Dynamic strength of anisotropic conductive joints in flip chip on glass and flip chip on flex packages

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Received 26 February 2003; received in revised form 5 May 2003

Abstract

The work presented in this paper focuses on the behavior of anisotropically conductive film (ACF) joint under the dynamic loading of flip chip on glass (COG) and flip chip on flexible (COF) substrate packages. Impact tests were performed to investigate the key factors that affect the adhesion strength. Scanning electron microscopy (SEM) was used to evaluate the fractography characteristics of the fracture. Impact strength increased with the bonding temperature, but after a certain temperature, it decreased. Good absorption and higher degree of curing at higher bonding temperature accounts for the increase of the adhesion strength, while too high temperature causes overcuring of ACF and degradation at ACF/substrate interface—thus decreases the adhesion strength. Higher extent of air bubbles was found at the ACF/substrate interface of the sample bonded at the higher temperature. These air bubbles reduce the actual contact area and hence reduce the impact strength. Although bonding pressure was not found to influence the impact strength significantly, it is still important for a reliable electrical interconnect. The behaviors of the conductive particles during impact loading were also studied. From the fracture mode study, it was found that impact load caused fracture to propagate in the ACF/substrate interface (for COG packages), and in the ACF matrix (for COF packages). Because of weak interaction of the ACF with the glass, COG showed poor impact adhesion.

1. Introduction

To synchronize with the advances in very large scale integration (VLSI) Si technology, a high density input/output (I/O) connection is required in the packaging of the Si chip. Flip chip bonding technology has been developed as a first level interconnects technology. It utilizes Pb–Sn solder bumps deposited on the UBM. However, the use of lead in the electronic packaging is under consideration because of environment and health concerns. The Environmental Protection Agency in the USA is requesting that lead-based solders be phased out or greatly reduced in microelectronics applications. Law in Europe will prohibit the use of lead in electronics in 2006, according to the Waste from Electronic and Electrical Equipment proposal [1]. Hence, how to cut down the use of lead in soldering and also how to develop lead-free interconnect materials are urgent materials issues in advanced microelectronics technology.

Electrically conductive adhesive (ECA) has attracted much interest as it offer numerous advantages over traditional solders, including fine pitch capability, flexible and simple process at low temperature, fluxless formulations and environmental friendliness [2]. ECA provides both electrical and mechanical interconnects between chip and the supporting substrate as like solder alloys. Two critical reliability issues of conductive adhesives applications are contact resistance shift and poor impact performance. Extensive studies have been done about the contact resistance shift of ECA [3,4], but slightly work on the latter. Adhesion strength is a critical parameter of fine pitch ACF interconnects that are fragile to shocks encountered during assembly, handling and lifetime. Initial efforts at this aspect mostly focused...
on isotropic conductive adhesive (ICA) for surface mount lead attachment, which involved structure-property-performance study [5], and dropping mounted chipboard assemblies onto hard surfaces from a certain height [6].

Unlike ICA, anisotropic conductive adhesive (ACA) conducts electricity only in one direction. ACA contains less conductive particles (lower percentage of metal fillers in volume) than ICA. The concentration of particles is controlled in such a way that just enough particles are present to assure reliable electrical conductivity in the \(z\)-direction (i.e. chip to substrate) while concentration is far below a critical value to achieve percolation conduction in the \(x-y\) plane (i.e. between adjacent input/output of the chip) [3]. Thus it has gained much attention in ultra-fine capability application [7].

Because of the anisotropic property, ACA can be deposited over the entire contact region as film (known as anisotropic conductive film, ACF). Thus it is predicted to increase mechanical reliability [2,7]. However, there is still some sort of uncertainty in using ACF considering proper formulation, optimized curing profile, balanced pressure which are crucial to contact resistance, and impact performance. There was little work done elsewhere on the impact performance of flip chip interconnect using ACF. In another paper of research, we studied on the peel strength of chip-on-flex using ACF and tried to improve adhesion through plasma cleaning of the flex substrate [8]. This work focused on the understanding of the factors that affect the impact strength of COG and COF.

