J Mater Sci (2008) 43:3072–3093
DOI 10.1007/s10853-007-2320-4

A review of the influencing factors on anisotropic conductive adhesives joining technology in electrical applications

Y. C. Lin · Jue Zhong

Received: 28 August 2007 / Accepted: 13 November 2007 / Published online: 15 March 2008

Abstract New interconnect materials are always necessary as a result of evolving packaging technologies and increasing performance and environmental demands on electronic systems. Polymer-based conductive-adhesive materials have become widely used in many electronic packaging interconnect applications. Among all the conductive-adhesive materials, the anisotropic conductive adhesives (ACA) (or anisotropic conductive adhesive films, ACF) have gained popularity as a potential replacement for solder interconnects. The interest in using ACA instead of solder comes partly from the fact that the use of ACA for the direct interconnection of flipped silicon chips to printed circuits (flip chip packaging) offers numerous advantages such as reduced thickness, improved environmental compatibility, lowered assembly process temperature, increased metallization options, reduced cost, and decreased equipment needs. In this review, a summary of our understanding of the electrical, physical, thermal, chemical, environmental, and cost behaviors of ACA in conjunction with various packaging applications is elaborated. First, the formulation and curing kinetics of ACA materials, as well as the conduction mechanisms of ACA joints, are introduced; second, the influencing factors, including the boding process (boding temperature, boding pressure, curing conditions, reflow and misalignment processes, etc), the environmental factors (temperature, humidity, impact load, etc), and the properties of the components (the properties of the ACA, substrates, conductive particles, the bump height, etc), on the reliability of ACA joining technology are presented. Finally, future research areas and remaining issues are pointed out. The purpose is simply to pinpoint the most important papers that have played significant role for the advancement of the ACA bonding technology.

Introduction

Electronic packages nowadays are becoming smaller, lighter with higher in/out (I/O) count and better performance that are more cost competitive. The trend in electronic packaging runs from bulky plastic ball grid array (PBGA) with solder joints to miniature flip chip with polymer-based conductive adhesive interconnects. Meanwhile, the environmentally friendly manufacturing is another most important goal for the electronic packaging industry. In particular, the use of electrically conductive adhesives (ECA) instead of soldering and underfill encapsulation helps to achieve such goals. The ECA mainly consist of an organic/polymeric binder matrices and metal filler. The conductive fillers provide the electrical properties and the polymeric matrices provide the physical and mechanical properties. Therefore, electrical and mechanical properties of ECA are provided by different components, which is different from the case for metallic solders that provide both electrical and mechanical properties. Among all the ECA materials, the anisotropic conductive adhesives (ACA) (or anisotropic conductive adhesive films, ACF) have gained popularity as a potential replacement for solder interconnects in surface mount technology processes. The interest in using ACA instead of solder comes partly from the fact that the use of ACA for the direct interconnection of flipped silicon chips to printed circuits (flip chip packaging) offers numerous advantages

---

Y. C. Lin (✉) · J. Zhong
School of Mechanical and Electrical Engineering,
Central South University, Lushan South Road,
Changsha, Hunan Province 410083, P.R. China
e-mail: linyongcheng@163.com; yclin@mail.csu.edu.cn

such as reduced thickness, improved environmental compatibility, lowered assembly process temperature, increased metallization options, reduced cost, and decreased equipment needs [1–12]. ACAs have been widely used for packaging technologies in flat panel displays (FPDs) such as liquid crystal displays (LCDs) for last two decades. So far, various packaging technologies such as tape carrier package (TCP) on LCD panel or PWB, chip on flex (COF), and chip on glass (COG) using ACAs have been realized to meet the requirement of fine pitch capability and make the FPDs smaller, lighter, and thinner for high-performance consumer products, such as cell phone and laptop computers [13]. Therefore, the substrates of ACA joints are various, including glass substrates [14–18], flexible circuits [19–22], rigid board [23–25], and ceramic substrate [26–28].

In recognition of the importance and issues of polymer-based ACA, tremendous research and development effort has been spent on the high-performance ACA during the last 20 years. The efforts so far have been mainly addressed on various material properties and assembly aspects of ACA. The results of their studies would allow development of ACA joints using fine pitch flip chips on flexible/rigid substrates with better reliability and performance. The scope of this review is to summarize some recent activities and advances on ACA bonding technology. It should be noted that despite numerous benefits, ACA-type packages bare several reliability problems and cannot replace tin–lead metal solders in all applications, especially for high-power devices such as microprocessors. The purpose of this review is to have a better understanding of the nature of ACA and the significant progress made on the materials research and development, as well as to point out the future challenges. Additionally, this review is simply to pinpoint the important papers that have played significant role for the advancement of the ACA bonding technology.

Classes and formulation of ACA

Polymer-based anisotropic conductive-adhesive materials have become widely used in many electronic packaging interconnect applications. An ACA is a composite composed of fine conductive particles that are uniformly dispersed in the adhesive matrix. The electrical connections are established through conductive particles and the mechanical interconnections are maintained by the cured adhesive. Generally, there are two main forms of ACA: (1) Paste, referred to hereafter simply as an anisotropic conductive adhesive (ACA); (2) An anisotropic conductive film (ACF) [4, 6, 12]. In an ACA joint, the filler particles normally constitute between 5 and 10 vol%, and do not cause any direct metallic contact before the assembly process is completed.

Both thermosetting and thermoplastic materials are used as the adhesive matrix. Epoxy, cyanate ester, silicone, polyurethane, etc. are widely used thermosets, and phenolic epoxy, maleimide acrylic preimidized polyimide, etc. are the commonly used thermoplastics. Thermoplastic adhesives are rigid materials at temperatures below the glass transition temperature (T_g) of a polymer. Above the T_g, polymers exhibit flow characteristics. When using this type of material, assembly temperatures must exceed the T_g to achieve good adhesion. The principal advantage of the thermoplastic adhesives is the relative ease with which the interconnection can be disassembled for repair operations. Thermosetting adhesives, such as epoxies and silicones, form a three-dimensional cross-linked structure when cured under specific conditions. As a result of this irreversible cure reaction, the initial uncross-linked material is transformed into a rigid solid. The curing reaction is not reversible. This fact may hinder disassembly and interconnection repair. Thermosetting adhesives are by far the most common binders due to the superior balanced properties, such as excellent adhesive strength, good chemical and corrosion resistances, and low cost [12, 29]. The most widely used epoxy resins of the ACA materials are diglycidyl ether of bisphenol A (DGEBA) and diglycidyl ether of bisphenol F (DGEBF). The outstanding performance characteristics of the resins are conveyed by the bisphenol A moiety (toughness, rigidity, and elevated temperature performance), the ether linkages (chemical resistance), and the hydroxyl and epoxy groups (adhesive properties and formulation latitude, or reactivity with a wide variety of chemical curing agents). Bisphenol F epoxy resin is of the same general structure as the bisphenol A. Except for low viscosity, the physical and chemical properties are similar. While the most widely used epoxy curing and catalyst agents are 1-(2-cyanoethyl)-2-ethyl-4-methylimidazole (2E4MZ-CN), 3-(2-methylimidazole-1-yl)-propionitrile(2MZ-CN), 2-ethyl-4-methylim-idazole (2E4MZ), and 1,3-phenylenediamine (MPDA) [30–32]. For the selection of the adhesive, the robust bonds should be formed to all surfaces involved in the interconnection. Numerous materials surfaces can be found in the interconnection region including SiO_2, Si_3N_4, SiON, polyester, polyimide, FR-4, glass, gold, copper, and aluminum.

Meanwhile, it is very important to select the appropriate materials used as conductive particles. From the view of the cost, electrical conductivity, current carrying ability, chemical reactivity, electromigration, corrosion, and oxidation under heat and humidity conditions, silver (Ag), gold (Au), copper (Cu), and nickel (Ni) may prohibit for large volume applications and limits the widely used applications in conductive adhesives. Therefore, the most common type has a plastic core that is over-coated with a good conductor like gold or silver and the most popular conductive particle is a polymer sphere that has been first plated with nickel and then pure gold. The metal (Ni and Au) plated polymeric particles may offer the best combination of properties at moderate cost and therefore are commonly used in fine pitch interconnection.

Curing kinetics of ACA

The physical, electrical, and mechanical properties of the cured conductive adhesives depend to a large extent on the degree of cure of the epoxy composition in the conductive adhesive. Thus, a full understanding of the cure mechanisms of conductive adhesives can provide tools to optimize the cure schedule so that residual stress in the conductive adhesive joints is minimal. Basic to such an optimal curing process is the need to first understand the physical curing mechanism and cure kinetics underlying the process and then be able to model the cure process accurately. An accurate model not only helps to predict cure behavior for process design and control but also can be used to predict aging and degradation of thermosetting polymer systems and compare the cure behavior of different systems. The most widely used curing techniques include heat, UV light, and added catalyst. ACA assembly process requires the application of pressure during adhesive cure. Curing of adhesive needs standard method to supply the energy and initiate the chemical reaction. Heat is the typical used method while sometimes ultraviolet (UV) radiation is also used to initiate the reaction. These energy sources are easily incorporated into the process. Special equipment is needed to apply pressure during cure. Typically, heat is supplied from the thermode used for component pick-up, whereas UV is usually brought through the substrate by optical fiber bundles [33–39].

To date, seldom studies have been systematically reported on the cure-kinetics modeling of the anisotropic conductive adhesive system. In 1999, Xiao et al. [36] investigated curing kinetics study for designing of novel electronic adhesives (free radical curable monomers). The experimental results show that either a strong electron donor is difficult to cure and should co-cure with an electron acceptor. However, electron acceptors can achieve sufficiently fast cure without co-cure agents. A pair of electron donor and acceptor reagents with 1:1 mole ratio gives superior fast cure. A system containing a fast cure electron acceptor and a slow cure electron acceptor shows superior fast cure and is independent on stoichiometry. Molecular modeling results are consistent with the above experimental observations and provide in-depth understanding of the relation between the electronic characteristics of the monomers and their curing rate. In 2003, Chan et al. [34] studied the curing reaction of two types of ACF with a differential scanning calorimeter (DSC) under isothermal conditions in the range of 120–180 °C. They found that the curves of the time-dependence cure degree at each cure temperature for ACA materials show the sigmoidal shape, which reveals that the cure reaction follows an autocatalytic mechanism, i.e., at least one of the reaction products is also involved in the propagating reaction [40, 41]. Additionally, an autocatalyzed kinetic model was used to describe the curing reaction. The rate constant and the reaction orders were determined and used to predict the progress of the curing reaction. A good agreement is found between the proposed kinetic model and the experimental reaction-rate data.

Considering amine epoxy reaction, three principal curing reactions are considered to occur (reactions 1–3): the reaction of epoxy with primary and secondary amines and the etherification reaction of epoxy with hydroxyl generated in the amine-epoxy reactions, as shown in Fig. 1. For

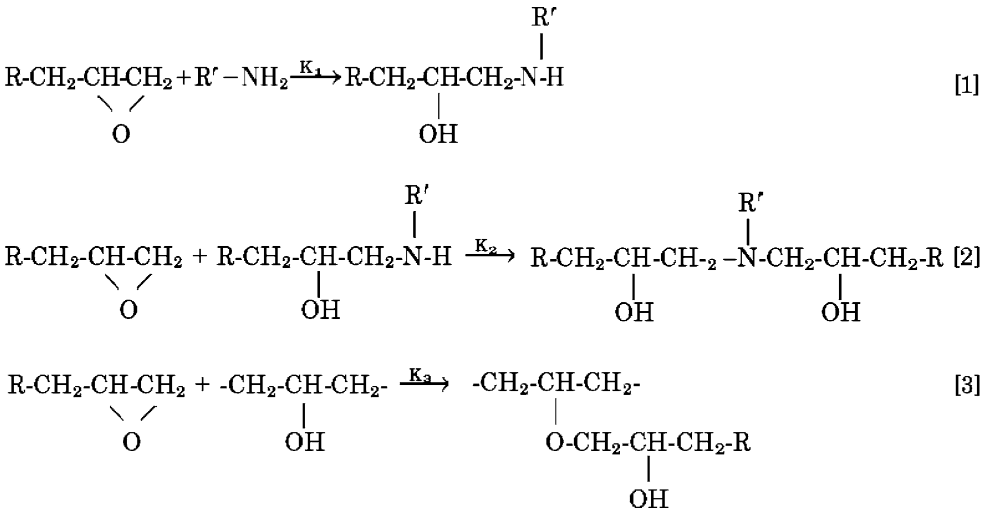

Fig. 1 Crosslinking reaction of amine epoxy curing system [34]

1:1 stoichiometry or when amine is present in excess, reaction 3 is generally insignificant with respect to reaction 1 and 2. In the majority of epoxy systems, the primary and secondary amines have similar reactivates. When the reactivity of the secondary amine is significantly lower, separate exotherms are found: one for the reaction of primary amine with epoxy and another for secondary amine with epoxy and/or etherification. However, the etherification is usually much slower than the amine-epoxy reactions [42–44].

