Reliable Anisotropic Conductive Adhesives Flip Chip on Organic Substrates For High Frequency Applications

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Abstract

Flip chip assembly on organic substrates using ACAs have received much attentions due to many advantages such as easier processing, good electrical performance, lower cost, and low temperature processing compatible with organic substrates. ACAs are generally composed of epoxy polymer resin and small amount of conductive fillers (less than 10 wt.%). As a result, ACAs have almost the same CTE values as an epoxy material itself which are higher than conventional underfill materials which contains lots of fillers. Therefore, it is necessary to lower the CTE value of ACAs to obtain more reliable flip chip assembly on organic substrates using ACAs. To modify the ACA composite materials with some amount of conductive fillers, non-conductive fillers were incorporated into ACAs.

In this paper, we investigated the effect of fillers on the thermo-mechanical properties of modified ACA composite materials and the reliability of flip chip assembly on organic substrates using modified ACA composite materials.

Contact resistance changes were measured during reliability tests such as thermal cycling, high humidity and temperature, and high temperature at dry condition. It was observed that reliability results were significantly affected by CTEs of ACA materials especially at the thermal cycling test. Results showed that flip chip assembly using modified ACA composites with lower CTEs and higher modulus by loading non-conducting fillers exhibited better contact resistance behavior than conventional ACAs without non-conducting fillers

Microwave model and high-frequency measurement of the ACF flip-chip interconnection was investigated using a microwave network analysis. ACF flip chip interconnection has only below 0.1nH, and very stable up to 13 GHz. Over the 13 GHz, there was significant loss because of epoxy capacitance of ACF. However, the addition of SiO_2 filler to the ACF lowered the dielectric constant of the ACF materials resulting in an increase of resonance frequency up to 15 GHz. Our results indicate that the electrical performance of ACF combined with electroless Ni/Au bump interconnection is comparable to that of solder joint.

1. Introduction

As the improvement of electronic devices proceeds on, the electronic packaging technology trends move toward lower cost, finer pitch, higher electrical performance, and better reliability. As a result, flip chip technology gains popularity as one of the best chip packaging candidates to meet these trends.

Although flip chip assembly using solder balls is in the main stream of flip chip technology, flip chip assembly using conductive adhesives such as isotropic conductive adhesives (ICAs) and anisotropic conductive adhesives (ACAs) has been under development because of their potential advantages compared with soldered bumps. [1] ~ [4] Some advantages of ACA flip chip assembly are (1) lower processing temperature (epoxy curing less than 150 °C compared with 240 °C solder reflowing temperature), (2) finer pitch interconnect (less than 50 μm pitch achieved at chip on glass (COG) technology), (3) lower cost due to less processing steps, and (4) green process (no lead, fluxes, and cleaning solvents).

ACAs, basically composite materials composed of an adhesive polymer resin and conductive particles, such as metallic or metal-coated polymer particles, have brought much attentions as an alternative for flip-chip-chip on organic boards.

For the full implementation of flip chip using ACAs, it is necessary to provide good reliability data to prove the availability of ACAs flip chip technology. The most commonly observed flip chip failure is during the thermal cycling test, which is due to the thermal expansion mismatch between chips and substrates. Therefore, underfill materials with matched coefficient of thermal expansions (CTEs) between chips and substrates are needed to guarantee better reliability. However, underfill materials cannot be used for ACA flip chips, because chips are attached to substrates using ACAs. Therefore, the problem of CTE mismatch between chips and substrates becomes serious with the ACAs flip chip assembly because of high CTE of ACAs materials. For this reason, we have patented the new dielectric filler added ACAs which function not only electrical interconnection but also the underfill at the same time. [5] Our previous study showed that low CTE adhesive layer with high filler content had lower shear strain induced by CTE mismatch between the chip and the board under temperature cycling. [6] And lower dielectric constant of the ACF will enhance the high frequency characteristics of ACF materials.

The purpose of this study is to investigate the effect of added dielectric fillers on ACAs materials characteristics, reliability and high frequency behavior for flip chip on organic boards application.

2. Experiments

To investigate the reliability of ACA flip chip assemblies, three ACA composites with different filler contents were formulated, and materials properties were tested. The effect of various ACAs on the reliability of ACA flip chip on organic boards was measured using thermal cycling test.

