Journal of the Microelectronics & Packaging Society
Vol. 12, No. 1, p. 9-16. 2005

Flip Chip Assembly Using Anisotropic Conductive Adhesives with Enhanced Thermal Conductivity

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Abstract: This paper presents the development of new anisotropic conductive adhesives with enhanced thermal conductivity for the wide use of adhesive flip chip technology with improved reliability under high current density condition. The continuing downscaling of structural profiles and increase in interconnection density in flip chip packaging using ACAs has given rise to reliability problem under high current density. In detail, as the bump size is reduced, the current density through bump is also increased. This increased current density also causes new failure mechanism such as interface degradation due to intermetallic compound formation and adhesive swelling due to high current stressing, especially in high current density interconnection, in which high junction temperature enhances such failure mechanism. Therefore, it is necessary for the ACA to become thermal transfer medium to improve the lifetime of ACA flip chip joint under high current stressing condition. We developed thermally conductive ACA of 0.63 W/m·K thermal conductivity using the formulation incorporating 5 μm Ni and 0.2 μm SiC-filled epoxy-based binder system to achieve 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. Electrical reliability of thermally conductive ACA flip chip joint under current stressing condition was also improved showing stable electrical conductivity of flip chip joints. The high current carrying capability and improved electrical reliability of thermally conductive ACA flip chip joint under current stressing test is mainly due to the effective heat dissipation by thermally conductive adhesive around Au stud bumps/ACA/PCB pads structure.

Key words: Flip chip, anisotropic conductive adhesives, thermal conductivity, current carrying capacity

1. Introduction

Flip chip technology has been widely 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

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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 mechanism6). 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 interconnection properties including current carrying capability and reliability of flip chip assembly using thermally conductive ACAs under high current density stressing condition were also investigated.

2. Experiment

2.1 Material Preparation and Characterization

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 Flip Chip Bonding Process Using ACAs

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.

There are generally three process steps for the

Table 1. Specification of Test Samples

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

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 Fig. 1(a).

2.3 Current Carrying Capability and Current Stressing Experiment

For current stressing test, the special test equipment as shown in Fig. 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.

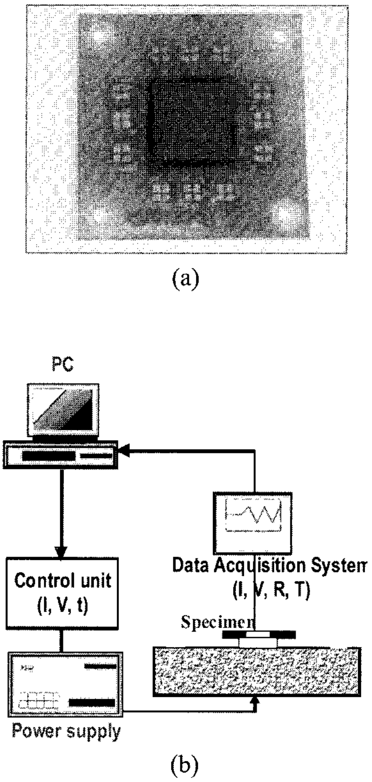


Fig. 1. (a) Top-view of an assembled test vehicle, and (b) a schematic drawing of test equipment for current stressing test.

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 interconnection. 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. We also measured and plotted the behavior of junction temperature on the surface of flip chip IC assemblies under current stressing condition as a function of time by thermal image analysis.

3. Results and Discussion

3.1 Material Properties of Thermally Conductive

ACAs

Fig. 2 shows the thermal conductivity behavior of ACAs as a function of SiC fillers with fixed content of Ni filler. Fig. 2 also shows the thermal conductivity behavior of adhesives with only SiC filler. The thermal conductivity increased almost linearly as the content of SiC filler increased. It is interesting to find 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 the 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 the effect of conductive filler size and content on the thermal conductivity of ACAs should be investigated and optimized.

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

Fig. 4(a) shows the temperature scan curve of developed thermally conductive ACA. The curing reaction started when temperature reached around 102°C, typical temperature of conventional ACA, and had peak temperature of 125°C. The general

