Driving Mechanisms of Delamination Related Reliability Problems in Exposed Pad Packages

Willem D. van Driel, Marcel A. J. van Gils, Xuejun Fan, *Senior Member, IEEE*, G. Q. Zhang, *Member, IEEE*, and Leo J. Ernst

***Abstract*—Exposed pad packages were introduced in the late 1980s and early 1990s because of their excellent thermal and electrical performance. Despite these advantages, the exposed pad packages experience a lot of thermo-hygro-mechanical related reliability problems during qualification and testing. Examples are dielift, which occurs predominantly after moisture sensitivity level conditions, and die-attach to leadframe delamination leading to downbond stitch breaks during temperature cycling. In this chapter, nonlinear finite element (FE) models using fracture mechanics based J-integral calculations are used to assess the reliability problems of the exposed pad package family. Using the parametric FE models any geometrical and material effects can be explored to their impact on the occurrence diepad delamination, and dielift. For instance the impact of diepad size is found to be of much less importance as the impact of die thickness is. Using the fracture mechanics approach, the starting location for the delamination from thermo-hygro-mechanical point of view is deducted. The results indicate that when diepad delamination is present, cracks are likely to grow beneath the die and dielift will occur. The interaction between dielift and other failure modes, such as lifted ball bonds, are not found to be very significant. The FE models are combined with simulation-based optimization methods to deduct design guidelines for optimal reliability of the exposed pad family.**

***Index Terms*—Finite element (FE) method, moisture sensitivity level (MSL).**

I. INTRODUCTION

EXPOSED pad packages, such as high power low profile thin quad flat package (H(L/T)QFP), heatsink very-thin quad flat-pack no-leads (HVQFN), and high power thin shrink small outline plastic packages (H(T)SSOP), were introduced in the late 1980s and early 1990s because of their excellent thermal and electrical performance. Despite these advantages, a lot of thermo-hygro-mechanical related reliability problems are observed during qualification and testing of the exposed pad family. Examples are as follows.

- Dielift, predominantly after moisture sensitivity level (MSL) conditions. Dielift means delamination between die/attach and leadframe, and in some cases delamination between die/attach and the die. As a result of the dielift, lifted ball bonds may occur during thermal cycling.
- Downbond stitch breaks associated with diepad delamination after MSL assessment and subsequently thermal cycling testing. There might be a correlation between diepad delamination and dielift.

These reliability problems are driven by the mismatch between the different material properties, such as coefficient of thermal expansion (CTE), hygro-swelling, vapor pressure induced expansion, and degradation of the interfacial strength due to moisture absorption. The associated negative business consequence is significant. Until now, there is no solution available in the industry that solves the reliability problems of the exposed pad family. Clearly, the driving mechanisms of these delamination related problems should be explored before possible solutions can be found, such as double downset leadframes, grooves in the diepad, locking holes, other die/attach types, etc. to limit the dielift and/or delamination. This paper highlights our results to find the driving mechanisms for delamination-related reliability problems in exposed pad packages using state-of-the-art virtual prototyping/qualification techniques.

First of all, novel interfacial adhesion test techniques are developed to measure the interfacial strength as functions of both temperature and moisture. These techniques are modifications and improvements of the well-known four-point-bending with prenotch crack and ball-on-ring methods. Using smartly designed samples, the interfacial strengths between moulding compound and exposed pad, and between die/attach and exposed pad are quantitatively characterized.

Secondly, several reliable nonlinear finite element method (FEM) models in 2-D are developed to predict the moisture diffusion, deformation, stress, and interfacial energy history as functions of processes, temperature and moisture loading. Thus, the effect of hygro-swelling, vapor pressure, interfacial degradation, and thermal expansion on the failures in the exposed pad family is predicted. A lot of effort has been spent on developing reliable material models, based on our dedicated material characterization methods covering both thermo-mechanical and moisture properties. As a result, accurate material models, such as anisotropy for silicon, visco-elasticity for moulding compound and die/attach, elasto-plasticity model for copper, is used in our multiphysics damage modeling. It is expected that for the

Manuscript received June 28, 2006; revised December 11, 2006. This work was recommended for publication by Associate Editor A. Chandra upon evaluation of the reviewers comments.

W. D. van Driel and G. Q. Zhang are with NXP Semiconductors, Nijmegen 6534 AE, The Netherlands and also with the Delft University of Technology, Delft 2628 CN, The Netherlands (e-mail: willem.van.driel@nxp.com).

M. A. J. van Gils is with NXP Semiconductors, Nijmegen 6534 AE, The Netherlands.

X. Fan is with the South China University of Technology, Guangzhou, China and also with Lamar University, Beaumont, TX 77710 USA (e-mail: xuejun.fan@ieee.org).

L. J. Ernst is with the Delft University of Technology, Delft 2628 CN, The Netherlands.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TCAPT.2007.901724

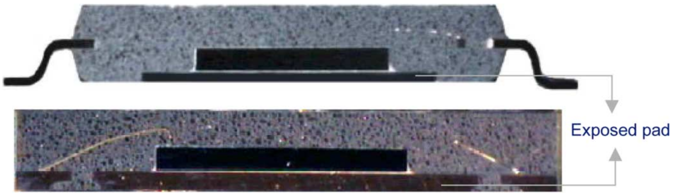


Fig. 1. Examples for exposed pad packages: gull wing leads (top) and QFN version (bottom).

thin die attach film (thinner than 25 μm) its thermo-mechanical and moisture properties are significantly different than those from bulk form and thick polymer film, due to size-effect.

Finally, by combining the FE modeling with simulation based optimization methods, design guidelines can be derived for reducing reliability problems for the exposed pad family. Such results also provide generic insight in the mechanisms of delamination-related problems for the exposed pad family.

II. Exposed Pad Family

An exposed pad package is a package composed of an integrated circuit (IC) attached to an exposed pad and in a later stage encapsulated with an epoxy moulding compound. It has been introduced into the semi-conductor market as a thin, cost effective, thermal and high frequency package solution [1]. The exposed pad is a metal plate that is located on the bottom of the package. Exposed pads on the top of the package are less common but they exist. Many variations exist; exposed pads are found on many packages types. Mature package types with gull wing leads, such as TSSOP, offer exposed pads as an optional configuration. The exposed pad is a standard feature for quad flat no-lead (QFN) packages. For the leaded packages with a gull wing lead, exposed pad products are made using leadframes with a "deep downset" paddle which is exposed to the outside of the package after the mold process. Fig. 1 shows two examples for a gull wing exposed pad package and a QFN package. Exposed pad features and benefits are:

- low profile (1.2 mm max mounted height);
- low loop inductance;
- excellent thermal performance;
- cost effective.

