

The Interfacial Structure Analysis of Aluminum Nitride Cofire Multi-layer Ceramic Substrate

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Abstract

In the field of semiconductor devices, aluminum nitride (AlN) has been considered as a material for ceramic packages in view of the recent trends in the semiconductor industry toward higher speed, power dissipation and packaging density. A tungsten paste is proposed with SiO₂ glass as the only additive for cofire multi-layer ceramic substrate. If 0.45%wt SiO₂ is added in the paste, the sintering stress is decreased to such degree that it cannot affect the substrate shrinkage. AlN substrate is little porous at interface. AlN grains at interface are no different from those in the bulk. The substrate contains nine levels. The sheet resistance is 10m $\Omega/\square$, substrate warp is less than 50 μ m/50mm and adhesion strength is greater than 30MPa.

Key Word: AlN, cofire, multi-layer ceramic substrate, matching, sheet resistance, adhesion strength.

I . INTRODUCTION

In the field of semiconductor devices, aluminum nitride (AlN) has been considered as a material for ceramic packaging in view of the recent trends in the semiconductor industry toward higher speed, power dissipation and packaging density. This is because of its natural properties. These properties include a high thermal conductivity ($\geq 200\text{W/m}\cdot\text{K}$), a high mechanical strength and a thermal expansion coefficient close to that of silicon. Other electrical characteristics of AlN, such as insulation resistance, dielectric constant and dielectric loss are very close to those of Al₂O₃. These characteristics are suitable for semiconductor packaging that is required to have particularly high reliability.

Thus, AlN substrate is useful for multi-chip module as packaging material and for solid-state power electronic devices^[1].

Multi-layer ceramic substrate is needed in the packaging of multi-chip module. AlN co-fire multi-layer ceramic substrate can be obtained by metalizing green-sheet ceramic bodies. A tungsten or molybdenum paste can be applied because the sintering is performed at 1600~1900°C. W and Mo have very high melting points (3140°C and 2610°C respectively) and paste could not be sintered if it has only either one of them. Such pastes would have very poor adhesion strength to AlN substrate and high variable sheet resistance. Additives, such as AlN powder and metal oxides are used in W or Mo pastes

recently^[2,3]. Otherwise, some of metal elements are also used as additives^[4]. These additives can promote adhesion strength between AlN sheets and conductor pastes. But those pastes have high sheet resistance and are not useful in practice.

Low sheet resistance and good matching between substrate and paste are the principal requirements for conductor paste in multi-layer cofire substrate. In the process of sintering, sintering stress occurs at the interface between conductor paste and green-sheet ceramic body if shrinkage ratios are different on the two sides of the interface. The stress states cause bad matching, increase sheet resistance, curl over substrate and cause substrate damage. In order to overcome these defects, we need to start their sintering at same temperature and to ensure conductor paste and green-sheet ceramic bodies have the same shrinkage rate. Furthermore, adhesion strength is promoted greatly if green-sheets react with those additives in conductor paste.

In this sense, SiO₂ is a good additive. SiO₂ is used as a component in many kinds of pastes. The softening point of pure SiO₂ glass is at about 1600°C, the same temperature at which AlN green-sheet ceramic bodies start shrinkage. SiO₂ can react with AlN and form sialon glass. In this paper, a tungsten paste is proposed with SiO₂ glass as the only additive.

II. EXPERIMENTAL PROCEDURE

AlN is 98% in purity and 2μm in grain size. Y₂O₃ and CaO are sintering aids, whose concentrations are 4.0%wt and 2.0%wt respectively. AlN powder is mixed with these aids in ball mill for 24 hours. The slurry composed of AlN powder with sintering aids, organic binders and vehicles is cast into green sheet by a conventional doctor blade technique. W is 1.7μm in grain size. SiO₂ is 18μm in grain size. The paste is mixed with W powder and SiO₂ powder in proportion. The tungsten conductor paste is applied onto the punched sheet by screen-printing. The metalized sheets are laminated and heated to burn-out the

organic components, and sintered at 1800°C for 4 hours in N₂ ambient.