2-1. ACA Materials

Silica fillers of different content (5 - 45 wt.%) and nickel fillers were mixed with liquid epoxy to produce ACAs of 10 wt.%, 30 wt.% and 50 wt.% total filler content. Surface modification of fillers was performed to get uniform dispersion of filler inside epoxy matrix of ACA composite. The ACA were formulated by mixing fillers, liquid epoxy resin, and a hardener. The mixtures were stirred and degassed under a vacuum for 3 hours to eliminate the air induced during stirring. The differential scanning calorimeter (DSC) was performed to investigate curing properties of ACA composites. The cured ACA samples were prepared by placing the adhesive mixture in a convection oven at 150 °C for 30 min and cutting with 0.6 mm thick dimension for the thermo-mechanical characterization such as dynamic mechanical analysis (DMA), thermogravitational analysis (TGA) and thermo-mechanical analysis (TMA) test. The uncured ACA solutions were also prepared to interconnect flip chip on organic substrates.

2-2. Bump Formation

It is necessary to form bumps on the I/Os of the chip to be interconnected on the substrate using ACA materials.

At first, the gold stud bumps were formed on each I/O pad of test chips using a modified wire bonding machine. And then, stud bumps were coined by pressing against a flat surface to make bumps height uniform. Fig. 1 (a) shows coined stud bumps formed on aluminum I/Os of test chip.

Figure 1 . Scanning electron microscopy of coined Au stud bumps formed on Al pads of test chip.

2-3. Flip Chip Assembly using ACA

The modified ACAs in this study consist of an insulating epoxy thermosetting adhesive, conductive fillers, and non-conductive fillers. The modified ACAs were adhesive pastes without solvent. The substrate used for flip chip assembly was 1 mm-thick FR-4 board. The specifications of test chip and test board are summarized in Table. 1.

Table 1. Specification of test chip and organic substrate

Specification	Substrate
Material	FR-4
Size (mm × mm)	34 × 37
Final metallization	Au
Specification	**Test IC**
Size (mm × mm)	5 × 5
I/Os	48
Pitch (μm)	130
Pad size (μm diameter)	60
Bumps	Au stud bumps

There are three process steps for the ACA flip chip assembly on an organic substrate. First, the gold stud bumps on the chip and the I/O pads on the test substrates were aligned. And then the ACA was dispensed on the substrate to interconnect the chip. Finally, bonding pressure of 2 ~ 3 kgf/cm^2 and temperature of 150 °C for 5 min was applied to bond the chip on the substrate. Thus the chip is electrically connected to the substrate via entrapped conductive fillers of the ACA. Non-conductive fillers with smaller diameter than conductive fillers do not contribute the electrical contacts. Fig. 2 shows schematic of flip chip bonding process using ACA and the appearance of chip on an organic FR-4 substrate using an ACA composite material.

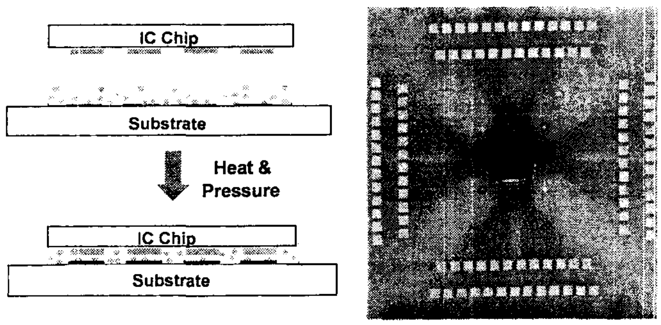


Figure 2. (a) Schematic of flip chip bonding process using ACA and (b) the appearance of flip chip assembly on an organic substrate such as FR-4 using an ACA composite material.

2-4. Reliability Test

To investigate the reliability of ACAs flip chips on an organic substrate, contact resistance of a single interconnect is the most important characteristic. The initial contact resistance was measured using a 4-point probe method and after each time interval, in-situ contact resistance were measured during the completion of reliability tests. For the reliability test conditions, 85°C/85%RH high humidity and temperature condition for 1000 hours, 85°C/dry high temperature/dry condition for 1000 hours, and –60 °C to 150 °C air to air thermal cycling for 700 cycles condition were adapted.

