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ACHIEVING OPTIMUM ADHESION OF CONDUCTIVE ADHESIVE BONDED FLIP-CHIP ON FLEX PACKAGES

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Abstract. Anisotropic conductive adhesives film (ACF) is a thermosetting epoxy matrix impregnated with small amount of electrically conductive particles and used as an interconnect materials for flip chip on flex (FCOF) packages. However, it remains a challenge to develop the reliable packaging know-how in processing of ACF materials. Considerable research has been conducted recently to investigate the effect of different parameters on the performances. One of the main reliability factors in characterizing the performance of ACF joints is adhesion strength. This review article will discuss the critical issues that can easily control the adhesion of ACF joints in flip chip on flex packages. These mainly include surface cleanliness, bonding tracks, process parameters, and operating environmental related issues. The findings can serve as a guide for optimizing the process parameters in the packaging of flip chip on flex with ACF. By preventing the usual degradation, the manufacturer can easily proceed for mass commercialization of ACF as an environmental friendly solder replacement in the electronic packaging industry.

1. INTRODUCTION

One of the most promising technologies of today's chip-level interconnection is flip-chip technology, which has emerged as a high density and high performance interconnection method for integrated-circuit chips [1]. The concept of flip-chip process, where the semiconductor chip is assembled face down onto a circuit board, is ideal for size considerations. Because there is no extra area needed for contacting the sides of components. Hence, their performance in high frequency application and reliability is also better than other interconnection methods due to the minimized length of the connection path [2].

A potential revolutionary technology is the use of polymer as conductive medium in replacing metals and semiconductors in such applications [3]. The attaching of flip chip without solder bumps/balls is to use of conductive adhesive is a typical example. Anisotropic conductive adhesives film (ACF) is such a thermosetting epoxy matrix impregnated with small amount of electrically conductive particles and used as an interconnect materials. They have recently gained much attention as an environmentally friendly alternative to tin/lead (Sn/Pb) solders [4]. Conductive adhesive not only avoid the toxicity and environmental concerns from lead and chlorofluorocarbon-based flux cleaners, but also have the following technological advantages over their counterparts: (1) the lower curing temperature required for adhesive reduces the joint fatigue and stress cracking problems enabling the use of heat sensitive or non-solderable materials; (2) fewer processing steps enable an increase in production throughput; (3) the higher flexibility & the closer match in coefficient of thermal expansion enable a more compliant connection & minimize failures. Adhesive could also provide most of the needs for flip chip technology by themselves: create short electrical path, ensure good horizon-

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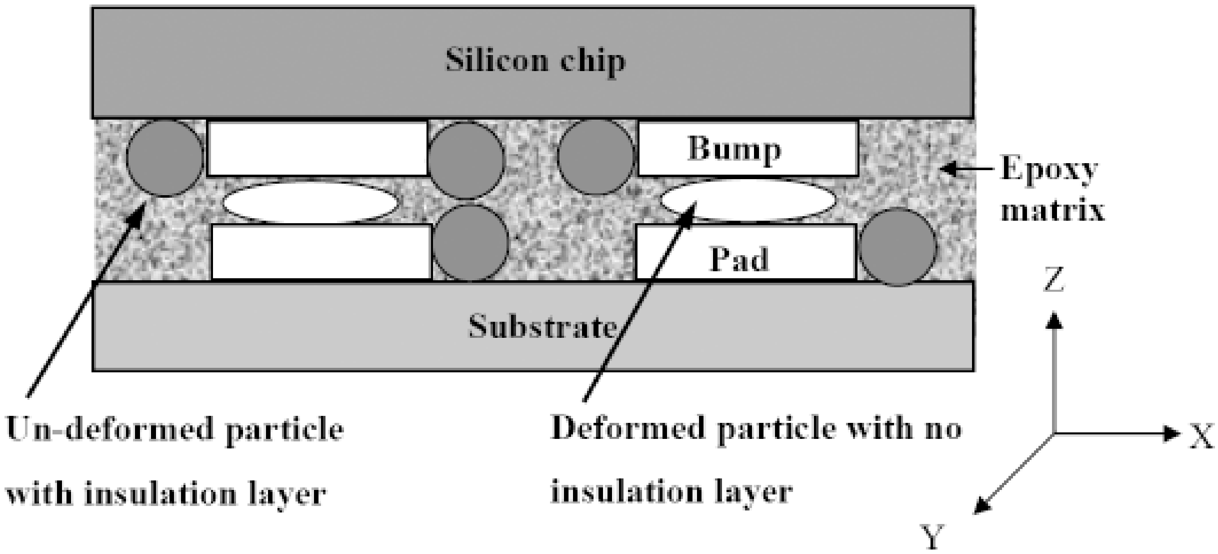