Exposed pads increase the maximum power dissipation of packages due to its increased thermal performance. In most applications, the exposed pad is used as an electrical ground. To do so, so-called down-bonded wires are attached from the IC to the exposed diepad.

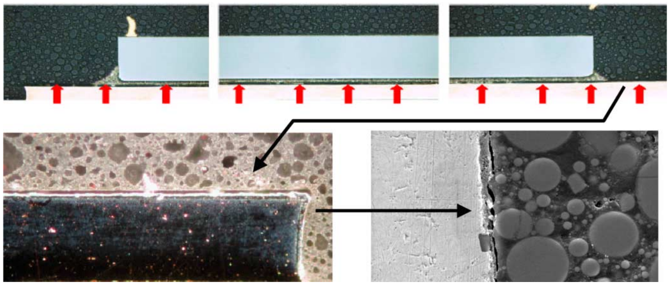


Fig. 2. Typical delamination locations in exposed pad packages: dielift (top), top diepad delamination (bottom-left), and side diepad delamination (bottom-right). Note that the crucial delamination to induce lifted ball bonds is delamination of the moulding compound from the topside of the IC (not shown).

Despite the advantages, a lot of thermo-hygro-mechanical related reliability problems are observed during qualification and testing of the exposed pad family. A common failure mode in exposed pad packages is downbond stitch breaks after temperature cycling testing. It is known that this failure mode is associated with diepad delamination after MSL assessment [2]. Another common failure mode in the exposed pad family is the so-called dielift mode. Dielift means delamination between die/attach and leadframe, and in some cases delamination between die/attach and die. Dielift is predominantly found after an MSL assessment and not only depends on the moisture and temperature conditions but also on material choices and process conditions. Dielift may endanger the thermal performance of the exposed pad package. As a result of the dielift, lifted ball bonds may occur during thermal cycling. Even more, there might be a correlation between diepad delamination and the dielift phenomenon. As such, dielift is a complicated failure mode, which needs further analysis to answer the following questions.

- What are the domination factors for occurrence of delamination in exposed pad packages? For instance, what is the impact of diepad size and die thickness.
- What location is the starting point for the delamination from thermo-hygro-mechanical point of view? Is it more likely to occur at the diepad top or side?
- What is the interaction between dielift and other failure modes, such as lifted ball bonds?

Fig. 2 shows typical examples of delamination areas in the exposed pad package.

III. Novel Adhesion Test Techniques

Delamination in packages is strongly related to the interfacial strength of two adjacent materials. The interfacial strength or toughness can be characterized with the energy release rate G [3], [4], defined as

$$G = \frac{1}{B}\left(\frac{dU_e}{da} - \frac{dU_s}{da}\right) \tag{1}$$

where B is the width of the sample, U_e the external work applied during the test, U_s the strain energy stored in the sample, and a the crack length. In principle, the energy release rate is a material parameter. In other words, the measured value is not dependent on the test method and the sample geometry. It characterizes the interface toughness or crack resistance through the interface of two materials. It consists of the energy associated with rupture of the intrinsic adhesion force, the energy dissipated in visco-elastic and plastic deformation processes occurred in the vicinity of the crack tip. The energy release rate is a function of the phase angle around the crack tip. The phase angle is defined as the tangential ratio between the normal stress and shear stress in front of the crack tip. Based on the test method used, an analytical model from (1) can be derived to calculate G from the measured data. At present, different techniques are available to measure the interface strength between two materials, including the following.

- Button shear/tensile test.
  For measuring the adhesion properties of moulding compounds on silicon, leadframe, FR4-substrates etc., simple pull and shear tests are often performed on small studs

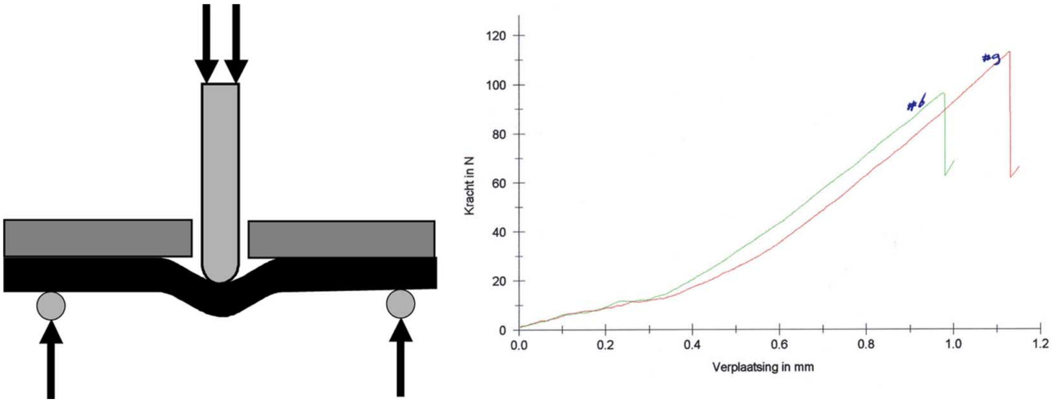


Fig. 3. Setup of the blister test (left) and typical recording (right).

made of compound [5]. These traditional adhesion tests have many weaknesses, including poor repeatability; sensitivity to variables that are unrelated to adhesion, or unduly complicated analysis. While such techniques can be useful for making qualitative comparisons of the adhesion in similar material systems, it is difficult to obtain quantitative information about dissimilar systems. Furthermore, these interface strength values are not applicable as input in quantitative simulations. Therefore, these tests are often used as qualitative comparison.