2. Experimental procedure

2.1. Test chip and substrates

The dimension of the test chip is \(11 \times 3\) mm\(^2\), with \(50 \times 50\) \(\mu\)m\(^2\) square shaped bump and a total of 368 bumps on the periphery. There are 60 daisy-chained bump groups that run parallel to the length of the chip for electrical connection and another 68 bumps along the width to contribute to mechanical support. The bumps are plated with gold and the bump height is around 18 \(\mu\)m. Two kinds of substrate are used to evaluate the adhesion property. The flexible substrate is made of polyamide film of 50 \(\mu\)m thickness with pads matching the chip’s bump pattern. The pads and the conductive trace pattern of the flexible substrate are Au coated Cu metallization of 12 \(\mu\)m thickness. The substrate is fixed to a rigid board during the mechanical test. The glass substrate is 1.1 mm thick without bump at pads, and the conductive trace pattern is sputter-deposited indium tin oxide (less than 1 \(\mu\)m thick).

2.2. ACF materials and bonding parameters

Two different types of commercial ACF (ACF1 for COG and ACF2 for COF) were used in this study. ACF1 is \(35 \pm 5\) \(\mu\)m thick with Ni/Au plated resin particles of diameter 3.5 \(\mu\)m. ACF2 is 30 \(\mu\)m thick with Au plated resin particles of diameter 3.5 \(\mu\)m.

The substrates were carefully cleaned using organic solvent before the bonding process in order to remove any contaminants. The ACF was then cut to the correct size to cover the bonding area and was preliminarily bonded to the substrate using light pressure and low temperature for short time. After preliminary bonding of ACF on the substrate, the separator was peeled off from the adhesive film immediately. Then the substrate pattern and the position of the chip bumps were aligned automatically by the flip chip bonder (Toray SA2000). Finally, the chip was bonded to the substrate by applying heat and pressure simultaneously for a specific duration. The detailed specifications and bonding conditions are summarized in Table 1.

2.3. Impact test

An air cylinder-driving instrument was designed to study the dynamic impact performance as illustrated in Fig. 1. The substrate was fixed to a sensor gauge for recording, and the chip was clamped with a rigid head to apply load. When the compressed air in the cavity of the cylinder was released through the air pipe, the piston (valve stem) drew back quickly, providing rapid loading to carry out high rate clipping between chip and substrate. The average speed of piston was about 0.1 m/s. Sixteen samples for each condition were tested to get the

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>Pre-bonding temperature</td>
<td>90 °C</td>
</tr>
<tr>
<td>Pre-bonding time</td>
<td>3 s</td>
</tr>
<tr>
<td>Pre-bonding pressure</td>
<td>1 MPa</td>
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<tr>
<td>Bonding temperature</td>
<td>170–230 °C</td>
</tr>
<tr>
<td>Bonding time</td>
<td>15 s</td>
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<tr>
<td>Bonding pressure</td>
<td>30–110 MPa</td>
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average and the extent of deviation of the impact strength values for COG and COF.

The fracture surfaces were observed afterwards by scanning electron microscopy (SEM) under secondary electron (SE) mode to study the fractography characteristics of both chip and substrate sides.

3. Results and discussion

3.1. Effect of bonding temperature on adhesion

Under the bonding pressure of 60 MPa, the impact results of COF and COG versus bonding temperature are plotted in Fig. 2. The impact load required to loose the bond for both the packages rises up to the bonding temperature of 190 °C, while decreases after 210 °C. Impact test results of different ACFs show similar trend for both COF and COG, which indicates that bonding temperature has serious effects on adhesion strength of the ACF interconnects. During bonding process, temperature is maintained to increase the fluidity of ACF and then to cure the ACF quickly when maintaining constant pressure on the chip.