Fig. 1. Schematic cross-sectional view of flip chip conductive adhesive joints.

tal gap insulation, reduce joint stress and provide strong mechanical adhesion. Furthermore, no cleaning/flux is required, secondary underfill is not necessary, and placement of adhesives is not critical. Therefore, more recently, conductive adhesives are playing an increasingly important role in the design and production of electronic packages application [5].

There are two kinds of conductive adhesives – isotropic conductive adhesive (ICA) and anisotropic conductive adhesive (ACA). ICA contains sufficient amounts of conductive particles to conduct electricity in all directions. ACA contains lesser conductive particles (lower percentage of metal fillers in volume) than that of the ICA. The concentration of particles is controlled in such a way that just enough particles are present to assure reliable electrical conductivity in one direction only. Fig. 1 shows the schematic cross-sectional view of flip chip conductive adhesive joints. The conductive particles are made up of polymer spheres plated with a thin layer of nickel and gold followed by a thin insulation layer. During the bonding process, when the anisotropic conductive adhesive film (ACF) is being compressed thermally, the conductive particles between the connecting bumps and pads are sandwiched and would change from being spherical to oval. At this stage, insulation layer of the conductive particles wears out and electrical connections are formed in the *z*-direction. The other conductive particles remain as usual with insulation layer and prevent electrical conduction in the *x*- and *y*-direction. ACF also has the capability achieving of ultra-fine pitch [6].

The FCOF packages are made up of three different parts, namely flexible substrate silicon chip, and ACF [7]. They can be in different structure with different types of materials.

1.1. Flexible substrate

It contains a polyimide film as a base material, copper (Cu) trace as the conductor and an adhesive in between. This adhesive is an epoxy-based polymer. The square shaped (typically 50×50 μm^2) Cu pads are serially lies in the center of the substrate. The thickness of the polyimide base film, adhesive and copper trace are 50, 10, and 5 µm, respectively. The thickness of the Nickel coating and Gold (Au) flash was about 1~2 µm and 0.1~0.4 µm, respectively.

1.2. Silicon chip

The Flip chip also contains with square shaped (typically 50×50 μm^2) opening around the periphery. These opening consist of aluminum metal with 1% silicon limited by chip-passivation layer on the periphery of the die. Such type of chip is called bumpless chip. Additional electroless Nickel layer of 4-5 µm height with/without Gold (Au) flash can be deposited on that aluminium metallization to form Ni bump. The bump pattern of the chip is similar to the pad pattern of the flex substrate to make exact alignment.

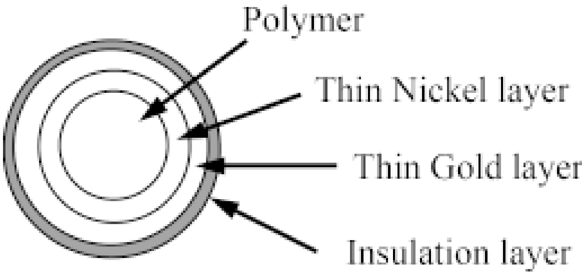


Fig. 2. Schematic cross-sectional view of a typical conductive particle.

1.3. Anisotropic conductive adhesives film (ACF)

The type of ACF used in this study consists of an epoxy layer and is filled with conductive particles. The conductive particles are made up of polymers plated with a thin layer of nickel and gold followed by a thin insulation layer. Fig. 2 shows the schematic cross-sectional view of a typical conductive particle. The insulation layer of the particles trapped between the bumps & substrate pads, will become soft and cracked during the bonding process to achieve electrical conduction in the *z*-direction. While insulation layer of the other particles will not experience pressure and remain unchanged for keeping insulation in *x*, *y* planes to prohibit short circuit between the adjacent joints. The thickness of ACF is 35 μm and particle diameter is 3.5 μm. Concentration of the conductive particles is about 3.5 million /mm^3. The glass transition temperature (T_g) of the ACF is 130 ºC.