- Dual or double cantilever beam test.
  The dual cantilever beam (DCB) test method is a well-known method for determining mode-I fracture toughness of materials and interfaces. Samples used are sandwich like specimens where on both ends cantilevers are connected to apply a vertical load. The interface fracture energy can be measured at a phase angle $\psi = 0^\circ$ (nearly mode I) with the double cantilever beam specimen. An alternative version is the tapered double cantilever beam (TDCB), which is designed so that, over a large range of values of crack length, the rate of change of compliance with crack length is constant and independent of the value of crack length. Good examples of this method applied to packaging interfaces are found in [6], [7].
- Wedge test.
  In recent years, the Boeing Wedge test has been widely used to evaluate surface treatments under adverse environmental conditions as a means of determining the durability of bonded joints. The test introduces a known tension in an adhesive joint. This fracture test is an ASTM standard (ASTM D 3762) and utilizes a mode I specimen configuration [8]. The force is produced by elastic deformation of two adherent plates through the introduction of a wedge. The test consists of creating an initial crack by inserting a wedge, and then following the propagation of the crack with time. The driving force for the propagation of crack comes primarily from the stiffness of the beams separated by the wedge and this driving force decreases as the crack propagates. It is important to note that in this test the cracked specimen also experiences simultaneous environmental attack at the crack site (when the specimens are placed in that environment). The length of the crack at equilibrium gives both the effective fracture energy and the peel strength of the adhesive assuming no plastic yielding in the specimen.

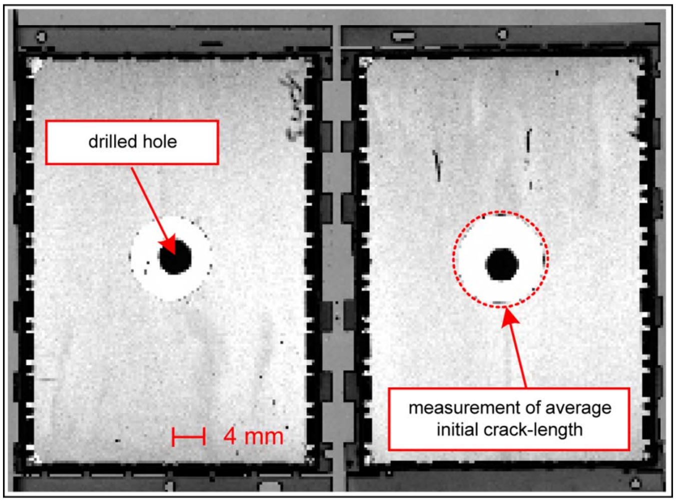
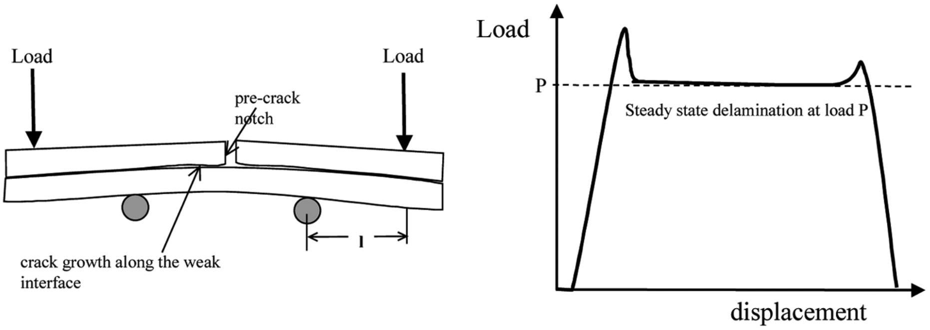


Fig. 4. Top view on sample used for blister test, SCAT result showing the drilled hole.

- Modified ball-on-ring test (or blister test).
  The modified ball-on-ring or shaft-loaded-blister test is a typical mode I interfacial strength measurement technique. Fig. 3 shows the experimental setup of this test and a typical force recording. A stainless steel cylindrical shaft with a concave end is attached to the load-cell of a universal-testing machine. The specimen with the hole facing up is put on a ring support so that the path of the shaft will not be obstructed. A steel ball is placed inside the blind hole and the shaft is adjusted to just touch the steel ball. A crosshead speed is set on the universal testing machine. The applied load versus shaft displacement is recorded simultaneously throughout the entire loading process. An example of this method applied to packaging interfaces is given here. We have measured the adhesion of moulding compound to copper leadframe by using the blister test as a function of temperature and moisture. Special samples are prepared and scanning acoustic measurements (SCAT) is used to determine the size of the interface delamination; see Fig. 4. Values found are in the order of 4–6 N/m for



(a) (b)

Fig. 5. Schematic presentation of (a) four-point bending with prenotch crack and (b) a typical resulting load-displacement curve showing the steady state delamination growth.

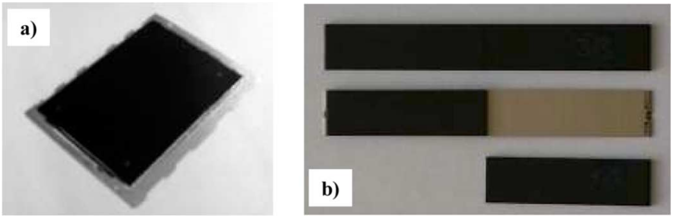


Fig. 6. (a) Overmoulded dedicated leadframe and (b) sawn samples as used for the four point bending test.

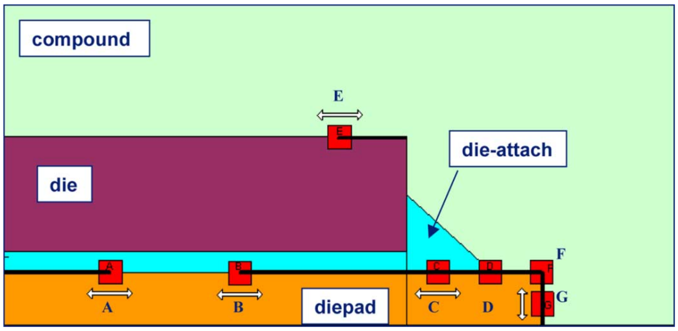


Fig. 7. At locations A–G, the J-integral values are predicted.

this interface at room temperature, which can drop down to <1–2 N/m at reflow temperatures of 240 °C.

- Four-Point bending with pre-notch crack.

