture escape and transport behavior during reflow was determined to be the root cause for this type of failure. A fundamental understanding of the failure mechanisms was obtained through comprehensive finite element simulation and material characterization. The root cause finite element model established the relationship between moisture uptake, material properties such as diffusivity and porosity, and vapor pressure buildup. Further, several types of die-attach films were evaluated based on full stacked and discrete die packages. It has been found that not all die-attach films with very low modulus are sensitive to the reflow profiles and substrate designs. A general methodology for selecting die attach films for UT/SCSP applications was developed based on the advanced measurement techniques and finite element simulation.

## 2. Effect of Substrate Thickness and Reflow Profiles

### 2.1 Experimental Results

A controlled experiment with varying substrate material components was evaluated to determine the effect of thickness on moisture related reliability performance. Die-attach film labeled 'DA1' has been applied throughout this experiment. The substrate contains solder mask (SM)/BT core/copper layer (Figure 3). The following parameters were varied (1) BT core thickness to study the thickness effect of the diffusion path on delamination; (2) SM thickness to check its high solubility effect which makes it as a moisture reservoir. After preconditioning stress, the delamination rate was monitored by TSAM.

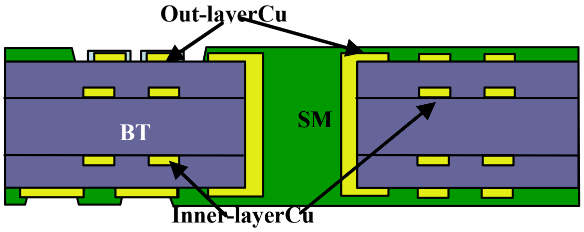


**Figure 3** Schematic of substrate

Table 1 summarized JEDEC moisture sensitivity Level (MSL) 3 test results with TYPE I reflow profile shown in Figure 2. Results clearly showed that the thicker the BT-core, the higher the delamination rate. All failures occurred at the first die-attach film layer with cohesive voiding/cracking. In each experimental leg the sample size was 240. Please note that only the relative thickness values were shown in Table 1, in which x represents solder mask reference thickness, y the BT-core reference thickness and z the total reference thickness, respectively.

**Table 1.** Delamination rate for different substrate designs

| Thickness | Leg 1 | Leg 2 | Leg 3 | Leg 4 | Leg 5 |
|---|---|---|---|---|---|
| Solder Mask | 1x | 1.02x | 1.04x | 1.04x | 1.4x |
| Inner Cu density | 0% | 50% | 50% | 50% | 50% |
| BT-Core | 1y | 1.1y | 1.4y | 1.5y | 1.5y |
| Total | 1z | 1.20z | 1.47z | 1.47z | 1.53z |
| Delam Rate | 0% | 7% | 32% | 47% | 100% |

We further investigated the sensitivity on reflow profiles. As shown in Figure 2, TYPE II profile ramps to the peak temperature much slower than the TYPE I profile does, although both profiles satisfy the JEDEC standards. The relatively slower ramp period from time 0s to 270s prior to the peak temperature resulted in a significantly lower failure rate. The delamination rate was ~7% for TYPE II profile and ~80% for TYPE I profile.

### 2.2 Package Material Characterization

In order to understand the failure mechanism, the effect of moisture on material properties and moisture transport in package materials were evaluated. Figure 4 plotted the Young's modulus of the die attach film as a function of temperature with and without the presence of moisture. It can be seen that the $T_g$ decreased significantly after moisture absorption. The film DA1 has a very low modulus at reflow temperature. The modulus is less than 5MPa and is in the order of the saturated vapor pressure (4.7MPa at 260°C, to be discussed in next section). Figure 5 shows the moisture weight gain curve for a 30µm DA1 at 30°C/70RH%. An in-situ moisture absorption method was used to accurately obtain the moisture diffusivity and solubility (see [2] for measurement details). It showed that the film reached moisture saturation within 5 minutes even at room temperature. The same measurement method was applied to study the moisture properties of the thin BT-core material with 70 µm thickness at different temperature/humidity conditions [2]. The extrapolated diffusivity at the reflow temperature (e.g. 260°C) is an order higher than the data in the literature (e.g. [3]). This is an important finding because it implies that moisture desorption through BT substrate plays a more significant role than indicated in the literature, specially for ultra-thin substrate.