One of the main critical reliability issues of conductive adhesive in this application is the poor adhesion strength. Due to poor adhesion with the bonding tracks, void may nucleate at the interface, which might propagate to the interconnection and losses the electrical conduction [6]. Interfacial delamination may be initiated at areas of poor adhesion, at corners or locations with stress singularities. High adhesion strength is a critical parameter of fine pitch interconnection that is fragile to shocks encountered during assembly, handling, and lifetime [7]. Successful bonding involves the contaminant free surface, the selection of proper bonding parameters, suitable bonding tracks in a proper operating environment. Therefore, there is still some sort of uncertainty of using ACF considering above-mentioned issues which lead to degradation in performance such as poor adhesion strength, unstable contact resistance, etc.

The adhesion strength mainly depends on [8]

1. Surface cleanliness
2. Mechanical properties of the cured ACF
3. Interfacial factor
4. Operating and environmental condition

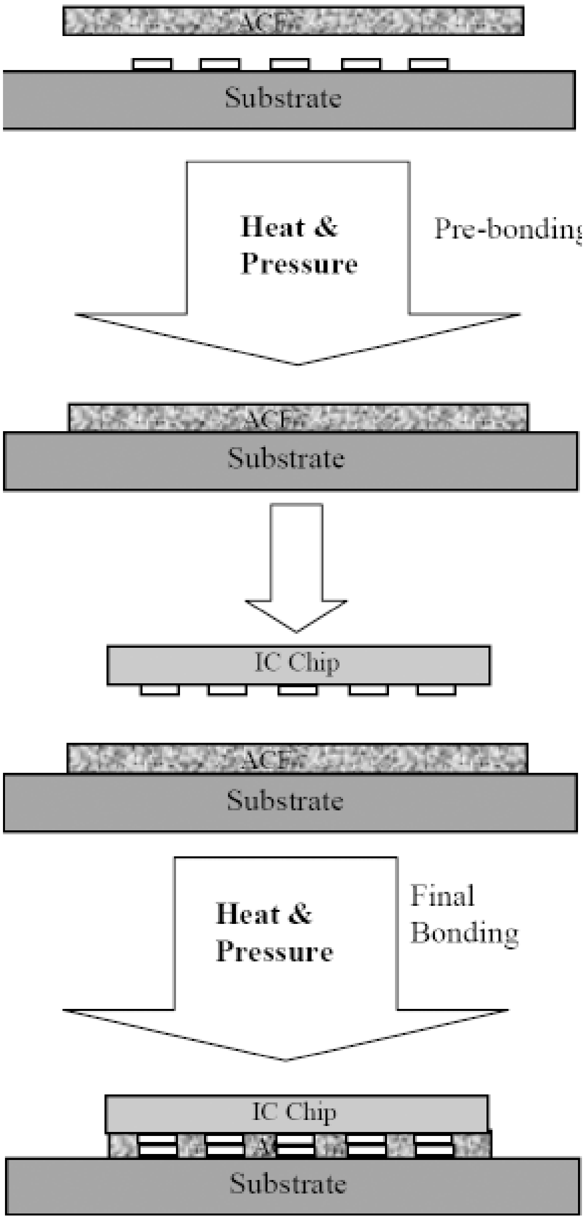
Therefore the above-mentioned issues are uniquely critical for preventing the degradation of ACF bonded flip chip joints. Our purpose of this review is to have a better understanding of the critical issues in manufacturing the highly reliable flip chip on flex packages with better adhesion. The very related issues are consequently described in the subsequent sections.

2. DEGRADATION DUE TO SURFACE CONTAMINATION

As the integrated circuits get smaller and with the use of advanced materials, contaminant free active surfaces are crucial to obtain high yield reliable products [9]. Therefore an important part of the product reliability achievement is the control of contamination and ensure the good bondability between various mating surfaces [10]. Contaminants may introduce in ACF bonded flip-chip packages during the production of the flexible substrate & flip chip and also from the environments. Therefore these impurities must be thoroughly removed before the bonding process [11]. Air bubble entrapped in the adhesive is also a concern for reliable adhesion. Air bubbles may entrap during ACF lamination process. Such defect reduces the contact area and also provides stress propagation path for crack, resulting in easy delamination under low force [12]. Thus a challenge for flip chip bonding by ACF is the surface cleanliness and induced delamination of the chip and/or ACF from the flex.

