Some Characteristics of Anisotropic Conductive and Non-conductive Adhesive Flip Chip on Flex Interconnections

J. F.J.M.Caers, J.W.C. de Vries, X.J.Zhao, and E.H.Wong

Abstract— **In this study, some characteristics of conductive and non-conductive adhesive interconnections are derived, based on data from literature and own projects. Assembly of flip chip on flex is taken as a carrier. Potential failure mechanisms of adhesive interconnections reported in literature are reviewed. Some methods that can be used to evaluate the quality of adhesive interconnections and to evaluate their aging behavior are given. Possible finite element simulation approaches are introduced and the required critical materials properties are summarized. Response to temperature and moisture, resistance to reflow soldering and resistance to rapid change in temperature and humidity are elaborated. The effect of post cure during accelerated testing is discussed. This study shows that only a combined approach using finite element simulations, and use of appropriate experimental evaluation methods can result in revealing, understanding and quantifying the complex degradation mechanisms of adhesive interconnections during aging.**

Index Terms— **reliability, flip chip, soldering, post cure, delamination**

I. INTRODUCTION

Using conductive or non-conductive adhesives instead of solder, can have distinct advantages e.g. for flip chip assemblies on flex or on board. Adhesive interconnects offer a simple and Pb-free process with fine pitch capabilities (40μm and below). Typical bonding conditions for adhesive interconnections are a bonding temperature between 200°C and 220°C, a bonding pressure of 10N per bump and a bonding time of 5 to 20 sec. The assembly technology with conductive and non-conductive adhesives plays an increasingly important role in new electronic products and semiconductor modules. Although this technology is already widely used, e.g. for drivers of liquid crystal displays, the degradation mechanisms are not completely documented and aging kinetics are poorly understood. As a result, proper reliability assessment for any new application is impossible. The growing interest in adhesively bonded interconnections in electronic packages makes it important to study their characteristic behavior in more detail. In particular this applies to the quality and reliability aspects. The most appropriate way to do this is to combine the life cycle load profile of the product in the application with its design and with the properties of the materials. From this, a draft of potential damage modes for the product can be made and a tailored test program can be designed. Together with failure analyses the failure mechanism that is most likely to happen, can be disclosed and the aging kinetics can be derived.

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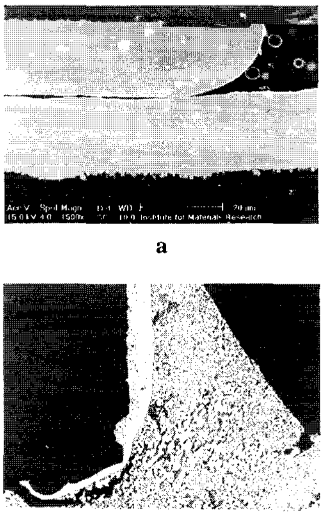
II. POTENTIAL FAILURE MECHANISMS

In contrast to soldered interconnections, where a real metallurgical joint is formed in the liquid phase, adhesive joints are very well comparable with non-permanent pressure contacts. A contact pressure is built up during the bonding process by the bonding force and the shrinkage of the adhesive during curing. The contact pressure will increase further during cooling down to room temperature because of the mismatch in coefficient of thermal expansion (CTE) between the adhesive and the contacting metals (bump and track). Because of the different character of solder and adhesive interconnections, the failure modes and mechanisms will be different too. Figure 1 illustrates the different failure mode for a solder joint and for an anisotropic conductive adhesive interconnection in a temperature cycle test.