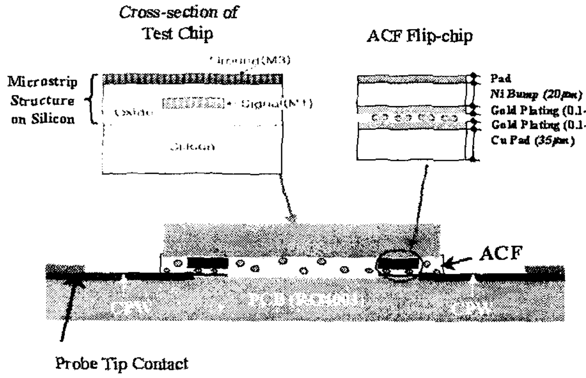
2-5. High frequency characterization

To investigate SiO_2 filler addition effect on high frequency behavior of ACA, two kinds of anisotropic conductive adhesives with different filler system, (1) Ni particle (conductive particle) only and (2) Ni particle (conductive particle) + SiO_2 particle (non-conductive particle), were formulated.

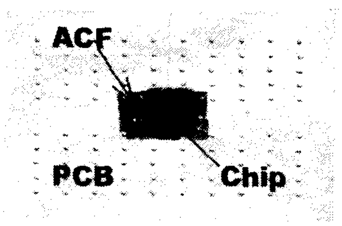
To extract the ACA flip-chip model parameter, the test chip with 20-μm width microstrip and 5 mm×5 mm chip area was fabricated using a 1-poly and 3-metal 0.6 μm Si process.

The S-parameters of the test chip and test PCB were measured using HP8510 network analyzer and cascade probe tip in the frequency range 200 MHz – 20 GHz. Also, S-parameter of flip chip bonded device was measured. From these measured S-parameters, impedance parameter model of flip chip interconnect was investigated based on a microwave network analysis.

The configuration of test chip bonded on PCB for the model extraction and high frequency measurement is shown in Fig. 3, including coplanar waveguide(CPW) on PCB, ACF, Ni/Au bump and microstrip on silicon.



(a)



(b)

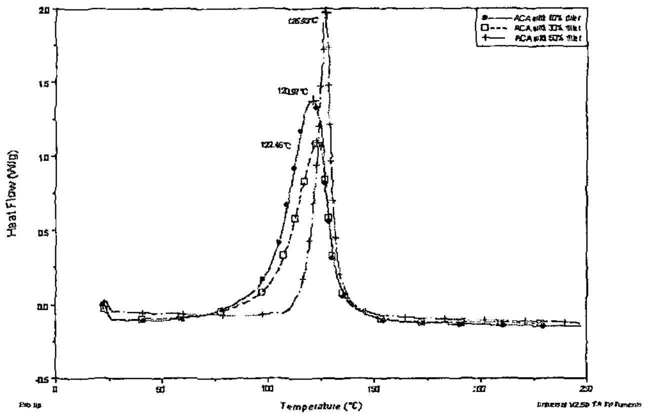
Figure 3. Configuration of the test PCB and chips for the extraction of interconnect impedance model using the S-parameter measurement.

3. Results and Discussion

3-1. Material Characterization Results

3-1-1 DSC results

The DSC curves in Fig. 4 show the effect of filler contents on the curing profiles of ACA composite materials. Similar curing behaviors and glass transition temperature of three different ACA composite materials were observed. However, the increase in the filler content slightly shifted the curing onset temperature and peak temperature to the higher



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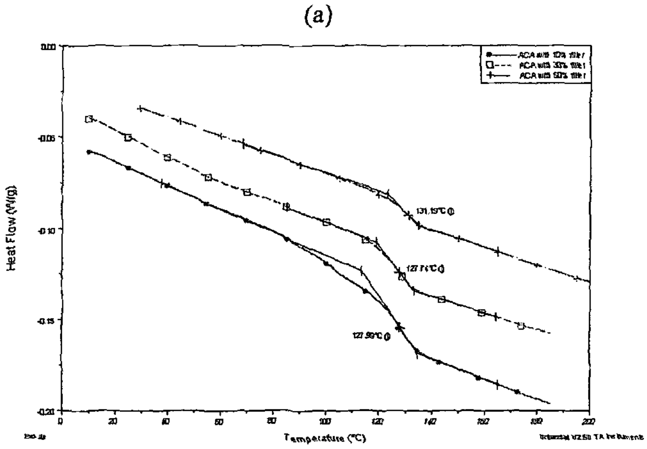


(b)

Figure 4. DSC curves of ACA samples with nickel and silica fillers of different contents (10, 30, 50 wt.%) Effect of the filler contents on (a) the curing profiles and (b) the glass transition curves of three ACA composites.

temperature as shown in Fig. 4 (a). The addition of nickel and silica fillers slightly modified the shape of the DSC curves and increased the Tg. The increase of Tg by addition of fillers has been known as general phenomenon [6].