  Recently, the adhesion strength of low-k materials with its adjacent materials is measured by using this technique [9]. A schematic representation of the test setup is visualized in Fig. 5. The sample consists of a bi-material sample with an initial notch loaded in a four-point bending test. Stable crack propagation results in a constant load during delamination, which simplifies the determination of the fracture resistance because it is independent on the delamination length. A typical ideal load-displacement response of this test is visualized in Fig. 5. Analytical formulas for the resulting energy release rate can be determined. In general, the evaluation of the fracture toughness from this test requires numerical calculations, however, with special geometric assumptions, an analytical solution for the energy release rate G_c is possible

$$G_C = \frac{M^2\left(1-\upsilon_2^2\right)}{2E_2}\left(\frac{1}{I_2}-\frac{\lambda}{I_C}\right) \tag{2}$$

$$\lambda = E_2\left(1-\upsilon_1^2\right)/E_1\left(1-\upsilon_2^2\right)$$
$$I_2 = \frac{1}{12}h_2^3$$
$$I_C = \frac{1}{12}h_1^3 + \frac{\lambda}{12}h_2^3 + {}^{\lambda h_1 h_2 (h_1+h_2)^2} / 4(h_1+\lambda h_2). \tag{3}$$

  The subscript 1 indicates quantities relevant to the top layer, whereas the subscript 2 denotes the corresponding quantities for the bottom layer. Subscript c refers to the composite beam. Note that the moment per unit width $M = Pl/2B$, with P being the constant load. E and ν denote the Young's modulus and Poisson's ratio, h is the thickness, b is the width of the specimen, and l is the distance between the inner and outer support points. A more general analytical evaluation of the four-point bending test can be found elsewhere [10].

- Any other, either combinations or deviations of above.

  Other adhesion test methods reported in the literature are, for instance, the 90°-peel test, and three point bending with precrack. The 90°-peel test can be used to measure the adhesion in an adhering system. In the peel test, thin films are attached to a Silicon substrate and peeled off in a 90° angle. The three point bending with precrack test is identical to the four point bending variant, with the difference that a precrack is put between both materials by using a specific releasing agent.

  In our study, we have used the four-point bending test to determine the interface fracture toughness between the following.

- Moulding compound-substrate, moulding compound-solder resist, and moulding compound-copper traces as a function of temperature and moisture content. The results are described elsewhere [11].
- Moulding compound-leadframe, die/attach-leadframe as function of compound and die/attach material types, temperature, and moisture content.

To investigate the interfacial adhesion between moulding compound and leadframe, a dedicated frame is designed existing of a large diepad. This diepad can be overmoulded and in a next process step sawn into the samples needed. The design is a 0.2-mm-thick, QFN-based, copper frame with a preplated (ppf) NiPdAu finish. The leadframes are stored under oxygen-free conditions to avoid oxidation. Using standard processes, a

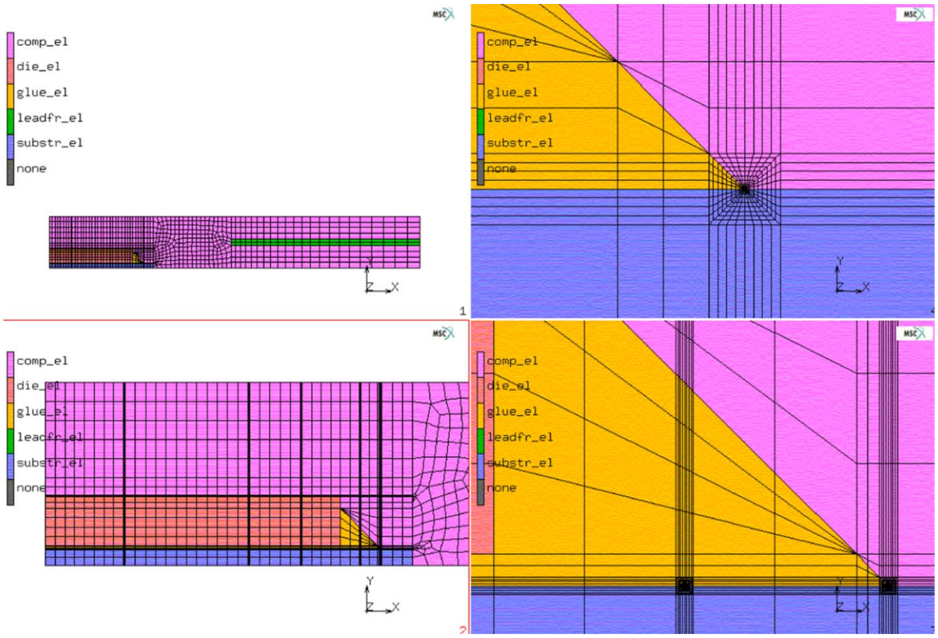


Fig. 8. FE mesh for the HLQFP exposed pad package (left) and typical crack-tip meshes to calculate J-values (right).

0.65-mm-thick layer of moulding compound is added to the frame. For the four point bending tests, pieces of 9-mm-wide and 60-mm-long are used and a notch of 85% depth is sawn into the samples. Fig. 6 shows both the overmoulded frame, and two sawn 60×9 mm^2 samples. Besides the moulding compound—leadframe samples, samples are created in which first a 25-mm-thick die-attach layer is spread out over the leadframe after being overmoulded. Interface strength characterization is performed as function of temperature and moisture content (dry versus MSL1). Four different commercially available moulding compounds are used, denoted by MCA/MCB/MCC/MCD, and two die-attach materials, denoted by DA1/DA2.

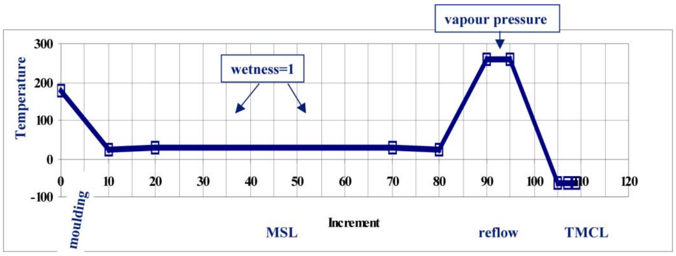


Fig. 9. Loading scheme: thermal, moisture, and vapor pressure are subsequently added.