Figure 1a shows a cross-section of a flip chip on flex interconnection; Figure 1b shows a cross-section of a solder joint of a chip resistor. In the solder joint, a coarsening of the microstructure is observed in the area with the highest strain during the temperature cycle test. Cracks are initiated in this area and eventually grow to a catastrophic failure. In the adhesive interconnect, no real damage can be observed, despite the increased electrical resistance of the contact; the damage mechanism is probably a decreased contact pressure.



a

b

Fig. 1 Comparison of the degradation of anisotropic conductive adhesives (a) and solder interconnections (b) under cyclic temperature loading

For adhesive interconnects, the relationship between contact pressure and contact resistance has been extensively studied. Wu *et al.* [1] derived a logarithmic relationship, capable of addressing the conducting phenomena for both rigid and deformable particle systems. Caers *et al.* [2] report an exponential relationship, based on experiments. Based on these relationships, it can be expected that every factor leading to a decreasing contact pressure will hence negatively influence the electrical conductivity of the interconnection. These can be swelling of the adhesive because of moisture ingress [2,3,4], thermal degradation of the interface [5,6], stress relaxation of the adhesive [2], cracks in the adhesive and delamination [3] and water-induced reduction of the bond strength through hydratation [7,8]. Moisture ingress can also cause corrosion of the bumps, tracks or conductive particles inside the adhesive, which can result in a direct increase in contact resistance [3,4,6,7,9,10]. Likewise, the presence of air bubbles close to the bumps weakens the bonding strength [14]. Temperature excursion can also lead to contact degradation due to local and global mismatch in coefficient of thermal expansion (CTE) [3,7,8,9,10,11,12,13,14]. The local mismatch is caused by a different CTE between adhesive and substrate, adhesive and bump, as well as adhesive and die; the global mismatch is caused by the different CTE between die and substrate. Adding non-conductive filler particles to the adhesive matrix can be used to reduce the local CTE mismatch [8]. Further, the type of bumps in combination with the type of conductive particles and type of substrate [4], and the co-planarity of the substrates and the bumps [14], are important factors on the quality of contact. For anisotropic conductive adhesives, the elasticity of the filler is beneficial in maintaining mechanical contact between the filler and the bump/pad in case of stress relaxation of the adhesive [10,14]. A similar effect can also be obtained if the adhesive contains hard conductive particles, which penetrate the bump or track [10]. Preventing the assembly from bending increases the robustness of the interconnection [4].

It thus clearly transpires that temperature and humidity are two of the major influence factors that determine the durability of adhesive interconnections. Real transforms relating field conditions with accelerated test conditions and vice versa are not well established, however.

III. EVALUATION METHODS

From the potential failure mechanisms, it is clear that the contact pressure is a key parameter. Test dice are available to measure stresses in x- and y-direction [15]. It is very difficult, however, to measure the z-component with this kind of test dice. On the other hand, the electrical contact resistance is a direct and functional criterion for the actual contact quality. The electrical contact resistance can be monitored off-line or on-line, during accelerated testing. An example of a test structure with peripheral bond pads at a 300µm pitch is given in Figure 2. In Figure 2, the black lines represent the metallization on the die. The test structure allows measuring the contact integrity of a series of bumps in a daisy chain (between "in" and "out"). The test structure shown contains also 4 positions to measure the contact resistance of one bump interconnection, using a four-wire method.

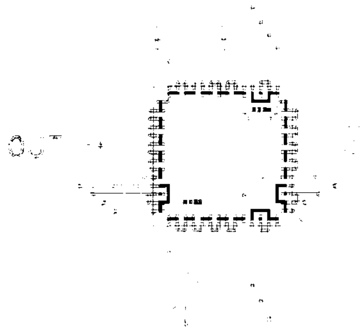
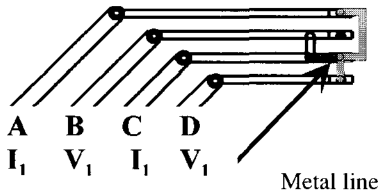


Fig. 2. Test structure for the daisy chain and for the four-wire contact resistance measurement.



Metal line contributing to the measured contact

Fig. 3. Detail of the test structure to measure the contact resistance of one bump interconnection.

A detail of the test structure to measure the contact resistance with the four-wire method is given in Figure 3. As shown in Figure 3, the contact resistance measurement with this test structure includes the resistance of a short length of copper rack on the substrate.

Acoustic microscopy and X-ray can detect delamination at any interface and voids in the adhesive. Infrared microscopy can also be used for this purpose, making use of the transparency of silicon at 1100nm (see Figure 4) [16].