3-1-2. DMA results

The dynamic mechanical properties of ACA composites from room temperature to 200 °C were studied using DMA. Fig. 5 shows the variation of the storage (E') and loss (E'') modulus as a function of the temperature for the ACA composites with different filler contents. The modulus of the ACA materials, particularly the storage modulus, increased as the content of silica increased at room temperature and decreased as the temperaure increased. Fig. 5 shows that the glass transition temperature characterized by a knee in the E' curves and the maximum in the E'' curves increase as filler contents increase. These behavior can be due to the increased interactions of polymer/filler in ACA composites. The composites will acquire some increase in free volume when fillers are filled into the matrix materials. If the filler content is increased continually, the internal friction due to increase of polymer/filler interface will rise quickly, hindering the movement of the polymer molecules even though the free volume of the composite increases. This increase in friction resulted in a higher value for Tg as filler content increased. [7] Softening of ACA composites is almost the same for three composites at about 120 °C. However, the start of the softening process of composites is slightly delayed to a higher temperature when composites contain higher filler contents. And this is presumably due to the high interface area of silica/polymer, when high content of silica fillers are added. [8]

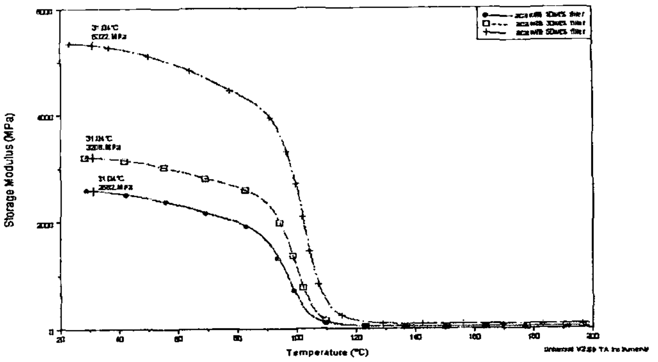
For underfill materials of solder ball flip chip assembly, high modulus is needed to effectively redistribute the solder joints stress to the chip and substrate through the assembly warpage [9]. Similarily, since ACA materials assembled on an organic substrate function as both underfill and electrical conductor, high modulus of ACA by adding high content of fillers is needed.

The optimum modulus of an underfill material for flip chip on an organic substrate generally ranges 6 ~ 10 GPa.[10] The content of filler remarkably affects the storage modulus of the cured materials at room temperature. The room temperature storage modulus of the cured ACA materials in this study increases up to 5.3 GPa with 50 wt% filler content. Therefore, high content of filler is preferred, unless the viscosity of ACA composite is too high to be used in the dispensing process.

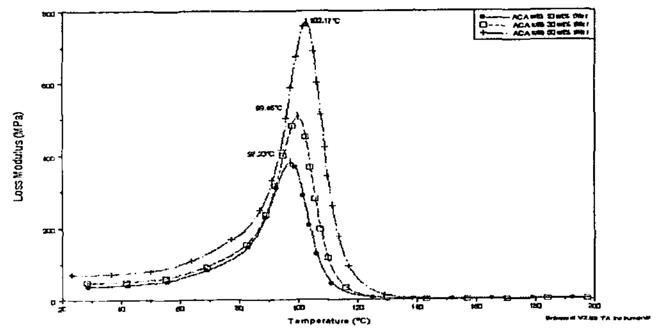
3-1-3. TMA results

Fig. 6 show the TMA curves of three ACA composite materials with different filler content. The inflection point of thermal expansion curve is defined as TMA Tg (Tg ^{TMA}). This figure shows that higher filler content cause the increase in Tg ^{TMA} of the cured samples due to stiffening effect of composite materials with the higher interface area between fillers and epoxy resin as discussed in DMA results. The CTE of the ACA composite below the Tg ^{TMA}, defined as $\alpha 1$, and the CTE above the Tg ^{TMA}, defined as $\alpha 2$, are important parameters in determining the reliability of the ACA flip chip assembly.

Table 2 indicates that the filler content has significant effect on the $\alpha 1$, but no noticeable effect on the $\alpha 2$. From the Tg ^{TMA} and the CTE behaviors, higher content of filler is desirable for the reliability improvement of ACA flip chip assembly.