Conduction mechanisms of ACA joints

The principles of ACA joints are that the electrical connections are established through conductive particles and the mechanical interconnections are maintained by the cured adhesive. For example, Fig. 2 shows a typical chip-on-glass (COG) process based on ACF's thermo-compress interconnection techniques. First, an ACF is laminated to a glass substrate with ITO (indium tin oxide) tracks. Pressure and temperature are applied during the lamination process to ensure positioning accuracy, uniformity, etc. Then, the bumps on integrated circuits (ICs) are aligned with the tracks on the glass. Finally, the IC chip is pressed onto the glass at a specified high temperature and pressure. The conductive particles are trapped between the bumps and tracks, while the adhesive resin is squeezed out. The interconnections are established by the compressive force between the electrodes due to the shrinkage of the adhesive after curing. Consequently, the electrical conduction is restricted to the *z*-direction and the electrical isolation is maintained in the *x*–*y* plane. Additionally, it is necessary to know the deformation of conductive particles during die mounting process. Generally, the conductive particles consist of a polymer core material coated with a thin metal layer (nickel and/or gold), and then insulated again with a polymer material on its exterior surface. The conductive particles in an ACF are of ball shape before die bonding. When the IC chip is pressed onto the glass at a high temperature and pressure, the particles are entrapped and deformed between the bumps of the chip and the glass substrate, and then the external insulation layer of the particle is damaged and the interior metal layer is exposed. Thus, the electrical connections are established through conductive particles.

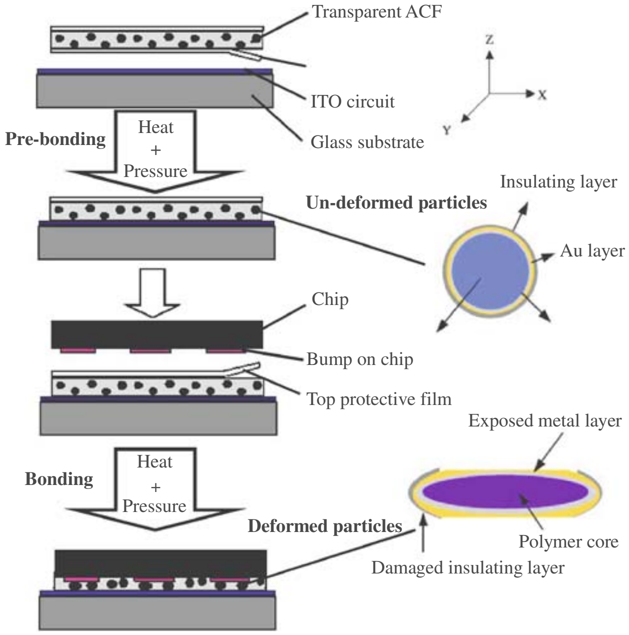

Fig. 2 Interconnection process for a COG assembly

Despite the success of ACA interconnects, the drive to further exploit its fine pitch capability in smaller scale applications and high frequency fields is held back seriously due to the difficulty in predicting the electrical contact resistance in these cases. In recent years, a number of different models were developed for understanding and predicting electrical contact resistance in ACA interconnects [45–52].

The earliest model considered for predicting contact resistance in ACA interconnects was provided by Williams et al. [45] in 1993. For the bonding force versus contact area relationship, the elastic and plastic contact was considered in the developed model. However, the model does not consider the case of a metal-coated polymer or the influence of surface roughness. For the contact area versus resistance relationship, the constriction component for only one out of the four surfaces was considered. The bulk resistance of the conductive particle and tunneling resistance were neglected.

Hu et al. [46] presented a different approach in 1997 to relate the bonding force to the contact area. The linear elastic and plastic deformations were considered. For the relationship between contact area and electrical resistance, a detailed deformation analysis of the conductive particle was performed to predict the bulk resistance, in which a nonconstant volume was assumed for both linear elastic and plastic cases. However, constriction resistance was not taken into account in this model. As with the previous model, the tunneling resistance and surface roughness were neglected and the case of a metal-coated polymer particle is not considered.

The approach used by Yim et al. [47] in 1998 for predicting the relationship between bonding force and contact area considered the elastic and plastic contact. The bulk resistance was assumed constant considering an equivalent cross-sectional area of a cylinder whose volume is equal to the sphere with diameter *D*. Tunneling resistance and surface roughness were neglected in this model.

Another ACA contact resistance model was developed by Shi et al. [48] in 1999. The elastic and plastic contacts were considered for the relationships between the bonding force and contact area. This model was very similar to the Williams' [45] model, but considered two constriction resistance components instead of one and the bulk resistance of the conductive particle. A variation in the bulk resistance of the particle with deformation was also taken into account assuming a nonconstant volume in both cases, elastic and plastic deformations. Tunneling resistance and surface roughness were neglected in this model.

Numerical or finite element analyses for the contact resistance and contact area relationship have been performed by Oguibe et al. [49] and Fu et al. [50]. Oguibe et al. [49] computed contact resistance in ACA assemblies for a given contact radius. They also estimated the maximum temperature rise from the constriction voltage at the contact interface. Comparing this maximum temperature rise with the characteristics melting temperature of the bodies in contact, they found that melting can occur for cases of high resistances and small contact areas. Fu et al. [50] performed calculations with the same objective, i.e., to predict contact resistance given a contact area or vertical deformation displacement. In their simulations, the position of the particle with respect to the center and edge of the contacting tracks was varied. The results showed that resistance increases when the particle is moved from the center to the edge due to the increasingly deformed equipotential profile.

Furthermore, Williams et al. [45], Hu et al. [46], Yim et al. [47], Shi et al. [48], and Fu et al. [50] extended their theoretical analysis of single particle contact to multiple conductive particles directly, and more realistic contact resistance models have been accounted.

A recent article [51] presented a detailed review and direct comparisons of the different models that have been used to predict electrical contact resistance in ACA interconnects, and large discrepancies exist among these models and between contact resistance values experimentally measured and what these models predict were found.

In 2006, a following article [52] pointed out that none of the previous analyzes took into account the fact that the real area of contact is always less than the apparent area of contact calculated by deformation models. A factor contributing to the consistently smaller calculated resistances results from assuming the electrical area of contact is equal to the physical area of contact between the particle and the surface of the bonding pad. The author asserted that the electrical contact area is much smaller than the apparent physical area of contact, which was supported from the visual image of a compressed particle and can be used to explain the discrepancy between the observed and calculated resistance.

Influencing factors on ACA joining technology

Effects of bonding process on the reliability of ACA joints

During bonding of ACA joints, temperature, pressure, and curing conditions are the critical bonding parameters for optimal bonding conditions. Also, the effects of reflow and alignment process are significant. Many investigators have studied the effects of these critical factors during flip-chip-on-substrate assembly in relation to the performance of the ACA interconnect. The results of their studies would allow development of ACA joints using fine pitch flip chips on flexible/rigid substrates with better reliability and performance.

Effects of bonding temperature on the reliability of ACA joints

Epoxy resin based ACA are temperature sensitive, therefore their structure is highly dependent upon the bonding temperature chosen. When temperature increases, the ACA will melt and transform into low viscosity liquid, and finally cross-linkage will be performed to form the three-dimensional crystallized networks which contributes to its stable physical properties. The cross-link density of ACA is relatively important in determining its reliability performance. Due to the temperature-sensitive characteristics of the ACA, the mobility of the conductive particles is different at different stages during ACA curing. During the bonding process of ACA joints, the ACA is being cured and becomes soft and rubbery. This transformation allows the ACA to flow, which in turn allows the conductive particles within to move and distribute themselves evenly throughout the ACA joints. When the curing process is completed, the ACA becomes hardened and the mobility of the conductive particles is lost. A reliable interconnect should have sufficient amount of conductive particles between the bump and pad in close contact and that they do not flow away during bonding [53–55]. Therefore, the root cause of the instability of contact resistance maybe due to the incorrect selection of bonding temperature during ACA bonding, and some investigations have been carried out to understand the effects of the bonding temperature on the reliability of flip chip assemblies using ACAs [55–64].

In a paper by Chan et al. [55] in 2002, the effects of different bonding temperatures during flip-chip-on-flex (FCOF) assembly in relation to the performance of the anisotropically conductive film (ACF) interconnect were investigated, and their study focused on the effects of different bonding temperatures on the contact resistance of ACF joints. The results showed that Ni bumps formed

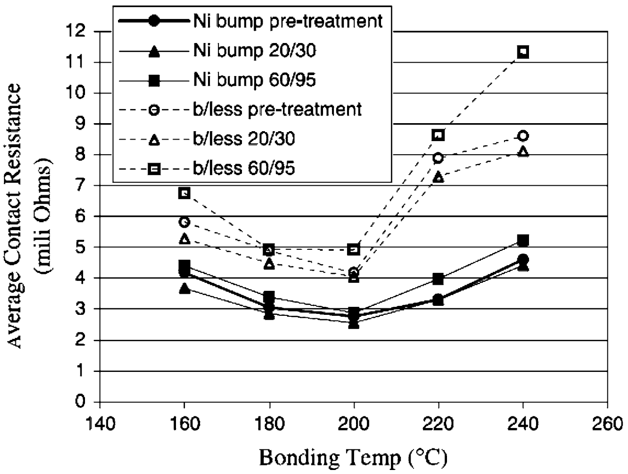

Fig. 3 Average contact resistance of Ni bump and bumpless (b/less) FCOF packages assembled at various temperatures with different storage conditions [55]

better interconnections than bumpless FCOF packages. From Fig. 3, it can be seen that the contact resistance for both Ni bump and bumpless (flip chips with Al pads rather than Ni bumps) FCOF packages show the same trend. The contact resistance of the packages bonded at 160–200 °C decreased steadily but then increased when the bonding temperature used was above 200 °C. FCOF packages assembled at 200 °C gave the best contact when compared to those assembled at a different temperature. For the Ni bump and bumpless FCOF packages assembled, the contact resistance dropped slightly after 336 h of "dry" storage (20 °C/30% RH), while increased slightly after 336 h of moisture absorption (60 °C/95% RH). Aluminium oxide was observed and was thought to be the main cause of the increased in contact resistance after the moisture-soak tests. Also, the bumpless FCOF packages gave higher contact resistance values than Ni bump packages, especially with bonding temperatures above 200 °C, the contact resistance doubled. Conductive particles in the Ni bump FCOF packages were tightly trapped between the bumps and pads and hence gave better connections.

Zhang et al. [57] published a paper in 2002 where they systematically discussed the influence of bonding temperature and bonding pressure on the adhesion of bumpless die (aluminum surface) with two kinds of ACF. It was found that the adhesion strength between the ACF and aluminum is not affected seriously by bonding pressure but it increases while bonding temperature increases.

In 2004, Wu et al. [58] studied the effects of bonding temperature on the behavior of ACF joint of flip COG and flip chip on flexible (COF) substrate packages by impact tests. The results showed that 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 over-curing of ACF and degradation at ACF/substrate interface—thus decreases the adhesion strength.

In 2004, Tan et al. [60] investigated the effect of different bonding temperatures on the thermal stability of ACFs. The experimental results showed that the temperature for maximum decomposition rate of ACF decreased with increasing bonding temperature. Some networks scissoring happened on C–N bond during the bonding process, which was the main reason why the ACF bonded at high temperature 225 °C gave relatively low thermal stability. The contact resistance results suggested that ACF bonded with 10 s at 205 °C, yielding a curing degree of 85% was the best bonding parameter to obtain a low contact resistance after thermal aging. FTIR results showed there was a significant increase in the absorbance peak of carbonyl group after thermal aging. Thermal oxidation reactions which took place at high bonding and aging temperature had broken the polymer networks in the ACF and caused electrical failure.

The same year, in a paper by Uddin et al. [61], a systematic study was carried out to clarify the effects of the bonding temperature on the cross linking of the ACF matrix which in turn affects the performance of the interconnection. The contact resistance has also been studied as a function of bonding temperature and curing degree.

In 2005, Rizvi et al. [62] published a paper which focused on the effect of bonding temperatures on the curing of ACFs, and their adhesion strength and electrical performances after high temperature ageing. The results showed that higher bonding temperatures had resulted in better ACF curing and stronger adhesion. After ageing, the adhesion strength increased for the samples bonded at lower temperatures and decreased for the samples bonded at higher temperatures. ACF assemblies with higher degrees of curing showed smaller increases in contact resistance after ageing. Conduction gaps at the bump-particle and/or particle-pad interfaces were found and are thought to be the root cause of the increase in contact resistance.

In 2006, Chen et al. [63, 64] published a paper where the effects of different bonding temperature and bonding temperature ramp on the electrical performance and the adhesive strengths of ACF interconnection were investigated. The test results showed that the contact resistances change slightly, but the adhesive strengths increase with the bonding temperature increased. The optimum temperature ranges for ACF bonding are concluded to be at 180–200 °C.

Effects of bonding pressure on the reliability of ACA joints

The deformation degree of conducting particles during bonding greatly determines the contact area and the electrical characteristics of the interconnection, because the bonding pressure is applied to force the conductive particles to make contact between the flip chip and flexible/rigid substrate. Ideally, the conductive particles should be squashed until just before the metallic layers begin to break. At this point, the contact area between the bonding surfaces is the largest [65]. However, it is not easy to determine how much the conductive particles should deform for the best interconnections, and their initial size varies slightly. Meanwhile, the distribution of the conductive, which greatly influences the contact resistance of the ACF joints, is determined by the amount of pressure applied during the bonding process to some extent. This is because if the particles are too spread out between adjacent bumps or pads, caused by too much pressure applied, they may end up contacting each other creating the same effect as short-circuiting; whereas if the bonding pressure is too low, the particles may not be able to make contact between the connecting bumps and pads [65]. Therefore, much research and development effort has been spent on understanding the effects of the bonding pressure on the reliability of ACA joints in flip chip assemblies [55, 56, 64–77].

