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High Thermal Die-Attach Paste Development for Analog Devices

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***Abstract*— In recent years, various die attach (DA) materials have been developed to cope with the higher power dissipation requirements of semiconductor devices. DA materials based on metals such as solder or sintered silver (Ag) are used for very high heat generating power devices. While they show outstanding thermal performance, the mechanical properties of these materials are less than ideal. This limits the application window for adoption of these DA materials. Many semiconductor devices such as analog circuits, microcontroller units (MCUs) and application-specific integrated circuits (ASICs) that are widely used in electronic products do not require as much heat dissipation as high-power devices but could benefit from increased thermal capacity and can have larger die sizes. For such products, a DA material with a large amount of Ag powder is added to epoxy resins or acrylic resins to lower the elastic modulus. However, when a polymer is added to the system, the interface resistance increases between the DA material and the die, or between the DA material and the lead frame must be considered. As a result, even if the DA material includes a large amount of Ag, the thermal resistance of the entire package is not improved as expected due to the increase in resistance. To solve this problem, a new DA material concept has been jointly developed that can be applied to a large die size to improve the bulk and interface resistance. This paper will discuss material properties, improved thermal resistance of the package and reliability test results for this material.**

I. INTRODUCTION

In recent years, heat generation of a silicon (Si) die has been increasing more and more with the increase in speed and integration of semiconductor devices. Generally, to more efficiently remove heat generated by the Si die, a structure with the Si die mounted on it is exposed as a heatsink to the package (PKG) surface (an E-Pad structure) (Figure 1, Figure 2). Also, in the package of the E-Pad structure, solder bonding may be applied to efficiently dissipate the heat, and a metal layer on the back surface of the Si die such as a stacked film of titanium-nickel-gold (Ti/ Ni/ Au), is often used. Tin-silver (Sn-Ag) or tin-antimony (Sn-Sb based lead-free solder may be used as the DA material, but lead-rich Sn-Pb based solder DA material is generally used because of its mechanical properties. such as ductility, melting point and thermal fatigue. However, lead containing solder alloys cause various environmental problems, such as soil pollution and effects on the human body. Therefore, there is an active movement worldwide to develop alternative materials for lead containing solder DA materials.

Figure 1. Package appearance of exposed Quad Flat Pack (QFP)

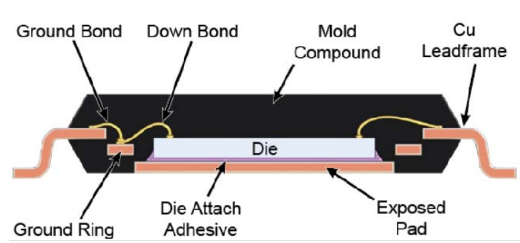

Figure 2. Cross section of exposed QFP

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Concurrently, the ratio of Si die manufacturing costs to the total cost of semiconductor products is increasing due to increasingly complex system designs and the physical limitations of miniaturization. Therefore, reducing Si die manufacturing costs is a major issue. One of the reasons for the increase in cost is the formation of a metal layer on the back surface of Si die used for the solder connection. Generally, it takes about several dozens of dollars to process a back-side metal (BSM) layer on an 8-inch wafer, and as the die size increases, the influence on the cost increases as well. Therefore, in this research, an alternative material to lead solder DA material was developed, which does not impair the heat radiation characteristics, and which does not require metal formation on the back surface of the Si die to reduce the cost of manufacturing Si die.

II. Development challenges and Required Characteristics for the Ag Paste

An Ag paste is a thermosetting epoxy resin material containing Ag particles that can be bonded to the die and die pad without requiring a metal layer on the back of the Si die. Therefore, it is considered as an alternative material to the lead-containing solder DA material. However, since the thermal conductivity of epoxy resins are generally very low, about 1 W/m·K, it is necessary to add a large amount of a metal filler to reduce the thermal resistance. As the amount of metal filler increases, the bending strength and elastic modulus of the DA material increase. As a result, interface delamination and cohesive failure of the DA material occur due to reflow resistance and an α mismatch in the thermal cycle test, which causes in an increase in thermal resistance. There is a trade-off between lowering thermal resistance and ensuring product reliability and it can be said that the larger the die size, the more difficult it is to achieve both. By eliminating the metal layer on the back surface of the Si die, as the die size increases, the cost reduction per die is expected to increase. Therefore, it is desired for the mainstream die size of 8x8mm in large scale integration (LSI) systems.