IV. MULTIPHYSICS FE MODELING

A 2-D nonlinear FE model including isotropy for silicon [12], visco-elasticity for moulding compound and die/attach [12], elasto-plasticity for the copper leadframe constructed. A multiphysics FE methodology is used which can take into account the moisture and thermo-mechanical related mechanisms. The effects of hygro-swelling, vapor pressure, and thermal expansion on the failures in the exposed pad family are modeled. We have used the "wetness" approach [13]–[18], which assumes continuity of the weighted moisture concentration across interfaces of different materials. The wetness is defined as $W = C/C_{\text{sat}}$, with C the moisture concentration. It is assumed that the moisture uptake in the polymer materials can be described with Fick's Law of Diffusion. The following parameters are needed to describe the moisture uptake in the materials.

- The diffusivity, $D(T)$: measures the rate of mass diffusion and is defined as the amount of mass flux per unit concentration gradient (m^2/s).
- The saturated moisture concentration, C_{sat} : the maximum mass of moisture per unit volume of the substance (kg/m^3).

Moisture diffusivity, D, and the saturated moisture concentration, C_{sat}, are measured using moisture absorptions measurements at MSL1 (85 °C, 85%RH) and MSL3 (30 °C, 60%RH) conditions. The weight gain of the samples as function of time is measured by a thermal gravimetric analyzer (TGA) and serves as input for determining the material properties by curve fitting of the measured data. For the determination of the moisture expansion coefficient (CME), combined TMA/TGA experiments have been performed at 85 °C on saturated samples. Combining the obtained results of moisture desorption and shrinkage as function of time, the CME can be estimated [13].

For predicting delamination growth of an existing delamination, linear elastic fracture mechanics (LEFM) is applied using the J-integral approach. The J-integral value is calculated at the interface and represents the available energy to delaminate the interface. Based on plane strain assumption 2-D FE models are constructed to calculate the value of the J-integral, as function of hygro-thermo-mechanical loading. J-integral values are calculated at different interfaces within the package; see Fig. 7.

Fig. 8 shows the fully parametric 2-D FE model with some typical crack-tip meshes. Through a solid mesh sensitivity analysis the eventually used mesh size is fixed. Different integration-paths are analyzed to fix the path to calculate the eventual J-value. Fig. 9 shows the loading scheme, including the

TABLE I
INTERFACE FEATURE TOUGHNESS FOR THE DIFFERENT VARIATIONS AND CONDITIONS

	Interface Fracture Toughness [J/m2]	
Sample ID	**Dry**	**Wet**
Moulding Compound		
MCA, 20ºC	5.7	3.2
MCB, 20ºC	6.2	5.9
MCC, 20ºC	6.9	-
MCD, 20ºC	14.8	7.3
MCA, 20ºC, with LF oxidation	2.5	1.9
Die-attach		
MCA + DA1, 20ºC	10.5	-
MCA + DA2, 20ºC	24.0	13.1

thermal, moisture, and vapor pressure loading that is used in the FE model.

V. RESULTS

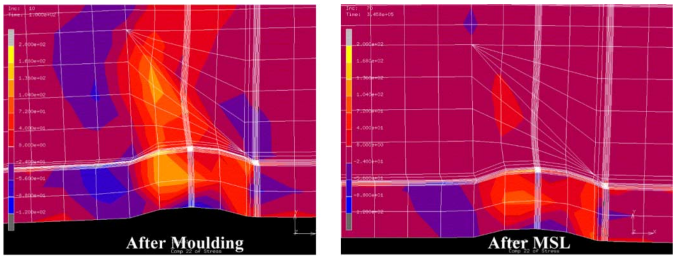
A. *Interface Strength Test*

Table I lists the results of the different material combinations and various conditions. At 20 °C and under dry conditions, the adhesion strength between compound and leadframe is approximately 6 J/m^2. The FE model is used to calculate the mode mixity of the current setup, revealing a value of 38°. These values comply with those found in the literature. Tay *et al.*. [19] measured an interface strength of 4.5 J/m^2 for the leadframe—compound interface at a mode mixity of $\psi = 0°$.

Comparing the various compounds at 20 °C, the adhesion strength between MC A, B, and C are close to each other, but MCD has a significant better bonding to the leadframe. When moisture is present at the interface, the results show that the adhesion strength may decrease with 50% for MCA and MCD. MCB is less sensitive to the moisture. Clearly, moisture absorption degrades the interfacial strength. With increasing moisture content, the polymer molecules at the interface bond with water molecules and hydrogen bonds replace the attachment with the leadframe.

To explore the effect of oxidation and contamination, a set of leadframes are exposed to air for 48 h after being overmoulded. As expected, oxidation and/or contamination shows a strong degrading effect, more than 200%. Surface conditions (contamination, treatment, etc.) and processing have a large influence on the adhesion strength.

The specimens with DA1 and DA2 show a higher adhesion with the leadframe compared with the compounds. This is due to the fact that die-attach materials are chemically tuned to adhere to surface finishes on leadframes. For DA2 the interface fracture toughness is even more that 200% times higher than for DA1. This is an effect of a different chemistry. Again, when moisture is presented at the interface, the adhesion strength may decrease to 50%.



(a) (b)

Fig. 10. Deformed structure at the die edge in the exposed pad and die/attach area (a) after moulding and (b) MSL loading conditions.

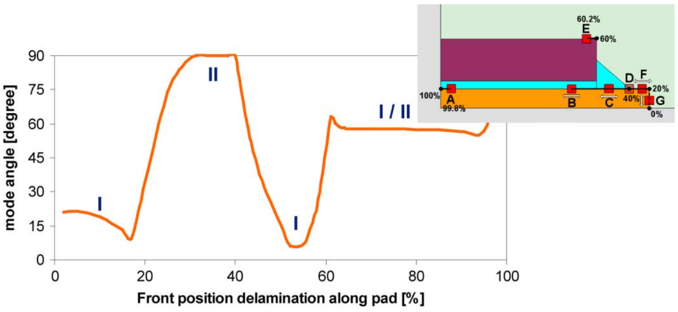


Fig. 11. Mode mixity along the diepad interface.

B. *Multiphysics FE Modeling*

Fig. 10 shows the locally deformed structure after moulding and MSL loading conditions. It is clear that the die/attach pulls at the exposed pad and high J-values are expected. Due to the moisture loading, the swelling of the compound/die/attach decreased these local deformations, and thereby, closes any interface present.