In order to have reliable ACF or ACA interconnects, the number of conductive particles trapped between the bump and substrate pad should be enough and less conductive particle between adjacent bumps. In 1993, Williams et al. [66] studied the effects of the random distribution of particles in the material on resistivity variation and the probability of shorting/open joints between fine-pitch interconnections. They tried to estimate the probability for open joints by assuming that the particles are placed in the bonding area according to the Poisson distribution. Mannan et al. [67] investigated the probability for bridging, which is possible due to there being too many particles in the gap between adjacent connections. The results showed that the lowest combined probability for bridging and skipping occurs at a volume fraction of between 7 and 15% with appropriate bonding pressure. This volume fraction range is also generally used for commercial ACA materials today. Zou et al. [68] studied the effects of the number and the distribution of ACA conductive particles on RF transition of the joint using three-dimensional finite difference in time domain (FDTD) methodology. The results indicated that the number and the distribution of conductive particles have very little influence on the high frequency performance of an ACA flip-chip joint, because the size of the conductive particles (3–15 μm) is too small compared with the wavelength even for the maximum frequency of the signal passing through the flip-chip transition. These conductive particles can be regarded as a direct conductive interconnection. However, it should be mentioned that this statement is not valid for high-power applications where the limitations in the current density in the conducting layer need to be considered. Yim et al. [69] investigated the number of trapped conductive particles on bumps of COG assembly by changing the thickness ratio of ACF and NCF layers in the thickness of 25 μm of the double-layered ACF, which was fabricated by double coating of ACF layer and NCF layer. The results indicated that the number of conductive particles on bump decreased and was stabilized as the bonding pressure increased, and the contact resistance also decreased as the pressure increased, but there was open circuit at 30 MPa. They also found that at 30 MPa, the conductive particle was not deformed for low bonding pressure resulting open circuit of COG joint. As the gap between Au bump and pad decrease with increasing bonding pressure, conductive ball deforms more and contact area between conductive fillers, bump and pad surface also become larger.

Kang et al. [70] reported in 1996 an assembly and interconnection technology for micromechanical structures which provides many advantages using an ACF. The results showed that the optimum bonding conditions are achieved at 180 °C with a pressure of 5 kg/cm^2 applied for 10 s.

In 1998, Pinardi et al. [72] carried out a deformation study of the PCB during the flip chip assembly process using ACA. It was shown that the process-induced stress is much higher than the bonding pressure applied at the structure. The results also showed that by varying the bonding load and the temperature, the process-induced stress in the structures could be optimized, so that the failure of the structure could be minimized.

In 1998, Yim et al. [47] published a paper where the theoretical electrical conduction model with physical contact mechanism was simulated and experimentally proven. The results showed, in general, as bonding pressure increases, a sharp decrease of contact resistance followed by a constant value is observed after reaching the critical bonding pressure. However, an excessive bonding pressure rather increased the connection resistance of ACF interconnection.

In 1999, Yim et al. [73] published another paper where the effect of bonding pressure on the electrical and mechanical properties of ACF joint between FPC and ITO glass substrate was investigated. The results showed that as bonding pressure increases, decrease of contact resistance followed by a constant resistance increase was observed after reaching the critical bonding pressure, 3 kgf/cm^2. An excessive applied bonding pressure made contact resistance increase and induces internal elastic stress build up at the bonding interface. This stress was released under temperature and humidity tests and resulted in gaps at the interface which lead in a contact resistance increase and open circuits.

In 2002, Chan et al. [65] published a paper where the effects of different bonding pressure during FCOF assembly in relation to the performance of ACF interconnect were investigated, and their study focused on the effects of different bonding pressure on the contact resistance of ACF joints. Two types of ACF were used in their study. ACF 1 is designed to create good interconnection when the connecting bumps and pads are in close contact while ACF 2 can give good connections when the conductive particles are in contact with the bumps and pads, hence the deformation of conductive particles within ACF 2 FCOF packages were less than that within ACF 1 packages. The results showed that ACF 2 gave much better interconnection performance when compared to ACF 1 indicating that ACF 2 is more flexible and can tolerate a wider range of bonding pressure.

In 2004, Seppälä et al. [76] studied the adhesive flip chip bonding process and failure mechanisms of ACA joints. The results showed that the lower the used pressure, the higher was the failure percentage. Also, the magnitude of the pad depression into the substrate could be minimized using a low bonding pressure. However, the pressure below the recommended bonding pressure was shown to be inadequate. In order to further minimize the magnitude of the pad depression, two-step heating process was used. They emphasized that the effect of the degree of depression on the reliability of the joints must be studied in the future.

In 2006, Chen et al. [64] published a paper where the effects of different bonding pressure on the electrical performance and the adhesive strengths of ACF interconnection were investigated. The test results showed that the contact resistance and adhesive strength both are improved with the bonding pressure increased, but the adhesive strengths decrease if the bonding pressure is over 0.25 MPa, which may result from the fact that the thickness of the ACF becomes thin with bonding pressure increased, as shown in Fig. 4(a). After thermal cycling test of 1,000 h, the average peeling force decreases of 12.8% as shown in Fig. 4(b). After high temperature/humidity aging test of 500 h it is observed that the average peeling force of the specimens decreases of 39.9% as shown in Fig. 4(c). The excessive bonding pressure might induce high compressive stress and internal stress in the epoxy adhesive. The stored elastic compression can be released and leads to a loss of the contact area during testing which results in the decrease of adhesive strength after the reliability test. The optimum pressure ranges for ACF bonding are concluded to be at 0.15–0.2 MPa.

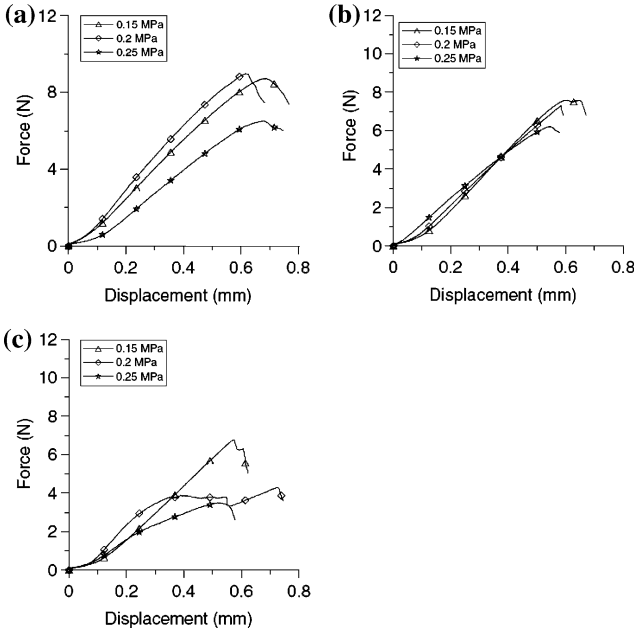

Fig. 4 Force–displacement curves at various bonding pressures: (**a**) different bonding pressures; (**b**) after thermal cycling test; (**c**) after high temperature/humidity aging test [64]

Effects of curing conditions on the reliability of ACA joints

Generally, adhesive materials can be cured in a short time under high curing temperature. High curing temperature usually leads to an increase in cross-link density and a homologous increase in heat resistance. Nevertheless, under high temperature curing process problems will occur such as the inclination for the shrinkage, cracks, and voids of adhesive materials, which will probably lower the dielectric properties. In order to understand the curing kinetics of anisotropic conductive adhesive film, and effects of curing conditions on the reliability of assemblies using ACF joint, some investigations have been carried out [64, 78–84].

In 1999, Miessner et al. [80] published a paper where a reliability study of flip chip on FR4 interconnections with ACA was carried out and the influence of different process parameters like pre-baking, cure temperature, and heating ramps on the properties and appearance of the adhesive layer was investigated.

In 2004, Cao et al. [81] published a paper where they investigated optimum curing degree and curing temperature to achieve the best performance of ACA. It was shown that the electrical and mechanical performance is dependent on curing conditions. Contact resistance was found to be strongly dependent on the curing degree, but also revealed no related with curing temperature.

In 2005, Lee et al. [83] investigated a new type of UV curable ACA for chip-on-flex application. The adhesive bonds of the chip-on-flex application were cured at different cure cycles within a range of UV frequencies. Cure cycles in this work were the different periods of time that were needed to cure the ACAs under different UV light intensities. The result showed that the longer the curing time and the larger the UV intensity, the higher the curing degree can be obtained. Furthermore, the curing time in the UV curable ACA was much shorter than that of the conventional thermal curable ACAs.

In 2006, Zhang et al. [84] studied the effect of environment on the anisotropic conductive adhesive film (ACF) capability parameter, glass change temperature (T_g). In their study, the DSC is used to discover the changes of T_g of ACF before and after curing. Also, the changes of T_g with different curing time were investigated. The results showed that the glass change temperature decrease is the one of reasons of ACF bonding strength decrease.

In 2006, Chen et al. [64] published a paper where the effects of curing time, different Teflon thickness and post-processing on the electrical performance and the adhesive strengths of ACF interconnection were investigated. The test results showed that the curing time has great influence on the adhesive strength of ACF joints, and the peeling strengths become higher with the curing time increased (Fig. 5(a)). As curing time increase, stronger chemical bonding at the interface results. After thermal cycling test of 1,000 h, the average peeling force decreases 3.5%, but the adhesive strengths increase with the curing time increased (Fig. 5(b)). After high temperature/humidity aging test of 500 h, the average peeling force decreases 41.7% (Fig. 5(c)). An interesting observation from this experiment is that for 9.9 s curing time the peeling force decreases 72.7% after high temperature/humidity aging test, which results in the worst reliability. The test results show that the shorter curing time, the lower peeling strengths. However, long curing time introduces low manufacture efficiency. The reasonable curing time is 18–25 s. Additionally, the contact resistance and the adhesive strength both become deteriorated with the increase of the Teflon thickness. The tests of different post-processing conditions showed that the specimens kept in 120 °C chamber for 30 min present the best performance of the ACF joints.

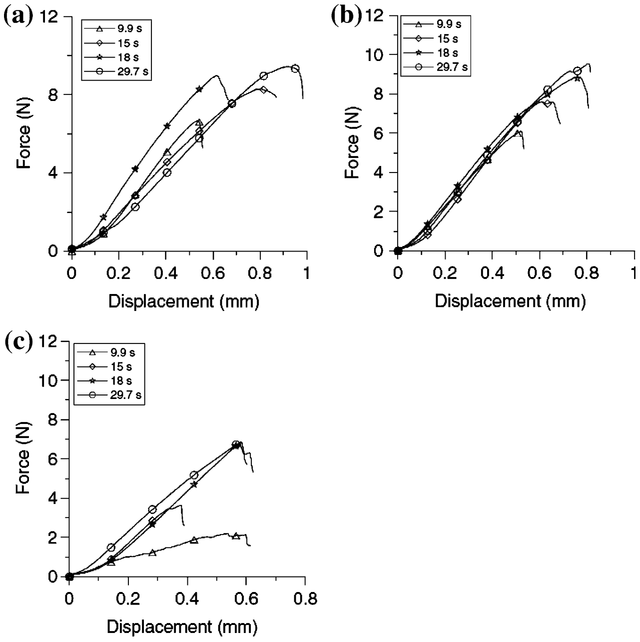

Fig. 5 Force–displacement curves at various curing times: (**a**) different curing time; (**b**) after thermal cycling test; (**c**) after high temperature/humidity aging test [64]

Effects of the reflow process on the reliability of ACA joints

Because many electrical devices have at least one solder reflow process performed after the ACF bond, i.e., in the process of manufacturing this type of devices, the first step is usually to use ACF bonding to achieve high accuracy for fine-pitch placement of some components, and then this is followed by a standard solder reflow process for the formation of the solder interconnections, the ability of ACF to withstand multiple solder reflows is a major milestone in its growing acceptance within the semiconductor packaging industry. Therefore, some investigations have been performed to study the effect of solder reflow on the reliability of ACF interconnections [85–92].

In 2000, Sugiyama [86] and Törnvall [87] reported that the ACA material from Sony can withstand the soldering profile three times without causing reliability problems; however, reported different results in terms of the effect of soldering processes, showing that an ACA flip-chip module cannot withstand a normal soldering process.

In 2003, Yin et al. [88, 89] studied the effect of reflow process on the contact resistance and reliability of ACF interconnection. It was shown that the contact resistance of ACF interconnection increased after reflow process due to the decrease in contact area of the conducting particles between the mating I/O pads. However, the relationship between the contact resistance and bonding parameters of the ACF interconnection with reflow treatment follows the similar trend to that of the as-bonded (i.e. without reflow) ACF interconnection. The contact resistance also increased as the peak temperature of reflow profile increases. During the reflow process, the entrapped (between the chip and substrate) adhesive matrix tries to expand much more than the tiny conductive particles because of the higher coefficient of thermal expansion (CTE), the induced thermal stress will try to lift the bump from the pad and decrease the contact area of the conductive path and eventually, leading to a complete loss of electrical contact.

In 2004, Yin et al. [91] investigated the effects of solder reflow process on the reliability of the ACF interconnection for flip-chip on flex (FCOF) applications. The results showed that the contact resistance of ACF interconnections increases after the reflow and the magnitude of the increase is strongly correlated to the peak reflow temperature. The interface between the particle and its surrounding materials is significant and it is the highest at the interface between the particle and the adhesive matrix.