Based on the above, the challenges for the development of DA material include low thermal resistance, low stress, and high adhesion of the materials. Also, the characteristics required for products are heat dissipation characteristics, reflow resistance and long-term reliability at a level similar to when lead-containing solder is used. To provide this capability, Sumitomo Bakelite Co., Ltd., Toshiba Electronic Devices & Storage and Amkor collaborated to develop DA materials and evaluate product characteristics and package reliability.

III. Development of DA material

Solder has been used as a DA material for power semiconductor devices for many years because solder shows good thermal and electrical conductivity. However, there is a risk of cracks occurring when solder is used for large die because of high stresses due to a high modulus of elasticity. In addition, solder needs metallization on the back side of the Si to form an alloy layer to the metal and provide the adhesion mechanism. On the other hand, Ag paste has been widely used as a DA material for semiconductor devices because of good stress relaxation and high adhesion to various material surfaces, and Ag pastes normally show lower thermal dissipation compared to solder.

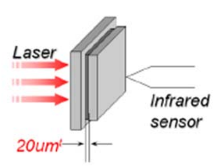
In this study, a Ag paste was used: A) to achieve high thermal dissipation and B) for application to large die without BSM plating.

A. High Thermal Dissipation

When discussing the thermal dissipation of a DA material, the thermal conductivity of the bulk Ag paste material itself is typically considered. However, the thermal resistance among die, DA paste and lead frame layers also affect the thermal dissipation of the package. Therefore, the thermal properties were evaluated using a three-layer model which can be evaluated including the interface resistances. The three-layer model is composed of silicon die - DA material - silicon die and has an interface part and a bulk part, so the model is better to discuss thermal dissipation than just the thermal conductivity of the bulk Ag paste. The thermal properties of the entire three-layer model were evaluated by laser flash measurements (Figure 3).

The main components in the Ag paste are Ag and resin, that exist at each interface. If the ratio of Ag, a very high thermal conductive material, is high near the interface, effective thermal dissipation can occur between the interface and the Ag-paste layer. Pastes were prepared with different sizes and shapes of Ag fillers to study the effect of Ag existence ratio near interface to thermal diffusivity with the three-layer model.

The Ag existence ratio within a range of 3 μm from the interface was calculated by analyzing a scanning electron microscope (SEM photo of the cross section (Figure 4). Using a fine-size Ag filler, the grade showed higher Ag existence ratio near the interface than bulky fillers and the correlation between the Ag existence ratio and thermal diffusivity was clearly observed (Table 1). Although fine Ag size filler has better diffusivity, for easy and consistent dispense-ability, the viscosity must be considered as well. So, sample c) which contains both bulky and fine Ag filler is better to achieve thermal diffusivity and low viscosity than sample d).



Top die: 7x7mm, 720umt
Bottom die: 10x10mm,
Thickness of DA material: 20um
Evaluation temp.: 25'C

Figure 3. Thermal diffusivity evaluation of three-layer model by laser flash

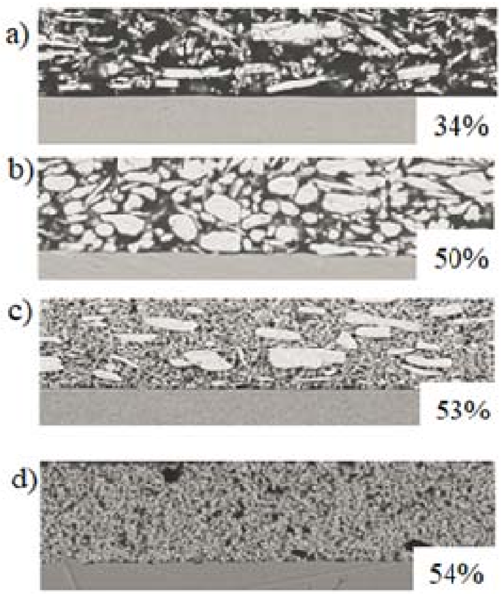


Figure 4. Cross-section observation photo by SEM

Ag filler type of paste in each photo are; a) bulky and low content, b) bulky, c) both bulky and fine, d) fine. (Value in the photo shows Ag existence ratio near the interface (< 3um).)

