Macro-micro modelling of moisture induced stresses in an ACF flip chip assembly

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Abstract
Purpose – This paper discusses the use of modelling techniques to predict the reliability of an anisotropic conductive film (ACF) flip chip in a humid environment. The purpose of this modelling work is to understand the role that moisture plays in the failure of ACF flip chips.
Design/methodology/approach – A 3D macro-micro finite element modelling technique was used to determine the moisture diffusion and moisture induced stresses inside the ACF flip chip.
Findings – The results show that the ACF layer in the flip chip can be expected to be fully saturated with moisture after 3 h at 21°C, 100% RH, 2 atmosphere test conditions. The swelling effect of the adhesive due to this moisture absorption causes predominantly tensile stress at the interface between the adhesive and the metallization, which could cause a decrease in the contact area, and therefore an increase in the contact resistance.
Originality/value – This paper introduces a macro-micro modelling technique which enables more detailed 3D modelling analysis of an ACF flip chip than previously.

Keywords Modelling, Moisture, Electrical connections

Paper type Research paper

1. Introduction

With the trends in the requirements of electronic packaging toward higher I/O counts, greater performance, higher density, and lighter weight, flip chip is becoming an increasingly attractive technology. However, conventional lead-tin soldering is incompatible with extremely fine pitch interconnection and undesirable from an environmental point of view. Anisotropic conductive films (ACFs) are a key technology in addressing these issues, having been introduced as a promising flip chip interconnection material, due to its potential in achieving high density I/O interconnection, low-processing temperature and relatively mild impact on the environment (Liu, 1999). In particular, flip chip on flexible substrate (FCOF) assemblies using ACFs are now widely used in smart cards, disk drivers and driver chips for LCDs (Chan et al., 2000). A typical ACF interconnection system is shown in Figure 1.

In spite of the increasingly important role of ACFs in the assembly of electronic products, there are some concerns about the reliability of any device with ACFs in it. Among the many factors that affect the reliability of ACF devices, moisture is one of the most important ones. Previous experimental and modelling studies (Mercodo et al., 2003; Wei et al., 2002; Caers et al., 2003; Tan et al., 2003), have revealed that the reliability of ACF is strongly affected by moisture and it is considered to be the dominant factor in ACF flip chip failures.

However, previous modelling work (Mercodo et al., 2003; Wei et al., 2002; Caers et al., 2003) were mostly limited to the analysis of simplified 2D models and 3D effects were ignored. Even in the work in which a 3D model of an ACF joint was used, e.g. (Yin et al., 2004) the shear stress caused by mismatches in the coefficient of thermal expansion (CTE) could be underestimated because the global effect of the model was ignored. The difficulty here is that, due to the vast range of length-scales in an ACF assembly, and the large number of conducting particles, an “exact” model which includes all the particles and interconnections is simply not achievable with today’s computer technology.

In this paper, a 3D macro-micro modelling method was used to overcome the difficulty caused by the multi-length-scale nature of the problem. Two models, one macro and one micro, with very different mesh densities were built. The macro model was used to predict the overall behaviour of the whole assembly under humid conditions. The displacements obtained from this macro model were then used as the boundary conditions for the micro model so that the detailed stress analysis in the region of interest could be carried out.

2. Computer modelling

In order to allow comparison with related experimental work, a typical flip chip on flex (FCOF) assembly with an 11 × 3 × 1 mm chip and a total of 368 Ni-Au peripheral

The current issue and full text archive of this journal is available at www.emeraldinsight.com/0954-0911.htm

Soldering & Surface Mount Technology
18/2 (2006) 27-32
© Emerald Group Publishing Limited [ISSN 0954-0911]
[DOI: 10.1108/09540910610650107]

The authors would like to acknowledge their financial support from the University of Greenwich and City University of Hong Kong. C. Y. Yin would also like to thank Miss Sai Cheo Tan of City University of Hong Kong for her help with the SEM experiments and helpful discussions.
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Figure 1 A typical ACF interconnection system

pads was used throughout this analysis. The dimensions of the bumps were 50 × 50 × 20 μm. The conductive particles in the ACF were assumed to be nickel/gold coated polymer particles with a diameter of 3.5 μm. The substrate was 25 μm thick polyimide and the metal pads on the substrate are made of nickel-gold plated copper. The thicknesses are 12, 4 and 0.5 μm for the copper pad, nickel and gold coatings, respectively. The gold layer was neglected in the model. The layout of the chip is shown in Figure 2. PHYSICA, a multi-physics computational modelling package which uses both finite element and finite volume methods, has been used in this modelling work.