In 2005, Chiang and Chan [92] presented the reliability of the ACA joint tested under reflow soldering. The results showed that the ACA joint behaved differently under different reflow soldering profiles. The lower reflow temperature resulted in more reliable ACA joints by maintaining low contact resistance. By contrast, high contact resistance was found in assemblies treated with higher reflow.

Effects of the misalignment on the reliability of ACA joints

Another important issue in flip chip technology, the adhesive has a very low surface tension, and therefore no selective wetting. With the use of adhesive, ACA does not self-align that would allow misplaced chips to be pulled into correct position corresponding to substrate electrodes by surface tension forces of molten solder [93]. Misalignment will at least decrease the contact area, and thereby increase the resistance. Worse still, there is the possibility of open connections or short-circuits. Misalignment can be caused by placing error, bump height variation and lack of flatness of the bump pads, uneven assembling pressure, and nonuniformity in thickness of ACA. Especially, for the fine-pitch assembly such as flip chip, the conductor pad sizes and conductor spacing are very small. The tolerance to the misalignment is very limited. However, in the manufacturing process, the occurrence of misalignment could not be absolutely avoided. Therefore, some investigations have been carried out to understand the effect of the misalignment on electrical characteristics of ACA joints, and some effective measures to reduce the misalignment effect have been proposed [94–96].

In 2002, Fan and Chan [94, 95] studied the effect of the misalignment on electrical characteristics of ACA joints. It was found that the misalignment significantly affects the electrical characteristics of ACA joints. Fig. 6(a, b) shows the relationship of connection resistance vs. misalignment in x-direction of ACF joints using Au coated polymer ball-filled and Ni conductive particles, respectively. It can be found that the connection resistance increases along with the misalignment. At first, when the misalignment increased from zero (perfect alignment) to about 5 µm, the connection resistance increases fast. Then, along with the severity of misalignment, the increase rate of connection resistance becomes slow. Finally, when the misalignment approaches to 20 µm, the increase rate becomes larger again.

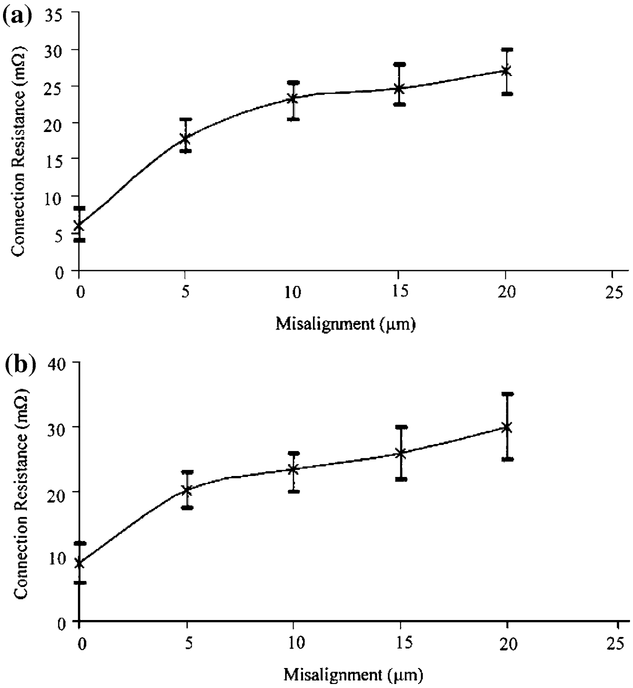

Fig. 6 Plot of connection resistance vs. the misalignment in x direction. (**a**) Au coated particle ACF joints; (**b**) Ni particle ACF joints [94]

In 2006, Xie et al. [96] found that the bonding temperature difference between IC and glass and ACA material properties were also found to have significant effect on the misalignment. The experiments showed less temperature difference can cause less misalignment.

Effects of environmental factors on the reliability of ACA joints

On the other hand, the effects of the environmental factors, including temperature, humidity, thermal cycling, impact load, etc, on the reliability of ACA joints are also significant. It is well known that the polymer-based ACA joints are often subjected to high relative humidity environment and are susceptible to moisture sorption, especially at elevated temperatures, which is one of the major reliability concerns for the ACA joints. Prolonged hygrothermal aging may lead to irreversible degradation to the epoxy resin system due to susceptibility of the resin polymer to hydrolysis and oxidation, as well as due to the change in the effective average cross-link molecular weight. The absorbed moisture has deleterious effects on the physical properties of epoxies and can, therefore, greatly compromise the performance of an epoxy-based component. Meanwhile, the polymeric materials swell upon absorbing moisture, while other components of the electronic assemblies (such as the ceramic and glass substrates) almost cannot absorb the moisture. Therefore, the mismatch of the thermal and moisture expansion coefficients of the materials lead to the thermal stress and hygroscopic stress among the polymeric materials constituted in the electronic package, also the interfaces between different electronic components. The combined effects are most important for the failures of ACA joints. For example, Fig. 7 shows possible failures of ACA joints of a COG assembly in a mobile telephone under hygrothermal conditions. Obviously, the cracks and delaminations, along with some air bubbles, can be easily found at the interface between the chip and glass substrate. Some researchers have studied the effect of moisture on the epoxy resin properties, including tensile strength, elastic modulus, etc., and the effects of hygrothermal aging on ACA material and ACA joints. Therefore, reliability tests in terms of temperature cycling, high humidity and temperature, and high-temperature and dry condition test were performed to understand the failure mechanisms of ACA joints under different environmental factors [57, 73, 97–140].

Liu [97] published a paper in 1993 where he investigated the feasibility of using ACA to join surface-mount devices as solder replacement as one of the earliest work in this field. Based on industrial demands, two ACA were chosen for the experimental work. It was concluded that some anisotropic conductive adhesive joints are stable in the 85 °C/85% RH environment and therefore have better corrosion resistance than other ACA joints. But none of them passed temperature cycling from −55 to 125 °C, 1,000 cycles test required by the military standard 88 °C.

Stam et al. [98] carried out in 1995 a reliability study of ACA for fine pitch package assembly. It was shown that although mechanical strengths and electrical resistances were obtained similar to those expected for solder assembly; reliability, humidity testing in particular, needs to be addressed in greater detail in order to make the application of ACA a viable alternative to solder.

In 1996, Lai and Liu [99] published a paper which was also the earliest work in this field where ACA is used on rigid board. They carried out a systematic experiment study on flip-chip bonding assembly using an ACA on rigid board, including aging, constant humidity, temperature cycling, humidity cycling, shear, vibration, and shock testing. The results indicated that under optimum process conditions, high quality and high reliability joints can be achieved. The analysis showed that failure is dependent on competition between driving factors: thermal stress, elastic stress, expansion due to moisture absorption on one side, and the resistant factor, i.e., inter-atomic force.

In 1999, Liu et al. [100] performed an evaluation of environmental impact and reliability when using ACA for flip-chip joining in radio base station applications. The results of reliability testing, including the temperature cycling test and aging test, showed that relatively small resistance changes were observed after the reliability test. The environmental impact evaluation was done in the form of a material content declaration and a life cycle assessment (LCA). By using flip-chip ACA joining technology, the content of environmentally risky materials has been reduced more than ten times, and the use of precious metals has been reduced more than 30 times compared to conventional surface mount technology.

The same year, Yim et al. [73] published a paper where environmental effects on contact resistance and adhesion strength such as thermal aging, high temperature/humidity aging, and temperature cycling were also investigated. The results showed that temperature cycling and temperature humidity tests displayed the detrimental effects of increasing contact resistance and electrical failure in ACF interconnection. Increasing contact resistance and

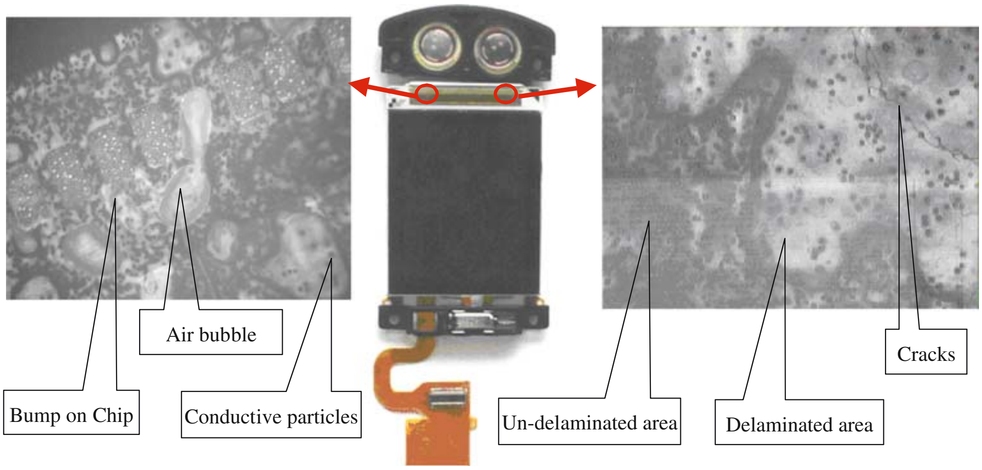

Fig. 7 Failures of a COG assembly in a mobile telephone under hygrothermal conditions

decreasing adhesion strength after harsh environmental tests were mainly due to the loss of contact by thermal stress effect and moisture absorption, and also partially due to the formation of metal oxide on the conductive particles.

In 2000, Weidler et al. [101] studied the electrical properties and the reliability of ACA film interconnection between aluminum pads on a glass substrate and electrolysis tin coated copper pads on a polyimide flexible circuit as a function of temperature and humidity aging. The interconnect was aged over 1,400 h in an 85 °C/79% RH environment, while the electrical bond resistance was recorded in situ. Samples bonded at 20 kgf showed the smallest average resistance change as well as the smallest standard deviation of the average. Although the interconnections to the aluminum metallurgy preformed well, the weakness part of the bond was determined to be the adhesive-aluminum interface. Cracks were observed to originate at this surface, and nearly all the electrical resistance was shown to also be due to the aluminum metallurgy.

In 2000, Lefebvre [102] revealed that the adhesion between an epoxy and glass was lowered abruptly when the epoxy was equilibrated with air whose relative humidity (RH) exceeded a critical value. The critical humidity marking the onset of adhesion loss was also associated with a sudden increase of water uptake by the epoxy. The critical humidity effect was due to the trapping of water by hydroxyl groups which become available as inter-chain hydrogen-bonded structures are broken. The critical humidity effect might be an ‘order–disorder’ transition associated with the formation of ring structures closed by hydrogen-bonded water linkages between polar groups. The first-order energetics of this type of transition is consistent with the abrupt nature of the critical humidity effect.

In 2001, Liu [103] developed a theoretical model for predicting the number of cycles to catastrophic failure during the temperature cycling for any anisotropic conductive adhesive joint used for electronics interconnecting purposes. The model only needs data from two resistance measurements, i.e. they are at zero cycles and at any other number of cycles measured together with information regarding the conductor particle deformation behavior. The model can predict the resistance of the joint increase as a function of the increasing crack length and also as a function of the number of temperature cycles.

In a paper by Fujiwara et al. [104] in 2002, connection reliability and connection deterioration mechanism regarding a flip-chip attachment method were examined using anisotropic conductive film to connect Si chips having Au bumps to the printed wiring substrate. A connection reliability of 1,000 cycles or more was obtained in a −30/80 °C temperature cycle test by optimizing the Au bump-flattening load and chip junction load. Traces from sliding were confirmed on the substrate wiring after a temperature cycle test. An increase in resistance in the temperature cycle test was thought to have been caused by Au plating on the wiring rubbing off due to sliding on the Au bump and wiring interface as a result of the difference in coefficients of linear expansion for the chip and substrate, and this rubbing causes a reduction in contact area.

Zhang et al. [57] published a paper where they systematically discusses the influence of humidity on the adhesion of bumpless die (aluminum surface) with two kinds of ACFs. Evaluated by die shear test, the adhesion strength at the ACF/aluminum interface increases while the adhesion at the ACF/glass surface decreases after aging in the same high temperature and high humidity environment. It was found the adhesion of ACF/aluminum layer enhanced after humidity aging. Moisture mainly diffused into aluminum and resulted in oxidation reaction instead of diffusing into adhesive to make it swell. There is less swelling of the adhesive, and a smaller delamination strength at the ACF/aluminum interface. So the adhesion strength of shear samples increased after temperature/humidity exposure. In addition, the oxidation reaction can provide fresh rougher surface that may enhance adhesion strength.

In 2002, Wu et al. [105] presented a reliability assessment of adhesive joints using COG technology at various aging temperatures and at high humidity. It was found that aging generally caused a decrease in shear strength while the aging temperature was below the glass transition temperature (T_g) of ACF. When the aging temperature was slightly above the T_g of the ACF, a significant decrease in shear strength was observed. Moreover, the results revealed the presence of some voids near the component bumps, resulting in high stresses at the high aging temperature, and the ACF was not fully cured, allowing moisture absorption more seriously than a fully cured ACF, leading to joint degradation. It can be seen that delaminations occurred as a result of moisture absorption. Liquid was also observed to be present within these delaminated regions. This means that water had diffused along the glass-resin interface, and had caused damage such as oxidation of the epoxy resins in the ACF during thermal aging.