An example of "passive" infrared microscopy for flip chip on flex is given in Figure 5, showing delamination at one of the corners of the die. A drawback of the method is that the backside of the die has to be polished to achieve enough resolution. Also the area close to bump is masked by the die metallization. In the "active mode", the method can be used to detect an increased contact resistance in a non-destructive way [17]. In the "active" mode, a current is forced through the daisy chain. An infrared detector is used to monitor hot spots, due to a local increased resistance. For the "active" mode, the surface quality of the backside of the die is not critical.

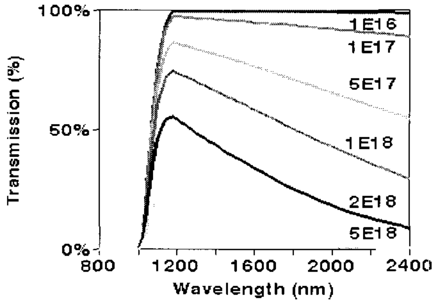
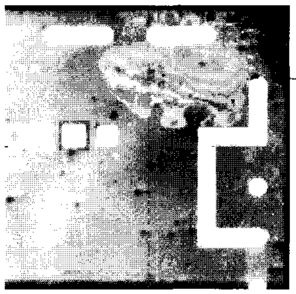


Fig. 4. Transmission calculated through 0.7mm Si for different doping levels.



delamination

Fig. 5. Delamination at the die corner in a flip chip on flex assembly shown by infrared microscopy.

Jongen *et al.* [18] claim that the increase in the low-frequency noise of the interconnection is a more sensitive criterion compared to a DC measurement, in studying the degradation of adhesive interconnections.

IV. MATERIAL PROPERTIES

Some characteristic material properties of a Namics non-conductive adhesive are summarized in table 1.

Table 1. Summary of material properties of a Namics adhesive.

Description			Result
Chemical	$T_{decomp.}$ Residue	°C wt%	379 28
Thermo-mechanical	CTE1 CTE2 Tg E@25°C	ppm/°C ppm/°C °C GPa	60 172 153 (DMA), 118 (TMA) 3.3
Moisture	Diffusivity @ 30°C/60%RH 85°C/60%RH 85°C/85%RH	cm^2/s	2.57E-09 4.99E-08 3.87E-08
	Csat @ 30°C/60%RH 85°C/60%RH 85°C/85%RH	mg/cm^3	18.9 15.0 26.5
	CME @ 85°C 120°C 170°C 220°C		0.25 0.45 0.55 0.57

In addition to the thermo-mechanical properties and the moisture diffusion properties listed in table 1, stress relaxation properties and curing properties are important. For thermo-rheological-simple materials, a time-temperature superposition can be used to describe the time and temperature dependant relaxation modulus

$$E(t, T_r) = E(\varsigma, T) \quad \text{eq (1)}$$

where t and T_r are the reference time and reference temperature respectively; ς and T are the reduced time and temperature respectively. The time-temperature shift factor a_T defined as

$$a_T = t / \varsigma \quad \text{eq (2)}$$

is a function of temperature and is usually described with WLF equation

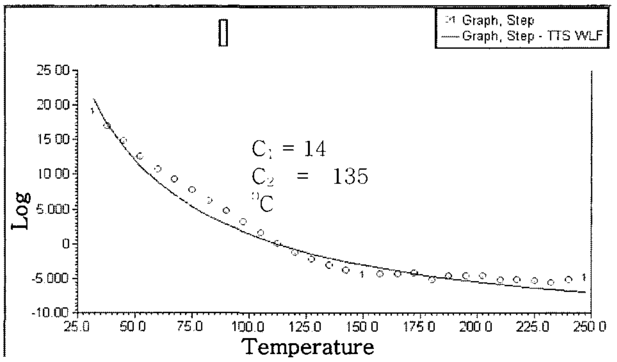


Fig. 6. Time-temperature shift curve for Namics adhesive.

$$\log(a_T) = -\frac{C_1(T - T_r)}{C_2 + (T - T_r)} \quad \text{eq (3)}$$

where C_1 and C_2 are material constants. The time-temperature shift curve for the Namics adhesive obtained from DMA multiplexing analysis is shown in Figure 6.

