Predicting reliability behavior in HBM packages through numerical simulation

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***Abstract*— A typical HBM (High Bandwidth Memory) package consists of multiple memory dies in a stack formation. A passivation material may be inserted between the dies by laminating each with a NCF (Non Conductive Film) prior to stacking. This enables a thin joint gap, and therefore a higher number of stacked dies in keeping with increasing density demands. Of particular interest in the present study is the interface between an Si die and adjacent NCF in a 2.5D SiP arrangement. These interfaces may carry the risk of acting as sites where cracks could form if exposed to a severe load or high stress. It is necessary to quantify their robustness and ensure their reliability during processing and end-user applications. We employ FEM(Finite Element Method) simulation to investigate the degree of stress created by a thermal load in HBM packages. Simulation is also employed to model the path by which moisture is absorbed into the NCF-Si interface. We then combine these considerations into an Interface Reliability Index which quantifies and predicts the reliability at any given site along the NCF-Si interface. The same parameters are also incorporated into a TC (Thermal Cycle) Index, which predicts the fail cycle under TC load at the same interface. Both Indices demonstrate a high degree of correlation with experimental results. This makes them a highly useful tool to quantify and predict the reliability behavior of HBMs in various arrangements and conditions. As such, it becomes possible to optimize the geometry and materials of each component for maximum resilience, and to ensure that even the most severe reliability demands and requirements are met or exceeded.**

Keywords*— *HBM, NCF, Reliability, Moisture Absorption, Thermal Stress, FEM

I. Introduction

A typical HBM (High Bandwidth Memory) package consists of multiple memory dies in a stack formation. A passivation material may be inserted between the dies by molding a polymer after the die stack is complete, or by laminating each die with a NCF (Non Conductive Film) prior to stacking, as shown in Fig. 1. Between the two methods, NCF application enables a thinner joint gap, and therefore a higher number of stacked dies in keeping with increasing density demands.

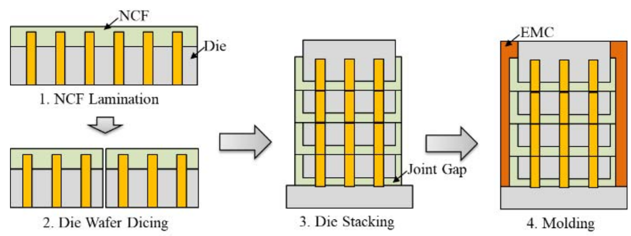

Fig. 1. HBM stacking process with NCF lamination

However, the use of an NCF material creates additional interfaces: with the Si dies, with the EMC, and between each NCF layer. As these interfaces are not fully cohesive and are formed between materials with differing material properties, they may carry the risk of acting as sites where cracks may form under stress imposed by a thermal or mechanical load. It is therefore necessary to quantify the robustness of the NCF interfaces and ensure their reliability during processing and end-user applications, especially given demands for higher die stacks and more HBMs arranged in SiP arrangements.

Of particular concern in the present study is the interface between an Si die and adjacent NCF in a 2.5D SiP arrangement; that is, one or more ASIC devices surrounded by multiple HBMs on a substrate. The production process will inevitably impose thermal stress on each component. Moreover, the potential introduction of moisture into the package due to the nature of its storage and production could become a complicating factor, which in turn might degrade the adhesive strength at the interface.

In the present study, we employ FEM(Finite Element Method) simulation to investigate the degree of stress created by a thermal load in HBM packages: individually, arranged in arrays, and in the final 2.5D SiP product. Simulation is also employed to model the path by which moisture could be absorbed into the NCF-Si interface, and the impact of the surrounding environment on the absorption rate. We then combine these considerations into an Interface Reliability Index which predicts the reliability at any given site along the NCF-Si

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interface due to moisture absorption and thermal stress. The same parameters are also incorporated into a TC (Thermal Cycle) Index, which can predict the fail cycle under TC load at the same interface through correlation with measured data for cycles to failure. Both the Interface Reliability Index and TC Index are found to demonstrate good agreement with lab-scale experimentation of HBM packages in arrays: moisture soaking followed by high-temperature reflow for the former, and TC cycling for the latter. The simulation models are therefore a promising tool to predict and ensure high interfacial reliability in products to be developed in the future. Moreover, models provide confidence that the HBM packages will be highly robust and reliable throughout both production and use in even the most demanding environments.