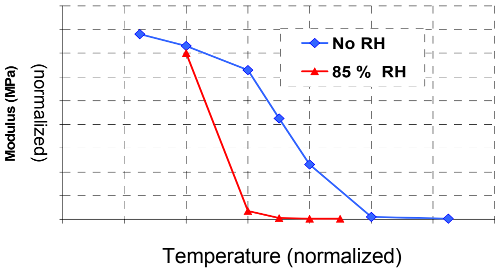


**Figure 4.** Modulus as function of temperature for DA1 film

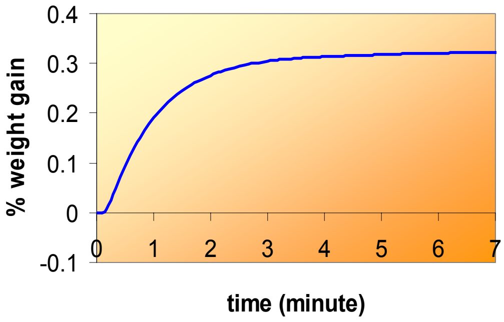


**Figure 5.** Moisture uptake vs. time at 30°C/70RH% for a 30 µm DA1 film.

Figure 6 plots the saturated moisture concentration at 60RH% and 30RH% with various temperatures for the 70 µm BT-core material. It confirms that the saturated moisture concentration for BT material is independent of temperature up to 80°C.

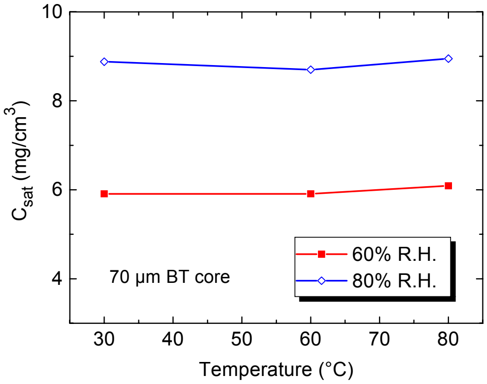


**Figure 6.** Saturated moisture concentration as function of temperature

### 2.3 Finite Element Analysis

In this section, the moisture diffusion and vapor pressure modeling are performed to explain the drastic delamination performance for different types of substrate and different reflow profiles.

Figure 7 shows the moisture distribution after preconditioning for two different substrates (leg 2 and leg 5 in Table 1) [5]. The results showed that the substrate and the first layer of die attach film are fully saturated with moisture for both cases. This means that the initial moisture concentration in die attach film 1 (area enclosed by dashed line, thickness being exaggerated for visual clarity) is same for both substrates right after soaking. From the moisture contour plot, it can also be observed that moisture diffuses very slowly in the molding compound (MC). Therefore, inside film 1 moisture is mainly from the diffusion through the substrate, and the moisture in other layers of die attach films comes from diffusion through the molding compound.

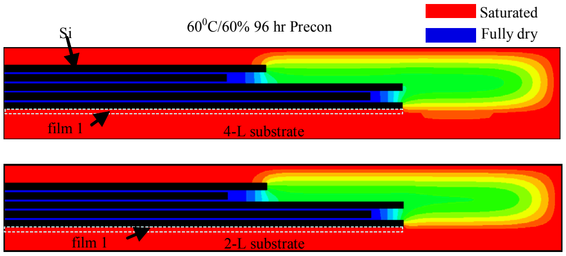


**Figure 7.** After MSL 3 moisture absorption, the moisture in the film 1 is saturated in both substrates. Other layers of DA films are dry due to the moisture blocking effect of Si, provided that the other film layers are initially dry.

During reflow, the moisture vaporizes to generate high vapor pressure, which may lead to cohesive delamination. At the same time, moisture escapes out of the package by diffusion. Two scenarios of vapor pressure build up are illustrated in Figures 8 and 9, respectively [1, 6-7]. In the scenario 1 shown in Figure 8, the moisture in the micro-pores is always in liquid phase, thus the saturated vapor pressure remains and increases exponentially with temperature. Since the film modulus is very low, the cohesive failure will occur when vapor pressure exceeds the material strength. On the other hand, in the scenario 2 shown in Figure 9, since the moisture diffuses out of package during reflow, the amount of moisture in the pores will decrease with temperature during reflow. After certain period of time the residual moisture in die-attach film might not be sufficient to remain in liquid phase. In this case, the vapor pressure will not increase as much as that indicated in scenario 1, and it may decrease [e.g. ref 4]. Therefore, the cohesive delamination failure will not happen.

