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ScienceDirect
Microelectronics Reliability 47 (2007) 1690–1694
MICROELECTRONICS RELIABILITY
www.elsevier.com/locate/microrel

Sequential environmental stresses tests qualification for automotive components

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Received 2 July 2007
Available online 16 August 2007

Abstract

The purpose is to create a new qualification methodology for plastic encapsulated electronic components used in an automotive environment at high temperature. It is based on the acceleration of failure mechanisms like ball bond lift (due to intermetallic Au–Al thickness growth), by combination of environmental stresses. The delamination measurement was used as an indicator of potential assembly weaknesses. An optimized package sequential qualification test flow is proposed.

1. Introduction

The automotive market is highly demanding of components reliability while in the meantime increasing requirements for performance, harsh environmental conditions and shorter time to mass production. Our study focuses on package robustness and proposes an effective stress test approach to detect a potential weakness of die-to-leads connections. As high temperature usage is targeted, the interest is related to ball bond lift failure, as a consequence of the delamination increase.

Usual tests performed according to the automotive qualification standard AEC-Q100 do not allow identifying failures at package level within a short duration. The rapid identification of package related limitations was previously noticed by using the unique combined test: preconditioning, liquid/liquid thermal shocks and HAST humidity (highly accelerated stress test no bias). Therefore, we supposed the relevance of the test flows could be improved by an appropriate combination of environmental tests. The combination of environmental stresses is expected to overcome the lack of potential failure mechanism knowledge resulting of the current AEC qualification.

This paper examines the effect of combined stresses on the delamination, identifies the most significant factors, evaluates the stress acceleration, and shows the correlation between thermo-mechanical characteristic degradation of moulding compound and the acceleration of the delamination increase. Finally, we propose an optimized package sequential test flow for a failure-driven package qualification.

2. Bibliographic statements

According to previous studies, [1,2], it could be necessary to limit the temperature during qualification stress test for the reliability evaluation of plastic encapsulated microcircuits (PEMs), owed to a major factor, the transition of molding compounds from a glassy to a rubbery state. This transition occurs at a temperature called the glass transition temperature (T_g). When a temperature of a component is close to or exceeds T_g of a molding compound (MC), electrical, thermal and mechanical properties of the encapsulant might significantly change, leading to an acceleration

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0026-2714/$ - see front matter
doi:10.1016/j.microrel.2007.07.004

of the appropriated failure mechanism but maybe also to the introduction of new degradation mechanisms.

These effects were largely well reflected by studies of harsh environmental conditions (such as thermal shocks and cycles [2,3], HAST [1,2], high thermal storage [1,2,4,5], etc.).

On the one hand a thermal aging at high temperature over a long-duration might affect the rate of degradation of epoxy resins used in MCs. For example, the presence of oxygen results in thermo-oxidative decomposition and significantly accelerates degradation and failures of in epoxy composite materials [5]. On another hand, long-term high temperature storage of MC epoxy in air at temperatures from 175 °C to 225 °C resulted in about 15 °C increasing of T_g and in about 20% decreasing of thermal expansion rubbery sate (CTE2) [1]. This reflected that the resin continues polymerizing; this might be due to additional cross-linking in polymer chains and indicates that the thermal stability of MC does not depend on T_g.

In HTS, the main failure is lead to ball bond degradation. In the setting of resins containing a flame retardant system such as bi-phenyl epoxy resin, the failure process could divided into the following steps: (1) release of chemically active molecules (Br) by thermal decomposition from the flame retardant additives in MC; (2) diffusion of the molecules; and (3) chemical reaction with the different Al/Au intermetallic phases (dry corrosion) [4,6]. If diffusion is the limiting stage of this process, then exceeding T_g might accelerate transport of the corrosive molecules to the wire bond intermetallic and thus enhance the rate of degradation [6].

It has also been found that the failure rate is much higher when the temperature exceeded the T_g, resulting in the activation energy decrease, from $E = 2$ eV (at $150\ °C < T < 177\ °C$) to $E = 1.5$ eV at higher temperatures. These two activations energies reflect that two different failure mechanisms occur, the second one becoming preponderant at temperatures approximately 50 °C higher than T_g [6].