3. EFFECT OF APPLIED BONDING PARAMETERS

The procedures for flip chip mounting included several steps: ACF placement, pre-bonding, IC placement and final bonding [7]. Figs. 3a and 3b show the schematic of the typical bonding process and the appearance of the assembly after bonding. A manual flip-chip bonding machine (Karl Suss 9493 Mauren) can be used to carry out the pre-bonding, i.e. placement of ACF on flex. The typical pre-bonding pressure is 1 MPa, while the temperature and time are 100 °C and 7 s respectively. A semi-automatic flip chip bonding machine (Toray



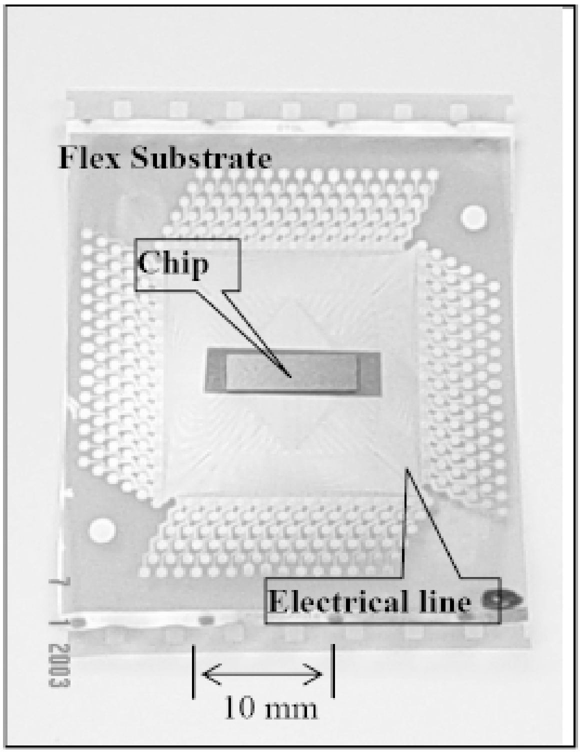


Fig. 3. (a) Schematic of the bonding process of flip chip on flex packages, (b) Appearance of the flip chip on flex packages after bonding.

SA2000) can be used to conduct the final bonding. The substrate pattern and the position of the chip bumps can be aligned automatically by the flip chip bonder. Finally, the chip can be bonded to the substrate by applying heat and pressure simultaneously. For final bonding, the typical pressure and time range are 60-100 MPa and 7-10 s respectively, while the bonding temperature can varied from 150-230 °C. The alignment accuracy can reach up to ±2 μm.

During bonding of ACF joints, applied bonding conditions (temperature and pressure) are the critical parameters for optimal curing conditions of ACF. During component assembly, the epoxy resin is cured to provide mechanical connection. 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 of the ACF [7]. Therefore, the applied bonding conditions are very critical to develop the ultimate mechanical properties of ACF.

3.1. Effect of bonding temperature on adhesion strength

The applied bonding temperature directly controls the curing degree of ACF. Therefore the parameter has very strong influence on the adhesion strength. Successful bonding involves the selection of proper bonding temperature during which chemical reaction precedes to completion the bonding and develops its proper service strength [13]. The adhesion strength normally increases with the bonding temperature. As bonding temperature increase, the curing degree of this epoxy-based adhesive also increases. The curing degree of ACF plays an important role in determining the reliability of the ACF joints. As the curing of ACF proceeds, the linear polymer chain in the epoxy resin grows and branches to form cross-links resulting in stronger chemical bonding at the interface and leading to increase in adhesion. At the lower degree of cross-linking, the polymer chains are capable of moving relatively easily and exhibit less adhesion strength. Again, as the bonding temperature increases the degree of cross-linking as well as adhesion also increases, because the polymer chains locked together and their movement becoming consequently somewhat restricted. Cross-linked polymer chains are chemically bound together to give a three-dimensional "chicken wire" structure [14]. So, the higher the curing degree, the stronger the chemical bonding and the better adhesion strength at the ACF interface. High temperature also promotes the physical adsorption and diffusion between adhesive and adherent. Moreover, high temperature is beneficial to wetting and flowing of the ACF due to lowering in its surface energy. As a result adhesion strength increases significantly with the increase of bonding temperature [7].