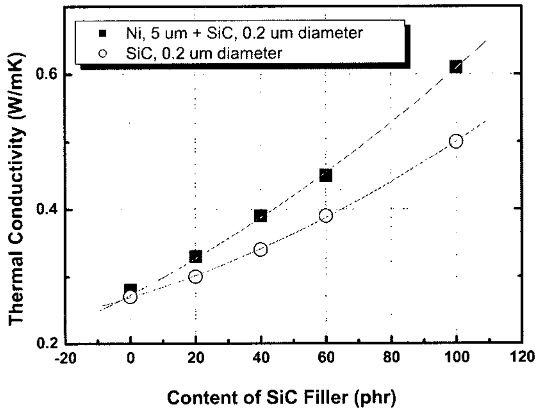
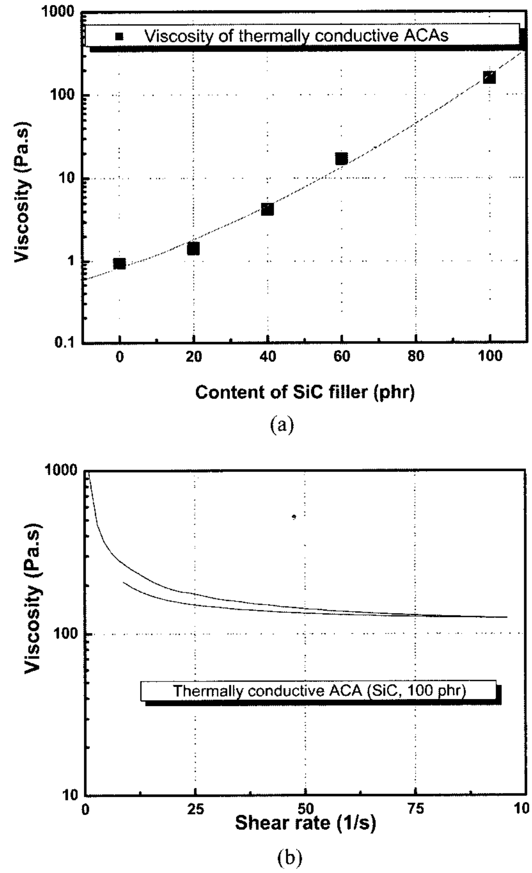


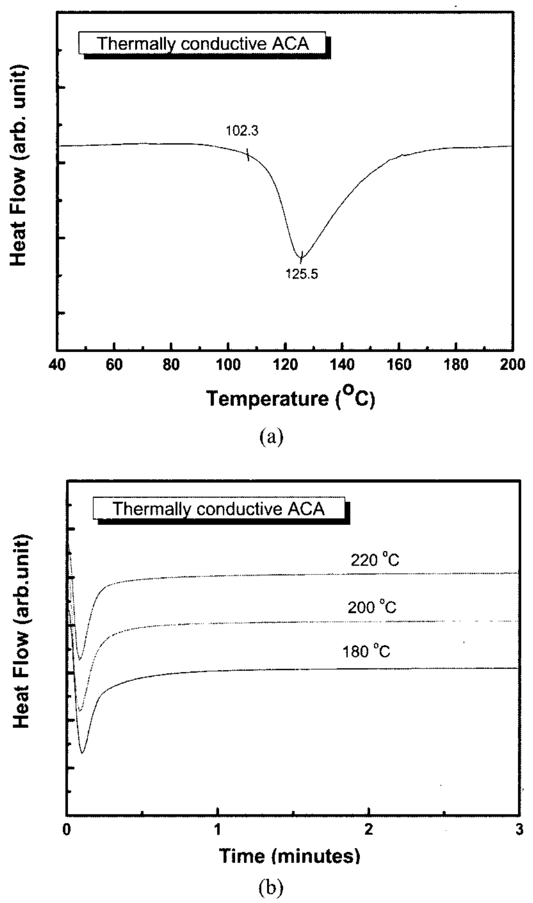
Fig. 2. Thermal conductivity of ACAs as a function of SiC fillers. The conductive filler is metallic Ni with 5 μm diameter and fixed content of 4.8 wt%.



(a)

(b)

Fig. 3. (a) Viscosities of thermally conductive ACAs as a function of SiC filler content. (b) viscosity of thermally conductive ACA with SiC filler of 100 phr as a function of shear rate.



(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.

temperature range of ACA flip chip bonding is approximately from 180°C to 220°C for 10 to 30 seconds. Fig. 4(b) shows the isothermal cure curves of thermally conductive ACAs at 180, 200, and 220 °C. From those curves, the developed thermally conductive ACAs can be cured for 30 seconds at 180°C, 15 seconds at 200°C, and 10 seconds at 220°C, respectively. From the result of curing property, it is found that the developed thermally conductive ACA has similar curing behavior to conventional ACA.

Table 2. Material Properties of Thermally Conductive ACAs

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

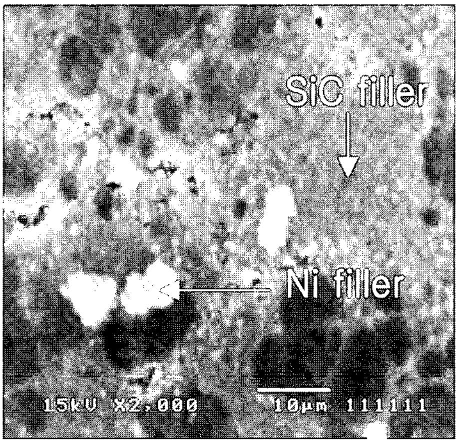


Fig. 5. SEM cross sectional view of thermally conductive ACA with 5 µm diameter Ni and 0.2 µm diameter SiC fillers. (×1500).