B. *Application to Large Die without Back Side Metal Plating*

If a large die size is used, the thermal stress in the DA material layer becomes higher. Therefore, reducing the stress with a lower elastic modulus and higher adhesion is important to prevent cracks and delamination. In terms of elastic modulus and adhesion, the resin component in Ag paste can contribute to achieving the desired properties. Resin remains after curing, so the modulus of the paste can be made lower. Also, after curing, the resin also has high adhesion to various metal surface including the Si. After curing, the properties of different Ag pastes were evaluated compared to a high lead solder (Sn5%Pb95%).

The modulus was evaluated by Dynamic Mechanical Analysis (DMA) of cured samples 4 mm x 20 mm x 250-µm thick. Ag paste samples a) and c) showed lower modulus than the solder (Table 1). Adhesion was evaluated with a Si die and a Cu surface lead frame which were bonded with the DA material. The Ag paste showed high adhesion to Si, but solder does not adhere to Si. Thermal diffusivity of Ag paste sample a) showed a very low value, but sample c) showed a value comparable to solder.

C. *Summary of Paste Study*

Thermal dissipation improves by increasing Ag existence ratio near the interface by using fine size Ag filler.

Low modulus and high adhesion to Si are achieved by resin that remains after curing. As a result, Ag paste sample c) is a good candidate for packages with large die and without BSM plating.

TABLE I. PROPERTY OF VARIOUS MATERIAL (TYPICAL VALUE)

Grade	Solder (Sn5% Pb95%)	Ag paste sample a)	Ag paste Sample c)
Filler type	-	Bulky	Bulky and fine
Remining resin after cure	No	Yes	Yes
Modulus at 25'C (GPa)	20[a]	10	16
Adhesion to Silicon (N)	No adhesion	>20	>20
Thermal diffusivity(cm2/s) with Silicon die	No data	0.18	0.59
Thermal diffusivity(cm2/s) with Silicon die with BSM	0.68	0.18	0.64
Bulk thermal conductivity (W/mK)	40	1	15

IV. MEASUREMENT RESULTS OF THERMAL RESISTANCE

A. *The Result of Thermal Resistance Measurements*

Figure 5 shows a schematic diagram of the cross section of the die attach structure and the factors of thermal resistance. The thermal resistance of the DA material is formed by the interface thermal resistance between the DA material and the die back surface (Si) material, the interface thermal resistance between the DA material and the lead frame (Cu), and the bulk thermal resistance of the DA material. It is expressed by the equation shown in (1).

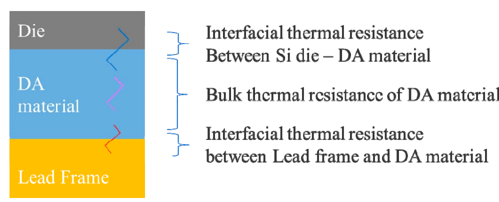


Figure 5. Schematic diagram of thermal resistance of DA material

DA material thermal resistance =
Interface thermal resistance between Si and DA material (1)
+ Interface thermal resistance between lead frame and DA material
+ Bulk thermal resistance of DA material

The interfacial thermal resistance and bulk thermal resistance of the DA material were measured and analyzed using dynamic thermal interface material (DynTIM) testing (*1). In this process, samples having different bond line thicknesses (BLT) (between 20 and 300 µm) are prepared and the thermal resistance is measured for each sample. The relationship between the BLT and the thermal resistance is proportional as shown with equation (2).

The interface thermal resistance is the difference between the y-intercept of the obtained graph (Figure 6, Figure 7) and the thermal resistance of the adherend alone as shown with equation (3), and the thermal conductivity is the slope of the obtained graph (Figure 6, Figure 7). The bulk thermal resistance of the DA material can be calculated from the thermal conductivity as shown with equation (4).