II. EXPERIMENTATION

Direct experiments on an SIP-level are difficult due to the availability of the customer's actual components, and limitations in recreating the specific dimensions of end-products. To reflect the HBM package's proximity to other components, while simultaneously allowing for variations in the SiP geometry depending on the application, the test vehicle employed in the present study arranges the various types of HBM packages into arrays of different configurations.

If delamination were to hypothetically occur at the NCF-die interface, the stress causing it would be induced by the imposition of a thermal load. Meanwhile, the interface bonding strength, or in other words, the resistance of the interface to delamination, could be degraded prior to the thermal load stress due to the absorption of moisture.

To replicate and quantify these conditions, the test vehicle is first exposed to humid environment at elevated temperature, and subsequently subjected to a thermal load in the form of a peak temperature. It is important to note that the inherent resilience of the samples means that the load conditions must be far more severe than would be expected for actual processing in order to induce delamination. The samples absorb moisture at 85°C/85%RH (Relative Humidity) for a duration of 0 to t_{max}. They are then exposed to a high temperature, designed to reflect an extreme variation of the reflow temperature, ranging from T_{min} to T_{max}. The delamination fail rate is then calculated as the percentage of possible sites at which delamination was actually detected.

The dependence of the delamination rate on the moisture soak time and peak reflow temperature are shown in Fig. 2 (a) and (b), respectively. Regardless of the array configuration, increased exposure to moisture leads to a higher delamination rate. This trend becomes especially noticeable after a certain amount of time has progressed, likely due to the initiation of interface degradation at that point.

In the absence of moisture, achieved experimentally via a prolonged bake at an elevated temperature, the interface is more strongly resistant to delamination and requires an extremely high temperature of Tmax for delamination to occur at all, as seen in Fig. 2 (b).

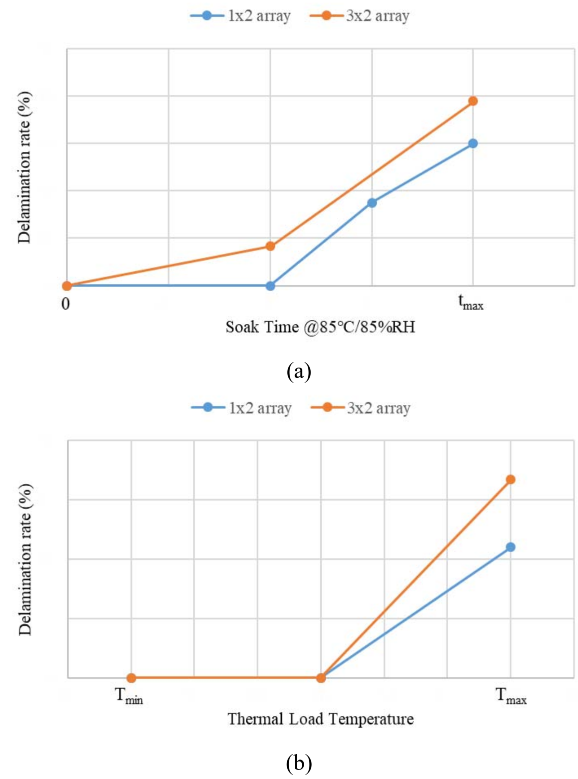


Fig. 2. NCF-Die delamination rate in 1x2 and 3x2 HBM test arrays depending on (a) soak time and (b) thermal load

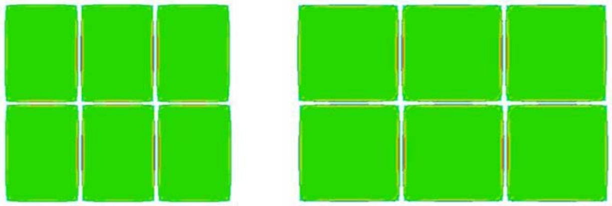
In terms of both moisture absorption and thermal stress, a larger array is observed to result in a higher delamination rate due to the higher number of components preventing stress release through unrestricted deformation.