However, very-higher bonding temperature can degrade the ACF joint by increasing the brittleness of ACF and reducing the stability. Some polymer networks scissoring happened on C–N bond during the high temperature bonding process, which is the main reason for relatively low thermal stability. Nevertheless, under high temperature curing process problems will occur such as the inclination for the shrinkage, cracks, and voids of adhesive materials, which also probably lowering the dielectric properties [15].

3.2. Effect of bonding pressure on adhesion strength

The bonding force is used to compress the conductive particles against the conductive tracks and ACF matrix during the assembly process. The thinning behavior also controls the adhesion strength of the ACF joints. It can be seen that the strength increases very slightly as the bonding pressure increases. Pressure might have an effect on the adhesion by means of changing the thickness of the adhesive. However, here, pressure can only change the thickness of ACF between the bump (of chip) and pad (of substrate), which is limited by the extent of the deformation of the conductive particles. The thickness of ACF materials between the chip and substrate remains more or less the same, because the thickness depends on the summation of the height of bump, deformed particle and pad. Thus, pressure plays little role in the total adhesion [12].

Although pressure is not important in respect of adhesion, it should be pointed out that necessary value is needed for reliable bonding. First, proper pressure is applied to assure intimate intermolecular contact between adhesive and adherent (chip and substrate) so that Van der Waals interaction, electrostatic adsorption and other bonds at the interfaces can take place. However, too high pressure would cause excessive deformation of the core of the particles and crack in the Au/Ni layer of the particles. Inevitably, such cracking down of the conductive particles produces large residual mechanical stress around the particles, which might initiate crack and delamination at the bump/pad area. The excessive bonding pressure might also 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 which results in the decrease of adhesive strength after the reliability test [16]. The excessive thinning of adhesive thickness also decreases the adhesion strength.

4. INFLUENCE OF BONDING TRACKS MATERIALS

Both the bonding tracks (substrate and flip chip) structure and materials are importance for the quality and reliability of flip chip joints. The substrate hardness, geometry, and material also play important role on the reliability of ACF joints. The parallelism of substrates and components remains a major issue in obtaining consistency of conduction across assembly joints. On flexible substrates, in particular, the presence of conductor tracks can cause a non-flat surface. The uneven pressure distribution leads to non-uniform deformation of the contacting pads on the flexible board. The result of uneven pressure distribution is therefore poor bonding quality [17].

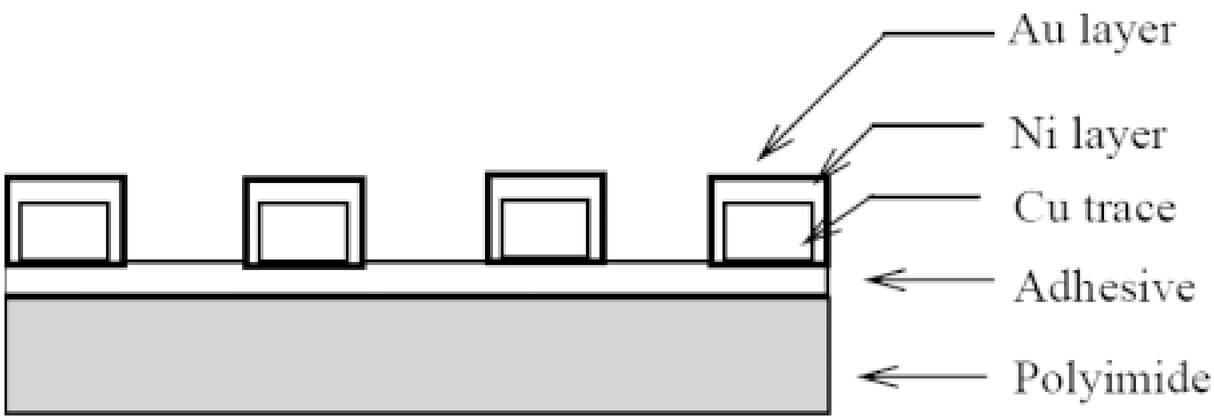


Fig. 4. Schematic of a typical cross-section of the flexible substrate.