Thermal resistance 8 BLT / thermal conductivity (2)

Interfacial thermal resistance =
y-intercept – thermal resistance of adherend (3)

Bulk thermal resistance =
BLT / (thermal conductivity x surface area) (4)

B. *Measurement Results*

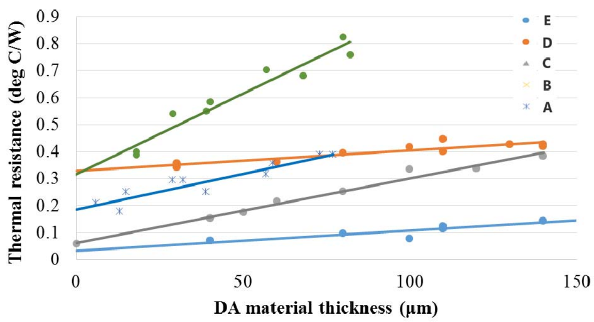


Figure 6. Interfacial thermal resistance measurement results of DA material and adherend Cu

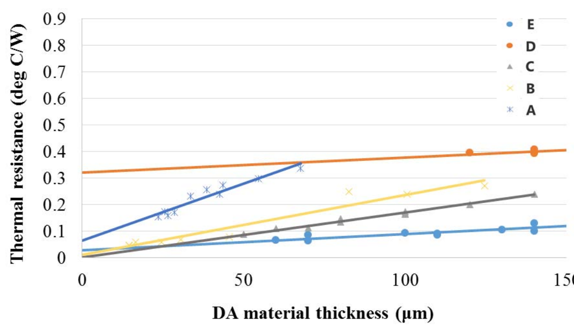


Figure 7. Interfacial thermal resistance measurement results of DA material and adherend Si

The most influential candidate for the DA material evaluated this time is "C," where a total of five levels with different Ag filler contents were prepared based on the measurement results (Table 2). Table 2 shows the thermal resistance measurement results. The higher the Ag filler content, the higher the thermal conductivity. Also, from the thermal conductivity of various DA materials, the bulk thermal resistance at a BLT of 40 µm and a die size of 13.0 x 13.0 mm tends to decrease as the Ag filler content increases. In addition, except for the DA material "E," the interface thermal resistance decreases as the Ag filler content increases. Based on these results, a comparison of the bulk thermal resistance and the interfacial thermal resistance are almost the same, and the interfacial thermal resistance component between the materials is not a negligible value when considering the heat dissipation design of the product.

TABLE II. MEASUREMENT RESULTS OF THERMAL RESISTANCE

No.	DA material	Ag content	Conductivity @DynTim (W/m·K)	Bulk thermal resistance @DA material thickness 40µm (K/W)	Interfacial thermal resistance (K/W)	Total thermal resistance (K/W)
1	A	75wt%	1.2	0.26	0.18	0.44
2	B	76wt%	2.9	0.09	0.10	0.19
3	C	85wt%	4.2	0.06	0.05	0.11
4	D	N.D	10.9	0.02	0.03	0.05
5	E	90wt%	11.0	0.02	0.30	0.32

The reason why the interface thermal resistance of the DA material "E" does not correlate with the Ag content is that the density of Ag on the adherend surface is low. Figure 8 shows the result of the cross-sectional analysis. The DA materials "C" and "E", and "D" which has almost the same thermal conductivity with "E" were compared. It can be observed that the DA material "E" has less Ag in contact with the interface than the DA materials "C" and "D".

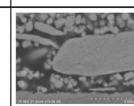
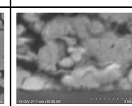
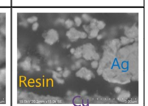
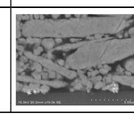
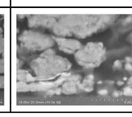
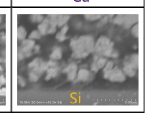
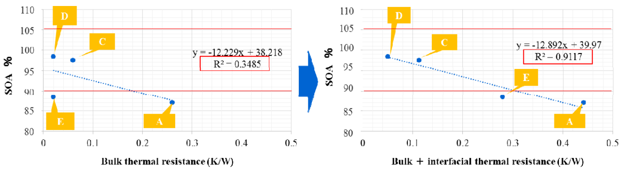
DA material	C	D	E
Thermal conductivity (W/m·K)	4.2	10.9	11.0
Interfacial thermal resistance (K/W)	0.05	0.03	0.30
DA material - Cu (x1500)			
DA material – Si die (x1500)			

Figure 8. Cross section analysis results

C. *DA Material Thermal Resistance and Product Safety Operation Area (SOA) Results*

Figure 9 shows the results of measurement for the safe operating area (SOA) of each DA material with different products. The SOA value indicates the ratio when the value of the solder DA material is 100%. SOA standards for products range from 90% to 105%.