3. Experimental procedure

Two combinations of tests have been analyzed for an AEC-Q100 grade 0 (150 °C) microcontroller assembled in QFN32 packages (Green Material: G770 SUMITUMO, having a measured value of the glass transition temperature of 100 °C, while that provided by the subcontractor is of 130 °C). The DOE (design of experiments) approach was used to measure either the effect of individual stresses, of their parameters or of their interaction.

The ageing was measured by electrical testing, CSAM (c-mode scanning acoustic microscopy) at various interfaces (resin/die, resin/lead frame and in whole package) and by Wire Pull and Ball Shear strength testing.

3.1. Aging conditions

The first experiment combines preconditioning, thermal shocks (TS) and HAST (DOE1) and the second one is preconditioning (PR), high temperature storage (HTS) and HAST (DOE2), both with different parameters and different sequences (see Tables 1 and 2). Preconditioning in our study is described by dry bake (24 h 125 °C), moisture soak (40 h 60 °C 60%RH) and convection reflow (260 °C).

3.2. Analyses

3.2.1. Wire pull and ball shear analysis

Ball shear data were obtained using a Dage BT-2400PC tester with a BS500 load cartridge. The shear speed was set to 100 μm per second at a shear height of 3 μm above the bond pad. Due to the low squash height encountered in fine pitch balls, this is sheared within the range of the fully-grown intermetallics. The shear tools were K and S Microswiss hard metal tools of 75 μm and 100 μm tip width.

Pull tests were performed on the BT-2400PC tester with a WP100 pull cartridge.

3.2.2. Delamination increase analysis

In order to quantify the change in each interface delamination (resin/die, resin/lead frame and total delamination in whole package) as a result of harsh environmental conditions exposure, samples were examined by scanning acoustic microscopy (SAM) before and after test, then

Table 1
DO1 experiments flow

No batch	Preconditioning, HAST & thermal shocks (DOE1)	Total stress
1	TS −55/125 °C 45 cycles & HAST 130 °C/85% RH 96 h	–
2	TS −55/125 °C 15 cycles & HAST 130 °C/85% RH 192 h	–
3	TS −55/125 °C 15 cycles & HAST 100 °C/85% RH 96 h & TS −55/125 °C 30 cycles & HAST 100 °C/85% RH 96 h	TS −55/125 °C 45 cycles & HAST 100 °C/85% RH 192 h
3 bis	TS −55/125 °C 15 cycles & HAST 100 °C/85% RH 96 h	–
4	TS −65/150 °C 45 cycles & HAST 100 °C/85% RH 96 h	–
5	TS −65/155 °C 15 cycles & HAST 100 °C/85% RH 192 h	–
6	TS −65/155 °C 15 cycles & HAST 130 °C/85% RH 96 h & TS −65/155 °C 30 cycles & HAST 130 °C/85% RH 96 h	TS −65/155 °C 45 cycles & HAST 130 °C/85% RH 192 h
6 bis	TS −65/155 °C 15 cycles & HAST 130 °C/85% RH 96 h	

Table 2
DO2 experiments flow

No. batch	Preconditioning, HAST & Temperature strong (DOE2)
7	HTS 175 °C 840 h & HAST 130 °C/85% RH 168 h
7 bis	HTS 175 °C 840 h & HAST 130 °C/85% RH 48 h
8	HTS 175 °C 336 h & HAST 130 °C/85% RH 168 h
8 bis	HTS 175 °C 336 h & HAST 130 °C/85% RH 48 h

the delamination percentage was monitored for each interface at all the read out points.

An overview of the Acoustic Microscopy screening technique can be found in Ref. [8]. The delamination analysis is based on the C-Scan measurement mode, this C-Scan mode or pulse echo provides a planar image at specific depth.

It is common practice to present A-scan (ultrasonic waveforms) displays next to the C-Scan images as a confirmation that the microscope is set correctly. A-scan depicts the phase inversion detection. The phase is determined by the acoustic impedance ($Z = P \cdot V$, where P is the density and V is the material velocity). The detection of phase inversion is described on the image from C-Scan analysis by a dark or white pixel (Fig. 1a).