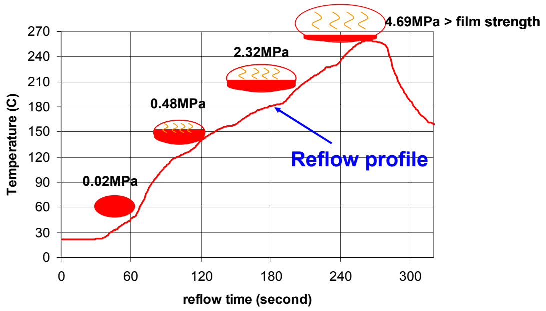


**Figure 8.** Scenario 1: vapor pressure buildup during reflow

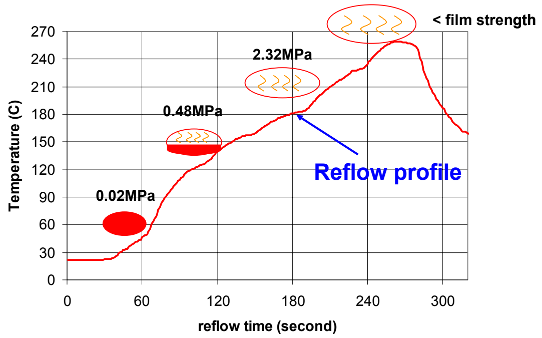


**Figure 9.** Scenario 2: vapor pressure buildup during reflow

The delamination performance difference lies in the moisture loss during the reflow process [8]. For thicker substrate, it takes longer time for the same amount of moisture to escape and to reduce the vapor pressure to a safe level, thus resulting in a higher delamination rate. For certain reflow profile such as TYPE II in shown Figure 2, more moisture is released before the temperature reaches a critical level, thus failure rate can be reduced significantly. The moisture diffusion analysis also explains there is no cohesive delamination in other layers of film. Other layers of die attach films are sandwiched by dies, so the moisture absorbed during soaking is far below the saturation level. If the initial moisture level is low, there should be of no cohesive delamination.

The contours of moisture distribution at 250$^o$C with two different thickness substrates (leg 2 and leg 5 in Table 1) are shown in Figure 10. The moisture content inside film 1 with thinner substrate was much less than that with the thicker substrate. The contours of vapor pressure at 260$^o$C are shown in Figure 11. For the package with the thinner substrate, the vapor pressure in DA film 1 is 50% less compared to that with the thicker substrate. The results correlated very well with the experimental results shown in Table 1.

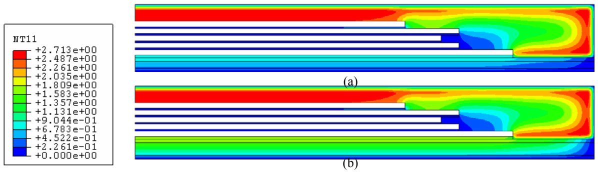


**Figure 10.** Moisture distribution after reflow for two different substrate thicknesses (a: thinner substrate, b: thicker substrate)

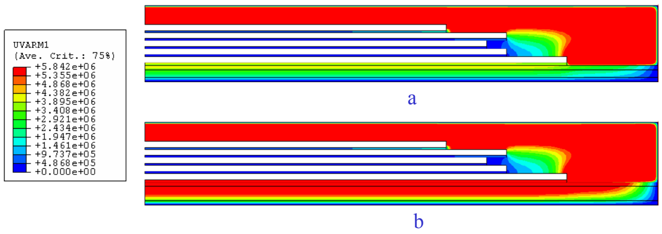


**Figure 11.** Vapor pressure distribution at the reflow temperature of 260°C for the two different substrates (a: thinner substrate, b: thicker substrate).

It is clear that die-attach film with low modulus poses a new risk for cohesive failures. However, it is not known at this point if the modulus is the key parameter for the reliability performance. This is because cohesive failure not only depends on modulus, but also on material microstructure, such as porosity [6-7]. In the following, further experiments were conducted with several different die attach films to understand the failure mechanism.

## 3. Die-Attach Film Selection

### 3.1 Experimental Details and Results

In order to investigate whether the materials with high Tg and/or high Young's modulus are necessary for preventing cohesive failures, four different die attach films (DA1, DA2, DA3 and DA4) were selected to build both stack and discrete assemblies, with the same substrate (thicker option). DA1 is the die-attach film we discussed in previous section and is used here as the control leg. The details of the design of experiment (DOE) are shown in Table 2.