Since adsorption theory is believed to be one of the most important mechanisms in achieving adhesion [9], intimate intermolecular contact between ACF and substrate/chip is needed to produce surface forces such as Van der Waals forces and hydrogen bond [10]. Hence, good wetting is essential to get good adsorption. High temperature is beneficial for wetting and flowing behavior of the ACF on substrate/chip by lowering its surface tension. Previously, we have extensively studied the curing behavior of the same ACFs used in this work [11–15]. The degree of curing of ACF played an important role in determining the reliability of the ACF interconnects. A certain degree of curing is needed to provide desired mechanical strength and durability of the adhesive joints. Generally, the higher the degree of curing, the stronger is the adhesion. The curing degree of ACF is very much dependent upon the bonding temperature. In the thermal curing process of the epoxy-based adhesive, higher temperature initiates and accelerates the crosslinking reaction by providing higher energy. We found that the curing degree of ACF increased as bonding temperature increased. About 85% curing was achieved for ACF bonded at 200 °C and 95% at 230 °C for 10 s. It was recommended that further curing beyond 95% is not suitable for high reliable product due to serious degradation of electrical performance [13,15].

However, too high temperature (230 °C) used in bonding decreased the impact strength of the ACF interconnects. The reasons for such decreasing trends of the impact strength are as follows: First, ACF matrix is thermosetting polymer, which degrades easily at high temperatures. Cracks and lumps in ACF cured at very high curing temperature were observed in our previous study [13]. At much more higher curing temperature, many complex reactions, such as thermal oxidation and dehydration, could take place and cause chain scissoring of the crosslinking network. Second, substances with small molecular weight may be produced and volatilized during high temperature curing process in the bulk adhesive. This kind of volatilization makes the polymer become porous as shown in Fig. 3, which is the microstructure of ACF cured at 230 °C. The porous structure not only loosened the whole material, but also reduced the intimate contact with the adherent due to reduced contact area, which seriously degraded the intrinsic adhesive ability of ACF. Third, higher curing temperature enables the ACF to set more quickly. Therefore, too high temperature and sharp heating/cooling variation may build up serious thermal stress at the particle core/coating interface, coating/ACF interface and ACF/chip.

Fig. 2. Impact load versus bonding temperature.

Fig. 3. Porous structure in ACF due to overcuring.
or substrate interface, which may weaken local parts of interconnect. Fig. 4 shows the fracture surface of a weak part of the overheated ACF. Fourth, overcuring may hurt the damping properties of the ACF. The establishment of high-density crosslinkage network and large molecules due to overcuring degrade the viscoelasticity of ACF, which reduces the polymer’s ability of absorbing impact mechanical energy and converting it to heat through molecular friction and chain breaking. The design target of adhesive to improve damping property is to maintain low Young’s module \( (E) \) and high loss factor \( (\tan \delta) \). Loss factor is defined as the ratio of the loss module \( (E'') \) and the storage module \( (E') \) [5]. When curing temperature is above the optimum point, \( E, E' \) and glass transformation temperature \( (T_g) \) of ACF under testing condition rises to some extent [16], so the damping property decreases.

3.2. Effect of bonding pressure on adhesion

Fig. 5 reflects the relationship between adhesion strength and bonding pressure when the bonding temperature is 190 °C. It can be seen that the strength increases very slightly as the bonding pressure increases. Pressure might have an effect on the adhesion by means of changing the thickness of the adhesive. However, here, pressure can only change the thickness of ACF between the bump (of chip) and pad (of substrate), which is limited by the extent of the deformation of the conductive particles. The thickness of ACF materials between the chip and substrate remains more or less the same, because the thickness depends on the summation of the height of bump, deformed particle and pad. Thus, pressure plays little role in the total adhesion.