In 2003, Tan et al. [107] published a paper where the behavior of ACF joints under environmental effects (high moisture and elevated temperature) was investigated by various mechanical loading (die shear and cyclic fatigue in shear). The results showed that epoxy-based ACF exhibits insignificant plastic deformation, especially for samples that have undergone autoclave test. Reduction trend was observed in the shear module over autoclave test time for ACF joints, as illustrated in Fig. 8. Fracture surface of ACF that failed in shear test shows spalling and less plastic deformation after exposed to autoclave test.

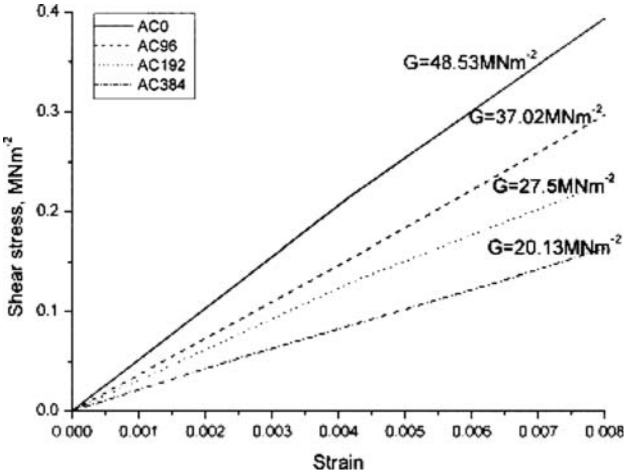

Fig. 8 Shear moduli for ACF joints obtained from experimental results at different autoclave test time [107]

In the same year, Tan et al. [108, 109] reported that the stress-corrosion cracking induced by autoclave test condition reduces the mechanical strength of anisotropic conductive joints and also increases the contact resistance by allowing more moisture to reach the aluminium metallization. The results showed that the epoxy-based ACF absorbs moisture and experiences hygroscopic swelling, hence degrading adhesion strength and elasticity in hazardous environments, e.g. if moisture at high vapor pressure, and test temperature near to its glassy temperature (T_g) are applied. Also, contact resistances show an increasing trend that is similar to that typical of a corrosion process, which is most probably due to the formation of an oxidation layer on top of the aluminium metallization and to the hygroscopic swelling of the ACF. Figure 9 illustrated the evidences of metal oxidation and stress-corrosion cracking at ACF joints.

Wang [110] published a paper in 2003 where he reviewed the current development of COG technology for mobile display applications, with the emphasis on the challenges in the reliability study. It was shown that delamination and indium-tin-oxide (ITO) corrosion are two major concerns faced by the industry. The former is typically caused by moisture in combination with high temperature. ITO corrosion is typically caused by moisture, contamination, and ionic impurities in ACF or on the glass surface. Further reduction of the pitches to be <35 µm in COG technology requires a major breakthrough in ACF material and careful reliability design.

Mercado et al. [111] investigated in 2003 the failure mechanism of ACF using finite element simulation. Simulation results showed that moisture-induced ACF swelling and delamination are the major causes of ACF failure. With moisture absorption, the loading condition at the interface is tensile-dominant, which corresponds to lower interface toughness (or fracture resistance). This condition is more prone to interface delamination. Therefore, the reliability of ACF packages is highly dependent on the ACF materials. The paper suggests a new approach toward material selection for reliable ACF packages. This approach has very good correlation with experimental results and reliability testing of various ACF materials.

In 2003, Zhang et al. [112] presented the initial contact resistance, electrical performance after reliability tests (such as high humidity and temperature and thermal cycling), and degradation mechanisms of ACF interconnection for FCOF assembly using very-low-height Ni and Au-coated Ni-bumped chips. The results showed that the degradation of electrical performance is mainly related to the oxide formation on the surface of deformed particles with non-noble metal coating, the severe metal oxidation on the conductive surface of bumps, and CTE mismatch between the ACF adhesive and the contact conductive-surface metallization. Additionally, some methods for reducing initial contact resistance and improving ACF interconnection reliability were suggested, i.e., the removal of the oxide layer and an increase of the Au-coating film to improve conductive-surface quality, appropriate choice of conductive particle, and further development of better polymeric adhesives with low CTE and high electrical performance.

The next year, Zhang et al. [113] studied electrical resistance reliability of ACF interconnection for chip on

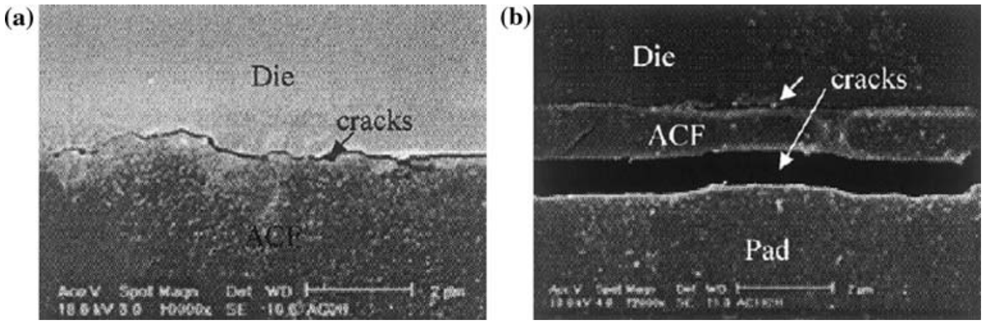

Fig. 9 Examples of cracks observed from autoclave tested ACF joints at (**a**) Die/ACF; (**b**) Pad/ACF interfaces (before Al bump) [109]

flex application using different bump/pad metallization couple. Contact resistance changes were monitored during reliability test, including high humidity and temperature, and thermal cycling. It is shown that both the higher initial contact resistance and rapid increment were investigated in ACF assemblies with Ni–Cu coupled metallization. The potential causes for the bigger degradation of Ni–Cu coupled ACF were related to (1) galvanic corrosion occurred at the interfaces of ACF joints with different contacting metallization, (2) micro-cracks in ACF joints, and (3) rougher surface of Cu pad metallization.

In 2004, Uddin et al. [114] performed a systematic experimental work was performed to evaluate the reliability of the ACF joint at high temperature for FCOF assemblies. It was found that initially, the contact resistance increased linearly with rising temperature, but later, it increased abruptly. This changeover was related to the glass-transition temperature (T_g) of the ACF matrix. The CTE is very high at temperatures above T_g; thus, the ACF swells too much, reducing the mechanical contact of the particles with the bump and/or pad. Again, as the adhesive strength becomes weaker at temperatures above the glass transition, it is unable to resist the thermal stress of the flex. The cumulative thermal stress at the edges dislodges the particles from the interconnection. Even below T_g, the thermal stress at the edges is higher than the middle point. Thus, the contact resistance varied from the middle joint of the chip to that of the corner at the same high temperature. To reduce the contact resistance at the corner joint of the FCOF packages bonded by ACF, a square-shaped chip instead of a chip with a higher aspect ratio should be used. It was also suggested to use an adhesive with a higher glass-transition temperature and lower CTE.

In 2005, Kwon et al. [117] published a paper where the thermally induced deformations and warpages of ACF flip chip assemblies as a function of distance from neutral point (DNP) and ACF materials properties were investigated using in situ high sensitivity moiré interferometry. The results indicated that the properties of ACF have a significant role in the thermal deformation and reliability performance during thermal cycling testing. An ACF with low CTE and high modulus can reduce the thermally induced shear strain in ACF layer, and thus can increase the overall thermal cycling lifetime of ACF joint compared with high CTE and low modulus ACF. It was also observed that low CTE and high modulus ACFs are less susceptible to delamination failures at free edges during thermal cycling testing. Therefore, optimized ACF properties can enhance ACF package reliability during thermal cycling regime.

In 2005, Yang et al. [118] investigated the warpage damage of chip for ACA film type electronic packages. In their study, the warpage of the chip was monitored by real time moiré interferometer during −50 °C to +125 °C temperature range. Moreover, the reduction in chip warpage due to increase in delamination length was obtained as in function of thermal fatigue cycles. Finally, a new model to predict damage level of ACA package and remained life was proposed.

In 2005, Teh et al. [119] investigated the reliability performance of the adhesive flip chip in the pressure cooker test and moisture sensitivity test conditions. Different sizes of bump/pad opening in the interconnections were discussed in the context of the significance of mismatch in coefficient of moisture expansion (CME) between adhesive and other components in the package, which induces a hygroscopic swelling stress. The effect of moisture diffusion in the package and the CME mismatch were also evaluated from the standpoint of finite element modeling. The failure modes were found to be interfacial delamination and bump/pad opening which may eventually lead to total loss of electrical contact. It was concluded that hygroscopic swelling assisted by loss of adhesion strength upon moisture absorption is responsible for the moisture-induced failures in these adhesive flip chip interconnects.

In 2006, Kwon et al. [120] investigated the deformation mechanism and electrical reliability of the ACA joint subjected to temperature cycling for flip chip on organic board (FCOB) assemblies. This paper presented some dominant deformation parameters governing the electrical degradation in an ACA joint between a chip and a substrate when flip chip assembly is heated and cooled. The results showed that as the temperature increases below T_g of ACA, the bending displacement of assembly decreases linearly. At the temperature higher than T_g of ACA, there is no further change in bending behavior and in-plane deformations of a chip and a substrate become approximately free thermal expansion.

In 2006, Lin et al. [121] published a paper where they studied the effects of hygrothermal aging on anisotropic conductive joints by experiments and theoretical analyses. The results showed that the strength of ACF joint decreases and the fracture mechanism gradually changes with the hygrothermal aging. That is, a transition from cohesive to interfacial mode of debonding occurs. Additionally, they developed an ACF joint aging model with hygrothermal environment by introducing a dimensionless parameter A, which was obtained from the interfacial fracture energy and used to describe the decrease of interfacial fracture energies.

In the same year, Lin et al. [122] studied the effects of hygrothermal aging on epoxy-based anisotropic conductive film. The results showed that there are some chemical modifications to the aged ACF materials, i.e., an increase in the alkyl group, carbonyl group, the aromatic ether linkage and *p*-phenylene groups, together with a corresponding

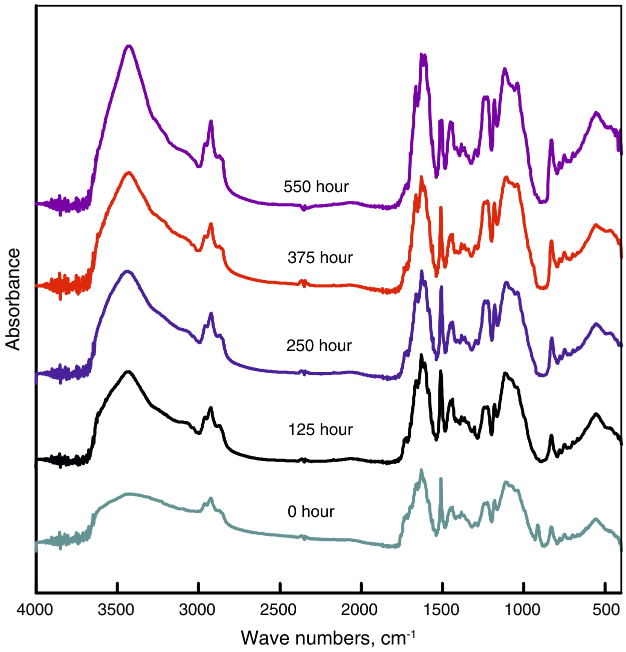

Fig. 10 Changes of different bands or functional groups at different test time in the band of (400–4,000 cm^{-1}) [122]

drop in the ester peak and the epoxy functional groups, as shown in Fig. 10. The changes of molecular conformation verify the contention that the material is subjected to chemical hydrolysis with increased aging of the ACF under the hygrothermal environments. Meanwhile, the quantitative analysis of the relative absorbance intensities of the epoxy functional groups showed that continuous cure reaction occurred with the hygrothermal aging.

In 2006, Zhang et al. [123, 124] investigated the damage for the adhesive interface. In their study, the cohesive zone type interface model was used in the ACF bonding samples, and the interface model could calculate 90° peel delimination. The constitutive equation for the interface was modified by introduction the thermal damage factor and humidity damage factor, which were derived from the experiment data. Their calculation results of the interfacial model with damage factors well agree with that of the 90° peeling experiments.

Because ACA or ACF are based on the epoxy system, some studies have been carried out to investigate the behaviors of the epoxy system under hygrothermal conditions.

In 2002, Luo et al. [125] presented a study on the mobility of water and polymer chains in epoxy materials and its influence on the rate of adhesion degradation in a humid environment. The results showed that absorbed water reduces the glass transition temperature of polymeric materials due to the plasticizing effect of water. However, the presence of moisture has no significant effect on the polymer chain mobility at temperatures below the reduced glass transition temperature. Water in an epoxy in its rubbery state above the glass transition has a much higher mobility than in a polymer in its glassy state. The mobility of water absorbed by a polymer in its rubbery state is similar to that of pure water. Higher rotational mobilities of water and polymer chains in the rubbery state lead to a significant increase of the water diffusion coefficient in the rubbery state polymer matrix as compared to a polymer in its glassy state. The higher mobility of absorbed water and the higher mobility of polymer chains in epoxy lead to faster adhesion degradation during aging in a humid environment.

Leung et al. [126] published a paper where the subcritical interfacial debonding process was described. The debonding rates of polymers with silane, titanate, and zirconate coupling agents were characterized at different temperatures by shear fracture tests and tapered double cantilever beam tests under mechanical loading and simultaneous exposure to controlled acidic environments. It was found that the elevated temperature and acidity have a strong effect on package reliability, but mechanical loading was found to have a minimal effect on the rate of adhesion degradation.