A key element in the bonding process is the shrinkage of the adhesive during curing. The contribution of the cure shrinkage to the eventual contact pressure between bump and track is important. Wu *et al.* [1] report how the dimensional change of the adhesive during curing can be measured from TMA. Caers *et al.* [2] show an experimental technique, developed to measure the cure force: a droplet of liquid adhesive is applied between two glass rods with low CTE. The adhesive is then cured with infrared heating. A micro-tester is used to measure the force required to keep the glass rods at a constant distance during the curing process. After proper correction for the local expansion of the glass rods, the cure force can be abstracted from this experiment.

V. FINITE ELEMENT SIMULATIONS

Finite element simulation is a very powerful tool to transform test results into performance in the field and to do parameter sensitivity studies. The assembly process plays an important role in the build-up of the contact pressure and should therefore be taken into account in the model. Some attempts have been made to simulate the complex behavior of conductive adhesive interconnects. A proper validation of the models, however, is very difficult. Rusanen *et al.* [12] have addressed the creep in adhesives. By letting the creep strain be a linear function of time, the authors relate the number of cycles to failure in a temperature cycle test to the applied strain through the Coffin-Manson-type equation.

In [2], an integrated modeling methodology has been developed in the commercial FE code ANSYS, that simulates the evolution of the contact pressure from the bonding process to subsequent stress relaxation due to exposure to steady state temperature-humidity conditions. For process modeling, a 2-D axisymmetric finite element model is used. The process modeling part is integrated into the aging modeling. From FEM simulations, it is shown that the adhesive interconnection is very stable under steady state 85°C/85%RH conditions.

Response to temperature and moisture

The contact resistance response of an adhesive interconnection to temperature and to moisture can be quantified by a temperature coefficient of the resistance (TCR) and a moisture coefficient of the resistance (MCR). These are respectively defined as:

$$TCR = \frac{R(T) - R(T_{ref})}{R(T_{ref})(T - T_{ref})} = \frac{dR/dT}{R(T_{ref})} eq \qquad (4)$$

$$MCR = \frac{R(T) - R(RH_{ref})}{R(RH_{ref})(RH - RH_{ref})} = \frac{dR/d(RH)}{R(RH_{ref})} eq \qquad (5)$$

The contact resistance response of an adhesive interconnection to temperature and moisture, at 30^{0}C and 85%RH, for two typical adhesives are tabulated in Table 2 & 3. Note that these responses are dependent on the contact pressure between the bump and the pad. The TCR can be calculated from measuring the resistance during ramping up or dawn of the temperature. Increasing or decreasing the humidity at a constant temperature level can obtain the MCR.

"*MCR down*" in table 3 means that the MCR is based on driving the moisture out by changing the environment at 85°C from 85%RH to 30%RH. Similar, "*MCR up*" is based on in-diffusion of moisture, while increasing the relative humidity from 30% to 85%. Compared to the direct response of the adhesive interconnect to temperature, the direct response to moisture is much smaller. The response to moisture is also more complex than to temperature, clearly showing a difference between moisture in-diffusion and moisture out-diffusion.

Table 2. Typical responses to temperature at 30°C.

Adhesive	TCR [°C^{-1}]	dR/dT [μOhm/°C]
NCP1	2.78 x 10^{-3}	4.09
NCP2	2.70 x 10^{-3}	4.01

Table 3. Typical responses to humidity at 85%RH.

Adhesive	MCR down [RH^{-1}]	dR/d(RH) [μΩ/RH]	MCR up [RH^{-1}]	dR/d(RH) [μΩ/RH]
NCP1	7.5 x 10^{-5}	0.14	1.8 x 10^{-4}	0.34
NCP2	6.5 x 10^{-5}	0.13	1.2 x 10^{-4}	0.23

A typical result of the evolution of the contact resistance during a steady state damp heat testing at 85°C/85%RH conditions, according to IEC 60068-2-3, test Ca, is shown in Figure 7. The contact resistance measurement is done on-line. The test structure is as indicated in Figures 2 and 3. To calculate the resistance increase, the values over the last 24 hours of testing are averaged and compared to the average during the first hours of testing, after the test conditions and the resistance are stabilized. As expected from the finite element simulations, the contact resistance is very stable under 85°C/85%RH. A summary of the results of the damp heat test is given in table 4 and in Figure 8, in the format of a cumulative distribution plot.