The determination of the real percentage of delaminated area was based on two steps: on the one hand the creation of template corresponding to the interface area was done by the template concept (Fig. 1b); on another hand the quantification concept aimed to estimate the percentage value of the delaminated area was used.

For "template concept", templates are used to define areas within the image for analysis. In "quantification concept", the quantification translates mainly the dark pixels amount in the image provided by the C-Scan analysis representing the phase inversion, contained in the interface area predefined by the template concept, in the delaminated area percentage. This follows an algorithm achieved by SONIX®. This methodology of the delamination percentage measurement is available in all acoustic microscopes.

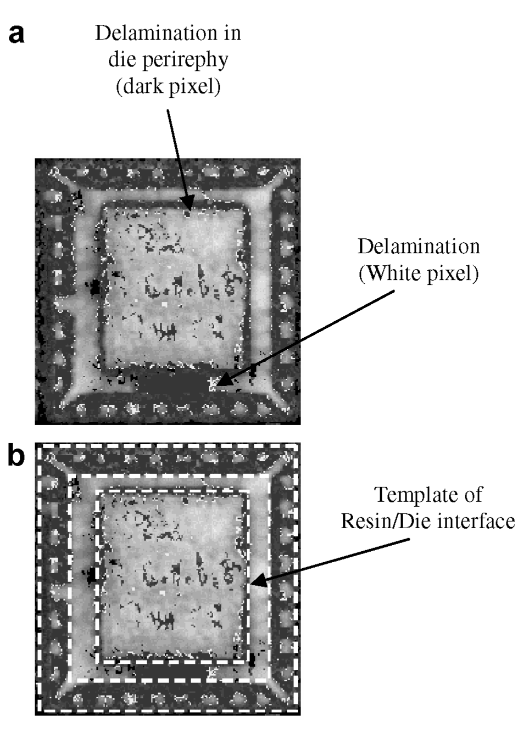

Fig. 1. C-SCAN image. (a) Delaminated area: red and yellow pixels; (b) image with templates, the hatched surface is lead to region of interest: the resin/die interface. For intrepretation of the figure in colour the author is referred to the web version of this article.

4. Analysis of the delamination results

During all our stresses, no electrical failure was detected. Mechanical tests (wire pull and ball shear strength measurements) did not show any significant variation. This is certainly due to the fact that the ball bonds remained in the plastic deformation domain of the Wöhler curve (the usual fatigue domain is not yet reached). The average value for mechanical tests was 8.81 (gm) for wire pull and 43.16 (gF) for ball shear.

The most significant results concerning the effect of the combined environmental stresses on the package reliability are those revealed by the CSAM observation. The delamination percentage was monitored for each interface (resin/die, resin/lead frame and package) at all the read out points.

Only the resin/die interface delamination results are illustrated in this paper (Figs. 2 and 4 are referred respectively to DOE1 and the DOE2 results). We got the same findings from the analysis of the other interfaces.

4.1. DOE1 analysis (preconditioning, TS and HAST)

4.1.1. Thermal shocks effect

The number of cycles has low effect on the increase of the delamination. On the other hand the higher the amplitude of the applied stress is, the higher the delamination is. Even if this is not a surprising result, this is due to two phenomena.

Firstly, the thermo-mechanical stresses level is higher at −65/150 °C than at −55/125 °C due to the difference between the CTE of the various materials, thus reporting on the one hand the temperature swing effect, commonly used as a major acceleration factor and reflects on the other hand that the higher the magnitude of the extreme cold temperature is, the lower the fracture toughness of plastic is. Thus the delamination is carried out more promptly.

Secondly, in both cases, the maximum temperature is above T_g (100 °C). This is also the case of the temperature used in the application. The acceleration factors of the mechanisms activated at these temperatures may be higher, as depicted in [6]. In another words, the ageing at 125 °C and at 150 °C are due to the same mechanisms, but an small increase of the testing temperature leads to a large acceleration of the ageing. Acceleration factors have to be quantified in a further work.

4.1.2. HAST effect

The duration was found to be a more significant factor than the applied temperature.