(a)



(b)

Figure 5. (a) Storage modulus and (b) loss modulus of ACA samples with 10 wt%, 30 wt%, and 50 wt% fillers.

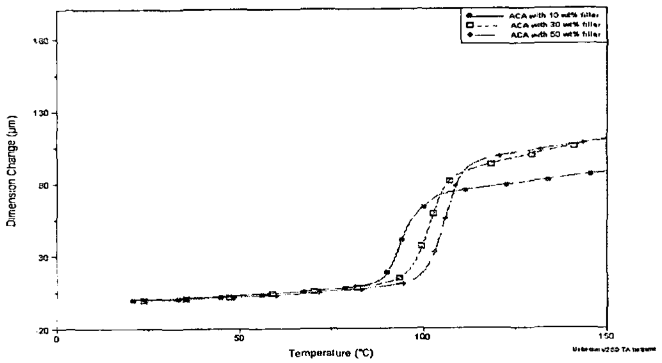


Figure 6. TMA curves of three ACA composite samples with different content of fillers.

Table 2. Tg ^{TMA} and CTE of ACA composites below and above Tg ^{TMA}

ACA composite	Tg^{TMA}(°C)	$\alpha 1$ (ppm/°C)	$\alpha 2$ (ppm/°C)
ACA with 10 wt% filler	87.62	87.9	3960
ACA with 30 wt% filler	93.53	76.1	3630
ACA with 50 wt% filler	98.77	60.7	3920

3-1-4. TGA result

The thermogravitational analysis was performed to evaluate the decomposition temperature of ACA composites with different content of fillers. The decomposition temperatures of three ACA composites were almost that same at 393 °C due to same epoxy resin used. The filler content in ACA composite doesn't influence on the decomposition temperature, but influence on the weight loss. Fig. 7 indicates weight loss increases as the filler content decreases.

Furthermore these decomposition temperatures were also similar to those of commercial underfill materials. The decomposition temperature is one of important properties for reworkable underfill used in flip chip package. [11]

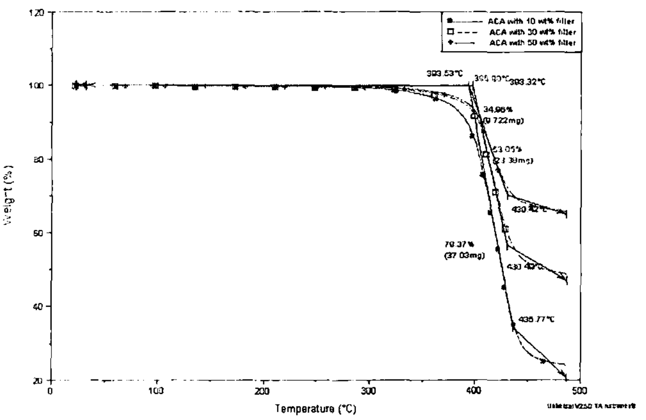
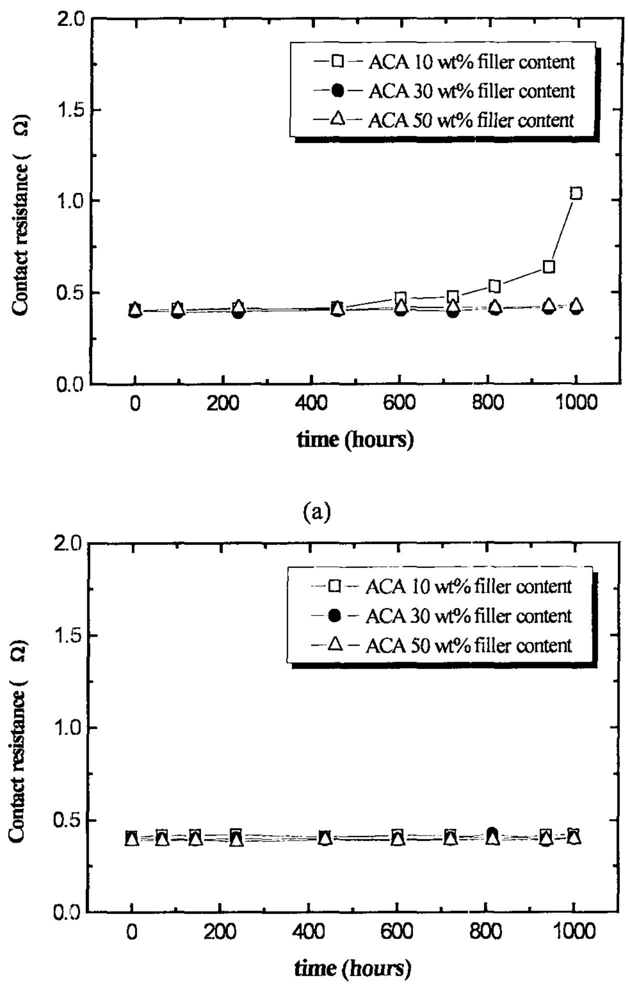