Driving the moisture in and out in a cyclic way results in a higher aging rate compared to the steady state aging. A typical example of the resistance drift during a cyclic humidity test is shown in Figure 9. During the test, the

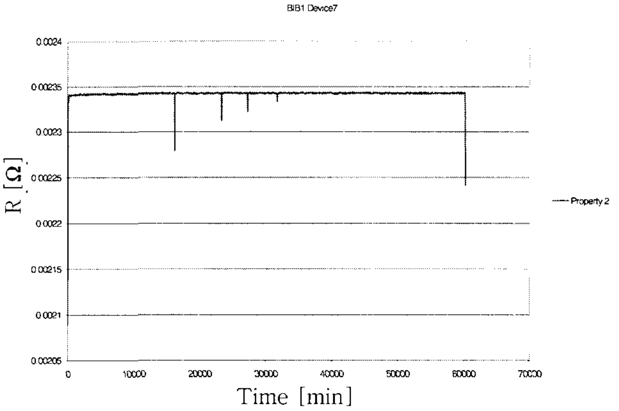


Fig. 7. Evolution of the contact resistance during steady state damp heat at 85°C/85%RH conditions.

Table 4. Median increase of resistance for FCOF in 85°C/85%RH conditions.

Time [hours]	Median resistance drift [ppm]
200 1000	200 1000

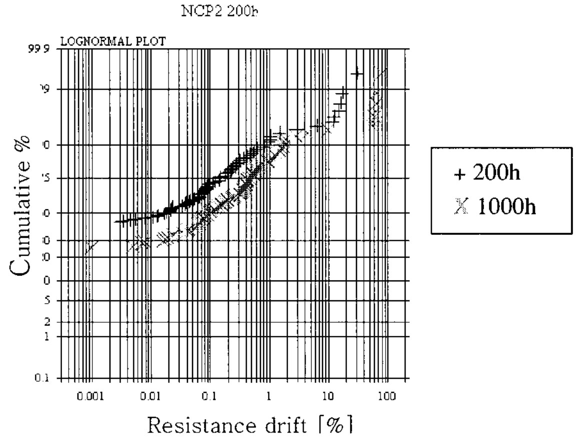


Fig. 8. Cumulative distribution plot of the resistance drift after 200h and 1000h @85°C/85%RH.

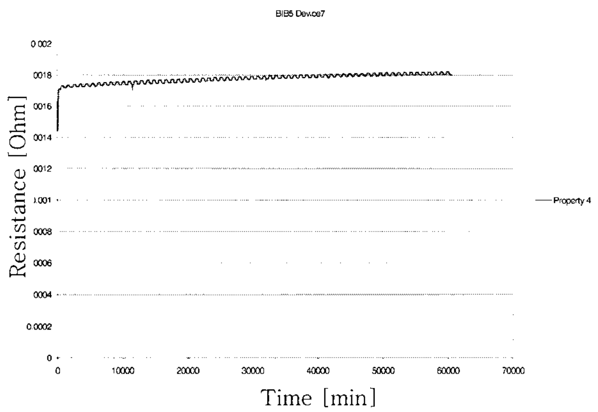


Fig. 9. Typical response to cyclic humidity test @ 85°C.

temperature is fixed at 85°C and humidity is cycled between 30%RH and 85%RH. Figure 9 shows clearly the response of the adhesive interconnect to the humidity cycles, every dimple in the curve being a humidity cycle. The median response is 8 to 10μOhm. The cycle time in the test is 16 hours, with 6 hours dwell time at 85%RH and at 30%RH. A comparison of the aging rate in steady state and cyclic humidity is shown in Figure 10, in the format of cumulative distributions. The comparison is made after 200h of testing. From Figure 10, it can be seen that the cyclic humidity test increases the rate of resistance drift by an order of magnitude compared with the steady state humidity test: the median resistance drift after 200h increases from 0.02% to 0.4%.