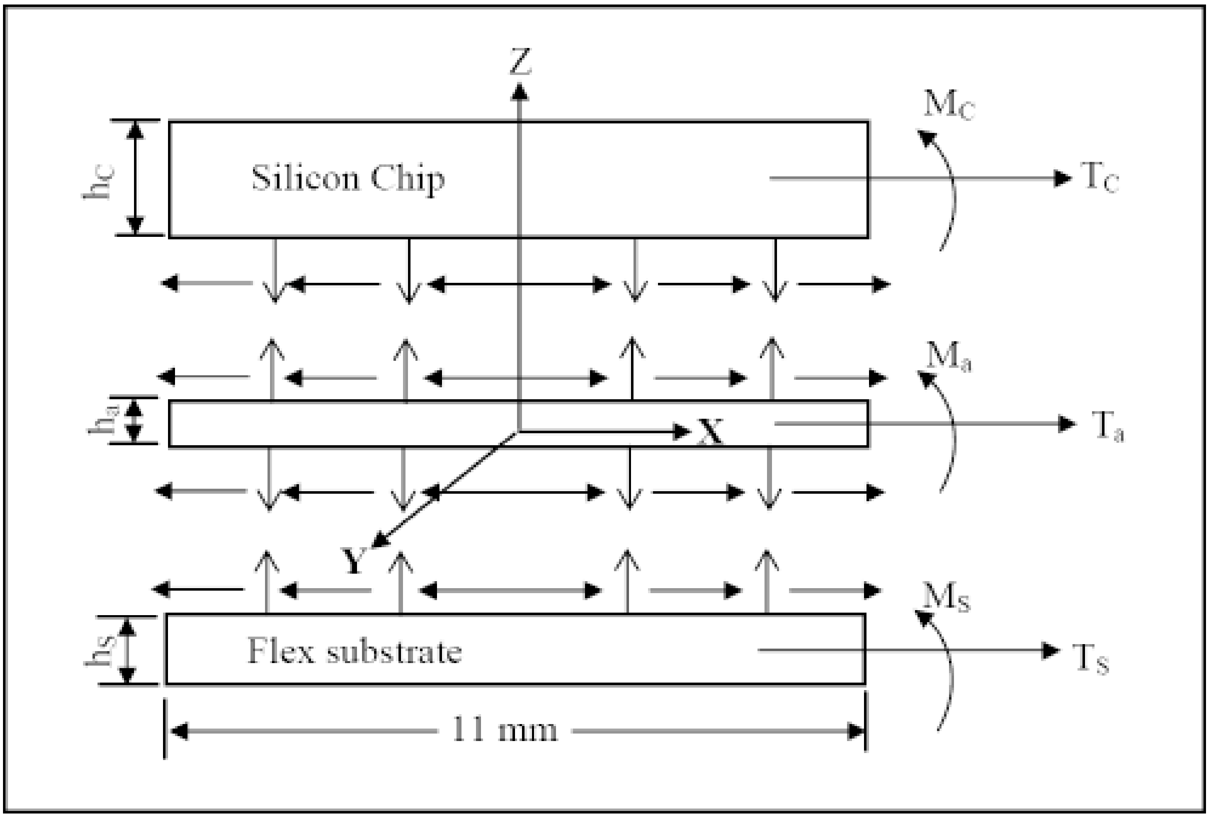


Fig 5. Free- body diagram of tri-material structure.

The most important feature of the flexible substrate is that the cured adhesive remains intact and adhered to the polyimide substrate even after the development of the copper (Cu) circuitry. So, ACF material would virtually be bonded with this residue adhesive in the substrate side instead of polyimide layer. Fig. 4 shows the schematic of a typical cross-section of that flexible substrate. The adhesive is widely used to bond the copper foil to the flexible substrate. The base polyimide film is covered by the thin adhesive layer, which is now acting as a barrier layer between the polyimide and the ACF. As this adhesive is already cured during Cu lamination and passes through additional process (e.g., Cu etching, dry film stripping, rinsing etc.) during Cu circuitry development, it no longer has any affinity to form strong bonding with the ACF. Moreover, the surface morphology of this adhesive is very smooth. Because of lower surface roughness value, mechanical interlocking between the flex and ACF was not much. Therefore the adhesion strength is comparatively lower for that kind

Table 1. CTE and linear expansion of ACF interconnection materials.