Fig. 11 shows the mode mixity along the diepad for the nominal model, 0% is the starting point at the side of the pad, 20% is the corner point, 40% is the point of the die-attach fillet, 60% is exactly below the die, 100% is at the symmetry line.

Fig. 11 shows the following.

- At the diepad side (between 0%–20%), the interface is loaded under a mode mixity of 20°. The interface toughness value for compound-leadframe at 20 °C is 6 J/m^2. Remember that these values may drop with a factor 3 when the leadframe is contaminated and/or oxidized.
- At the top of the diepad (between 20%–40%), the interface is loaded under a mode mixity of 90° (pure mode II, shear loading). The toughness value at 20 °C under this mode is >25 J/m^2.
- Under the die-attach fillet (between 40%–60%), the mode mixity drops to 10° (almost pure mode I, tensile loading) and rises to 60° when it reaches the die corner. The toughness values for this interface under this mode would be about 10–25 J/m^2 at 10° and rising to 100–125 J/m^2 at 60°.
- Under the die (between 60% to 100%), the mode mixity remains constant at 60°, where a toughness value of 100–125 J/m^2 is expected (probably even higher but no data is available/measured at this mode).

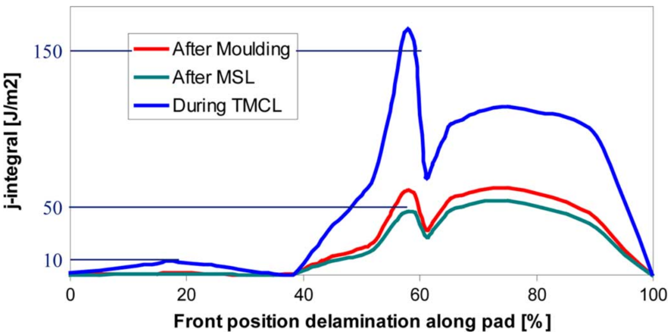


Fig. 12. J-integral values at the different locations as function of the process conditions.

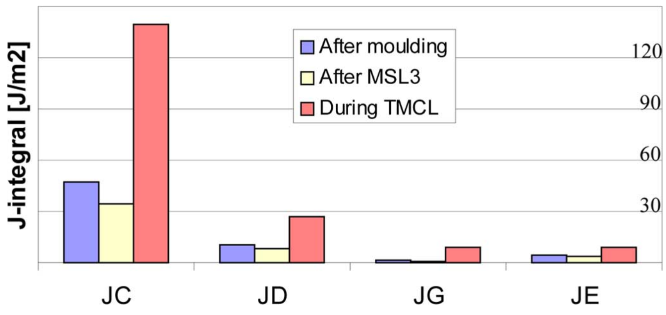


Fig. 13. J-integral values at specific locations during processing and testing.

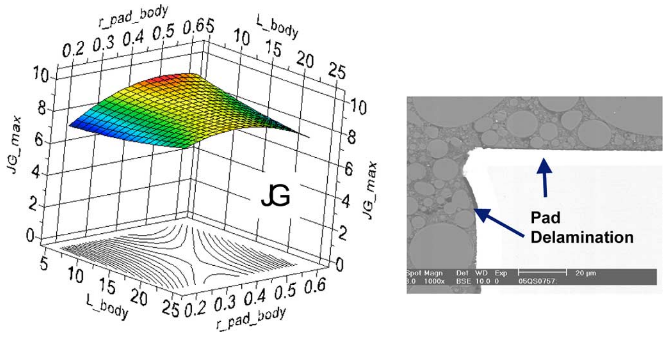


Fig. 14. Effect of delamination on the side of the pad (location G) as function of body size and pad-to-body ratio.

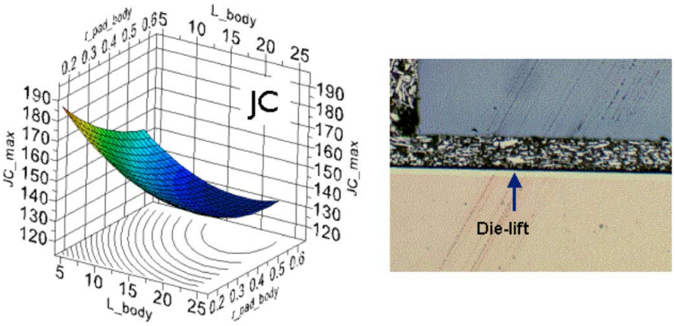


Fig. 15. Dielift occurrence as function of body size and pad-to-body ratio.

These values can be compared with the calculated ones during manufacturing, processing, and testing. Fig. 12 shows the calculated J-integral values at the different locations as function of the loading conditions. The following can be concluded from this figure. At the side of the pad (location G and F), the J-integral values are below 5 J/m^2 during processing, indicating that this interface will not fail from a thermo-mechanical point of view. It will only fail when this interface is contaminated, since the toughness value will drop below 2 J/m^2. During TMCL, the J-integral values increase to 10 J/m^2 and are getting closer to the toughness values. During cool down from the moulding temperature the J-integral values at the locations B and C (interface die-attach with leadframe) increased dramatically and seem to exceed the measured values. Especially at location C, directly below the die corner, the J-integral values rise until 50 J/m^2 after moulding and 150 J/m^2 during TMCL testing and are beyond the measured toughness values. During MSL testing, the J-integral values drop. This is due to the expansion of the compound as a result of moisture uptake. When swelling the compound closes the interface and J-integral values decrease. The effect of the moisture is purely degrading the interface toughness with 20%–40%. The results indicate that delamination will occur at the die-attach border, have the tendency to progress until point B, but not until point A (lower J).

As mentioned before, total dielift may facilitate other failure modes, such as lifted ball bonds on top of the IC, during TMCL testing. Fig. 13 shows J-integral values at the different locations C, D, G, and E. The J-integral value for location E (on top of the IC) is calculated when the total diepad is delaminated (thus including total dielift). This J-integral value at location E is very low indicating that the relation between dielift and lifted ball bonds is not that significant.

C. Optimization

A numerical DOE [20], [21] is performed using the following parameters.

- Body size, increasing from 3×3 mm^2 to 24×24 mm^2.
- Pad-to-body ratio (length based) from 15% to 60%.
- Die-to-pad ratio (length based) from 10% to 85%.