The microstructure was observed by SEM (scanning electron microscope) (Philip XL-30). Study was performed on the EPMA (Electron probe micro-analysis) (DX-4). The sheet resistance of the W conductor is examined using a four-probe resistivity detector. The adhesion strength is measured by nailhead pull test of pins soldered onto 2mm square pads with Au/Ni/Cr plated.

III. RESULT AND DISCUSSION

A. The Reaction between the Paste and AlN Substrate

1.1 Crystal phase formation

It is at 1600°C that AlN begins shrinkage evidently. CaO reacts with aluminum oxide on the AlN grain surface and generates calcium aluminate. Y₂O₃ reacts with aluminum oxide on the AlN grain surface and generates yttrium aluminate as shown in fig. 1^[5].

YAIO and CaAlO complex oxides have low melting point compare to the soaking temperature of AlN sintering. YAIO and CaAlO complex oxides become liquid phase in the process of sintering.

WO₃ on the W grain surface is detected by XRD even if part of it vaporizes during sintering stage^[6].

CaO can react with SiO₂ and Al₂O₃, Y₂O₃ reacts with SiO₂, forming new crystal phases as shown in fig. 1.

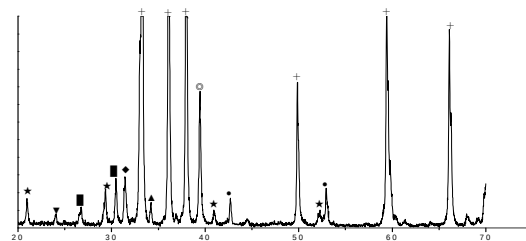


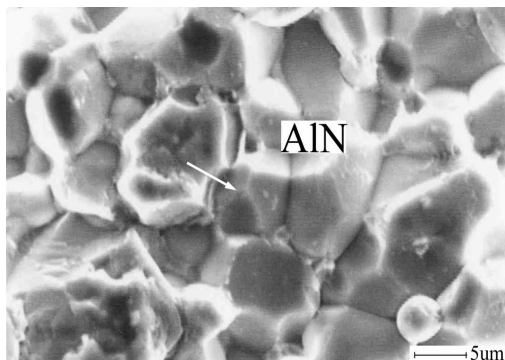
fig 1 XRD pattern of interfacial reaction between AlN and conductive paste (+) AlN; (⊙) W; (★) Y₂Si₂O₇; (●) Y₂SiO₅; (◆) Ca₂Al₂SiO₇; (▼) WO₃; (▲) Y₃Al₅O₁₂; (■) Ca₅Al₆O₁₄

1.2 Glass formation

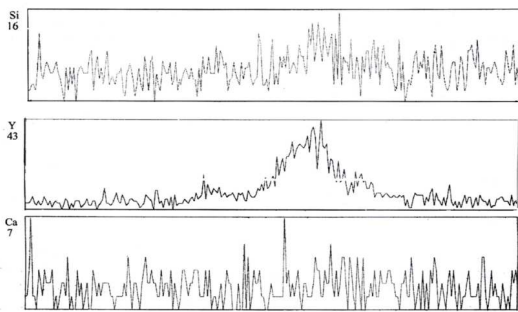
Liquid phase YAIO and CaAlO can diffuse onto AlN bodies' surface if AlN that contains a little of carbon is sintered in the ambient of N₂. Thus, This

liquid phase can diffuse into paste, too. The SiO_2 in conductor paste also diffuse into AlN substrate. Y_2O_3 reacts with SiO_2 and AlN, the resulting ysialon glass that forms at the interface between AlN grains is detected by EPMA. CaO reacts with SiO_2 and AlN, the resulting casialon glass that coats on AlN grains are also detected by EPMA as shown in fig. 2. The mixture of these glasses is shown in fig. 3. An arrow that is shown in fig. 2(a) is the path and direction of EPMA. The result is shown in fig. 2(b). These glasses are also detected in the paste. It is considered the capillarity because of the porosity of W paste^[5].

We see as in fig. 2(b), if the concentration of SiO_2 in the paste is low, it does not significantly affect the distribution of Y and Ca elements in the AlN substrate^[7].