Although pressure is not important in respect of adhesion, it should be pointed out that necessary value (about 60 MPa in this work) is needed for reliable bonding. First, proper pressure is applied to assure intimate intermolecular contact between adhesive and adherent (chip and substrate) so that Van der Waals interaction, electrostatic adsorption and other bonds at the interfaces can take place. Then, suitable deformation of particles is needed to get sufficient contact with the input/output of the chip (i.e. bump) to the pad of the substrate, which is required to maintain stable electrical conduction between particles and conductors. However, too high pressure would cause excessive deformation of the core of the particles and crack in the Au/Ni layer of the particles, which is not desirable from the point of view of electrical conduction. Fig. 6 shows high magnification SEM photos of such excessive deformation and splitting of the conductive layer of the particles. Inevitably, such cracking down of the conductive particles produces large residual mechanical stress around the particles, which might initiate crack and delamination at the bump/pad area.
3.3. Fracture manner

Finding the location of the fracture and analyzing the topology of the fracture surface are helpful to understand the fracture behavior. SEM in SE was used to study fracture surface of the COF and COG. Fig. 7(a) and (b) represents the typical surfaces of the chip side of COG and COF packages respectively after the impact test. From Fig. 7(a), it can be found that, the fracture surface is very smooth for COG package. Whereas, in Fig. 7(b) for COF packages, fracture surface is very rough with smearing of the ACF skin and the exposed conductive particles. However, the ACF remain adhered with the chip for both the cases. It indicates that the interface between the chip and ACF is very strong. Large amount of the specimens of COG packages were delaminated from the ACF/substrate interface, very few from ACF/chip interface or ACF matrix. As per expectation, severe deformation of the particles was only noticed on the bump areas. In other areas, conductive particles remained undeformed. In case of COF packages, large amount of the specimens were delaminated from the ACF matrix, very few from ACF/substrate or chip/ACF interface.

Two different fracture behaviors of the COG and COF could be explained in terms of the rigidity, surface roughness and chemical state of the substrate materials. When the ACF was subjected to compression during bonding, glass substrate acted like a hard obstacle and abruptly stopped the motion of the particles as they reached to the interface of the ACF/glass. Thus, the “blocked” particles (Fig. 8(b)) at the ACF/substrate interface acted as the origin of crack. In contrast, flex substrate acted like a soft “sponge” allowing the particles to travel without hard restriction. In this way, most of the particles just stayed inside near the top surface of ACF. So, the COG was more susceptible to debonding due to the stress at ACF/substrate interface induced by blocked particles. In addition, the whole COF structure could absorb more mechanical impact energy than COG since the flex substrate can accommodate deformation to some extent than the glass substrate during the test. It is well known that surface roughness is very low for glass, i.e. glass substrate is smoother than flex substrate. Therefore, the adhesion due to the contribution from mechanical interlocking between the glass and the ACF is very low. However, in the flex substrate, mechanical interlocking between the flex and the ACF is higher.
Considering chemical state of the glass surface and flex surface, it is very clear that the interaction force between inorganic silicon oxide and ACF matrix is much weaker than that of the polymeric flex substrate and ACF. During the curing process, there is a strong chance to interdiffuse ACF epoxy molecules into the polymeric flex. However, there is no chance to interdiffuse the ACF epoxy molecules into the glass. This is why the interface between ACF and COG is weak and fracture occurs through such weak interface. Whereas, for COF, the interface between ACF and flex is stronger and fracture occurs through the ACF matrix exposing the conductive particles, as shown in Fig. 7(b). This is the reason why we got higher impact load for COF than COG (Figs. 2 and 5).