III. NUMERICAL SIMULATION

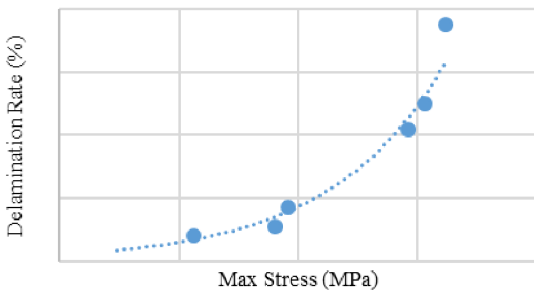
A. *Stress Simulation*

The primary factor that could lead to delamination at the interface between the NCF and Si die is the stress caused by the thermal load imposed on the site due to severe temperature changes during production. To quantify the influence of thermal stress, we simulated a thermal load for the HBM array test vehicles, using the FEM analysis tool ABAQUS. In order to accurately take into account the detailed geometry, the model also features the NCF shape as determined by microscopy images. Measured values are applied for the elastic properties of each of the component materials. The load imposed on the system is a temperature differential from Tinit to Tfin.

Fig. 3 (a) shows examples of the thermal stress simulation results, plotting stress distribution at the NCF/Core interface for arrays of different HBMs. The regions of high thermal stress are located at the edges between HBMs, and coincide with the sites where delamination occurs after moisture absorption and reflow at an extremely high temperature. Fig. 3 (b) is a plot of the



(a)



(b)

Fig. 3. Correlation between the FEM simulated stress versus (a) delamination sites, and (b) delamination rate

simulated thermal stress against the measured rate of delamination. The two factors show a high degree of correlation (R2=0.97), further confirming that thermal stress is the primary cause of the delamination.

To further investigate how stress could be distributed in a SiP environment, we modeled a hypothetical SiP. The geometry is a generalized version of a typical SiP layout featuring a central ASIC device surrounded by four HBMs.

Fig. 4 shows the thermal stress contour for the NCF at the height at which delamination was observed to primarily occur in array-level severe condition experimentation. Regions of high stress are concentrated at the NCF edges, and especially where there is another HBM or ASIC component adjacent. This is likely due to the restriction of stress release by deformation, and is in line with the experimental results.

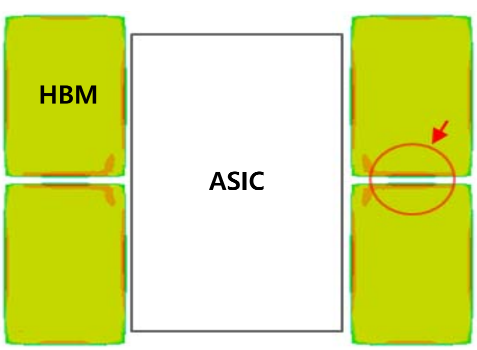


Fig. 4. Thermal stress contour of NCF in SiP-level HBM

B. *Moisture and Diffusion Simulation*

While the delamination between NCF and die can be driven by thermal stress as investigated above, it is prevented in most circumstances by a high adhesive strength at the interface. This interface adhesive strength, however, could potentially be weakened due to moisture absorption. To quantify this effect, it is necessary to predict the moisture concentration in various environments.

The material properties to determine this behavior are the diffusivity (mm2/s) and Csat (saturated concentration%) at various temperatures. These properties can be difficult to measure directly, but for the purposes of the present study we were able to obtain effective values for the EMC and NCF materials by correlating with measured absorption rates at MPGA-level. The data were obtained for absorption at differing degrees of severity for the moisture absorption environment in terms of temperature and relative humidity, ranging from least (Env1) to most (Env3) severe. As shown in Fig. 5, the calculated absorption rate from these effective property values are in good agreement with the measured data.

