Anisotropic Conductive Adhesives with Enhanced Thermal Conductivity for Flip Chip Applications

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Abstract

In this paper, we present the development work of anisotropic conductive adhesives with particular emphasis on the enhanced thermal conductivity of ACAs for flip chip application.

To ensure good thermal conductivity, we incorporated silicon carbide (SiC) fillers in the ACA formulation. Silicon carbide is used in formulation as functional fillers due to its excellent thermal conductivity and electrical non-conductivity. The effect of SiC fillers on the thermal conductivity, thermo-mechanical properties of modified ACA materials and the reliability of flip chip assembly on organic substrates using ACAs with enhanced thermal conductivity was investigated. Loading thermally conductive and electrically non-conductive fillers with smaller size than conductive fillers didn't affect the electrical anisotropic property of ACA joints, but improved thermal transmittance and other mechanical properties such as CTE of ACA between chip and substrate.

For the characterization of modified ACAs with enhanced thermal conductivity by loading different content of SiC fillers, measurement of thermal conductivity and thermo-mechanical analyses such as dynamic scanning calorimeter (DSC), dynamic mechanical analysis (DMA), and thermo-mechanical analysis (TMA) were performed.

The current carrying capability and reliability of flip chip joint using conventional ACA and novel ACA with enhanced thermal conductivity were compared to investigate the role of ACA as new thermal transfer medium in the flip chip assembly. We developed new ACA with high thermal conductivity which can bring wide use of adhesive flip chip technology with improved reliability under high current stressing. This paper is part of a broad study of thermally conductive ACAs for flip chip package and other electronic packaging technology.

1. Introduction

Flip chip technology has been developed and used to meet the package requirements of increasing density and higher electrical performance for electronic devices to be still smaller, shorter and thinner. Flip chip bonding is also more effective in dissipating the heat from high density IC due to short thermal path than conventional plastic mold package [1].

Especially, flip chip assembly using Anisotropic Conductive Adhesives (ACAs) has been gaining much attention for its simple and lead-free processing as well as cost effective packaging method. ACAs do not need additional underfill and potentially can be processed in much shorter times than the conventional solder/underfill method, and already successfully implemented in the package methods of reliable direct chip attach such as Chip-On-Glass (COG), Chip-On-Film (COF) for flat panel displays and Chip-On-Board (COB) for mobile electronics [2] ~ [5].

ACAs consist of mixtures of conductive particles in an insulating matrix. The anisotropic electrical conductivity of these materials comes from the trapped conductive particles between conductive bumps on the flip chip IC and the corresponding pads on the substrate, and conductive particles not connecting electrically between pads. In general, these materials are poor thermal conductors due to thermally insulated polymer matrix and low content of conductive filler.

The continuing downscaling of structural profiles and increase in interconnection density in flip chip packaging using ACAs has given rise to another problem. In detail, as the bump size is reduced, the current density through bump is also increased. This increased current density also cause new failure mechanism such as interface degradation due to intermetallic compound (IMC) formation and adhesive swelling due to high current stressing, especially in high current carrying joint of ACA flip chip assembly, in which high junction temperature enhance such failure mechanism [6]. Therefore, it is necessary for the ACA to be thermally conductive medium which allows effective heat dissipation from ACA flip chip joint through adhesive resin to the substrate for the flip chip package and improve the lifetime of ACA flip chip joint by reducing interface and adhesive degradation due to high current density and heat accumulation.

In this paper, we developed thermally conductive ACAs for the reliability enhancement of flip chip assembly. The material properties such as curing property and coefficient of thermal expansion (CTE) of thermally conductive ACAs were evaluated. The interconnection properties including current carrying capability and reliability of flip chip assembly using thermally conductive ACAs were also investigated.