Figure 7. TGA curves of three ACA samples with different content fillers

3-2. Reliability Test Results

The contact resistance variations of flip chip assembly using three different ACA composites during 85 °C /85 relative humidity condition for 1000 hrs and 85 °C /dry condition for 1000 hours were shown in the Fig. 8 (a) and (b). As can be seen from the Fig. 8 (a), the contact resistance of ACA with 30 wt.% and 50 wt.% filler content show very stable value. However, the resistance of ACA with 10 wt.% filler content was stable up to 800 hours and increased a little after 800 hours. No catastrophic failure was observed. The contact resistance of ACA flip chip assembly was stable during 85 °C /dry condition regardless of filler content as shown in Fig. 8 (b). In summary, the electrical resistance changes were in an acceptable range of below 10 % during 85 °C /85 relative humidity condition and almost negligible at the dry condition.

The comparison of reliability results between the 85 °C /85 relative humidity condition and the 85 °C / dry condition reveal that the increase of contact resistance of ACA flip chip assembly is mainly due to the humidity attack on the adhesive layer. [12] This effect of humidity on the contact resistance of ACA joint was predominant in case of low content of fillers presumably because of higher CTE and lower modulus resulting from higher portion of epoxy resin.



(a)

(b)

Figure 8. Contact resistance of flip chip interconnects using ACA with different filler content during (a) 85°C/85%RH test and (b) 85°C/dry condition test.

Fig. 9 shows the contact resistance behaviors of ACA flip chip during -60 °C to 150 °C thermal cycling condition. The flip chip assembly using ACA with 10wt.% filler content could not pass 400 cycles, and the assembly using ACA with 30 wt% filler content could not pass 500 cycles. However, flip chip assembly using ACA with 50 wt% filler content ACA 1000 cycles. These results of the thermal cycling test indicates that the filler content in the ACA composite has noticeable effect on the reliability of ACA flip chip assembly on an organic substrate. The higher content of filler in ACAs causes lower CTE and higher storage modulus resulting in a better reliability of ACA flip chip assembly on an organic substrate during 85°C/85%RH test and thermal cycling test.

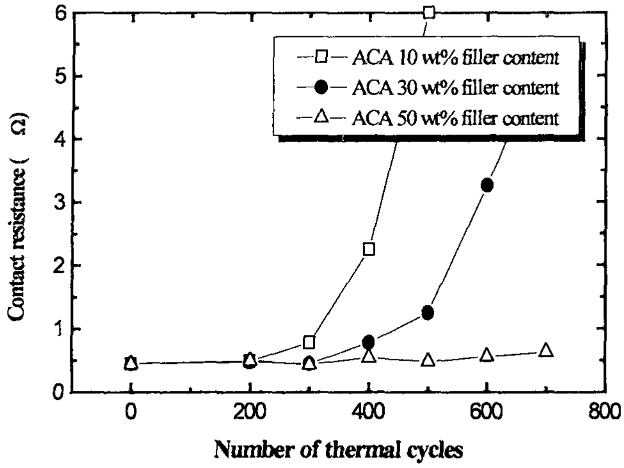


Figure 9. Contact resistance of flip chip interconnects using ACA with different filler content during thermal cycling test from –60 °C to 150 °C for 700 cycles

3-3. High Frequency Measurement Results of ACAs

Insertion loss (S_{21}; transmission coefficient) of test device consisted of the microstrip line on lossy silicon, CPW on the test PCB and ACA were shown in Fig. 10. Below resonant frequency, the insertion loss of the test chip is mostly dominated by the microstrip loss on the lossy silicon chip.

This abrupt downside peak in the insertion loss is related with the resonance of interconnect.

Our previous study showed that the resonance frequency conventional ACF is located around 13GHz. [13]

Interestingly, the Ni ball ACF including SiO_2 filler has resonant frequency slightly higher than the conventional Ni ball ACF. The resonant frequency of Ni ball ACA with SiO_2 was located around 15GHz.