In 2005, Lin and Chen [127, 128] studied the effects of hygrothermal conditions on the mechanical behavior of DGEBA epoxy system. The results showed that due to the effect of the hygrothermal condition, the tensile strengths and tensile elastic modules of the water-saturated, desorbed, and resaturated group samples are both reduced much, compared to the original unaged or dry group samples. This probably arises because of the plasticization effect of absorbed moisture. The extent of this plasticization process seems to increase markedly with hygrothermal history, except there is slightly shifted back of the tensile strength and elastic module for the desorbed samples. Also, the moisture sorption–desorption–resorption characteristics of the DGEBA/DDA epoxy system have been investigated by the hygrothermal aging and molecular dynamic (MD) simulation.

The same year, Lin and Chen [129] investigated the effect of hygrothermal conditions on epoxy system by fractography and computer simulation. The tensile fracture surfaces have been analyzed by a scanning electron microscopy (SEM) for the initial dry, moisture-saturated, and completely desorbed specimens, respectively. Furthermore, fracture surface patterns are simulated by computer, based on the theory that the conic-shaped pattern is due to the intersection between a moving planar crack front and a radically growing circular craze or secondary crack front. The results showed that there is a close relationship between the velocity ratio of crack velocity to craze or secondary crack velocity and fracture surface patterns. Additionally, the transition of brittle/ductile appeared due to the effect of hygrothermal conditions.

Additionally, the effects of electrochemical corrosion, which can exist between the material used for the particle and the pad on the reliability of the ACA assemblies, are significant. It is commonly accepted that metal oxide formation at the interface between the conductive adhesive and the non-noble metal surface is responsible for the contact resistance shift. Two different mechanisms, simple oxidation and galvanic corrosion, both can cause metal oxide formation. Since oxidation and galvanic corrosion are two different processes, different approaches should be employed to prevent them. Therefore, in order to stabilize contact resistance by preventing metal oxide formation, it is essential to identify the dominant mechanism for the metal oxide formation and for the contact resistance shift. However, no prior work was conducted to confirm which mechanism is the dominant one underlying the contact resistance shift phenomenon before 1999. Lu et al. [131] carried out a series of experiments to differentiate these two mechanisms and found that the galvanic corrosion rather than simple oxidation of a non-noble metal was the dominant mechanism for the metal oxide formation and for the unstable contact resistance between conductive adhesives and the non-noble metal finished surface mount components. Based on this understanding, ECA with stable contact resistance on non-noble metals were developed. One of the approaches of developing ECA with stable contact resistance is to select proper polymeric resin formulations. Another approach to stabilize contact resistance is to use corrosion inhibitors [132–134].

Effects of the properties of components on the reliability of ACA joints

Effects of bump height on the reliability of ACA joints

The bumps of the flip chip (FC) technology are usually made from nickel. Since pressure is applied to force the conductive particles to make a contact between the nickel bumps and the copper pads in printed circuit boards (PCB) or flexible circuits (flex), the deformation of the bump can affect the electrical conductivity. In particular, the height of the bumps can change the deformation characteristics, and hence the reliability of the interconnection in the FC assembly. Therefore, some researchers have investigated the effect of bump height on flip-chip joint reliability using ACA [141–147].

In 1997, Lam et al. [141] published a paper where structural reliability of direct-chip-attach bonded with anisotropic conductive film was investigated. The results showed that tall bump height can reduce the potential for electrical failure in ACF interconnects when ACF/bump interfacial fracture is the dominant failure mode.

In 1998, Lai et al. [142] studied the effect of bump height on the reliability of ACA flip chip joining with FR4 rigid and polyimide flexible substrate. In the temperature cycling test, the assemblies on FR4 substrate showed that reliability decreases with increasing bump height. While, with the flexible substrate, the electrical performance of the ACA flip chips did not change. It was also shown that the different mechanisms are attributed to the different stiffness of the substrate.

The same year, Persson et al. [143] published a paper where electroless nickel/gold bumps of the different heights have been used to study effect of bump height on flip-chip joint reliability using ACA. The chips have been assembled on FR-4 substrates and the samples have been subjected to temperature cycling from −40 to 125 °C. The results showed that the bump height is of importance for the quality and reliability of flip chip joints, and the high bumped joints showed poor reliability, which could be due to the formation of pores. Theoretical calculations given the relationship between the mechanical strength and the bump height at various distances form the centre of the chip.

Pinardi et al. [144, 145] also reported a work on the effects of bump height on the strain variation during the thermal cycling test of ACA flip-chip joints in 2000. The results showed that the effects of bump height are significant in the interface between the bumps and the pads. Bigger volume area of high strain is found for higher bump in the interface between the bumps and the pads. Their calculations show that there is practically no effect of the bump height on the strain variation in the bumps and in the pads.

In 2000 and 2001, Wu et al. [146, 147] studied the effects of bump height on the reliability of ACF in flip-chip also. In their study, flip-chip (FC) assemblies on printed circuit board (PCB) and flex, with bump heights of 4, 20, and 40 μm, and with a constant copper pad height were compared by modeling of the bonding process and of thermal cycling from −40 to 125 °C. It shows that the stress increased with increasing nickel bump thickness. Also, possibly because of the larger difference of CTE, a larger residual stress was found in the cases of ACF in FC-on-flex when compared with the cases of FC-on-PCB. This trend was almost the same for the cases at the low temperature of −40 °C of the thermal cycle. When comparing the stresses, larger levels of stress were found at the low temperature of −40 °C. Additionally, the stresses in the anisotropic conductive film for the FC-on-flex assembly were also found to be generally larger than for the FC-on-PCB.

Additionally, the planarity of the bumps within one chip is essential to improve the reliability of the ACA joints. If there is a large variation in bump height a cross the chip, it will be impossible to exert a uniform pressure over the entire chip. It is important to have bumps of uniform height across the chip. Otherwise bonding quality cannot be guaranteed.

Effects of ACA material properties on the reliability of ACA joints

As the bump size in the flip chip assembly is reduced, the current density through the bump also increases. This increased current density causes new failure mechanisms, such as interface degradation due to intermetallic compound formation and adhesive swelling resulting from high current stressing. This process is found especially in high current density interconnection in which the high junction temperature enhances such failure mechanisms. Therefore, it is necessary for the ACA to become a thermal transfer medium that allows the board to act as a new heat sink for the flip chip package and improve the lifetime of the ACA flip chip joint. As the estimation for the reliability of flip chip interconnection, fatigue life of ACF interconnection, which is limited by the thermal expansion mismatch between chip and substrate, could be increased by the variation of interconnection material properties. In general, the interconnection material between chip and substrate should have close CTE value to those of the chip and substrate for the reduction of thermally induced strain and stress. So, understanding the effect of CTE value of ACFs on thermo-mechanical properties will impact on the better performance and reliability of flip chip packages by choosing right ACF materials and ACF materials development. Some investigators have carried out a lot of work in this field [148–155].

In 2000, Yim et al. [148] discussed the flip chip assembly on organic board using ACF and electroless Ni/Au bump. Three ACF materials with different CTE values were prepared by incorporation of nonconductive particles and bonded between Si chips and FR-4 boards for the thermal strain measurement using moiré interferometry. The results showed as the content of nonconductive particle increases, the CTE value of cured adhesive film decreases. The thermal strain of the ACF interconnection layer was decreased according to the decreasing CTEs of ACF materials. This result indicated that the thermal fatigue life of ACF flip chip assembly on organic boards, limited by the thermal expansion mismatch between the chip and the board, could be increased by low CTE ACF.

In 2001, Yim et al. [149] published a paper where they investigated the effect of non-conducting fillers on thermo-mechanical properties of modified ACA composite materials and the reliability of flip chip assembly on organic substrates using modified ACA composite materials. The contact resistance changes were measured during reliability tests such as thermal cycling, high humidity and temperature, and high temperature at dry condition. It was found that the reliability results were significantly influenced by CTEs of ACA materials, especially at the thermal cycling tests. Their results show that flip chip assembly using modified ACA composites with lower CTEs and higher modulus by loading non-conducting fillers exhibited small contact resistance variation than conventional ACAs without non-conducting fillers. An ACF with a lower CTE and higher modulus can reduce thermally induced shear strain in ACF layer during the thermal cycling environment and thus can increase the overall thermal cycling lifetime of ACF joints

In 2003, Kwon et al. [150] investigated thermally induced deformations of ACF flip chip assemblies as a function of ACF materials properties and distance to neutral point (DNP). To elucidate the effects of ACF material properties and the distance from chip center (DNP) on the thermal cycling reliability of ACF assembly, Weibull analysis for the lifetime estimation of ACF joint were performed, and compared with thermal deformations of ACF flip chip assembly investigated by moiré interferometry. The results indicated that the properties of ACF have a significant role in the thermal deformation and overall reliability during thermal cycling testing. Therefore, optimized ACF properties can enhance ACF package reliability during thermal cycling regime.

Teo et al. [151, 152] developed a methodology to identify ACA material properties that are critical for enhanced moisture sensitivity test (MST), temperature cycling (TC), high temperature storage (HTS), and pressure cooker test (PCT) performance. Correlation analysis suggested that ACA material properties for good PCT performance were higher adhesion strength after exposure to test conditions and lower CME. The preservation of adhesion strength after PCT was critical to maintain the integrity of the ACA joint while a low CME value implied lower hygrostress. This also confirmed hygrothermal stress as the driving force for PCT failure. For better MST performance, desired material properties identified were low modulus (E) and high adhesion after moisture preconditioning. This implied thermo-mechanical stress as the main driver for MST failure. Findings indicated that the best properties for high reliability assemblies were: high adhesion strength after subjecting to reliability test conditions (stress aging), low coefficient of moisture expansion (CME), and low elastic modulus (E).

In 2005, Hwang et al. [153] investigated the effects of thermoplastic resin content of anisotropic conductive films on the pressure cooker test reliability of anisotropic conductive film flip-chip assembly. In their study, the changes in ACF resin morphology due to the phase separation of thermoplastics, and subsequent changes of physical and mechanical properties were investigated as a function of thermoplastic contents of ACF formulation. The results showed that as thermoplastic contents increased, CTE of ACFs increased, and elastic modulus (E') of ACFs decreased. In contrast, water absorption rate decreased as thermoplastic content increased. As a result, PCT reliability of ACF flip-chip assembly was improved adding up to 50 wt.% content of thermoplastic.

In the next year, Hwang et al. [154] also investigated the effects of the functionality of an epoxy monomer on the composite properties and reliability of ACFs in a flip-chip package. Three epoxy monomers with different functionalities ($f = 2$–4) were considered. The results showed that the ACFs prepared using epoxy monomers with higher functionality resulted in lower molecular weight between crosslinks (M_c). As the M_c decreased, the elastic modulus (E') and CTE were improved. The ACFs prepared by using higher functional epoxy monomers showed improved reliability performance of the flip chip on organic substrate assemblies.

In 2006, Yim et al. [155] investigated the degradation mechanism and the reliability behaviors of flip chip joint using ACAs and Au bumped chip for high current density packaging applications. The current carrying capability and current stressing reliability of flip chip assembly using three different types of ACAs were performed to investigate the effect of thermal conductivity of ACA and the conductive particle type on the current carrying capability and current stressing reliability of ACA flip chip joints. The results showed that the thermal conductivity of ACA has significant effects on the current carrying capability and resultant current stressing reliability of flip chip joints using ACAs.

Effects of the properties of the substrates on the reliability of ACA joints

Another important issue is the effects of the substrate hardness, geometry, and material on the reliability of ACA joints, and the parallelism of substrates and components remains a major issue in obtaining consistency of conduction across assembly joints. Therefore, some studies have been done to understand the mechanisms [27, 99, 156–158].

The planarity of the substrate can have a strong influence on the reliability of the ACA joints. On flexible substrates, in particular, the presence of conductor tracks can cause a non-flat surface. The result is uneven pressure distribution and therefore poor bonding quality. In 1996, Lai et al. [99] studied the reliability of ACA flip-chip bonding on rigid and flexible printed circuit substrates by a number of environmental tests, including aging, constant humidity, temperature cycling, humidity cycling, shear, vibration, and shock testing. The results indicated that the bonding pressure with the flexible board is always uneven. The uneven pressure distribution leads to no-uniform deformation of the contacting pads on the flexible board.

In 1998, Oguibe et al. [27] published a paper where successful assembly of 220 μm pitch bumped flip-chips on both FR5 and plated ceramic substrates with 10 μm diameter particle thermoplastic adhesive has been made. They found that the adhesive containing large particles accommodate planarity errors due to surface roughness and non-flat pad shape better than the smaller diameter particle, and they have the ability to be compressed sufficiently to disrupt the thin films in wide gap, while not being crushed in small gaps. On the other hand, it has proven to be difficult to obtain 100% consistence in conduction with un-bumped flip chip dies and with small diameter balls.

In 1999, Liu et al. [156] observed that, on an FR-4 substrate, the electrical conductivity and reliability of a joint depend on the distance to the glass fibre in the substrate. A long distance means a thicker layer of soft epoxy which may deform during the bonding. Insufficient particle deformation will therefore be obtained at that point. A short distance gives more resistance to this deformation and thereby results in better electrical conductivity and reliability.