The material characteristics of prototype thermally conductive ACA are shown in Table 2. Thermo-mechanical properties such as Coefficient of Thermal Expansion (CTE), storage modulus, decomposition temperature and Tg were 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)]

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

3.2 Current Carrying Capability and Electrical Reliability of Flip Chip Joint using Thermally Conductive ACAs

The effect of thermal conductivity of ACA on the current carrying capability of flip chip joints was investigated. Fig. 6 shows the comparison result of I-V characteristics when ACA flip chip joints is bias-

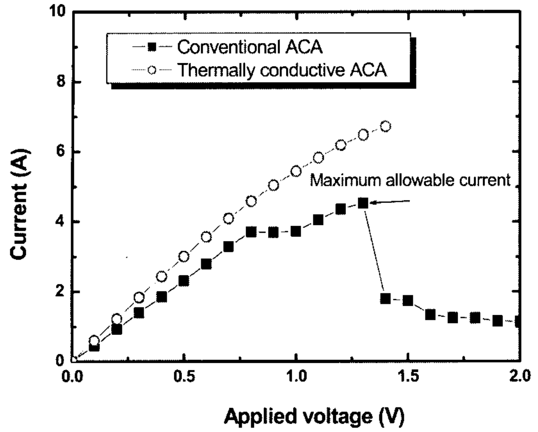


Fig. 6. I-V test (bias stressing) results at Au stud bumps/flip chip joints by conventional ACA and thermally conductive ACA.

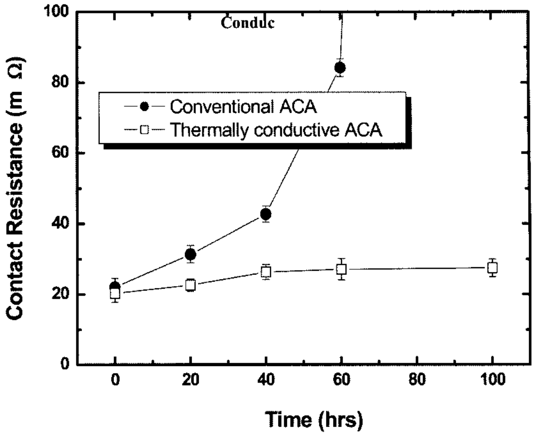


Fig. 7. Contact resistance changes of Au stud bump/flip chip joints using conventional ACA and thermally conductive ACA after 20, 40, 60, 100 hours under current stressing.

stressed at a pair of Au stud bumps/ACA joints. The conventional ACA without any thermal filler and developed thermally conductive ACA with 100 phr SiC fillers were compared.

As shown in Fig. 6, typical behavior of I-V characteristic was that current increased linearly and decreased abruptly above certain voltage value, that was due to the burning of Cu trace in PCB[8]. The conventional ACA flip chip joint shows the typical I-V curve with the 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 reason is related with the improved thermal conductivity of ACA adhesive resin.

Fig. 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 joint increased abruptly as time passed 50 hrs and had open circuits before 100 hrs. But the thermally conductive ACA flip chip joints showed the stable contact resistance behavior without any open circuit.

The failure or degradation mechanism of ACA flip chip joints under current biasing test can be suggested as follows; (1) Au-Al inter-metallic compounds (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 mostly 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 induced 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

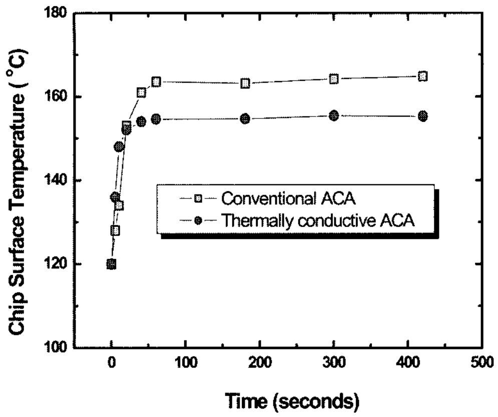


Fig. 8. Maximum chip surface temperature of flip chip assemblies using conventional and thermally conductive ACAs as a function of time under high current applying condition.

thermally conductive ACA flip chip joints need to be more investigated.

Fig. 8 shows the behavior of the chip surface temperature of flip chip IC assembly under current stressing condition as a function of time by thermal image analysis. The maximum chip surface temperature increased abruptly and became stable around 50 seconds of high current applying time. The chip surface using thermally conductive ACA became hot faster than conventional ACA joint, which meant thermally conductive adhesive dissipated the heat from the source more easily than conventional ACA did.

The maximum temperature of chip surface of flip chip assembly using thermally conductive ACA was lower than that of conventional ACA under constant current stressing. It was about 10°C difference. Therefore, the electrical reliability of flip chip joint under high current bias condition can be improved by dissipating the heat from hot spot and keep the chip temperature as cool as possible. This result also confirms that thermally induced degradation of flip chip assembly was prohibited or slowed down by using thermally conductive ACA.

4. Conclusion

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 was 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 using IR spectroscopy showed that relatively low temperature on flip chip IC was achieved by using thermally conductive ACA, and this was attributed to high electrical reliability of ACA flip chip joint under high current density environment.

Conclusively, new ACA with high thermal conductivity was developed, and it can be used for adhesive flip chip technology with improved reliability under high current stressing condition.

Acknowledgement

Financial support from Center for Electronic Packaging Materials (CEPM) of Korea Science and Engineering Foundation is gratefully acknowledged.

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