The graph in the left of Figure 9 is the results of graphing the relationship between the bulk thermal resistance and SOA. The graph shows that there is no correlation between the bulk thermal resistance and the SOA. In contrast, the graph on the right shows the result of graphing the relationship between the SOA and the total thermal resistance including the bulk thermal resistance and the interfacial thermal resistance. In this case, it is confirmed that there is a correlation of 90% or more. From these results, it is possible to predict the SOA value of the product by measuring the bulk thermal resistance and the interfacial thermal resistance. Based on above results, the DA material "C" is within the SOA standards and has the same level of heat radiation characteristics as the lead-containing solder. Therefore, it was confirmed that it can be used as a substitute for the lead-based solder DA material.



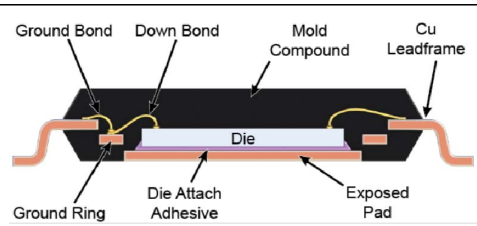
DA material				A	B	C	D	E
BSM				None	None	None	None	None
SOA			(%)	87	N.D.	97	98	88
Thermal resistance	Thermal conductivity		(W/m·K)	1.2	2.9	4.2	10.9	11.0
	Bulk thermal resistance		(K/W)	0.26	0.086	0.06	0.02	0.02
	Interfacial thermal resistance	DA material - Cu	(K/W)	0.15	0.1	0.028	0.015	0.16
		DA material - Si die	(K/W)	0.032	0.0045	0.025	0.015	0.14
	Bulk + interfacial thermal resistance		(K/W)	0.44	0.19	0.11	0.050	0.32

Figure 9. Relationship of SOA and thermal resistance of DA material

V. DA Process Evaluation

The DA process was evaluated using the DA material "C" that satisfies the required thermal characteristics. In this evaluation, DA condition, design and cure condition margin checks were performed to determine the process applicability of the DA material. Table 3 shows the specifications of the packages used in this evaluation.

TABLE III. Specification of the Motif Package for Process Evaluation

PKG type	Thin Heat spreader Quad Flat Pack (THQFP)
PKG cross-section image	
PKG size	14.0 x 14.0 mm
Pin count	100 pins
Die size	8.0 x 8.0 mm
Die thickness	0.29 mm

A. Margin Confirmation for DA Condition

In the DA process, there are various parameters that control DA quality, but the main parameters are DA load and time. DA load is the load applied when the die held by the bond head of the DA equipment is mounted on the lead frame while compressing the DA material. This parameter controls the wettability and BLT. The DA time shows how long the load is applied and is also a main parameter for controlling the workmanship. Therefore, a condition matrix evaluation using these parameters as factors in the design of experiments (DOE) was performed. In addition, as a parameter, it was confirmed whether or not it had the same margin based on that of the conventional material. Table 4 shows the condition matrix. The condition is shown as a ratio to the center condition.

TABLE IV. DOE of DA Condition Evaluation

Load Variance	Time Variance				
	-12.5 (%)	-6.25 (%)	Center	+6.25 (%)	+12.5 (%)
+14.0 (%)	Leg1				Leg8
+7.0 (%)		Leg3		Leg6	
Center			Leg5		
-7.0 (%)		Leg4		Leg7	
+14.0 (%)	Leg2				Leg9

Table 5 shows the results of the DA condition margin evaluation. The evaluation items are the fillet height, the BLT and the wettability area ratio. Wettability area ratio is the ratio of the spread area of the DA material to the die area. The numerical values in the Table 5 indicate the process capability index for the criteria set for various evaluation items. However, for BLT, actual measured values are provided as the reference data because criteria based on thermal characteristics have not been determined.