In wet/pressurized environment, the delamination at the resin/die interface generally occurs or grows only when the temperature of a die is close to or exceeds T_g, this due to the presence of compressive stresses at this interface [2]. It is absolutely the case for these combined stresses of this DOE1, as in our experiment we measured a glass transition temperature of about 100 °C in the initial state.

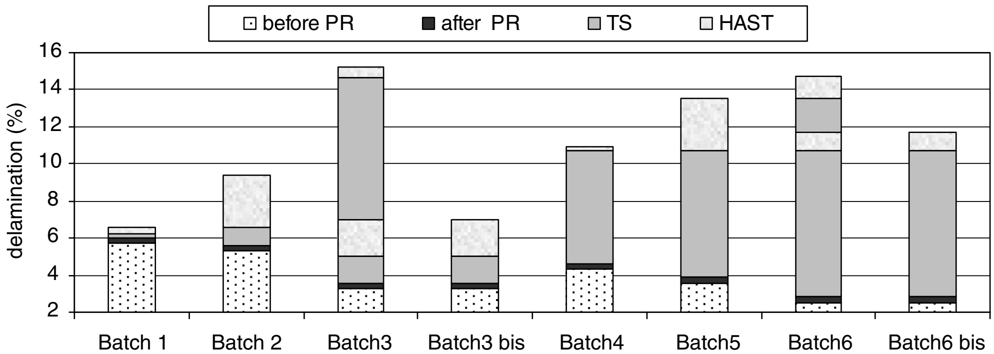

Fig. 2. Percentage of delamination at resin/die interface (average).

Moreover, from Ref. [2], relating an average decrease of T_g about 15 °C after humidity testing of PEMs (100 h at 85% RH and 130 °C) due to the plasticizing effect of moisture in polymers, we assume that all thermal storage levels in our HAST conditions are in reality above the T_g reduced in that hypothesis to about 85 °C.

This would explain the delamination increase during humidity testing (96 h or 192 h at 85% RH and 100 °C).

4.1.3. Effects of interaction

Another significant factor is the interaction between Thermal Shock amplitude and HAST conditions (see Fig. 3). When alternating thermal shocks amplitude with HAST conditions, the delamination increases.

But the order of the tests in the combination of the environmental stresses plays also a very important role on the delaminations increase.

When alternating TS with HAST tests increase the delamination, which mainly occurs during the TS phase. In a same manner, alternating HAST tests with TS, leads to see the same behavior, but on the HAST delamination increase.

For example, when a sequentially thermal shocks test is applied, such as on batch1 (45 cycles + HAST), 45 cycles of thermal shocks lead the delaminations increase to 0.19%, but alternating these same thermal shocks by the interposition of a HAST test , such as on batch3 (15 cycles + HAST + 30 cycles ~ 45cycles), lead the delaminations increase to 9.14%. The same effect is observed when the higher thermal shocks amplitude is (such as the comparison between batch 4 and 6). The moisture absorption leads to an acceleration of the delamination. This is similar to what was observed in [7] on 14 lead PIDIPs encapsulated in novolac compounds where the delamination increase can be accelerated in thermal shock or cycle test if parts are initially pre-soaked. The accelerating of the delamination increase, could lead to accelerate the degradation mechanism, also implying a higher failure rate. This acceleration also depends of the nature of the moulding compound.

Thus we can conclude that this combined stress type is more effective than an applied single stress in identifying failures within a short time.

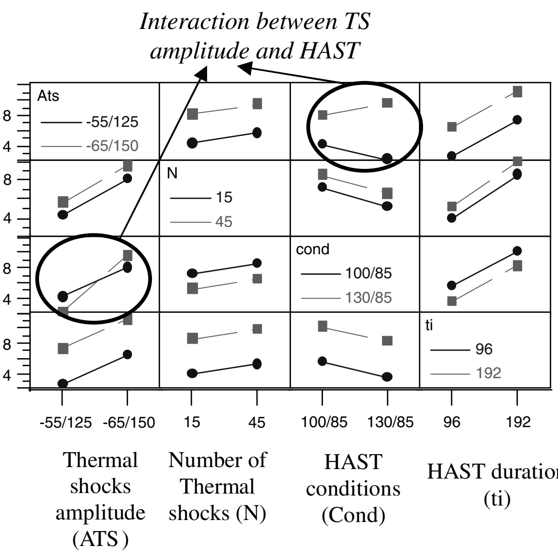

Fig. 3. Interaction graph for delamination resin/die interface (%).