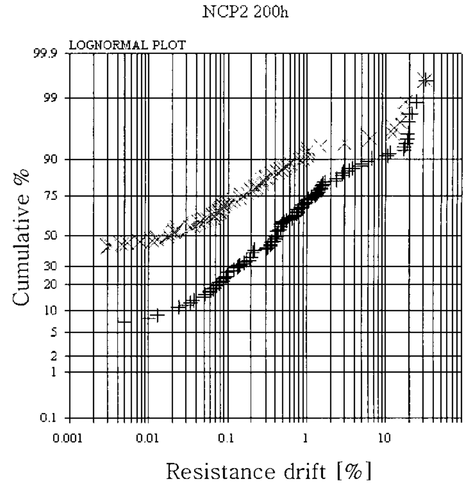


Fig. 10. Comparison of resistance drift in cyclic humidity (+) and steady state humidity (X) after 200h testing.

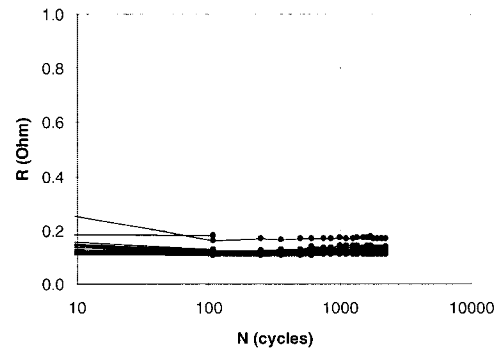


Fig. 11. Resistance drift in temperature shock test between –55 and +125°C.

The adhesive interconnects withstand very well cyclic temperature loadings. An example is given in Figure 11. Hardly an increase in resistance is observed after 1000 temperature shock cycles between -55°C and +125°C. The results shown in Figure 11 are obtained after preconditioning for 192h at 30°C/60%RH, followed by 3 times a eutectic Sn-Pb solder profile.

VI. RESISTANCE TO REFLOW SOLDERING

Flip chip on flex interconnections with (non-) conductive adhesives are attractive for semiconductor modules because of the fine pitch capabilities. Therefore,

(a) predried 85°C/24h

(b) soaked @ 85°C/85%RH, 24h

Fig. 12. Effect of preconditioning on the delamination of the adhesive in a damp heat test at 85°C/85%RH for 1000h.

they have to resist a solder reflow step for the next interconnection level. Moreover, the reflow process should not weaken the adhesive interconnection in order to meet field requirements. This has been a traditional weakness of adhesive interconnects. Figure 12 shows the effect of the preconditioning on the delamination of the adhesive after 3x exposure to a eutectic Sn-Pb solder reflow profile of a flip chip on flex assembly, followed by an exposure of 1000 h to 85°C/85%RH. It is shown that the 24h preconditioning at 85°C/85%RH results in considerably more delamination compared to the pre-dried samples. In Figure 12, delamination is observed with an optical microscope from the backside of the transparent foil.

VII. POST-CURE DURING ACCELERATED TESTING

Sometimes, a decrease in contact resistance is observed, during accelerated testing, mainly during the first hours of aging. An example is shown in Figure 13. The same trend can be seen in Figure 11. Most likely, this is due to a post cure effect of the adhesive. If post-cure of the adhesive is observed, two competing mechanisms are involved: the post-cure that increases the robustness of the interconnection and the degradation of the interconnection from aging. In the field, however, the post-cure might not occur. Therefore, if post-cure is observed in an accelerated test, the outcome of the test might be unrealistic and too optimistic.

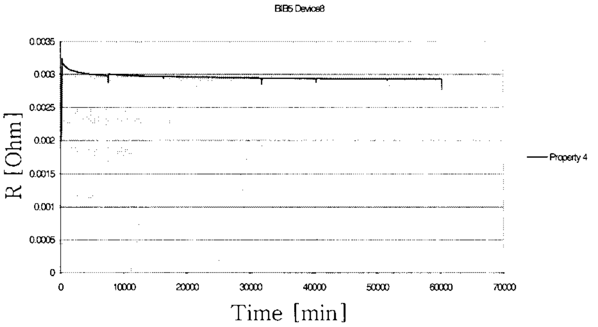


Fig. 13. Decrease of the contact resistance at 85°C/85%RH.