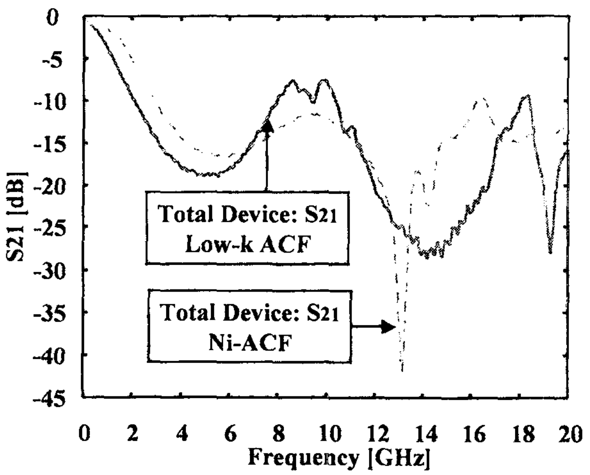


Figure 10. The measured insertion loss of test-device with PCB, ACA and silicon testchip. The measurements were conducted using a network analyzer from 200 MHz to 20 GHz.

The extracted impedance model parameters of a bonding pad for Ni ball ACF including SiO_2 filler were presented in Fig. 11. Interestingly, the Ni ball ACF including SiO_2 filler has resonance frequency slightly higher than the conventional Ni ball ACF. Up to 10GHz, resistance value of Ni ball ACF with SiO_2 filler is dominated by the skin effect loss of the conductive system. Above 10GHz, the conductive loss of polymer matrix becomes dominant. Then SiO_2 filler reduce the capacitive coupling & the conductive loss of polymer matrix by lowering the dielectric constant of ACF. Therefore, Ni ball ACF including SiO_2 filler exhibited the resonance phenomena around 15GHz. This different phenomenon is originated from dielectric constant change of polymer matrix.

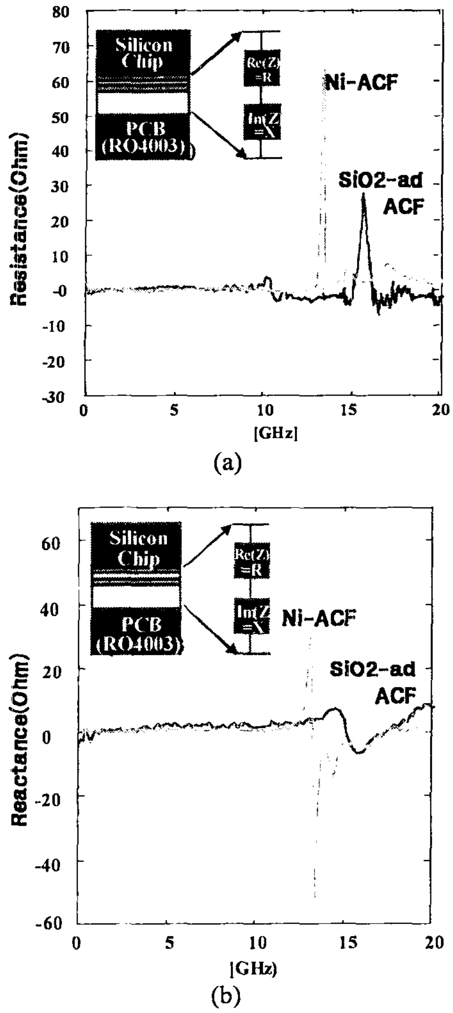


Figure 11. Impedance parameters of the ACF flip-chip interconnect including SiO_2 extracted from S-parameter measurement and network analysis. (a) Resistance(R), (b) Reactance (X)

4. Conclusion

In this paper, we investigated the effect of non-conducting silica filler content of the ACA composite materials on the curing properties, thermo-mechanical properties, reliability and high frequency behavior for the ACA flip chip assembly on an organic substrate. The content of non-conducting filler is the key factor which controls basic properties of ACA composite materials such as curing profile, Tg, CTE, modulus and electrical resonance of interconnect and eventually the reliability of ACA flip chip assembly. As the content of non-conducting filler increases, Tg, storage modulus, curing onset and peak temperature increase. And at the same time, the CTE below the Tg decreases. However, assembly using ACA, the content of non-conducting filler addition does not noticeably affect the CTE above the Tg and thermal stability. These effects of non-conducting filler addition on the ACA materials properties were verified by reliability tests. The reliability of ACA flip chip assembly using ACA with higher content of non-conducting filler is significantly better than that of flip chip assembly using conventional ACA or ACA with low content of filler due to lower CTE and higher modulus.