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2. Experiment

2-1. Material Preparation

The ACA were formulated by mixing fillers, liquid epoxy resin, and a hardener. The mixture was stirred and degassed under vacuum environment for 3 hours to eliminate the air induced during stirring. Silicon carbide (SiC) fillers of different content (0, 20, 40, 60, 100 part per hundred resin; phr) and nickel fillers with 4.8 wt% were mixed with liquid epoxy to produce thermally conductive ACAs. For the binder system, it is formulated based on bisphenol A and F type liquid expoxies, and latent imidazole type curing agent. SiC fillers are thermally conductive and electrically insulating material. SiC filler size is 0.2 μm in average diameter and Ni filler is 5 μm. Surface modification of fillers was performed to get uniform dispersion of fillers inside epoxy matrix of ACA composite.

For the material characterization, the thermal conductivity of ACAs composite as a function of SiC filler content was measured by model, QTM 500, Kyoto Electronics. Also the thermal conductivity of adhesives without conductive filler was measured to find the effect of conductive filler on thermal conductivity of ACAs. The viscosity of thermally conductive ACAs with change of SiC filler was measured using a viscometer, PK2-1 RV20 of Haake Rheometer. Based on the results of thermal conductivity and viscosity, we fixed the filler content and other formulation of thermally conductive ACA. The differential scanning calorimeter (DSC) was performed to investigate curing property of thermally conductive ACAs. The cured thermally conductive ACA sample were prepared by placing the adhesive mixture in a convection oven at 150 °C for 30 minutes and cutting with 0.6 mm thickness for the thermo-mechanical analysis (DMA) and thermo-mechanical analysis (TMA) test.

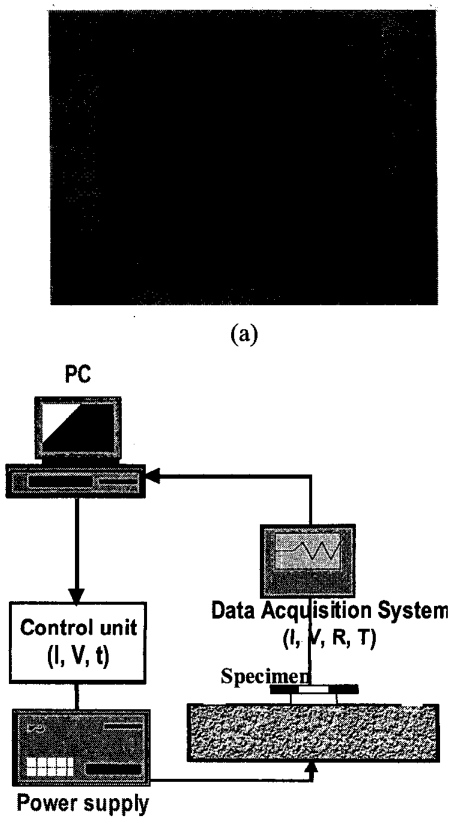
2-2. ACA Flip Chip Bonding Process

Test Si chip has peripheral-arrayed Al pads, and the pad pitch is 300 μm. Au stud bumps were formed using K&S 4522 manual wire bonding machine. Test substrate has patterned Cu/Ni/Au trace for measurement of contact resistance of each ACA joint. Table 1 summarized the specification of test samples used in flip chip assembly using developed thermally conductive ACAs.

Table. 1 Specification of Test Samples

Test IC	Chip size	X = 10 mm, Y = 10 mm
	Bump mat'l	Au (stud bumped)
	Bump height	~ 60 μm
	Bump size	85 μm (in diameter)
	Bump pitch	300 μm
Substrate	Base film	FR-4, 1 mm thick
	Conductor	Cu/Ni/Au, 18 μm thick

There are generally three process steps for the ACA flip chip assembly bonding. First, the gold bumps on the chip and the I/O pads on the test substrates were aligned. Then, two kinds of adhesive, thermally conductive and conventional ACAs, were dispensed on the substrate using manual dispensing machine. Finally, thermo-compression bonding by applying bonding pressure of 100 MPa and temperature of 180 °C for 30 seconds was performed to bond the test chip on the substrate. During ACA dispensing and bonding process, substrate heating of 80 °C is recommended for low viscosity of ACAs and concave fillet shape of cured adhesive. Thus the chip is electrically connected to the substrate via entrapped conductive fillers of the ACA and direct mechanical contact of Au stud bump on the electrical pad of the substrate. The assembled test vehicle using thermally conductive ACA is shown in figure 1(a).