With the built units, the stress tests were performed by following flow: assembly → time zero failure analysis (FA) → time zero TSAM analysis → bake → temperature cycling (5 cycles) → moisture soaking (MSL 3) → reflow at 260°C→ TSAM analysis → FA. The results are summarized in Table 2. As expected, the DA1 film had a high cohesive failure rate. Figure 12 showed the cross-section picture at film 1 region and the top-town lapping image, both confirmed the cohesive rupture and formation of voids after reflow.

For the DA2 film, no failure was observed for the discrete leg, but there were few failed units captured by TSAM for stacked packages. Failure analysis found there were the cohesive failures at the film 2 /die 1 interface but not in the film 1, as shown in Figure 13. Further analysis confirmed that the failure captured at the film 2/die 1 interface were caused by the film 2 contamination. This implies that DA2 is an acceptable candidate with no cohesive failure.

The DA3 film showed a very high failure rate. By the top-down lapping, large voids were observed at the center of film 1 for both discrete and stack packages. The cross-section images on the packages further captured that the failure mode was interface delamination at film 1/solder mask interface, as shown in Figure 14. The investigation confirmed that large voids were generated by the high pressure of the pick-up tool on the film 1 during the die attach process. The new builds after modifying the process parameters demonstrated 100% clean results, indicating that the DA3 film can be used as for both discrete and stack packages without failure.

The DA4 film exhibited the best performance. There were not any voids and delamination captured by the top-down lapping on a few units and the cross-sections on those speculative units identified by TSAM, as shown in Figure 15.

### 3.2 Material Characterization and Discussions

From the above experiments, it was found that only the DA1 film had cohesive failure when combined with the TYPE I reflow profile and a thicker substrate. The rest three films were not sensitive to the reflow profile or the substrate thickness. In order to understand the correlation between package performance and materials properties, the Young's modulus at high temperature and Tg were measured. Two kinds of experimental techniques, i.e., digital image correlation (DIC) and dynamic mechanical analyzer (DMA), were employed to measure the Young's moduli of the four films at different temperatures. The details of measurement techniques and methodology are given in Ref. 9, only the results of Young's moduli are presented in this paper. As seen in Table 3, DA1, DA2, and DA4 are all low-Tg die attach films with very low Young's modulus (less than 5MPa) at temperatures above 150°C. Although DA2 and DA4 have lower modulus at 150°C than DA1, both films did not exhibit cohesive failure. This suggests that materials with low-Tg and/or low modulus do not necessarily lead to cohesive failure during reflow. Since it is very difficult to obtain the accurate Young's modulus for thin film at elevated temperature, in particular, with humidity control, the values in Table 3 can be used for reference only. It should be noted that the die-attach film is usually confined between the die and the substrate, therefore, the effective hydrostatic stress might be much lower than the vapor pressure [9]. Therefore, the cohesive failure may not occur even when the Young's modulus is in same order of magnitude as that of the vapor pressure. Further more, the void rupture depends also on the void size. Therefore material behavior might be very different if their moduli are all very low at high temperature. We have measured the porosity of those four different films at room temperature, but no significant differences were observed.

**Table 2.** Summary of the DOE and TSAM results*

| Leg | Substrate | Stack | DA Film | Quantity | TSAM Results (delamed units/total units) | |
|---|---|---|---|---|---|---|
| | | | | | Pre-stress | Post-stress |
| 1 | Thick | 2+1 | DA1 | 48 | 0/48 | 45/46 |
| 2 | Thick | 2+1 | DA2 | 48 | 3/48 | 3/44 |
| 3 | Thick | 2+1 | DA3 | 48 | 3/48 | 29/44 |
| 4 | Thick | 2+1 | DA4 | 48 | 0/48 | 0/46 |
| 5 | Thick | Discrete | DA1 | 45 | 0/45 | 30/43 |
| 6 | Thick | Discrete | DA2 | 44 | 0/44 | 0/42 |
| 7 | Thick | Discrete | DA3 | 45 | 0/45 | 41/43 |
| 8 | Thick | Discrete | DA4 | 45 | 0/45 | 0/42 |

*The substrate used in the DOE is same as the Leg 2 given in Table 1. The unit difference in the total quantity before and after stress is used for failure analysis.