In addition, by lowering the dielectric constant of ACA with the addition of SiO_2, better microwave frequency property was obtained. Resonance frequency of ACF interconnect was shifted to the higher frequency.

Conclusively, the incorporation of non-conductive fillers in the ACA composite material significantly improves the material property of ACAs resulting in better reliability of ACA flip chip assembly on an organic substrate and enhance the high frequency property of ACA.

References

1. A. Torri, M. Takizawa, K. Sasahara, " Development of Flip Chip Bonding Technology using Anisotropic Conductive Film", in *Proc. 9th International Microelectronics Conference,* pp. 324 ~ 327, 1996
2. D. J. Williams et al., "Anisotropic Conductive Adhesives for Electronic Interconnection", *Soldering & Surface Mount Technology,* pp. 4 ~ 8, 1993
3. J. Liu, A. Tolvgard, J. Malmodin, and Z. Lai, " A Reliable and Environmentally Friendly Packaging Technology-Flip Chip Joining Using Anisotropically Conductive Adhesive", *IEEE Trans. Comp. Packag., Manufact. Technol. Vol. 22, No. 2,* pp.186~190, 1999
4. J. H. Constable, T. Kache, H. Teichmann, S. Muhle and M. A. Gaynes, " Continuous Electrical Resistance Monitoring, Pull Strength, and Fatigue Life of Isotropically Conductive Adhesive Joints", *IEEE Trans. Comp. Packag., Manufact. Technol. Vol. 22, No. 2,* pp.191~199, 1999
5. M. J. Yim and K. W. Paik, "Modified ACAs for chip chip on organic boards", Korean and US patent pended
6. M. J. Yim, Y. D. Jeon, and K. W. Paik, "Reduced Thermal Strain in Flip Chip Assembly on Organic Substrate using Low CTE Anisotropic Conductive Film", *IEEE Trans. On Electronics Packaging Manufacturing. Vol. 23, No. 3,* pp.171~176, 2000
7. R.K.Li, J.Z. Liang and S.C.Tjong, "Morphology and Dynamic Mechanical Properties of Glass Beads filled Low Density Polyethylene Composites," *J. of Materials Processing Technology,* Vol. 79, pp.59-65, 1998
8. A. Torro-Palau, J.C. Fernandez-Garcia, A. C. Orgiles-Barcelo, M. M. Pastor-Blas and J.M. Martin-Martinez, *Int. J. Adhesion Adhesives,* Vol. 17, p. 111, 1997
9. B. Jauregui-beloqui, J. C. Fernandez-Garcia, A.C. Orgiles-Barcelo, M. M. Pastor-Blas and J.M. Martin-Martinez, " Thermoplastic polyurethane-fumed silica composites: influence of the specific surface area of fumed silica on the viscoelastic and adhesion properties", *J. Adhesion Sci. Technol.,* Vol. 13, No. 6, pp. 695 ~ 711, 1999
10. J. Clementi, J. McCreary, T. M. Niu, J. Palomaki, J. Varcoe, and G. Hill, "Flip Chip Encapsulation on Ceramic Substrate," in *Proc. 43rd ECTC,* Orlando, FL, June 1993, pp. 175
11. L. Crane, A. Torres-Filho, C. K. Ober, S. Yang, J. Chen, and R. W. Johnson, "Development of Reworkable Underfills, Materials, Reliability and Processing", *IEEE Trans. Comp. Packag., Manufact. Technol. Vol. 22, No. 2,* pp.163~167, 1999
12. D. C. Lam, F. Yang and P. Tong, " Chemical Kinetic Model of Interfacial Degradation of Adhesive Joints", *IEEE Trans. Comp. Packag., Manufact. Technol. Vol. 22, No. 2,* pp.215~220, 1999
13. M. J. Yim, W. H. Ryu, Y. D. Jeon, J. H. Lee, S. Y. Ahn, J. H. Kim, K. W. Paik,, "Microwave Model of Anisotropic Conductive Film Flip-Chip Interconnections for High Frequency Applications", *IEEE Trans. Comp. Packag. Technol. Vol. 22, No. 4,* pp.575~581, 1999