(a)

(b)

Fig. 1. (a) Top-view of an assembled test vehicle, and (b) a schematic drawings of test equipment for current stressing test.

2-3. Current Stressing and Reliability Test

For current stressing test, the special test equipment as shown in figure 1(b) was designed to investigate I-V behavior and interpret current stress induced phenomena of flip chip interconnect using thermally conductive ACAs. For the determination of maximum allowable current, bias stressing was applied to a pair of Au stud bump and ACA joint. The current level at which current carrying capability is saturated is maximum allowable current. During the I-V test, applied voltage step is 0.1 V and duration time at each voltage level is 5 seconds. The maximum current limit of the test equipment, HP E3632A, is 7 A, and the test vehicles were placed on a flat surface at room temperature. The effect of thermal conductivity of ACAs on the current carrying capability was investigated by this experiment.

The effect of thermal conductivity of ACA on degradation mechanism under high current stress was studied by monitoring of ACA joint resistance. The supply current level of 4.1 A was determined from I-V characteristic of ACA flip chip. The contact resistance of ACA flip chip joint are related with failure mechanism of ACA flip chip joint, which is also related with the effectiveness of dissipating the heat inside flip chip assembly joints.

For the reliability test, die shear adhesion test was performed under high humidity and temperature environment. Dummy Si chip of 3 mm × 3 mm was flip chip bonded on FR-4 substrate by thermally conductive ACA, and die shear adhesion was measured by shearing the die with speed of 50 mm/min.

3. Results and Discussion

3-1. Material Characterization

3-1-1. Thermal Conductivity of ACA

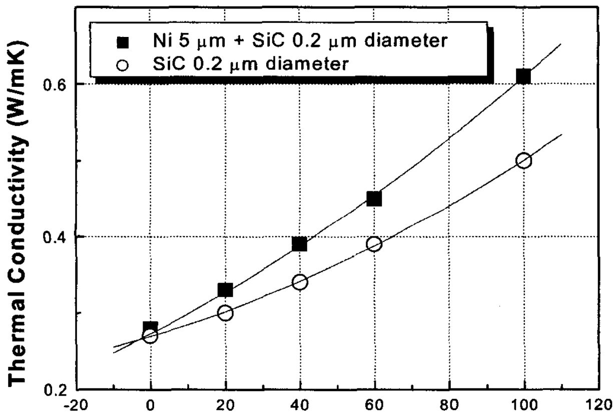
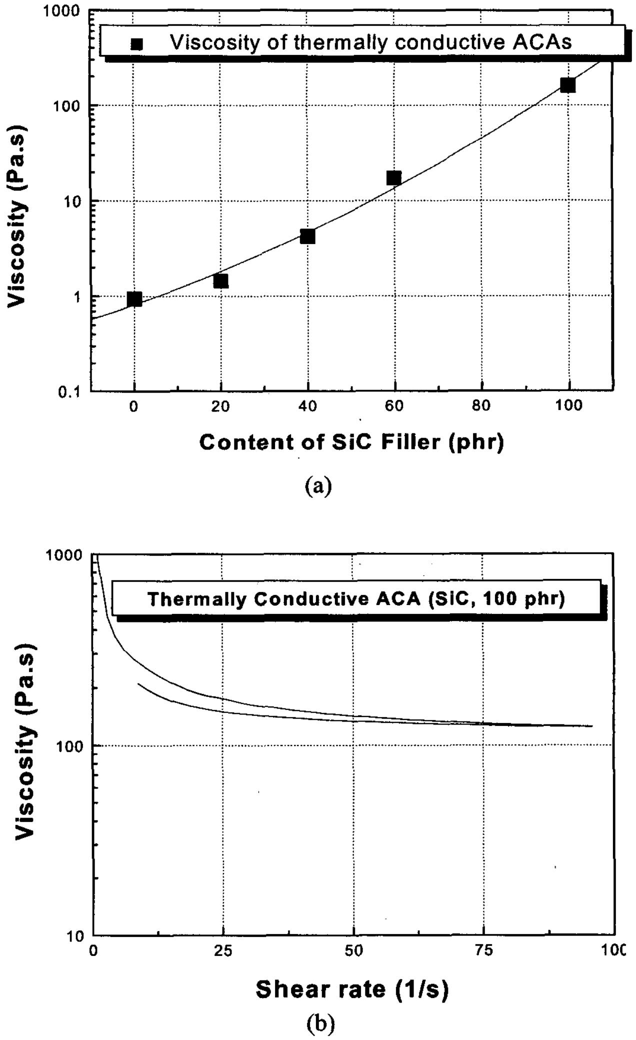