A space-filling Latin-Hypercube design consisting of 30 variations is constructed. For the responses, the J-integral values at the locations C and G are chosen. Fig. 14 shows the effect of body size and pad-to-body ratio on the calculated J-integral values on the G location (side of the pad). It is clear that both the body size and the pad-to-body size have no effect on the occurrence of pad side delamination. The same result is found for the die-to-pad ratio. Fig. 15 shows the effect of J-integral values below the corner of the die (location C), in other words the occurrence of dielift, as function of the body size and the pad-to-body ratio. As the body size and the pad-to-body ratio increase, the J-integral value decrease from 190 J/m^2 to 130 J/m^2 (32% reduction) indicating that for larger packages the thermo-hygro-mechanical effects for dielift occurrence diminish. Note that for larger packages, the interface toughness may increase or decrease due to some processing effects. From these results it can be deducted that dielift is not related to package size and/or package internal ratios. There is no need to setup a design rule for this feature. It is very important to secure interface toughness in exposed packages by proper processing (curing time, no/limited leadframe oxidation and/or contamination).

VI. CONCLUSION

Despite the electrical and thermal advantages, the exposed pad packages experience a lot of thermo-hygro-mechanical related reliability problems during qualification and testing. In this chapter, interfacial adhesion test results are combined with nonlinear FE models using fracture mechanics based J-integral calculations to assess the reliability problems of the exposed pad package family. Using the parametric FE models any geometrical and material effects can be explored to their impact on the occurrence delamination and/or dielift. For instance the impact of diepad size is much less as the impact of die thickness. Even more, the models can be used to find the starting location for the delamination from thermo-hygro-mechanical point of view. The results indicate that when diepad delamination is present, cracks are likely to grow beneath the die and dielift will occur. The interaction between dielift and other failure modes, such as lifted ball bonds, are not found to be very significant. Even more, the modeling work combined with the strength measurements have shown that from thermo-hygro-mechanical point of view this interface should not delaminate, unless it's toughness is not secured by a proper material choice and/or processing. The degradation of the compound and die-attach to leadframe interfaces combined with the imposed thermo-hygro-mechanical forces will lead to the reliability problems. Therefore, it is vital to secure processing conditions of the exposed pad family by proper curing of moulding compound and/or die-attach materials to obtain sufficient interface toughness, secure leadframe storage under controlled environmental conditions to prevent oxidation and/or contamination, and/or introduction of a cleaning step for those leadframes for which dielift is a known risk.

Delamination is a key trigger of mostly observed reliability problems in the microelectronic industry. As such, not only those materials having sufficient interface toughness should be selected but also design choices should be made able to withstand increased forces due to the occurrence of delamination. Prediction models may support these choices.

ACKNOWLEDGMENT

The authors wish to thank B. Ang and R. Pastrana, Philips Semiconductors Philippines, C. Chuang and G. W. Peng, Philips Semiconductors, Kaoshiung, and Y. Na-Tarlang, Philips Semiconductor, Thailand, for providing samples, ideas, and input in this research.

REFERENCES

[1] Amkor Technology, Inc., "ExposedPad," Tech. Rep., Chandler, AZ, 2007.

[2] W. D. van Driel *et al.*, "On wire failures in micro-electronic packages," in *Proc ESIME'04*, 2004, pp. 53–58.

[3] M. F. Kanninen, *Advanced Fracture Mechanics*, ser. 15. New York: Oxford Univ. Press, 2007.

[4] L. Banks-Sills, "A note on fracture criteria for interface fracture," *Int. J. Fracture*, vol. 103, pp. 177–188, 2000.

[5] W. D. van Driel *et al.*, "Prediction of interfacial delamination in stacked IC structures using combined experimental and simulation methods," *Microelect. Rel.*, vol. 44, no. 12, pp. 2019–2027, 2004.

[6] X. Dai, M. V. Brillhard, and P. S. Ho, "Adhesion measurement for electronic packaging applications using double cantilever beam method," *IEEE Trans. Compon. Packag. Technol.*, vol. 23, no. 1, pp. 101–116, Mar. 2000.

[7] J. Taweeplengsangsuke and R. A. Pearson, "Processing adhesion relations for die/attach adhesives and underfill resins," in *Proc. 48th ECTC*, 1998, pp. 160–167.

[8] R. D. Adams, "Engineered Materials Handbook," in *Adhesives and Sealants 3*. Materials Park, OH: ASM, 1995.

[9] G. Wang, C. Merrill, J.-H. Zhao, S. K. Groothuis, and P. S. Ho, "Packaging effects on reliability of Cu/lowk interconnects," *IEEE Trans. Dev. Mater. Rel.*, vol. 3, no. 4, pp. 119–128, Dec. 2003.

[10] I. Hofinger, "Modified four-point bending specimen for determining the interface fracture energy for thin, brittle layers," *Int. J. Fracture*, pp. 213–220, 1998.

[11] M. A. J. van Gils *et al.*, "Characterization and modeling of moistures driven interface failures," *Microelectron. Rel.*, vol. 44, no. 11, pp. 1317–1322, 2004.

[12] W. D. van Driel *et al.*, "Packaging induced die stresses—Effect of chip anisotropy and time-dependent behavior of a moulding compound," *J. Electron. Packag.*, vol. 125, no. 4, pp. 520–526, 2003.

[13] M. A. J. van Gils *et al.*, "Virtual qualification of moisture induced failures of advanced packages," in *Proc. ESIME'04*, 2004, pp. 157–162.

[14] E. H. Wong *et al.*, "Moisture diffusion and vapour pressure modeling of IC packaging," in *Proc. ECTC*, 1998, pp. 1372–1378.

[15] R. Dudek *et al.*, "Studies on moisture diffusion and popcorn cracking," in *Proc. EuroSimE*, 2002, pp. 225–232.

[16] L. K. The *et al.*, "Moisture-induced failures of adhesive flip chip interconnects," *IEEE Trans. Compon. Packag. Technol.*, vol. 28, no. 3, pp. 506–516, Sep. 2005.

[17] E. H. Wong, R. Rajoo, T. B. Lim, and Y.-W. Mai, "Swelling and time-dependent subcritical debonding of underfill during temperature-humidity aging of flip chip packages," *IEEE Trans. Compon. Packag. Technol.*, vol. 28, no. 4, pp. 862–868, Dec. 2005.