(a)



(b)

fig. 2 The distribution of the glass between AlN grains if 2.0%wt SiO_2 is added in the paste

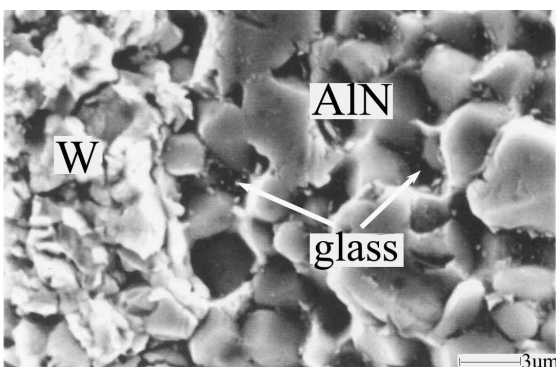


Fig. 3 Microstructure of AlN substrate and paste with 6.0%wt SiO_2 concentration

B. The Influence of SiO_2 Concentration

2.1 Sheet resistance

SiO_2 starts sintering at its soft point as 1600°C . Its stiffness decreases as temperature increases. W powders are wet by SiO_2 . The paste and AlN green-sheet ceramic bodies begin their shrinkage at the same temperature.

If the SiO_2 concentration is 0.05%wt in the paste, it cannot wet W powders completely. There is much porosity between W powders. Such porosity increase sheet resistance by decreasing section plane of the paste as demonstrated in table 1.

If the SiO_2 concentration is 2.0%wt in the paste, it can wet W powders in excessively. There are more glass filling among W powders than wanted and sheet resistance increases.

It is shown that sheet resistance is $10\text{m}\Omega/\square$ if 0.45%wt SiO_2 is added in the paste.

2.2 Matching

In the process of co-fire sintering, sintering stress occurs at their interface if shrinkage ratio of the conductor paste is different from that of ceramic body. Stress states are different in two stages: In the sintering stage, in-plane stresses are developed in W film which leads to high porosity, reduction of sintering rate and separation of paste from AlN ceramics; In the soaking stage, radial stresses are developed in AlN near the AlN/W interface, which reduce the shrinkage rate and density of AlN ceramic^[8].

The matching of co-fire ceramic substrate can be satisfied if W conductor paste and AlN green-sheets start their sintering at same temperature and during the process, conductor paste and ceramic bodies have the same shrinkage rates. SiO_2 starts to sintering at its soft point of 1600°C . The paste and AlN ceramic bodies begin their shrinkage at the same temperature. Thus

shrinkage rate is the main problem for matching in the sintering process.

It is at 1600°C that AlN begins shrinkage evidently. YAlO and CaAlO complex oxides become liquid phase in the process of sintering. This liquid phase wet and drag AlN grains close, which forms AlN substrate in the end.

This liquid phase can diffuse onto AlN bodies' surface if AlN that contains a little of carbon is sintered in the ambient of N₂. Thus, This liquid phase can diffuse into paste, too. The SiO₂ in conductor paste also diffuses into AlN substrate and promotes adhesion strength. Mismatching would occur if the amount of SiO₂ that diffuse into one and the other were not equal. The amount of SiO₂ that diffuses into AlN must be limited because the ceramic will continue its shrinkage in the soaking stage before it becomes solid^[8].

If the SiO₂ concentration is 0.05%wt in the paste, it cannot wet W powders completely since the amount of SiO₂ that diffuses into AlN is too small. There is much porosity in W powders even after sintering. The tungsten paste is shrinkage for AlN green-sheet bodies. Those porous between AlN grains at interface are no different from those in the bulk as shown in Fig. 4.

If the concentration of SiO₂ glass is greater than 1.0%wt in the paste, a great amount of SiO₂ diffuses into the green-sheets and mismatch occurs. Fig. 5 exhibits that conductor paste is divorced from AlN substrate.