Seppälä et al. [157] published in 2001 some important data on the reliability of the flip chip joining on FR-4 substrate using ACA. It was shown that the co-planarity of the substrate and the chip is important for the bonding quality. It was shown that by decreasing the bonding pressure, reliability of the test chip types can be improved.

In 2003, Fan et al. [158] investigated the effect of the substrate-pad physical properties (surface roughness and hardness) on the current-carrying capacity of the ACA joints. It was found that the variation of current carrying capacity (or connection resistance) of Au/Cu pad joints is larger than that of Au/Ni/Cu pad joints. The current-carrying capacity is related to the variation of the resistance of ACF joints. For the Au/Cu pad ACF joints, the deformation of the particles' upper and bottom sides is nearly symmetrical; the contact between conductive particles and pad has the character of "sliding contact," especially under high pressure. For the Au/Ni/Cu pad ACF joint, the contact between particles and pad determined the conduction characteristics of ACF joints. It has the character of "static contact." Thus, the current-carrying capacity (or connection resistance) of Au/Cu pad joints is more sensitive to the bonding pressure.

Effects of the conductive particles of ACA on the reliability of ACA joints

In ACA interconnections, the particles are electrical conductors providing current paths in the fine pitch electronic packaging as well as physical parts connecting with the chip bumps and the substrate pads through the mechanical deformation interfaces. However, the particles are randomly distributed in ACF materials, which can cause problems especially in ultra fine pitch applications. This is because the concentration and deformation of particles within the material varies at different locations, and hence may result in low reliability of the assemblies. In order to understand the effect of the conductive particles on the reliability of the assemblies using anisotropic conductive adhesive, some investigations have been done [47, 159–163].

In 1998, Yim et al. [47] studied the relationship between particle content of ACFs and the connection resistance. The results showed that, for ACFs with initial particle contents increase, the number of particles on the terminal increases and the connection resistance decreases. However, over the 4 wt.% of conductive particles, the connection resistance does not decrease further, but becomes stabilized. This is because the counter-effect of two opposing factors, the resistance increase caused by a decrease of contact area per one particle and the resistance decrease caused by increasing number of conduction path s at the same bonding pressure.

In 1999, Sarkar et al. [160] published a paper focused on the application of ACA as an interconnect material for Chip-On-Flex technology. The results showed that the number of conductive particles existing on a bump increases as the content of conductive particles increases. The content of the conductive particles can seriously affect the connectability by resulting in short circuit. The most suitable amount of content is within the range of 2.5–12.5 vol%. Further, the interconnection resistance decreases as the volume content of the conductive particles increases until reaching <7.5 vol%.

In 2001, Paik et al. [161] investigated the effect of fillers on the thermo-mechanical properties of newly modified ACA composite materials and the resulting reliability of flip chip assembly on organic substrates using modified ACA materials. It was observed that lowering CTEs of ACA material by adding the fillers significantly enhanced thermal cycling reliability.

In 2003, Dou et al. [162] investigated the electrical conductive characteristics of anisotropic conductive adhesive particles. The mathematical electrical resistance function of an ACA particle, an integral function of the transformation factor and the particle geometries, resin diameter, nickel layer thickness, and gold layer thickness, is worked out from the physical model of an ACA particle. The numerical solutions showed that the deeper the particle transformation, the thicker the metal coated layer thicknesses and the longer the resin diameter are, the lower the particle resistance is. In a word, the ACA particle resistance is determined by the particle transformation and the particle geometries; however, the transformation and the nickel layer thickness are more sensitive than the resin diameter and the gold layer thickness.

In 2005, Cao et al. [163] studied the effects of different conductive particles, as well as ACA resin and different curing agents, on flexible substrate of the flip-chip joint by formulating several ACA pastes, which consist of different sizes of silver (Ag) powders or gold (Au)-coated polymer spheres as conductive particles. The results showed that the size and type of different conductive particles have very limited influence on an ACA flip-chip joint.

Future challenges

A lot of papers have been published. The literature survey indicates that the following application challenges of ACA bonding in electronic assemblies need further study: (1) sufficient conducting particles must be trapped during the bonding process to guarantee the electrical contact with both conductor surfaces; (2) the deformation degree of conducting particles during bonding should be further analyzed, which determines the contact area and the electrical characteristics of the interconnection, because there were few works done about this topic; (3) it is necessary to make clear the failure mechanisms of the ACA joints under different environmental factors by fracture mechanics; (4) understanding the effects of the induced stress state after assembly on the mechanical performance under testing conditions and service is needed; (5) the warpage of the chip compromises reliability of the ACA joints. Therefore, further investigations about the mismatch between the components of ACA joints are required; and (6) further reduction of the pitches in ACA joining technology and more application in electronics packaging require a major breakthrough in ACF material and careful reliability design.

Conclusion

As one of the most important technologies for interconnects of electronics hardware, ACA joining technology has shown remarkable advantages and attracted many research interests. In this review, a summary of our understanding of the electrical, physical, thermal, chemical, environmental, and cost behaviors of ACAs in conjunction with various packaging applications is elaborated to have a better understanding of the nature of ACA and the significant progress made on the materials research and development. The most important task for more wide application of ACA joining technology in electronics packaging is to further study the remaining issues or challenges.

Acknowledgement This work was supported by China Postdoctoral Science Foundation (Grant No. 20070410302), the Science Research Foundation Program of Central South University, and the Postdoctoral Science Foundation of Central South University.

References

1. Liu J (1998) In: Conductive adhesives for electronics packaging. Electrochemical Publications, UK
2. Nagai A, Takemure K, Isaka K, Watanabe O, Kojima K, Matsuda K, Watanabe I (1998) In: Proceedings of the IEMT/IMC, Tokyo, Japan, 1998, p 353
3. Lu D, Tong QK, Wong CP (1999) In: Proceedings of the 49th ECTC, San Diego, CA, USA, 1999, p 347
4. Liu J, Lundstorm P (1999) In: Liu J (ed) Conductive adhesive for electronic packaging. Electrochemical Publications, New York, p 212
5. Lu D, Wong CP (2000) In: Proceedings of the international symposium on advanced packaging materials: processes, properties and interfaces, Braselton, GA, 2000, p 24
6. Liu J (2001) Solder Surf Mt Technol 13:39
7. Lau J, Wong CP, Lee NC, Lee SWR (2002) In: Electronics manufacturing: with lead-free, halogen-free, and conductive adhesive materials. McGraw Hill, New York
8. Tan AM, Lim SPS, Lee C (2003) In: Proceedings of the 5th electronics packaging technology, Pan Pacific Hotel, Singapore, 2003, p 390
9. Savolainen P, Saarinen I, Rusanen O (2004) In: Proceedings of the 4th international IEEE conference on polymers and adhesives in microelectronics and photonics, Portland, OR, 2004, p 99
10. Li Y, Wong CP (2004) In: Proceedings of the 4th international IEEE conference on 'polymers and adhesives in microelectronics and photonics', Portland, OR, 2004, p 1
11. Li Y, Moon K, Wong CP (2005) Science 308:1419
12. Li Y, Wong CP (2006) Mater Sci Eng R 51:1
13. Watanabe I, Fujinawa T, Arifuku M, Fujii M, Gotoh Y (2004) In: Proceedings of the 9th IEEE international symposium on advanced packaging materials: processes, properties and interfaces, Atlanta, GA, 2004, p 11
14. Reinke RR, Kennedy TW (1988) In: Proceedings of the SID international symposium on digest of technical papers, 1988, p 305
15. Hu DC, Ho SJ, Tang BY (1992) In: Proceedings of the 13th IEEE/CHMT international electronics manufacturing technology symposium, 1992, p 277
16. Lee CH, Loh KI (1995) In: Proceedings of the 45th ECTC, Las Vegas, NV, 1995, p 21
17. Baumbach J, Baur H, Lueder E, Yamauchi A, Dorfmueller L, Knoll PM (1999) In: Proceedings of the international symposium of society for information display, San Jose, CA, 1999, p 848
18. Watanabe I, Fujinawa T, Arifuku M, Kobayashi K, Gotoh Y (2004) In: Proceedings of the international IEEE conference on the Asian green electronics, Hongkong/Shenzen, China, 2004, p 229
19. Otsuki H, Morishita H, Kokogawa T, Adachi K, Matsukawa F, Takasago H (1991) In: Proceedings of the international symposium on microelectronics, 1991, p 86
20. Liu J, Boustedt K, Lai ZH (1996) Circ World 22:19
21. Miessner R, Aschenbrenner R, Reichi H, Ling S, Binh L, Lew A, Benson R, Nhan E (2000) In: Proceedings of the 50th ECTC, Las Vegas, NV, 2000, p 1133
22. Li L, Treliant F (2000) In: Proceedings of the 4th IEEE international conference on adhesive joining and coating technology in electronics manufacturing, Espoo, Finland, 2000, p 129
23. Gustafsson K, Mannan S, Liu J, Lai ZH, Whalley D, Williams D (1997) In: Proceedings of the 47th ECTC, San Jose, CA, May 1997, p 561
24. Liu J (1999) The advanced flip-chip workshop, Atlanta, USA
25. Miessner R, Aschenbrenner R, Reichl H (1999) In: Proceedings of the 49th ECTC, San Diego, CA, 1999, p 595
26. Ogunjimi AO, Mannan SH, Whalley DC, Williams DJ (1996) IEEE Trans Comp Package 19:257
27. Oguibe CN, Mannan SH, Whalley DC, Williams DJ (1998) In: Proceedings of the 3rd IEEE international conference on adhesive joining and coating technology in electronics manufacturing, Binghamton, New York, 1998, p 27
28. Zhong ZW (2001) Microelectron Int 18:15
29. Mannan SH, Williams DJ, Whalley DC (1997) J Mater Sci-Mater Electron 8:223
30. Cao LQ, Li SM, Lai ZH, Liu J (2005) J Electron Mater 34:1420
31. Sarker G, Mridha S, Chong TT, Tuck WY, Kwan SC (1999) J Mater Process Technol 484:89
32. Lai Z, Liu J (1996) IEEE Trans Comp Package B 19:644
33. Wu SX, Zhang C, Yeh CP, Wille S, Wyatt K (1997) In: Proceedings of the 47th ECTC, San Jose, CA, 1997, p 550
34. Chan YC, Uddin MA, Alam MO, Chan HP (2003) J Electron Mater 32:131
35. Zhuqing Z, Wong CP (2002) In: Proceedings of the 8th international symposium on advanced packaging materials, Piscataway, NJ, 2002, p 194
36. Xiao AY, Jacobson SH (1999) In: Proceedings of the 5th international symposium on advanced packaging materials, Chateau Elan, Braselton, GA, 1999, p 21
37. Rogers AD, Pearl LS (2003) Polym Eng Sci 43:14
38. Hsu DT, Kim HK, Shi FG, Tong HY, Chungpaiboonpatana S, Davidson C, Adams JM (2000) Microelectron Int 17:22
39. Wu X, Hao H (2005) J Manuf Sci Eng 127:411
40. Lee JY, Shim MJ, Kim SW (1997) Mater Chem Phys 48:36
41. Lin F, Bhatia GS, Ford JD (1993) Appl Polym Sci 49:1901
42. Roşu D, Caşcaval CN, Mustată F, Ciobanu C (2002) Thermochim Acta 383:119
43. Prime RB (1997) In: Thermal characterization of polymeric materials, 2nd edn. Academic Press, New York, p 1598
44. Barral L, Cano J, López J, López-Bueno I, Nogueira P, Torres A, Ramírez C, Abad MJ (2000) Thermochim Acta 344:127
45. Williams DJ, Whalley DC, Boyle OA, Ogunjimi AO (1993) Solder Surf Mt Techol 14:4
46. Hu KX, Yeh CP, Wyatt KW (1997) IEEE Trans Comp Package Manuf Technol A 20:470
47. Yim MJ, Paik KW (1998) IEEE Trans Comp Package Manuf Technol A 21:226
48. Shi FG, Abdullah M, Chungpaiboonpatana S, Okuyama K, Davidson C, Adams JM (1999) Mater Sci Semicond Process 2:263
49. Oguibe CN, Mannan SH, Whalley DC, Williams DJ (1998) IEEE Trans Comp Package Manuf Technol A 21:235
50. Fu Y, Willanter M, Liu J (2001) IEEE Trans Comp Package Technol 24:250
51. Chin M, Iyer KA, Hu SJ (2004) IEEE Trans Comp Package Technol 27:317