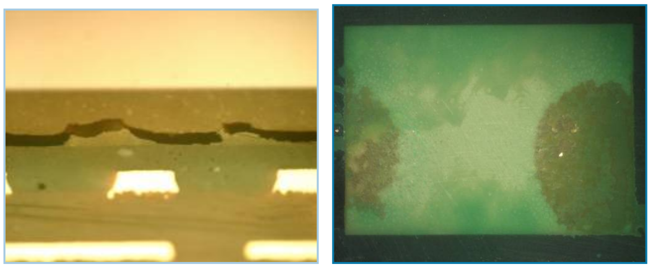

(a) (b)

**Figure 12.** Typical failure analysis results obtained from the non-clean units after the stress: (a) the cross-section picture shows cohesive rupture in the film 1; (b) the top-down lapping picture shows that large voids in the film 1.

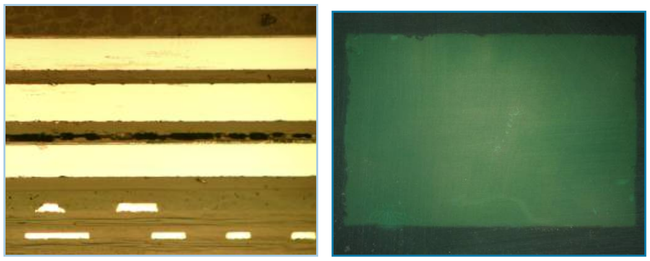

(a) (b)

**Figure 13.** Typical FA results obtained from the non-clean units after the stress: (a) the cross-section shows that the delamination occurred in the film 2/die 1 interface but not the film 1 in the stacked packages; (b) the top-down lapping shows that there was no delamination observed in the film 1 of the discrete packages.

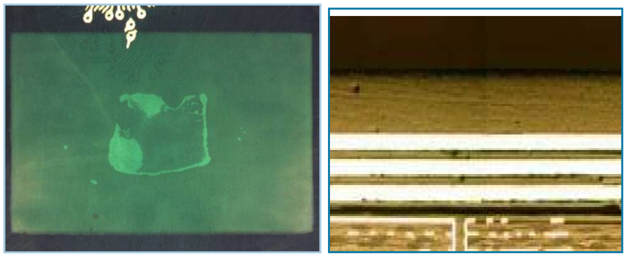
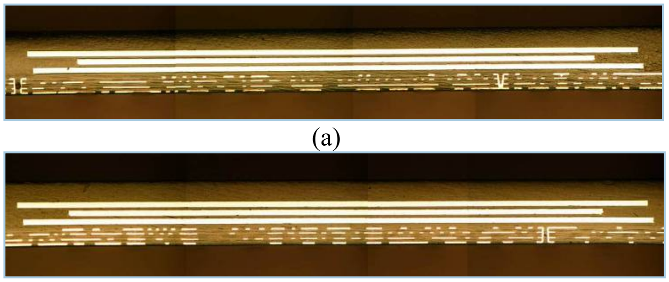

(a) (b)

**Figure 14.** Typical failure analysis results obtained from the non-clean [failed] units after the stress: (a) the top-down lapping shows that there were big voids captured at the center of the film 1; (b) the cross-section confirms that the failure mode is interface delamination between film 1 and substrate.


(a)

(b)

**Figure 15.** The cross-section pictures obtained from (a) an edge profile and (b) a central profile of one clean unit after the stress.

DA3 film has high Tg and high modulus. However, interface delamination was observed. As discussed in ref. [10], the adhesion of the die attach film at high temperature is always a critical parameter for screening die-attach materials. Although the film has very high Tg and/or high Young's modulus, if its adhesion is not good, the failure will occur as well.

The in-situ moisture absorption technique was used to measure the diffusivity and solubility of materials [2]. Table 4 lists the saturated moisture concentration for DA1 and DA4 at 60°C/60RH%. Though DA4 absorbs moisture as twice as DA1, and Young's modulus is in the same order of the vapor pressure, DA4 did not present any interface delamination and cohesive failure. This means that the saturated moisture concentration is not a critical parameter in selecting die attach film if no cohesive failure is observed.