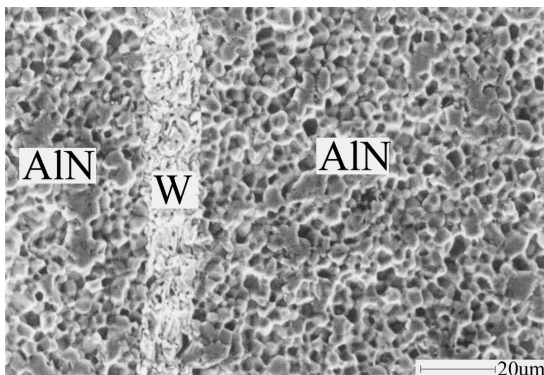


Fig. 4 Micrographs of AlN grains at interface and those in the bulk if 0.45%wt SiO₂ concentration is added in the paste

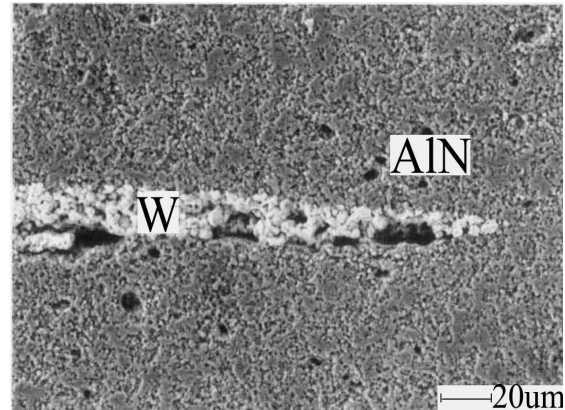


Fig. 5 Conductor paste is divorced from AlN substrate if 2.0%wt SiO₂ concentration is added in the paste

It is shown that AlN cofire substrate is matching if SiO₂ concentration changes from 0.05%wt to 0.6%wt in the paste.

2.3 Adhesion strength

Conductor paste adheres on the substrate via mechanical interlocking and chemical reaction. Adhesion strength can be promoted greatly if green-sheets react with those additives in conductor paste in the process of sintering.

Au/Ni/Cr films are plated on the pad before adhesion test. If the concentration of SiO₂ glass is 0.05%wt in the paste, the adhesion strength decreases as shown in table 1. In fig. 6, the pad that adhesion test has been done reveals that the break occurs in the paste, instead of occurring at the interface between paste and AlN substrate or the interface between paste and plated film.

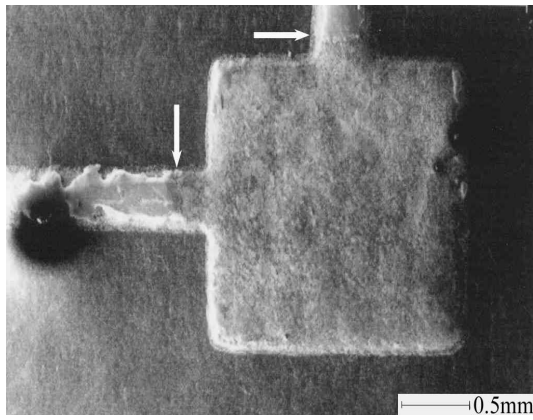


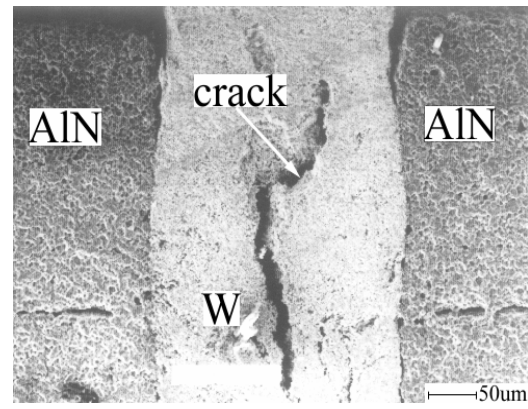
Fig. 6 Adhesion strength test reveals that the break occurs in the paste with 0.05%wt SiO_2 concentration

If the SiO_2 concentration is more than 10.0%wt in the paste, ysalon glass floats on the surface of the paste and can be detected by SEM and EPMA. The adhesion strength decreases as shown in table 1. The pad that adhesion test has been done reveals that the break occurs on the surface of the paste where ysalon and casialon glass is detected.