Resistance to rapid change in temperature and humidity

A different result between off-line and on-line measurement has been observed in a steady state damp heat test e.g. at 85°C/85%RH [19,20]: the on-line monitored samples showed hardly any increase in resistance; the off-line monitored samples taken from the same assembly batch, however, showed a clear increase in resistance. In these publications, this has been explained by a cyclic effect of in-and out-diffusion of the moisture by taking the samples out of the test chamber and putting them back during the test. On top of this, the samples get a temperature cycle, every time they are taken out of the chamber for measuring and put back. A similar phenomenon has been observed for some samples, when the test chamber was opened because of a technical problem with the system, during cyclic humidity testing at 85°C with on-line monitoring of the resistance. An example is given in Figure 14. Before

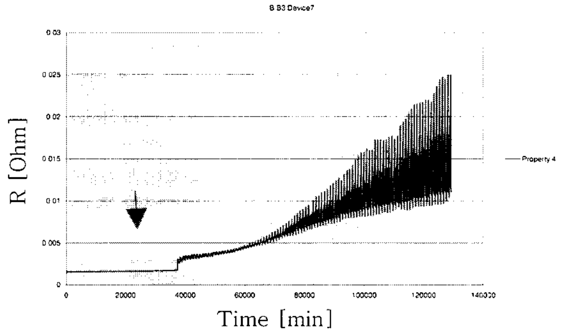


Fig. 14. Sudden increase of the resistance after opening of the test chamber at 85°C/85%RH.

opening, the resistance was very stable. After opening, a sharp increase in resistance was observed and degradation of the interconnection started to be much more pronounced. This phenomenon was mainly observed for contacts that had initially already a higher resistance.

VIII. DISCUSSION

From finite element simulations and experiments, it has been shown that non-conductive adhesive interconnects are very stable under steady state humidity conditions. The mean contact resistance drift rate, based on the current experiments is approx. 1ppm/h at 85°C/85%RH conditions. The corresponding mechanism behind this is most likely stress relaxation in the adhesive. A simplified transform towards other steady state conditions can be obtained from a time/temperature shift curve as shown in Figure 6, if relative humidity is not higher than 85%. According to Figure 6, 1000 test hours at 85°C/85%RH, is equivalent with $10^{12.5}$ or 3.6 x 10^{12} times 1000h at assumed field conditions of 30°C/85%RH. This transformation is only valid if the failure mode doesn't change in time and remains stress relaxation in the adhesive. Based on Figure 6, it is shown that a HAST test at 100°C/85%RH can reduce the test time by a factor of 10^5, compared to a damp heat test at 85°C/85%RH. Drawbacks of HAST conditions, however, are the higher temperature, which is closer to the glass transition temperature of the adhesives, the risk to evoke different failure mechanisms e.g. delamination, and the higher risk of post-cure of the adhesive during the accelerated test.

The resistance of adhesive interconnections to cyclic temperature is good. First attempts are found in literature to relate the results of a temperature cycle test to the expected performance in the field.

From a comparison between table 2 and 3, it is shown that the resistance response of the adhesive interconnects to moisture is much smaller than to temperature. Based on this observation, one would expect a much faster degradation in a temperature shock test than in a cyclic humidity test, which is not the case, as shown in Figure 11. Although the measuring resolution for the samples from the damp heat test in Figures 9 and 10 and the T-shock test in Figure 11 are completely different, and some post-cure may have happened during the T-shock test, this means probably, that the measured response to temperature of approx. 4μΩ/°C is mainly from the temperature coefficient of the bump and of the track and only to a small extent from the pressure contact itself. The moisture response of approx. 0.3 μΩ/%RH is only due to the moisture effect on the pressure contact, as temperature was kept constant at 85°C during the experiment.