The effective absorption-related material properties then enable us to simulate moisture absorption at either the SIP or HBM array level, indicating both qualitatively where the moisture is concentrated, and quantitatively how much has been absorbed. Fig. 6 shows the simulated moisture concentration of the NCF in SIP arrangement after soaking for a given period and environment. The contour suggests that moisture enters the SiP and spreads to the HBM via the underfill between the components, since it acts as a high-diffusivity path. This leads to a higher moisture concentration at the HBM edges, weakening the adhesive interface strength there and making them more susceptible to subsequent thermal stress.

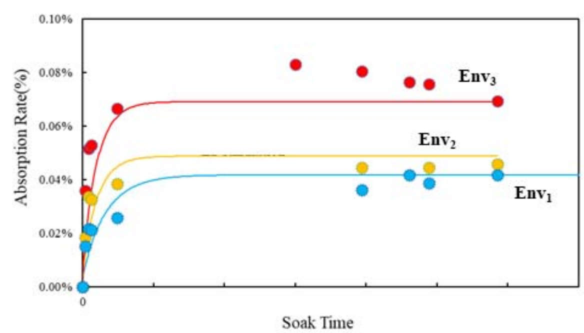
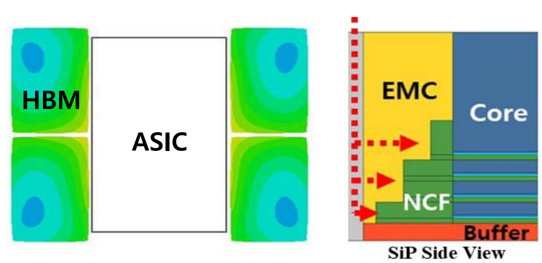


Fig. 5. Measured vs. simulated moisture absorption rates at MPGA level for least (Env1) to most (Env3) severe environments



(a) (b)

Fig. 6. Simulated moisture concentration (a) at NCF in SiP, and (b) with underfill acting as high-diffusivity path

IV. RELIABILITY ASSESSMENT AND PREDICTION

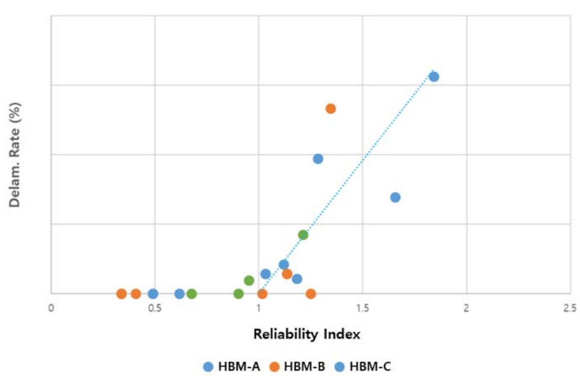
A. Preconditioning

By combining the results of the HBM array soak and reflow tests, the thermal stress simulations, and the moisture absorption simulations, we can conclude that the risk of delamination at a given site between NCF and Si Die will be i) proportional to the imposed thermal stress; ii) proportional to the moisture concentration; and iii) inversely proportional to the interface adhesive strength. By taking into account all three of these tendencies, we can therefore quantify the delamination risk in an index form, defined as below:

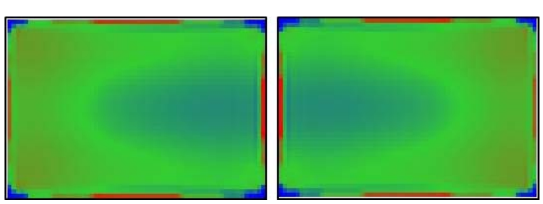
$$R.I. = C_f \times e^{\left[\frac{(Stress_{thermal} - S_m \times Moisture}{BF_{dry} - (BF_{saturated} - BF_{dry})\frac{Moisture}{Moisture_{saturated}}}\right]} \quad (1)$$

The thermal stress and moisture are values obtained by simulation. The interface adhesive strength BF is taken from NCF-Die shear tests, with the assumption that strength deceases linearly with moisture intake. The Moisture Stress Factor Sm and Reliability Index Constant Cf are constant values calculated by matching the above data to HBM array experiment results.