3.4. Effects of air bubbles on adhesion

Air bubble entrapped in the adhesive/adherent interface is a serious concern for reliable adhesion. Many air bubbles and holes were found to exist in ACF and at ACF/substrate interface as shown in Fig. 8. This phenomenon can be explained if looking back to the bonding process (Fig. 9). During pre-bonding of the ACF on the substrate, some air is entrapped in the corner beside the pads and conductors at the ACF/substrate interface. During chip bonding, at first, ACF became thick liquid, then spread over to flow between the pads and between the bumps. However, at the beginning of bonding process, the temperature of ACF near chip side was higher than that of the substrate side since heat was applied through the chip on the z-direction downward. The ACF near the chip became viscous and cured earlier than that near the substrate. So, air bubbles that had been entrapped during ACF lamination process, tried to get out due to the applied pressure (Fig. 9). During the quick curing, some of the air did not get time to escape—thus remained inside ACF matrix especially at the interface between the substrate and ACF. If ACF set too quickly at much higher temperature, more air bubbles would remain in between the ACF and substrate. This kind of defect reduces the contact area and provides stress propagation path for crack, resulting in easy delamination along the ACF/substrate interface under low force.

3.5. Effects of particles on adhesion

Typically, 5–15% volume fraction of the ACF is metal-coated sphere particles with size ranging from 3 to 10 μm. They change the electrical, thermal and mechanical properties of the material. Specifically, they reduce coefficient of thermal expansion (CTE), increase module of elasticity, increase brittleness, and increase $T_g$ [17]. In the ACF matrix, random dispersion of particles introduces asymmetry and discontinuity in the whole material. The particles act as many “holes” to weaken the material’s impact resistability, especially at the part with high-density particles. Thus, the adhesion is influenced by the particles size and distribution in the ACF. It can be seen from Fig. 10 that there are gaps between the particles and polymer, which makes the particles lax and moveable under external loading. Many reasons contribute to this kind of separation. First, when bonding pressure was applied, the particles between bump and pad were compressed to “elliptical” shape. However, after the pressure has been released, the elastic recovery leaves interspaces between the particles and the cured polymer. Second, due to CTE mismatch among particle core, coating and ACF matrix, different expansion and shrinkage during the curing process might produce gaps between coating and ACF matrix as well as between core and coating. The higher the bonding temperature, the bigger was the gap between the particle and adhesive matrix. Third, poor adhesion between coating and polymer core is responsible for phase interface detachment when the material subjected to mechanical force. Fig. 11 shows that the frail coatings were shelled off and some holes were left by the particles.

![Fig. 9. Schematic showing the air entrapment in interconnect during bonding process.](image1)

![Fig. 10. Gap between particles and polymer (substrate side of COF).](image2)
4. Conclusions

From the impact tests and fracture surface study of the ACF interconnect we got the following conclusion. For both COG and COF packages, as bonding temperature increased, the impact strength increased at first, however, decreased after reaching a maximum value. According to the change caused by curing behavior of ACF, 190 °C was recommended as optimum bonding temperature for high strength of ACF bonding. For both COG and COF, the bonding pressure does not affect so much on the adhesion strength. But proper pressure is needed for the bonding, and 60 MPa was selected in this work.

For both COG and COF, particles and air bubbles were responsible for the weak intrinsic strength of the adhesive, because they not only changed the structure of ACF, but also behaved harmfully in the ACF matrix during curing processes and loading. The fracture of COG was mainly along the ACF/substrate interface, while that of the COF was mainly from the ACF matrix near the substrate side. Under the same bonding condition, the adhesion strength of COF is higher than that of the COG. Different kind of interaction of ACF with glass and flex substrate were responsible for the variation in fracture manner and adhesion strength of the two packages.

Acknowledgements

The authors would like to acknowledge the financial support provided by the Hong Kong Innovation and Technology Commission for Conductive Adhesive Technology Programme for Fine Pitch Electronic Interconnect (project no.: ITS/182/00) and by the Hong Kong Research Grant Council fund for Co-operative Research Center on Conductive Adhesive Technology for High Density Electronic Packaging (project no.: 8720003). The authors would also like to acknowledge the financial support provided by The National High Technology Research and Development Program of China (863 Program) for Application of Flip-Chip Technology to MEMS (project no.: 2002AA404110).

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