TABLE V. DA Condition Evaluation Results

Cpk (Min～Max)		Time (s)				
		-12.5%	-6.25%	Center	+6.25%	+12.5%
Load (N)	+14%	① 4.42 2.71 (22.0～29.8)				⑧ 4.89 0.84 (19.3～23.0)
	+7%		③ 3.63 2.32 (20.8～29.8)		⑥ 5.82 1.71 (19.8～24.5)	
	Center			⑤ 6.90 2.05 (21.3～26.8)		
	-7%		④ 3.58 2.22 (20.8～32.5)		⑦ 2.50 2.62 (19.5～25.3)	
	-14%	② 1.84 3.36 (21.8～29.8)				⑨ 3.08 1.35 (20.8～23.8)

The numerical values in the table indicate the process capability of the wettability area ratio is in the upper row, the process capability index of the fillet height is in the middle row, and the average value of the BLT is in the lower row.

Table 5 shows that the process capability index of the fillet height is less than 1.67 under the condition of DA time + 12.5%. However, the swing width under these conditions is confirmed in a range twice as large as the process control range (DA time: center ± 6.25%, load: ± 7.0%), and it is also confirmed that there is a sufficient condition margin. In addition, under the condition of time -12.5%, the process capability index is not less than 1.67, so it is considered that there is a margin on the lower side with respect to the DA time. At this point, it is considered that there is sufficient margin for the conditions.

B. Design Margin Evaluation

In the DA process, the die size is an important factor affecting the workmanship. The wettability area ratio, fillet height and BLT verified by the margin evaluation are greatly affected by the die size. Therefore, in the applicability evaluation of the DA material, it is necessary to verify the die size in view of the target product. Table 6 shows a matrix table of die sizes evaluated in this evaluation. Note that the condition numbers in the Table 6 are serial numbers from Table 5.

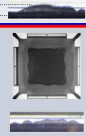
TABLE VI. DOE OF DESIGN EVALUATION

Die Thickness (mm)	Die size (mm)	
	6.00 x 6.00	8.00 x 8.00
0.29	Leg12	Leg5
0.15	Leg11	Leg10

Table.7 shows the results of the design margin evaluation. The evaluation items are the wettability area ratio, the fillet height, and the BLT. The numerical values in the table indicate the process capability index against the criteria of each evaluation item. However, for BLT, actual measured values are provided as reference data because criteria based on thermal characteristics have not been determined.

At a die thickness of 0.15 mm, the process capability indexes of the wettability area ratio and fillet height are less than 1.67. This indicates that the fillet height margin decreases as the die thickness becomes thinner than a certain thickness. However, this does not reduce the fillet height margin. There is a trade-off with keeping the wettability area ratio high, which is another process control item. Therefore, as the die thickness becomes smaller, the margin of the DA process becomes narrower. When the die thickness is 0.29 mm, the process capability index exceeds 1.67 for both 6.0 x 6.0 mm and 8.0 x 8.0 mm die sizes, and it means that there is sufficient process capability.

TABLE VII. DESIGN MARGIN EVALUATION RESULTS

Cpk (Min～Max)		Die size (mm)	
		6.00 x 6.00	8.00 x 8.00
Die thickness (mm)	0.29	⑫ 3.19 1.82 (12.3～16.0) 	⑤ 6.90 2.05 (21.3～26.8) 
	0.15	⑪ -0.27 1.29 (15.0～21.8) 	⑩ -0.45 0.94 (20.3～24.8) 

VI. THERMAL CYCLE TEST

A. Influence on TC due to Differences in DA Workmanship

Most of the heat generated from the Si die is released to the package mounting surface via the DA material and the die pad. In addition, the length and area of the heat transfer material are proportional or inversely proportional to the heat conduction characteristics. In other words, the wettability area and BLT affect the thermal characteristics of the package. Therefore, the workmanship of the DA process (the wettability area ratio and the BLT) was intentionally varied, and after thermal cycle tests, the thermal characteristic data were obtained. Table 8 shows the results of the DA process workmanship data. For Legs 1 to 6, samples in which the wettability area ratio is varied, and for Legs 7 to 9, samples in which the BLT is intentionally varied, were prepared.