Fig. 2. Thermal conductivity of ACAs as a function of SiC fillers. The conductive filler is metallic Ni with 5 μm diameter and fixed content of 4.8 wt%.

Figure 2 shows the thermal conductivity of ACAs as a function of SiC fillers with fixed content of Ni filler. In comparison, there is a curve showing the thermal conductivity behavior of adhesive filled with only SiC filler. The thermal conductivity increased almost linearly as the content of SiC filler increased. It is interesting finding that the slope of thermal conductivity curve of ACAs with 4.8 wt% of Ni filler is larger than that of adhesive without Ni filler. It shows that fixed content of conductive filler with larger size than thermal filler improved the thermal conductivity of ACAs. Therefore, it is anticipated that higher content of conductive filler with larger size can enhance the thermal conductivity of ACAs and effect of conductive filler size and content should be investigated and optimized.

3-1-2. Viscosity of Thermal Conductivity of ACA

The viscosity results of thermally conductive ACA are shown in figure 3(a). The thermally conductive ACA with fixed content of 4.8 wt% Ni filler showed increasing viscosity significantly when SiC content is over 60 phr. Based on the results of high level of thermal conductivity and acceptable viscosity level for the thermally conductive ACAs are to be applied for flip chip assembly, thermally conductive ACAs can be developed. The content of SiC is determined to 100 phr and Ni filler content is 4.8 wt%. Afterwards, the rheology of thermally conductive ACA with SiC filler of 100 phr was measured as a function of shear rate as shown in figure 3(b). The thermally conductive ACA showed decreasing viscosity as shear rate increased, which is thixotropic behavior of ACAs. This kind of behavior is appropriate for the processability of ACAs, such as screen printing or dispensing.