[18] S. Luo and C. P. Wong, "Influence of temperature and humidity on adhesion of underfills for flip chip packaging," *IEEE Trans. Compon. Packag. Technol.*, vol. 28, no. 1, pp. 88–94, Mar. 2005.

[19] A. A. O. Tay, Y. Y. Ma, S. H. Ong, and T. Nakamura, "Measurement of interface toughness as a function of temperature, moisture concentration and mode mixity," *Adv. Electron. Packag.*, vol. 26, no. 2, pp. 1129–1136, 1999.

[20] G. Q. Zhang, "The challenges of virtual prototyping and qualification for future microelectronics," *Microelectron. Rel.*, vol. 43, pp. 1777–1785, 2003.

[21] W. D. van Driel *et al.*, "Response surface modeling for non-linear packaging stresses," *J. Electron. Packag.*, vol. 125, no. 4, pp. 490–497, 2003.

Willem D. van Driel received the M.S. degree in mechanical engineering from the Technical University of Eindhoven, Eindhoven, the Netherlands.

He has broad R&D experience covering several multidisciplinary application fields. He is currently a Principal Scientist at NXP Semiconductors, Nijmegen, The Netherlands, and also holds an Adjunct position with the Delft University of Technology, Delft, The Netherlands. He is author and co-author for more than 80 scientific publications, including journal and conference papers, book (chapters), and invited keynote lectures. His scientific interests are microelectronics and microsystems technologies, virtual prototyping, virtual reliability qualification and designing for reliability of microelectronics and microsystems.

Mr. van Driel is a Guest Editor for the IEEE TRANSACTIONS ON COMPONENTS AND PACKAGING TECHNOLOGIES, a member of the Organizing Committee, IEEE Conference EuroSimE, and a member of the Technical Committee, ICEPT.

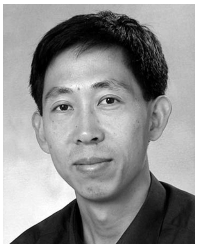
Marcel A. J. van Gils received the Ph.D. degree in mechanical engineering from Eindhoven University of Technology, Eindhoven, The Netherlands, in 1997.

He is currently working at NXP Semiconductors, Nijmegen, The Netherlands, in the field of MEMS reliability. He has worked in the areas of thermomechanical simulations, reliability testing and material characterization related to microelectronic packaging and IC technologies. He has published several conference and journal articles in these areas.

Xuejun Fan (SM'06) received the B.S. and M.S. degrees from Tianjin University, Tianjin, China in 1984 and 1986, respectively, and the Ph.D. degree in engineering mechanics from Tsinghua University, Beijing, China, in 1989.

He is currently an Associate Professor in the Department of Mechanical Engineering, Lamar University, Beaumont, TX, and a Chair Professor in the Department of Engineering Mechanics, South China University of Technology, Guangzhou, China. From 1997 to 2000, he was with the Institute of Microelectronics (IME), Singapore, heading a group of modeling and simulation in advanced packaging development. He moved to Philips Research Lab, Briarcliff Manor, NY, as a Senior Member Research Staff in 2000, and then to Intel Cooperation, Chandler, AZ, as Senior Staff Engineer in 2004. He held a faculty position at Taiyuan University of Technology, Shanxi, China, from 1989 to 1997. He received the Young Scientist Fellowship from Japan Society of Promotion of Science to work at the University of Tokyo in 1993. He was a Visiting Professor at the University of British Columbia, Vancouver, BC, Canada, from 1996 to 1997. He was promoted to a Full Professor at Taiyuan University of Technology, Taiyuan, Shanxi in 1991, and became one of the youngest professors in China that year when he was 27. He is a well-known industry expert in moisture induced failures in electronic packages. He has published more than 80 scientific papers and filed 14 U.S. patents. His interests and expertise lie in the areas of reliability, material characterization and thermal and mechanical modeling for microelectronic packaging.

Dr. Fan was one of the 30 Nominees for the title of "1991 Ten Outstanding Youth of China," and was one of five recipients for the second-best prize of Young Faculty Award for the Excellence in Teaching and Research in 1994 by Fok Ying-Tung Education Foundation.



G. Q. Zhang (M'03) is a Strategic Program Manager in the Strategy Department, NXP Semiconductors, Nijmegen, The Netherlands, and part-time Professor in the Department of Precision and Microsystem Enginering, Delft University of Technology, Delft, The Netherlands. Within NXP Semiconductors, he has been responsible for technology roadmap, strategy and partnership of "More than Moore" (MtM), covering the nontraditional CMOS technologies and applications, such as MEMS, Sensors, Actuators and SiP. He has authored/co-authored more than 100 scientific publications, and has been invited as keynote speaker by many international conferences and organizations. As an active player in European's Micro/Nanoelectronics arena, he has been leading and participating in several EC funded R&D projects, networks and initiatives. Currently he is leading the "MtM" technology domain team for the Strategic Research Agenda of Nanoelectronics of Europe.

Dr. Zhang is an Associate Editor for the IEEE TRANSACTIONS ON COMPONENTS AND PACKAGING TECHNOLOGIES. He has been chairing and co-chairing several international conferences (IEEE EuroSimE, IEEE ICEPT, etc.), and participating in technical committees of several international conferences (ECTC, EPTC, IEEE Nano Technology, ESREF, etc.), and scientific societies.

Leo J. Ernst received the Ph.D. degree in technical sciences from the Delft University of Technology, Delft, The Netherlands, in 1981.

He is Head of the Mechanics of Materials Group, Mechanical Engineering and Marine Technology Department, Delft University of Technology. He has worked in various fields of application in industry as well as in research. He became a Full Professor at the Delft University of Technology in 1986. His research was focused on various fields, such as theory of plates and shells, development of finite elements, thermal stress modelling, structural reliability and constitutive modelling. He has authored and co-authored over 160 professional publications in the very specialized field of mechanics of materials. Recently he became member of the Delft Institute of Microelectronics and Submicron Technology (DIMES). The last six years he focused research on mechanics of microelectronics.

Dr. Ernst is active in the organizing- and technical committees of various conferences in the field of mechanics of microelectronics. For the EuroSimE conferences, on "Thermal and Mechanical Simulation and Experiments in Microelectronics and Micro-Systems," he is acting as the Technical Chair.