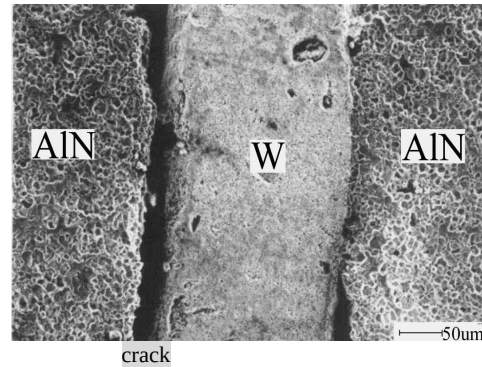
2.4 Via hole

The temperature expansion coefficient (TCE) of W and AlN is $4.6 \times 10^{-6}/^\circ\text{C}$. That is to say if the paste fills holes completely in the soaking stage, it can fill via holes completely as it cool down to room temperature. Different organic binders and vehicles are cast into tungsten conductor paste or AlN green-sheet bodies, which introduce different shrinkage quotients in the soaking stage. This causes cracks between substrate and paste in via holes.

If the SiO_2 concentration is 0.05%wt in the paste, it is bad fluidity and cannot fill via hole completely in the soaking stage. The adhesion strength between W powders decreases so much that cannot drag them together. There are cracks through pillar at via hole as shown in fig. 7(a). If the SiO_2 concentration is 0.15%wt in the paste, there are cracks between substrate and pillar at via holes as shown in fig. 7(b). In both of the above situations, there is much porosity occurs between W powders in the paste after sintering.



(a)



(b)

fig. 7 (a) Crack occurs through pillar at via hole as 0.05%wt SiO_2 concentration is added in the paste; (b) Crack occurs at via hole as 0.15%wt SiO_2 concentration is added in the paste

If the SiO_2 concentration is 2.0%wt in the paste, it has good fluidity and fills via hole completely in the soaking stage. But resistance increases if more SiO_2 glass is added. At the range of 0.45~0.7%wt of SiO_2 , it attains low resistance and there are few cracks in via holes.

Table 1 The value of Sheet resistance, Warp and Adhesion Strength according to SiO_2 concentration in the paste

SiO_2 concentration (%wt)	Sheet resistance ($\text{m}\Omega/\text{mm}^2$)	Warp ($\text{mm}/50\text{mm}$)	Adhesion Strength (MPa)
0.05	16	<0.05	19
0.25	13	<0.05	23
0.35	11	<0.05	27
0.45	10	<0.05	33
0.55	12	~0.05	37
0.7	17	0.1	41
1.0	25	0.75	55
2.0	40	3.47	58
6.0	108	10.4	63
10.0	167	14.7	42

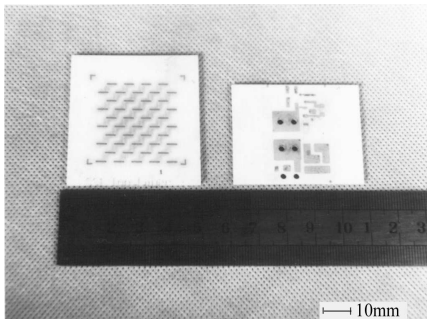


Fig. 8 AlN cofire multilayer ceramic substrates

Fig. 8 is for AlN cofire multilayer ceramic substrates. The left is a prototype with nine levels. The right is a substrate with four levels for DC/DC converter.

IV. CONCLUSION

The composition of conductor paste can affect the sintering for AlN co-fire multi-layer ceramic substrate. A tungsten paste is proposed with SiO_2 glass as the only additive for co-fire multi-layer ceramic substrate. We discussed the electro and mechanical characteristics of this co-fire ceramic substrate. SiO_2

reacts with CaO , Al_2O_3 and Y_2O_3 , producing CaSiAlO and YSiO phases which are detected at the interface between conductor paste and AlN substrate. Ysialon and casialon glasses also form at the interface. These chemical reactions increase the adhesion strength between the paste and substrate.

If 0.45%wt SiO_2 is added in the paste, the tungsten paste has low sheet resistance and matching shrinkage of AlN green-sheet bodies. At this concentration of SiO_2 in the paste, AlN substrate is little porous at interface. AlN grains at interface are no different from those in the bulk. The sintering stress is decreased to the degree that cannot influence the substrate shrinkage. The AlN substrate contains nine levels. The sheet resistance is $10\text{m}\Omega/\square$, substrate warp is smaller than $50\mu\text{m}/50\text{mm}$ and adhesion strength is greater than 30MPa .

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Note:

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