**Table 3** Summary of Young's moduli of the four films**

| Material | Tg (°C) | Young's Modulus (MPa) |
|---|---|---|
| | | **150°C** |
| DA1 | Low | 1X |
| DA2 | Low | 2X |
| DA3 | High | Very high |
| DA4 | Low | 1.5X |

** Values of Young's modulus at 200°C, 160°C and 150°C are characterized by digital image correlation (DIC), dynamic mechanical analyzer (DMA) and Intel's material suppliers, respectively.

**Table 4.** Saturated moisture concentrations for DA1 and DA4

| Material | Saturated Moisture Concentration |
|---|---|
| | **60°C/60RH%** |
| DA1 | 1x |
| DA4 | 2x |

## 4. Conclusions

Cohesive failure of die-attach film during moisture sensitivity test for stacked chip scale packages becomes a particular concern due to its extremely low modulus at soldering reflow temperature. The root cause of this type of failure is difficult to discern, even with extensive root cause analysis and focused design of experiments. It has been observed that for some die-attach films, such packages are very sensitive to soldering reflow and substrate thickness, with massive cohesive failure within the die attach film. Moisture escape and transport during reflow has been determined to be a significant factor for this type of failure. Further experiments based on a broad spectrum of die-attach films revealed that not all die-attach films with very low modulus are sensitive to the reflow profiles and substrate designs. If the film is not sensitive to reflow profile, even though the die-attach film has a very low modulus, the film modulus, diffusivity and saturated moisture concentration will not be critical parameters in screening die-attach films. In this case, the process control in optimizing the interfacial adhesion and minimize the voids becomes the key modulators. Since the die-attach film is usually confined between die and substrate, therefore, the effective hydrostatic stress might be much lower than the vapor pressure. On the other hand, when cohesive failures are present, the integrated modeling approach with material characterization can be applied to provide design guidelines for key parameters including manufacturing parameters (reflow profile control), package design parameters (layout and thickness) and the material parameters (diffusivity, solubility, modulus, and porosity).

## Acknowledgments

We are grateful to the MIFFT team (moisture-indcued failure focus team), in particular, Ibrahim Bekar, Edward Prack, Yi He, Anthony Fischer, Steve Cho, Bin Xie, Yiming Gong, Jeff Wang, and Zhengyu Huang for support and discussions.

## References

1. Edward Prack and Xuejun Fan, Root cause mechanisms for delamination/cracking in stack-die chip scale packages, *International Symposium on Semiconductor Manufacturing (ISSM),* 2006, September 25 - 27, Tokyo, Japan
2. Yi He and Xuejun Fan, In-situ characterization of moisture absorption, desorption, and diffusion in a thin BT core substrate, *IEEE Electronic Components and Technology Conference (ECTC),* 2007
3. J. E. Galloway and B. M. Miles, Moisture absorption and desorption predictions for plastic ball grid array packages, *IEEE Trans. Comp. Packag. Manuf. Technol.*, vol. 20, pp. 274-279, 1997.
4. Bin Xie, Daniel Shi, and Xuejun Fan, Sensitivity investigation of reflow profile and substrate thickness on wafer level film failures in 3-D chip scale packages by finite element modeling, Intel report, 2007
5. Zhenyu Huang, John Tang, Changmin Hu, Michael Wang, Mu Zhang, Bin Liu, Xuejun Fan, and Edward Prack, Moisture Induced Cohesive Delamination in Die-Attach Film in Ultra-Thin Stacked Chip-Scale Package, *Intel Assembly Test and Technology Journal*, 2006
6. G. Q. Zhang, W. D. van Driel, and X. J. Fan , Mechanics of Microelectronics, Springer, May 2006
7. X.J. Fan, J. Zhou, G.Q. Zhang, & L.J. Ernst, A Micromechanics based vapor pressure model in electronic packages, *ASME Journal of Electronic Packaging*, 2005, 127 (3), 262-267
8. Xuejun Fan, Ibrahim Bekar, Fischer, Anthony A, Yi He, Zhengyu Huang, Edward Prack, Delamination/cracking mechanism study for ultra-thin stacked-die chip scale packages, *Intel Conference on Manufacturing Excellence (IMEC)*, 2006, San Diego, CA
9. Daniel Shi, Xuejun Fan, Ibrahim Bekar, Xuejun Fan, Intel Report on Failure Analysis of Die-Attach Film Selection, 2006
10. Xuejun Fan, G.Q. Zhang, and L.J. Ernst, Interfacial delamination mechanisms during reflow with moisture preconditioning, *IEEE Transaction of Component, Manufacturing and Packaging Technology (accepted)*