Fig. 7 (a) shows that, correlated with the HBM array soak and reflow experiments for multiple 4H and 8H HBMs, the Reliability Index is found to be in good agreement, with an R2 value near 0.87. It is also important to note that the plot of the Risk Index in the NCF region, given in Fig. 7(b), shows a clear concentration of higher risk at the HBM edges, especially where adjacent to another device. This is in agreement with the actual delamination sites observed in the earlier severe condition tests.



(a)



(b)

Fig. 7. Reliability Index, (a) plotted against HBM experiment results, and (b) distribution within NCF region for a 1x2 array

B. Thermal Cycling

The simulation results for stress and moisture, combined with measured values for the interface adhesive strength, are arranged in the Reliability Index to quantify the package's reliability in preconditioning; that is, moisture soaking followed by reflow at high temperature. In addition, we found that the same three factors can be combined differently in a way that strongly correlates to the expected thermal cycles to failure at the same NCF-die interface.

Based on thermal cycling tests of 3 different HBMs, the thermal stress, moisture, and interface adhesive strength can be used to form a TC index, defined as

$$TC\ Index = \frac{a \times Thermal\ Stress \times Moisture}{Bond\ Force^{\,b}} \quad (2)$$

The TC index can then be considered an alternative to the creep or strain energy density, giving the cycles to failure as

$$N_f = C\left(Index_{TC}\right)^{-\gamma} \quad (3)$$

where C and γ are both constants determined by correlation between the equation and measured TC cycles.

Fig. 8 shows the measured cycles to failure plotted against the corresponding fitting equation as defined above. There is a strong correlation between the equation and measured data, with an R2 of 0.98. Further experimentation will be needed to accumulate more data, thereby verifying the accuracy of the model and modifying the life cycle equation accordingly.

This high degree of correlation between the Reliability Index and TC Index with the behavior of HBM packages observed in severe condition testing makes the models a promising tool to quantify and predict the reliability behavior of HBMs in various arrangements and conditions. Moreover, as the model takes into account both the geometry and material properties of each SiP or HBM component, it is possible to optimize both the geometry and materials used to ensure robust performance and satisfy reliability demands.

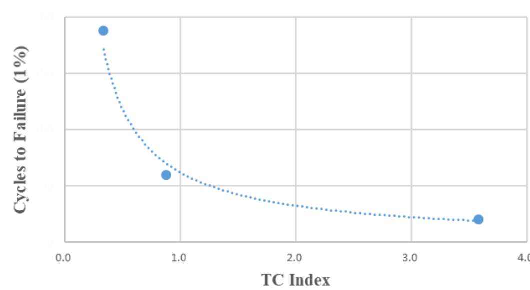


Fig. 8. Measured TC fail cycle vs. calculated TC Index

V. Conclusions

In the present study, we employed FEM numerical simulation to investigate the thermal stress and moisture absorption behavior in HBM packages. The simulation results demonstrated good agreement with experimental data. Defining the risk of delamination between NCF and Si Die as i) proportional to the imposed thermal stress; ii) proportional to the moisture concentration; and iii) inversely proportional to the interface adhesive strength, we quantified the risk as a Reliability Index. Moreover, the same three parameters can be combined differently to produce a TC Index which can be correlated with measured thermal cycles to failure in order to predict TC reliability. The Reliability Index and TC index were both found to be in good agreement with experimental results. This makes them a highly useful tool to quantify and predict the reliability behavior of HBMs in various arrangements and conditions. Furthermore, the models make it possible to optimize the geometry and materials of each component for maximum resilience, and to ensure that even the most severe reliability demands and requirements are met or exceeded.

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