52. Constable JH (2006) IEEE Trans Comp Package Technol 29:494
53. Chiu YW, Chan YC, Lui SM (2002) Microelectron Reliab 42:1945
54. Connell G, Zenner RLD, Gerber JA (1997) In: Proceedings of the 47th ECTC, San Jose, CA, 1997, p 274
55. Chan YC, Luk DY (2002) Microelectron Reliab 42:1185
56. Luk CF, Chan YC, Hung KC (2002) Microelectron Reliab 42:767
57. Zhang JH, Chan YC, Zeng ZM, Chiu YW (2002) In: Proceedings of the 52nd ECTC, San Diego, CA, 2002, p 1569
58. Wu YP, Alam MO, Chan YC, Wu BY (2004) Microelectron Reliab 44:295
59. Zhang JH, Chan YC (2004) In: Proceedings of the 6th IEEE conference on high density microsystem design and packaging and component failure analysis, Shanghai, China, 2004, p 277
60. Tan SC, Chan YC, Chiu YW, Tan CW (2004) Microelectron Reliab 44:495
61. Uddin MA, Alam MO, Chan YC, Chan HP (2004) Microelectron Reliab 44:505
62. Rizvi MF, Chan YC, Bailey C, Lu H, Sharif A (2005) Solder Surf Mt Technol 17:40
63. Chen X, Zhang J (2005) Key Eng Mater 297:918
64. Chen X, Zhang J, Jiao C, Yu L (2006) Microelectron Reliab 46:774
65. Chan YC, Luk DY (2002) Microelectron Reliab 42:1195
66. Williams DJ, Whalley DC (1993) J Electron Manuf 3:85
67. Mannan SH, Williams DJ, Whalley DC, Ogunjimi AO (1999) In: Liu J (ed) Conductive adhesives for electronics packaging, Ch. 4. Electrochemical Publications Ltd, Port Erin
68. Zou G, Grönqvist H, Liu J (2004) IEEE Trans Comp Package Technol 27:546
69. Yim MJ, Hwang J, Paik KW (2007) Int J Adhes Adhes 27:77
70. Kang IB, Haskard MR, Ju BK (1996) In: Proceedings of the SPIE—the international society for optical engineering, San Jose, CA, 1996, p 280
71. Yim MJ, Paik KW, Kim YK, Hwang HN (1997) In: Proceedings of the Pacific Rim/ASME international intersociety electronic and photonic packaging conference, New York, 1997, p 65
72. Pinardi K, Liu J, Haug R, Treutler C, Willander M (1998) In: Proceedings of the 3rd IEEE international conference on adhesive joining and coating technology in electronics manufacturing, Binghamton, New York, 1998, p 34
73. Yim MJ, Paik KW (1999) IEEE Trans Adv Package 22:166
74. Prabhakumar A, Constable JH (2001) In: Proceedings of the 51st electronic component and technology conference, Orlando, Florida USA, 2001, p 580
75. Frisk L, Seppälä A, Ristolainen E (2004) Microelectron Reliab 44:1305
76. Seppälä A, Ristolainen E (2004) Microelectron Reliab 44:639
77. Lim Pei Siang S, Tan AM, Lee C (2004) In: Proceedings of the 6th electronics packaging technology conference, Shenzhen, China, 2004, p 450
78. Lee KK, Ng KT, Tan CW, Chan YC, Cheng LM (2004) In: Proceedings of the international conference on 'the business of electronic product reliability and liability', Shanghai, China, 2004, p 134
79. Chan KK, Yeung NH, Chan YC, Tan SC, Lee KK (2003) In: Proceedings of the 53rd ECTC, LA, 2003, p 1701
80. Miessner R, Aschenbrenner R, Reichl H (1999) In: Proceedings of the 49th electronic component and technology conference, San Diego, CA, 1999, p 595
81. Cao LQ, Lai ZH, Liu J (2004) In: Proceedings of the 6th IEEE conference on high density microsystem design and packaging and component failure analysis, Shanghai, China, 2004, p 254
82. Inoue M, Miyamoto T, Suganuma K (2004) In: Proceedings of the 6th IEEE conference on 'high density microsystem design and packaging and component failure analysis', Shanghai, China, 2004, p 248
83. Lee KK, Tan SC, Chan YC (2005) J Electron Package 127:52
84. Zhang J, Jia H, Chen X (2006) J Electron Packag 6:33
85. Seppälä A, Ristolainen E (2004) Microelectron Reliab 44:639
86. Sugiyama T (2000) In: The latest bare chip bonding by ACF, documentation from Sony Chemicals Seminar at Chalmers University of Technology
87. Törnvall M (2000) In: Proceedings of a Swedish national seminar on environmentally compatible materials research for electronics packaging, IVF, Sweden, 2000, IVF 5
88. Yin CY, Alam MO, Chan YC, Bailey C, Lu H (2003) Microelectron Reliab 43:625
89. Yin CY, Lu H, Bailey C, Chan YC (2004) In: Proceedings of the international IEEE conference on the Asian green electronics, Hongkong/Shenzen, China, 2004, p 240
90. Chiang WK, Chan YC (2004) In: Proceedings of the international IEEE conference on the Asian green electronics, Hongkong/Shenzen, China, 2004, p 235
91. Yin CY, Lu H, Bailey C, Chan YC (2004) IEEE Trans Electron Package Manuf 27:254
92. Chiang WK, Chan YC (2005) J Electron Package 127:113
93. Wong CC (1993) In: Doane DA, Franzon PD (eds) Multichip module technologies and alternatives. Van Nostrand Reinhold, New York, p 429
94. Fan SH, Chan YC (2002) Microelectron Reliab 42:1081
95. Fan SH, Chan YC (2002) In: Proceedings of the 52nd ECTC, San Diego, CA, 2002, p 1605
96. Xie B, Shi XQ, Ding H, Qiao K (2006) In: Proceedings of the 10th intersociety conference on thermal and thermomechanical phenomena in electronics systems, San Diego, CA, 2006, p 848
97. Liu J (1993) Circ World 19:4
98. Stam F, O'Grady P, Barrett J (1995) J Electron Manuf 5:1
99. Lai ZH, Liu J (1996) IEEE Trans Comp Package Technol B 19:644
100. Liu J, Tolvgard A, Malmodin J, Lai Z (1999) IEEE Trans Comp Package Technol 22:186
101. Weidler JD, Burg RD, Decker JJ, Constable JH (2000) In: Proceedings of the 50th ECTC, Las Vegas, NV, 2000, p 906
102. Lefebvre DR (2000) J Adhes Sci Technol 14:925
103. Liu J (2001) In: Proceedings of the 1st international IEEE conference on 'polymers and adhesives in microelectronics and photonics', Potsdam, Germany, 2001, p 209
104. Fujiwara S, Harada M, Fujita Y, Hachiya T, Muramatsu M (2002) In: Proceedings of the 52nd ECTC, San Diego, CA, 2002, p 1124
105. Wu CML, ML Chau (2002) Solder Surf Mt Technol 14:51
106. Wei Z, Waf LS, Loo NY, Koon EM, Huang M (2002) In: Proceedings of the 4th EPTC, Grand Copthorne Waterfront Hotel, Singapore, 2002, p 133
107. Tan CW, Chan YC, Yeung NH (2002) Microelectron Reliab 43:481
108. Tan CW, Chan YC, Yeung NH (2003) Microelectron Reliab 43:279
109. Tan CW, Chiu YW, Chan YC (2003) Mat Sci Eng B-Solid 98:255
110. Wang ZP (2003) In: Proceedings of the 5th EPTC, Pan Pacific Hotel, Singapore, 2003, p 595
111. Mercado LL, White J, Sarihan V, Lee TYT (2003) IEEE Trans Comp Package Technol 26:509
112. Zhang JH, Chan YC (2003) J Electron Mater 32:228
113. Zhang JH, Chan YC (2004) In: Proceedings of the 6th IEEE conference on high density microsystem design and packaging and component failure analysis, Shanghai, China, 2004, p 277
114. Uddin MA, Chan YC, Chan HP, Alam MO (2004) J Electron Mater 33:14

115. Wu YP, Alam MO, Chan YC, Wu BY (2003) In: Proceedings of the 53rd ECTC, New Orleans, LA, 2003, p 544
116. Chen X, Zhang J, Wang ZP (2004) In: Proceedings of the 9th intersociety conference on thermal and thermomechanical phenomena in electronics systems, Las Vegas, NV, 2004, p 453
117. Kwon WS, Ham SJ, Yim MJ, Lee SB, Paik KW (2005) J Electron Package 127:86
118. Yang SY, Kwon WS, Lee SB, Paik KW (2005) Key Eng Mater 297–300:887
119. Teh LK, Teo M, Anto E, Wong CC, Mhaisalkar SG, Teo PS, Wong EH (2005) IEEE Trans Comp Package Technol 28:506
120. Kwon WS, Paik KW (2006) Microelectron Reliab 46:589
121. Lin YC, Chen X, Wang ZP (2006) J Adhes Sci Technol 20:1383
122. Lin YC, Chen X, Zhang HJ, Wang ZP (2006) Mater Lett 60:2958
123. Zhang J, Chen X, Jia H (2006) J Zhengzhou Univer 27:48
124. Chen X, Zhang J (2006) Key Eng Mater 324:471
125. Luo SJ, Leisen J, Wong CP (2002) J Appl Polym Sci 85:1
126. Leung SYY, Lam DCC, Luo SJ, Wong CP (2004) J Adhes Sci Technol 18:1103
127. Lin YC, Chen X (2005) Polymer 46:11994
128. Lin YC, Chen X (2005) Chem Phys Lett 412:322
129. Lin YC, Chen X (2005) Mater Lett 59:3831
130. Lin YC (2006) In: Investigation of characteristics for adhesive and bonding reliability for COG assembly under hygrothermal conditions, PhD thesis, Tianjin University, Tianjin, China
131. Lu D, Tong QK, Wong CP (1999) IEEE Trans Comp Package Manuf Technol C 22:228
132. Lu D, Wong CP (1999) In: Proceedings of the 2nd international IEEE symposium on polymeric electron packaging, 1999, p 1
133. Lu D, Wong CP (2000) IEEE Trans Comp Package Technol 23:440
134. Shimada Y, Lu DQ, Wong CP (2000) J Electron Manuf 10:97
135. Lin YC, Chen X, Wang ZP (2006) In: Proceedings of the 10th intersociety conference on thermal and thermomechanical phenomena in electronics systems, San Diego, CA, 2006, p 826
136. Rizvi MJ, Chan YC, Bailey C, Lu H (2005) Microelectron Reliab 45:589
137. Lin YC, Chen X, Wang ZP (2006) In: Proceedings of the 10th intersociety conference on thermal and thermomechanical phenomena in electronics systems, San Diego, CA, 2006, p 946
138. Rizvi MJ, Bailey C, Chan YC, Lu H (2006) In: Proceedings of the 10th intersociety conference on thermal and thermomechanical phenomena in electronics systems, San Diego, CA, 2006, p 855
139. Ali L, Chan YC, Alam MO (2005) Solder Surf Mt Technol 17:20
140. Islam RA, Chan YC, Ralph B (2004) J Mater Res 19:1662
141. Lam DCC, Shen C, Xie JF, Karim Z, Tong P (1996) In: Proceedings of the electronic packaging materials science IX. Symp, Boston, MA, 1996, p 297
142. Lai ZH, Lai R, Persson K, Liu J (1998) J Electron Manuf 8:217
143. Persson K, Lai Z, Zribi A, Liu J, Willander M (1998) In: Proceedings of the 3rd IEEE international conference on adhesive joining and coating technology in electronics manufacturing, Binghamton, NY, 1998, p 132
144. Pinardi K, Lai Z, Vogel D, Yi LK, Liu J, Liu S, Haug R, Willander M (2000) IEEE Trans Comp Package Manuf Technol 23:447
145. Pinardi K, Lai Z, Yi LK, Liu J, S Liu, Haug R (2000) In: Proceedings of the 50th ECTC, Las Vegas, NV, 2000, p 1118
146. Wu CML, Liu J, Yeung NH (2000) In: Proceedings of the 4th IEEE international conference on adhesive joining and coating technology in electronics manufacturing', Espoo, Finland, 2000, p 101
147. Wu CML, Liu J, Yeung NH (2001) Solder Surf Mt Technol 13:25
148. Yim MJ, Jeon YD, Paik KW (2000) IEEE Trans Electron Package Manuf 23:171
149. Yim MJ, Paik KW (2001) IEEE Trans Comp Package Manuf Technol 24:24
150. Kwon WS, Paik KW (2003) In: Proceedings of the 3rd international IEEE conference on polymers and adhesives in microelectronics and photonics, Montreux, Switzerland, 2003, p 351
151. Teo M, Mhaisalkar SG, Wong EH, Teo PS, Wong CC, Ong K, Goh CF (2003) In: Proceedings of the 5th electronics packaging technology conference, Pan Pacific Hotel, Singapore, 2003, p 718
152. Teo M, Mhaisalkar SG, Wong EH, Teo PS, Wong CC, Ong K, Goh CF, Teh LK (2005) IEEE Trans Comp Package Technol 28:157
153. Hwang JS, Yim MJ, Paik KW (2005) J Electron Mater 34:1455
154. Hwang JS, Yim MJ, Paik KW (2006) J Electron Mater 35:1722
155. Yim MJ, Kim HJ, Chung CK, Paik KW (2006) In: Proceedings of the 56th ECTC, San Diego, CA, 2006, p 338
156. Liu J, Lai Z (1999) In: Proceedings of the international intersociety on electronic packaging technical/business conference & exhibition, Maui, HI, 1999, p 1691
157. Seppälä A, Pienimaa S, Ristolainen E (2001) Int J Microcircuits Electron Package 24:148
158. Fan SH, Chan YC (2003) J Electron Mater 32:101
159. Yeung NH, Chan YC, Tan CW (2003) J Electron Package 125:624
160. Sarkar G, Mridha S, Tan TC, Wu YT, Sem CK (1999) J Mater Process Technol 89–90:484
161. Paik KW, Yim MJ, Kwon WS (2001) In: Proceedings of the 6th annual Pan Pacific microelectronics symposium, Kauai, HA, 2001, p 217
162. Dou GB, Chan YC, Liu J (2003) J Electron Package 125:609
163. Cao LQ, Li SM, Lai ZH, Liu J (2005) J Electron Mater 34:1420