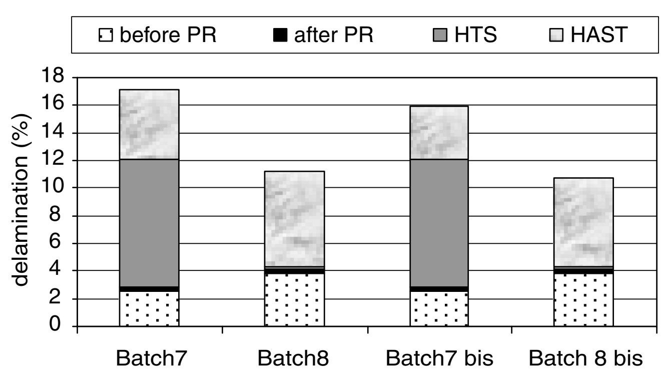

Fig. 4. Percentage of delamination at resin/die interface (average).

4.2. DOE2 analysis (preconditioning, HTS and HAST)

4.2.1. High thermal storage effect

Longer duration of the HTS leads to increased delamination. Teverovsky [1,2] noticed that, for various resins, long-term HTS (above the typical T_g) increases T_g by about 15 °C and decreases the CTE by about 20%. This increase of T_g and decrease of the CTE indicates that the resin continues polymerizing (additional cross-linking in the epoxy matrix). At 175 °C, the stabilization of the thermo-mechanical characteristics occurs after about 1000 h.

In our experimentation, the storage temperature (175 °C) is largely higher than the T_g of the resin (100 °C), and the longest duration (840 h) of our tests is shorter than 1000 h. Hence effects described in [2] (change in thermal and mechanical characteristics of moulding compound) may occur. This reduces the adhesion strength at the different interfaces resin/die and resin/lead frame, leading to an acceleration of the delamination increase at these interfaces. Despite the thermo-mechanical characteristic degradation of the resin, no acceleration and no introduction of new failure mechanism was identified.

The thermal storage duration can be considered as one of the most influential factors on the delamination increase. It would absolutely not be the case if the resin were completely polymerized; this would lead to no degradation of thermo-mechanical characteristics of the resin.

4.2.2. HAST effect

The wet/pressurized environment is more constraining than a dry environment. Thus, short duration storage at low temperature increases more the delamination than longer duration storage at high temperature in a dry environment.

4.2.3. Effects of interaction

No interaction has been found for this stress test combination.

5. Conclusion (optimized package sequential tests to package qualification)

Using the delamination measurement as an indicator of potential assembly weaknesses, our result show that:

- Combined stresses may increase the test acceleration.
- The alternate combined stress (Pr + TS + HAST) is more constraining than the sequential combined stress (Pr + HTS + HAST), and is much faster. This is due to the interaction effect between the thermal shock amplitude and the HAST conditions.
- The impact of the different test parameters on the delamination increase can be classified as follows: (1) thermal storage duration in dry environment, (2) duration in a wet/pressurized environment, (3) thermal shock amplitude, (4) interaction between the thermal shock amplitude and the HAST conditions and (5) HAST conditions. Thanks to these findings, we propose 2 optimized package sequential tests for package qualification. The first one, which refers to soft ageing conditions, is a test sequence that may only accelerate relevant failure mechanisms. As a consequence no defect should be noticed for a robust assembly process. It takes into account that the highest temperature of TS might be close to or lower than the T_g of the molding compound, to avoid the possible introduction of new failure mechanisms.
- Soft ageing: PR + TS −55/125 °C 15 cycles + HAST 100 °C/85% 96 h + HTS 175 °C 500 h.
  The second one is a fast ageing sequence, to optimize the failure acceleration in prospect of failure driven evaluation.
- Fast ageing: PR + TS −65/150 °C 15 cycles + HAST 100 °C/85% 192 h + HTS 175 °C 1000 h.
  These sequential test methods satisfy two critical objectives of an automotive qualification: the anticipation of potential failures and fast time to market.

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