2.1 Methodology

The temperature, humidity and pressure in the autoclave test for this modelling work were 121°C, 100%RH and 2 atm, respectively. During the autoclave test, it is assumed that the moisture uptake in the materials follows Fick’s Law of Diffusion (Mercodo et al., 2003; Wei et al., 2002) (equation (1)).

\[ \frac{\partial C}{\partial t} = D \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} \right). \]

Where, C is the moisture concentration, describing how much moisture is absorbed by the material, and D is the coefficient of moisture diffusion, describing how fast the moisture diffuses through the material.

Unlike temperature distribution, which is continuous at material interfaces, the distribution of the moisture concentration C is discontinuous at material interfaces because the saturated concentration values are not the same for different materials. This problem can be easily solved by using the wetness fraction approach (Wong et al., 1998).

When the temperature changes in an assembly made of more than one material, stresses will build up due to the CTE mismatch. Similarly, when moisture absorption takes place in an ACF assembly, stresses will also build up due to mismatches in the coefficients of moisture expansion (CME) or variations in moisture content. These are called hygroscopic stresses. Assuming that the mechanical, thermal, and moisture induced strains are independent of each other, equation (2) shows that the mechanical strain is the total strain less the thermal strain and the hygro strain (Mercodo et al., 2003):

\[ e_{\text{mechanical}} = e_{\text{total}} - e_{\text{thermal}} - e_{\text{hygro}}. \]

The stresses can be calculated from equation (3):

\[ \sigma_k = \frac{\lambda e_k \delta_k}{1 - 2\nu} - \frac{E}{1 - 2\nu} (\alpha \Delta T) \delta_k - \frac{E}{1 - 2\nu} (\beta C) \delta_k. \]

Where, \( \lambda, \nu, E \) and \( \mu \) are the Lamé constant, Poisson’s ratio, Young’s modulus and shear modulus, respectively, \( \beta \) is the CME, \( \alpha \) is the CTE, \( \Delta T \) is the temperature change, and \( C \) is the moisture concentration. The moisture related properties used in this modelling work were based on the work described in Wei et al. (2002), Kim et al. (2004) and Jain et al. (2005).

Owing to the vast range of the length-scales in an ACF flip chip, a macro-micro modelling method was used in order to make the full-scale modelling analysis possible. This procedure consists of the following three steps:

1. Creating the global and local meshes: the global mesh refers to the mesh used to model the entire structure. The local mesh refers to the mesh that models the local area of interest and is a more detailed mesh, designed to capture the local variations in stress/strain.

2. Interpolation of displacements from the global solution: the displacement data along the boundary of the local area in the global mesh are interpolated here. The interpolation of data from the global mesh is necessary because there are fewer global nodes on the global-local boundary as compared to the number of nodes on the boundary of the local mesh.

3. Solution of the local problem: the interpolated displacements are now applied to the boundaries of the local model and the problem is solved.

Compared with previous finite element analyses using a single model, the computational effort for the macro-micro methodology is significantly reduced as a result of the model containing much fewer degrees of freedom, which makes the full-scale modelling analysis of an ACF flip chip possible. This modelling technique is thought to be the best approach when a large-scale structure is analyzed, but where localised small-scale features are crucial to the design performance (Voleti et al., 1996).

2.2 Global modelling

The macro model of the ACF flip chip is shown in Figure 3. Only one quarter of the package was simulated, due to the symmetry of the ACF package. The model consists of a total of 32,198 hexahedral elements.

ACF flip chip bonding is a complicated process which involves heat transfer, fluid flow and solid deformation (Whalley et al., 2001). In order to simplify the analysis, the residual stresses created in the bonding process were assumed to be negligible. This means that the model is stress free at the reference temperature. As a further assumption, all materials in the model were assumed to be homogenous, isotropic, and the temperature dependence of material properties was
neglected. All the materials were treated as elastic materials. The basic material properties used are given in Table I. The moisture-related properties of the ACF and polyimide substrate are listed in Table II.

The moisture diffusion analysis was coupled with the stress analysis so that the displacement field and the moisture concentration were solved simultaneously. Figure 4 shows the moisture fraction distribution in the ACF layer at 0.1, 1, and 3 h during the autoclave test. The results show the adhesive to be fully saturated with moisture after 3 h.

2.3 Local modelling
The conductive particles play an important role in the performance of ACF interconnections. They act as the electrical conductors, providing current paths, as well as physical parts connecting the chip bumps and substrate pads through mechanical deformation of the interfaces (Dou et al., 2003). Therefore, it is very important to understand the local stress distribution in an ACF joint, especially the area around the conductive particle. Such information has been achieved using the micro model.