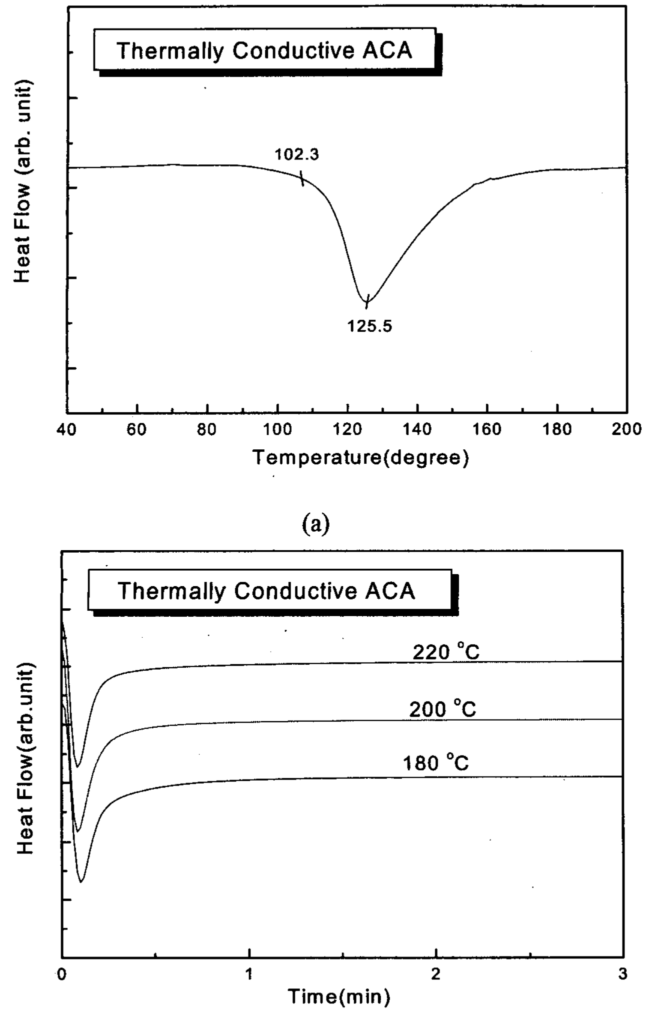
(a)

(b)

Fig. 3. (a) Viscosity behaviors of thermally conductive ACAs as a function of SiC filler content. (b) The rheology of thermally conductive ACAs with SiC filler of 100 phr.

3-1-3. Curing Property of Thermal Conductivity of ACA

Figure 4(a) shows temperature scan curve of developed thermally conductive ACA. The curing reaction was started when temperature reached around 102 °C, that is typical temperature of conventional ACA, and has peak temperature of 125 °C. The general temperature range of ACA flip chip bonding is approximately from 180 °C to 220 °C for 10 to 30 seconds. Figure 4(b) shows that isothermal cure curves and time for full cure of thermally conductive ACAs at 180, 200, and 220 °C. From those curves, the developed thermally conductive ACAs can be cured 30 seconds at 180 °C, 15 seconds at 200 °C, and 10 seconds at 220 °C, respectively. From the result of curing property, the developed thermally conductive ACA has similar curing behavior to conventional ACA.



(a)

(b)

Fig. 4. DSC curves of thermally conductive ACAs. (a) dynamic scan curve at 10 °C/min ramp rate and (b) isothermal scan curves at different temperatures of 180, 200 and 220 °C.

3-1-4. Other Material Property and SEM picture of Thermally Conductive ACA

The material characteristics of developed thermally conductive ACA are shown in Table 2. Thermo-mechanical properties such as CTE, storage modulus, decomposition temperature and Tg are summarized. Low CTE, high modulus and high decomposition temperature of ACA are preferred for the reliable flip chip assembly even though high filler content is loaded in thermally conductive ACA formulation to achieve high thermal conductivity [7].

Figure 5 shows the cross-sectional view of thermally conductive ACA. It is obvious that SiC fillers are dispersed uniformly and conductive Ni fillers are bigger than SiC fillers.

Table. 2 Material Properties of Thermally Conductive ACA

Properties		**Data**	**Unit**
Tg (DMA)		130	°C
CTE	<Tg	40	ppm
	>Tg	120	
Decomposition Temp.		400	°C
Storage Modulus		5.4	GPa
Non volatile (%)		99.9	

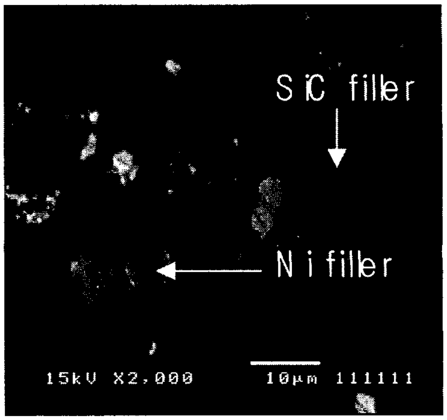


Fig. 5. SEM view of thermally conductive ACA with 5μm diameter Ni and 0.2μm diameter SiC fillers. (×1500)

3-2. Effect of ACA Thermal Conductivity on Current Carrying Capability of ACA Flip Chip Joint

The effect of thermal conductivity of ACA on the current carrying capability of flip chip joints was investigated. Figure 6 shows comparison result of I-V characteristics when ACA flip chip joints is bias-stressed at a pair of Au stud bumps/ACA joints. As described, conventional ACA without any thermal filler and developed thermally conductive ACA with 100 phr SiC fillers were compared.