TABLE VIII. LEG TABLE OF DA PROCESS WORKMANSHIP

Target value	Leg1	Leg2	Leg3	Leg4	Leg5	Leg6	Leg7	Leg8	Leg9
Wettability [%]	70	80	85	90	95	100	100	90	90
BLT [µm]	20～40	20～40	20～40	20～40	20～40	20～40	15	25	45
Purpose	Influence of wettability						Influence of thickess		

Figure 10 and Figure 11 show graphs of the DA process workmanship data. Figure 10 is a graph of the wettability area ratio, that varies linearly from about 70% to 100%. Similarly, Figure 11 shows that the BLT varies linearly from about 15 µm to 40 µm.

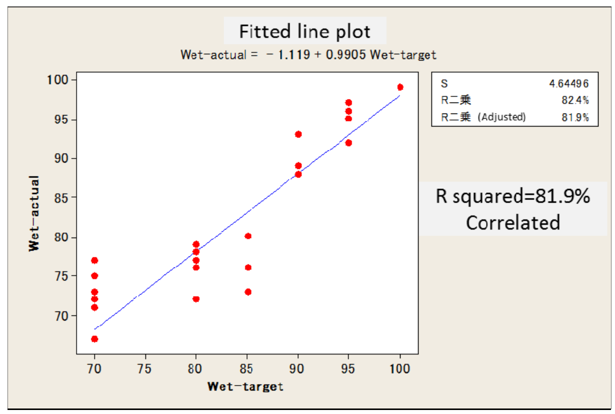


Figure 10. Graph of workmanship for wettability

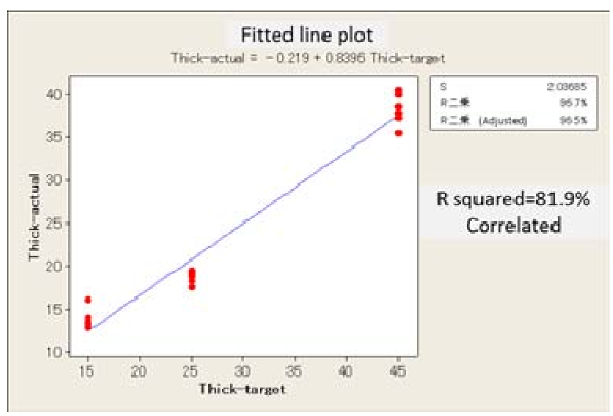


Figure 11. Graph of workmanship for BLT

Next, Figure 12 shows representative photographs of the SAT image for each leg after the Moisture Sensitivity Level (MSL) and the thermal cycle (TC) tests. When the wettability area and the BLT of the DA material are varied within the variation range, no significant delamination occurs or progresses, indicating that the initial adhesion state is maintained.

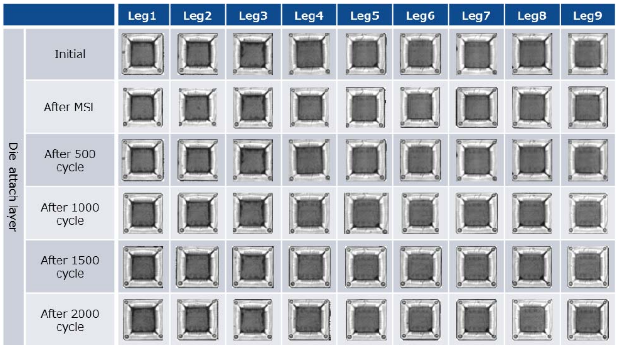


Figure 12. SAT image of after MSL and TC tests from DOE of DA workmanship

B. *Margin Confirmation for Cure Condition and Filler Content*

Delamination of the adhesive layer of the DA material is caused by package stress resulting from the physical properties of the package materials. The physical property value of the DA material is also a factor. As a physical property value of the DA material, the elastic modulus causes stress. In general, the higher the elastic modulus, the lower the stress relaxation, and the higher the risk of peeling off the adhesive layer or causing bulk breakage. Further, the elastic modulus varies depending on the curing conditions of the DA material and the variation in the filling amount of the Ag filler. Table 9 shows the elastic modulus data obtained by intentionally varying the curing conditions and Ag filler content. The results indicate that the elastic modulus increases as both the curing temperature and the Ag filler content increase.