From the results, it is shown that adhesive interconnects are more susceptible to cyclic moisture or sudden changes in temperature and/or humidity compared with steady state temperature and humidity conditions. The mechanism behind this phenomenon is not understood yet. As a result, there is no transform available.

Historically, the resistance to reflow solder profile is problematic. Recent results, however, show that the latest developed adhesives are much more robust in this respect [21].

Experiments have shown that adhesive interconnects have complex aging mechanisms, especially for moisture. Also a larger spread is observed in time to failure, compared to soldered interconnections. This is a major challenge for this type of interconnections. An example of a cumulative failure distribution of a flip chip on flex assembly with non-conductive adhesive in a cyclic humidity test at 85°C is given in Figure 15. A lognormal distribution is assumed. An increase of the resistance of

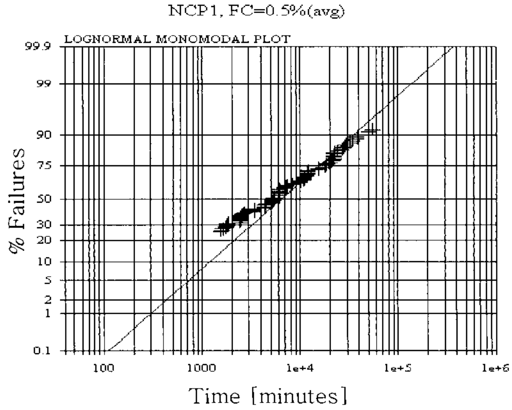


Fig. 15. Cumulative failure distribution of flip chip on flex with non-conductive adhesive in a cyclic humidity test.

0.5% is taken as failure criterion. The inverse of the slope of the line in Figure 15, is called the shape parameter, and is indicative for the width of the distribution. For the distribution shown in Figure 15, the shape parameter is approx. 1.3. The shape parameter for underfilled flip chip on board assemblies with solder bumps, subjected to a T-cycle test is typically 0.2 to 0.3, indicating a much narrower failure distribution.

Possible factors contributing to this are co-planarity of bonding tool and substrate during assembly, height differences of bumps and/or tracks over the die, contamination at one of the interfaces, adhesive residues between the bumps, and misalignment of the die. As the bonding time is very short, small variations may cause differences in the degree of curing of the adhesive, affecting the robustness of the interconnections.

Post cure effects during accelerated testing should be avoided. If it is desirable for specific applications to use an adhesive that is not fully cured, e.g. to increase the resistance to mechanical shock (see e.g. [22]), conditions for accelerated testing should be adapted accordingly.

This study shows that a combination of finite element simulations, proper material characterization and on-line measurement of the contact resistance drift, provides a very powerful tool to reveal, to understand and to quantify the degradation mechanisms during aging.

IX. CONCLUSIONS

Based upon literature and experiments on flip chip on flex interconnections with conductive and non-conductive adhesives, some characteristics of this type of interconnects are revealed. Te behavior of adhesive interconnects is quite complex but they are very robust in steady state temperature/humidity conditions and cyclic temperature conditions. Typical response to temperature and to moisture can be characterized by the temperature coefficient of the resistance and the moisture coefficient of the resistance. To a first approximation, the time/temperature shift curve can be used to relate the results from a steady state damp heat test to field performance under steady state temperature and humidity conditions. For cyclic temperature loading, a transform can be found in literature, based on a Coffin-Manson type approach.

Adhesive interconnects are more sensitive to cyclic humidity and to sudden changes in humidity and temperature. This phenomenon is not understood yet and requires more detailed study. Reflow soldering e.g. for the next interconnection level, can weaken the adhesive interconnects. Post-curing of the adhesive during accelerated testing has to be avoided.

This study shows that a combination of finite element simulations, proper material characterization and on-line measurement of the contact resistance drift, provides a very powerful tool to reveal, to understand and to quantify the degradation mechanisms during aging,

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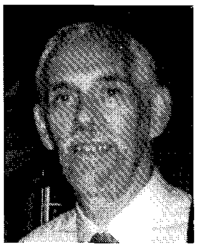

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