As shown in figure 6, typical behavior of I-V characteristic is that current increased linearly and decreased abruptly above certain voltage value, that is due to the burning of Cu trace in PCB [8]. The conventional ACA flip chip joint shows the typical I-V curve with maximum allowable current level of 4.53 A.

In contrast, flip chip joint using thermally conductive ACA shows almost linear increase of current as increase of voltage and maximum allowable current level is 6.71 A. Therefore the current carrying capability of ACA flip chip joint was improved by the use of thermally conductive ACA material. Although the correct reason for this difference in maximum allowable current level should be investigated in detail, the possible reasons are related with the thermal conductivity of ACA adhesive resin.

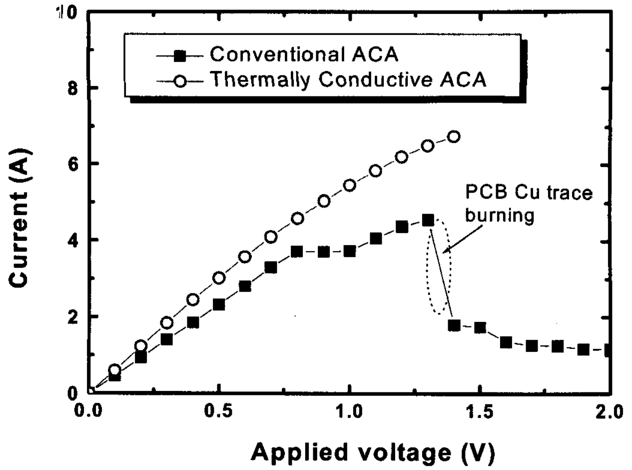


Fig. 6. I-V test (bias stressing) results at Au stud bumps/flip chip joints by conventional ACA and thermally conductive ACA.

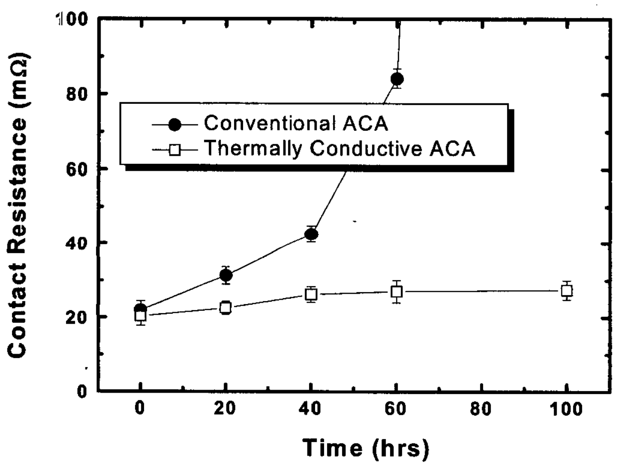


Fig. 7. Contact resistance changes of Au stud bump/flip chip joints using conventional ACA and thermally conductive ACA after 20, 40, 60, 100 hours under current stressing.

Figure 7 shows the resistance changes of flip chip joints using conventional ACA and thermally conductive ACA as a function of time under constant current of 4.1 A. The contact resistance value of upward electron flow (from PCB pads to chip pads) applied bumps (UEB) was measured. The contact resistance of conventional ACA flip chip joints increased abruptly as time passed 50 hrs and had open circuits before 100 hrs. But the thermally conductive ACA flip chip joints showed stable contact resistance behaviors without any open circuit.