Materials		CTE, ppm/ °C	Linear expansion for, ΔT= 100°C	
			ΔL_1 (*L*ength, L_1= 11 mm)	ΔL_2 (Width, L_2 = 3 mm)
ACF	30-120 °C	57	0.1485	0.0405
	140-180 °C	135		
Chip	Si	4	0.0044	0.0012
Flex	Polyimide	85	0.0935	0.0255

of substrate. The adhesive can be removed by appropriate plasma cleaning technique and adhesion strength can be improved significantly. Alternatively, adhesiveless two layer flexible substrate (PI and Cu) can be used, which is expensive due to additional process required in the fabrication. Adhesiveless copper on polyimide substrates typically include the polyimide base film, a thin metal tiecoat, a copper seedcoat, and a layer of electrodeposited copper. They can have single or double-sided metallization, and are often provided in roll format to streamline subsequent processing. The selection of flex substrate depends on the tradeoff between the cost of the original adhesiveless flex and the cost of the plasma treatment [18].

5. DEGRADATION DUE TO ENVIRONMENTAL EXPOSURE

The ACF joints of flip chip need to subjected through different kind of environment in the real operating field. Therefore the critical issues that can degrade the ACF joints need to be well understood. The typical harsh environments for the polymer are the high temperature and high humidity [19-20]. The effects of those harsh environments are described below.

5.1. Effect of high temperature exposure on adhesion strength

For many reason ACF joints of flip chip assembly need to expose in high temperature. Therefore it is also essential to know the degradation issues of ACF joints in such high temperature environments.

The adhesion strength of heat exposed sample substantially decreased due to [21]

1. When the temperature rises in a solid, it will expand and this thermal expansion is directly proportional to the coefficient of thermal expansion (CTE) of the material, its length and the temperature change. In a tri-material “sandwich” packaging structure; like ACF joints, each layer will attempt to expand in accordance with its CTE. However, if the layers are rigidly connected and, thus, forced to expand in an identical manner, each layer will impose a force along the interface on the other layer and cause stresses to appear [22]. The generation of these stresses may be understood from the sketch presented in Fig. 5. The generated stresses at the interface decreased the adhesion strength. Table 1 shows the CTE values and linear expansions in *x* and *y* directions of different interconnect materials of the FCOF package assuming the increased temperature (ΔT) is 100 °C.
2. Above glass transition temperature (T_g), the amorphous or semi-crystalline polymer is transformed to the rubbery viscous state and drops the mechanical integrity of the adhesive.

5.2. Effect of high humidity on adhesion strength

The polymer-based ACF joints are often subjected to high relative humidity environment and are susceptible to moisture absorption, especially at elevated temperatures, which is one of the major reliability concerns for the ACF joints. The absorbed moisture has deleterious effects on the physical properties of ACF and can, therefore, greatly compromise the performance of ACF joints [23].

The adhesion strength of ACF joints is decrease due to the exposure in high humidity environment. Owing to the trapping of water by hydroxyl groups, inter-chain hydrogen-bonded structures of epoxy materials are broken [24]. The hygroscopic swelling also induces the loss of adhesion strength [25]. Thus high humidity environments are responsible for the moisture induced failures in these ACF bonded flip chip interconnects. The absorbed water also reduces the glass transition temperature of ACF materials due to the plasticizing effect of water. Therefore the adhesion strength and stability is reduced [26].

6. CONCLUSIONS

The adhesion strength of anisotropic conductive adhesives film (ACF) joints is very critical to the success of the reliable packages of flip chip on flex (FCOF). The properties mainly depend on the processing of ACF and structure of bonding tracks. The processing includes the surface cleaning, proper bonding temperature & pressure and suitable operating conditions. They are all critical and it is not possible to look at one property alone to determine suitability. A balance of these properties is obviously needed for reliable packaging of flip chip on flex with ACF. From the recent studies, opportunities and technical challenges are highlighted, also the recommendations are given to address the technical challenges for the flip chip on flex packages.

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