The mesh information for the micro model is shown in Figure 5. This model represents an ACF joint attached to the corner of the flip chip, which is where the stress level is usually the highest. A representative conductive particle was included and finer elements were employed around the particle in order to capture the details of the stress distribution in and around the particle. A total of 23,376 elements were used in this micro model.

The displacement, temperature, and moisture concentration results from the macro model were used as the boundary conditions for the local model. In this work, the boundary mesh of the micro model is finer than in the corresponding parts of the macro model so the nodes of the two models do
not coincide at the boundaries. An interpolation technique was, therefore, used to transfer the result values from the macro model to the micro model’s boundary nodes.

2.4 Modelling results

The predicted Von-Mises stress distribution in the ACF joint due to moisture absorption is shown in Figure 6. A stress concentration was found at the interfaces between the adhesive and the bump/pad. The stress level is the highest around the spot where the pad, the flex substrate and adhesive meet. In experiments, this is usually the location where micro cracks are found as will be shown later.

The interfacial stresses along the top surface of the substrate pad are shown in Figure 7. It was found that both the normal and the shear stresses were higher in the area around the conductive particle. The shear stress is not significant compared to the normal stress, even though the modelled ACF joint is located at the corner of the flip chip. The loading conditions around the conductive particle are mostly tensile. This means that due to the moisture absorption of the adhesive, the ACF swelling effect pushes the die upwards, resulting in high stresses at the interface between the conductive particle and metallization. The electrical connections between conducting particles and the surrounding metallization are formed through the contact pressure caused by the elastic/plastic deformation of the particles. This contact pressure is maintained by the residual stress in the adhesive. Loss of the electrical contact may occur when the adhesive expands excessively in the vertical direction (Chan et al., 2000). An open circuit joint occurs when the contact area is completely lost.

The normal stress distribution around the conductive particle is shown in Figure 8. Higher stresses were found at the interfaces between the conductive particle and adhesive matrix.

Figure 9 shows a typical SEM image of a cross section of a failed ACF joint after 48h of autoclave testing at 121°C, 100%RH, 2 atm condition. In the cross section, joint opening was observed between the bump and pad, and cracks were found along the interface between the adhesive and flex/pad where the highest stress was identified in the modelling.
3. Conclusions

The effects of moisture on the reliability of ACF bonded flip chips have been investigated. A macro-micro modelling technique was used to overcome the difficulty caused by the multi-length-scale problem so that the full-scale analysis of an ACF flip chip is possible.

The modelling results show that the reliability of ACF is strongly affected by moisture and the ACF layer can be expected to be fully saturated with moisture after 3h in 121°C, 100%RH, 2 atm conditions. Owing to the CME mismatch, a higher stress was found at the interface between the adhesive and bump pad. The predominantly tensile stress found at the interface between the conductive particle and metalization could reduce the contact area, contributing to joint opening. These modelling results are consistent with the findings in the experimental work.

References


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C.Y. Yin received her BSc (1999) and MSc (2001) in Material Science and Engineering from Harbin Institute of Technology, China. From 2001 to 2002, she worked as a Research Assistant in the EPA Centre at City University of Hong Kong. In September 2002, she started her PhD study in the School of Computing and Mathematics Sciences at the University of Greenwich. Her research work has been focused on the reliability of fine pitch assemblies using conductive adhesives. C.Y. Yin is the corresponding author and can be contacted at: c.yin@gre.ac.uk

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Y.C. Chan earned his BSc degree in Electrical Engineering in 1977, MSc degree in Materials Science in 1978, and a PhD degree in Electrical Engineering in 1983, all from Imperial College of Science and Technology, University of London. He then joined the Advanced Technology Department of Fairchild Semiconductor in California as a Senior Engineer, working on Integrated Circuit Technology. In 1985, he was appointed to a Lectureship in Electronics at the Chinese University of Hong Kong. Between 1987 and 1991, he worked in various senior operations and engineering management functions in electronics manufacturing (including SAE Magnetics (HK) Ltd and Seagate Technology). He set-up the Failure Analysis and Reliability Engineering Laboratory for SMT PCB in Seagate Technology (Singapore). He joined City Polytechnic of Hong Kong (now City University of Hong Kong) as a Senior Lecturer in Electronic Engineering in 1991. After three promotions within City U, he is currently Chair Professor and Director of the EPA Centre, and Assistant Head for Applied Research and Public Relations in the Department of Electronic Engineering. He has authored or co-authored over 100 scientific publications in peer-reviewed journals and over 50 international conference papers. His current research interests include advanced electronic packaging and assemblies, failure analysis, and reliability engineering.

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