The failure or degradation mechanism of ACA flip chip joints under current biasing test are suggested as follows; (1) Au-Al IMCs formation, (2) Crack formation and propagation along the Au/IMC interface, and (3) Al or Au depletion due to electromigration [8]. All those causes of electrical degradation of ACA flip chip joints are caused by heat accumulation at the Au stud bumps/PCB pads and thermal degradation of adhesive due to joule heating under high current bias. Similar discussion on the heat induced failure mechanism of flip chip joint using isotropic conductive adhesive (ICA) under high current density was presented [9]. If the local temperature of flip chip joint by ACA/Au stud bump is relatively low due to effective heat dissipation throughout thermally conductive ACA, the thermally degradation process due to local joule heating and thermal degradation are slowed down, and electrical stability is obtained. Detail causes on the improvement of high current carrying capability and electrical stability of thermally conductive ACA flip chip joints need to be more investigated.

3-3. Die Shear Reliability of ACA Flip Chip Assembly

Figure 8 shows that flip chip assembly using thermally conductive ACA has initial adhesion strength of 230 kgf/cm^2 and over 200 kgf/cm^2 after high temperature and humidity test for 1000 hours. This result confirm that mechanical adhesion of flip chip assembly using novel thermally conductive ACA with high content of SiC fillers is stable when exposed to moisture attack due to 85 °C/85%RH condition. Electrical integrity by measuring of contact resistance should be confirmed in future work.

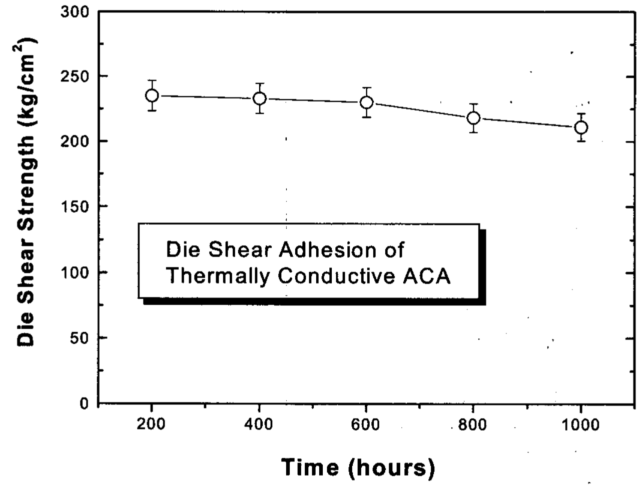


Fig. 8. Changes in die shear adhesion strength of flip chip assembly using thermally conductive ACA in a high-temperature, high-humidity test (85 °C/85%RH)

Conclusions

Anisotropic conductive adhesive with enhanced thermal conductivity has been developed for flip chip applications. The 5 μm Ni and 0.2 μm SiC filled ACA was formulated with epoxy-based binder system to achieve high thermal conductivity of 0.63 W/m·K, acceptable viscosity, curing property, and other thermo-mechanical properties such as low CTE and high modulus. The current carrying capability of ACA flip chip joints was improved up to 6.7 A by use of thermally conductive ACA compared to conventional ACA, that is normally poor thermal conductor. The high current carrying capability of thermally conductive ACA also resulted in stable electrical conductivity of flip chip joints under current biasing environment.

The high current carrying capability and electrical reliability of thermally conductive ACA flip chip joint under current bias test is mainly due to the effective heat dissipation by thermally conductive adhesive around Au stud bumps/ACA/PCB pads structure.

Junction temperature measurement and IR spectroscopy to characterize the temperature distribution on flip chip IC, and failure analysis on thermal degradation of ACA under high current biasing need to be done.

Conclusively, new ACA with high thermal conductivity was developed, which can bring wide use of adhesive flip chip technology with improved reliability under high current stressing.

Acknowledgments

This work was supported by Center for Electronic Packaging Materials of Korea Science and Engineering Foundation.

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