TABLE IX. DIFFERENCE OF ELASTIC MODULUS VALUE BY CURE TEMPERATURE AND AG FILLER CONTENT

	Cure condition		Ag filler Content (%)	Modulus @250 deg C (MPa)
	Cure time (min)	Temperature (deg C)		
Reference	X	Y	Z	4,000
Low temperature	X	Y -25	Z	3,000
High temperature	X	Y+25	Z	6,700
Low Ag content	X	Y	Z-1	4,800
High Ag content	X	Y	Z+1	6,400

Therefore, the curing condition and the Ag filler content were varied within the range in which the usage environment is considered, and the margin is confirmed by the MSL and the thermal cycle tests. Table 10 shows the DOE table for the cure conditions and the Ag filler content.

TABLE X. DOE TABLE FOR CONDITION EVALUATION ASSUMING ELASTIC MODULUS FLUCTUATION

	Leg1	Leg2	Leg3	Leg4	Leg5
Purpose	Ref	Low modulus	High modulus	Low modulus	High modulus
Ag filler content (wt%)	A	A	A	A-1	A+1
Cure temperature (deg C)	B	B-10	B+10	B	B
Cure time (min)	B	B-5	B+35	C	C

Figure 13 shows representative photographs of the SAT images for each leg after the MSL and the thermal cycle tests. When the curing condition and the Ag filler content are varied within the variation range, no significant delamination occurs or progresses, indicating that the initial adhesion state is maintained.

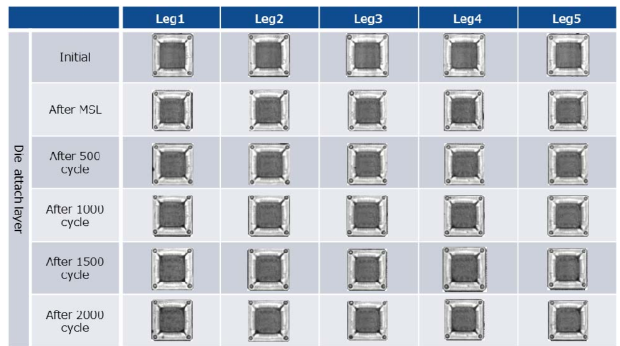


Figure 13. SAT image after MSL and TC tests from DOE of cure condition and Ag filler content

VII. DISCUSSION

Figure 14 and Figure 15 show cross-sectional photographs of the package assembled using the DA material developed for these tests. Effective bonding between the back surface of the Si die without the BSM and the interface between the Cu die pads can be achieved. In addition, a uniform Ag filler layer formed the bulk layer of the DA material. From the above results, a material having relatively low elasticity and stress relaxation has been developed while achieving thermal properties comparable to those of the solder DA material.

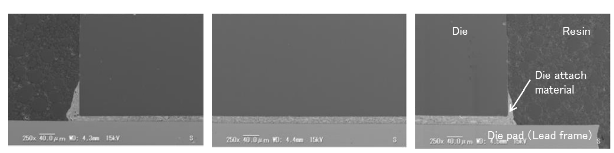


Figure 14. Cross-sectional image of package with new DA material (x250)

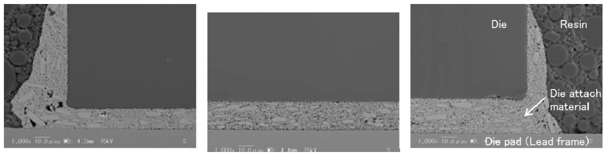


Figure 15. Cross-sectional image of package with new DA material (x1000)

VIII. CONCLUSION

A material with relatively low elasticity and stress relaxation has been developed, which has thermal properties comparable to solder DA materials. The development of this material has demonstrated the possibility of achieving a completely Pb-free package. However, this material is inferior in electrical properties to the solder DA material.

The future challenge is to develop materials that have electrical properties comparable to solder DA materials.

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