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High Thermal Conductivity AlN Substrate and Its Metallized Products*

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1 Introduction

As the demand increases for high speed, compact size, light weight and high reliability in electronic equipment, progress in producing semiconductor elements with larger size, higher integration and higher output is apparent. Accordingly, substrates on which semiconductor elements are to be mounted have also diversified. Aluminum nitride (AlN) ceramics show thermal conductivity about 10 times higher than that of alumina and have a thermal expansion coefficient similar to that of silicon (Si). AlN has attracted attention as a substrate material that can cope with the increased heat output resulting from high integration and high power output of the elements, as well as the increased mismatching of thermal expansion between Si and the substrate due to the increased size of elements. Furthermore, the practical use of AlN as a new ceramic substrate is also rapidly progressing, because it has other electrical and mechanical properties required for substrates which are equal or superior to those of alumina. Other ceramics of similarly high thermal conductivity have problems; for instance, beryllia (BeO) has strong toxicity, and silicon carbide (SiC) has a low breakdown voltage and large dielectric constant, so that they both have very limited use as a substrate compared with AlN.

Under such circumstances, Kawasaki Steel Corp. has strengthened its capability for manufacturing AlN substrates and their metallized products, has established the manufacturing process for mass production, and is proceeding with product development to match market needs.

2 AlN Bare Substrate

2.1 Manufacturing Method

AlN substrate is manufactured, like an alumina substrate, by being formed according to the doctor blade (continuous forming) method, before dewaxing and sintering under normal pressure. However, the kind of organic binder, and dewaxing and sintering methods used for an alumina substrate cannot be applied to the AlN type. Consequently, Kawasaki Steel has developed the required techniques for mass producing the AlN substrate.

2.2 Achieving High Thermal Conductivity

In order to obtain an AlN sintered body with high thermal conductivity, controlling the micro-texture and micro-structure is necessary by decreasing intragranular solid solute oxygen, grain boundary precipitates, pores, and voids. An AlN sintered body with high oxygen content develops an increased phonon scattering due to solid solute oxygen in the crystal lattice and a reduction in thermal conductivity. To obtain high thermal conductivity of the AlN sintered body, the following measures have been taken:

(1) Using a manufacturing process which permits as little oxygen pickup as possible.

(2) Retaining the oxygen necessary for liquid-phase sintering until densification has been completed, and selecting the optimum type and amount of sintering aids for decreasing intragranular oxygen.

Photo 1 shows an SEM micrograph of Kawasaki Steel's AlN substrate. This indicates practically the same size for all grains, no pores and a thin, uniform distribution in the grain boundary phase.

2.3 Characteristics of the AlN Substrate

Table 1 shows the properties of the AlN substrate developed by Kawasaki Steel for mass production. The substrate comes in two types, one with high thermal conductivity (H) and the ordinary type (R). The as-fired surfaces of both substrates are smooth and flat. Furthermore, the manufacture of a large-scale substrate (8″

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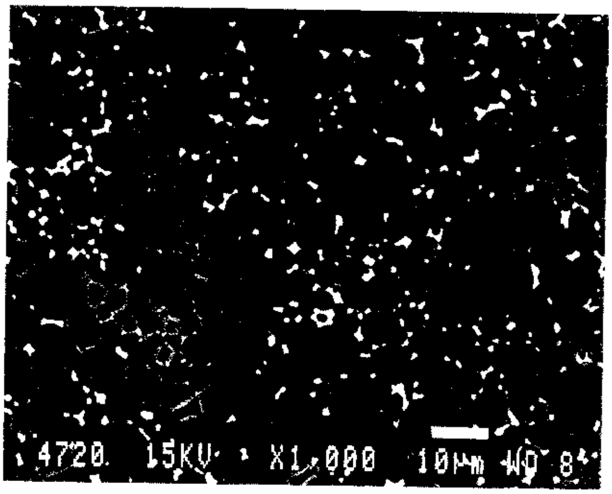

Photo 1 SEM micrograph of AlN (thermal conductivity 180 W/m · K)

Table 1 Properties of developed AlN substrate

Items	Properties	
	R grade	H grade
Thermal conductivity (W/m·K)	180	200
Electrical resistivity at RT (Ω·cm)	$>10^{14}$	$>10^{14}$
Thermal expansion coefficient (RT～200°C) (K^{-1})	3.9×10^{-6}	3.9×10^{-6}
Dielectric constant (at 1 MHz)	4.9×10^{-6}	4.9×10^{-6}
Dielectric loss at 1 MHz ($\tan\delta$)	8.9	8.9
Breakdown voltage (kV/mm)	>30	>30
Density (g/mm^3)	3.30	3.30
Modulus of rupture (kg/mm^2)	35	35
Surface roughness R_a (μm)	<0.5	<0.6
Warping (mm)	<0.1/50 mm	<0.1/50 mm

square) and a substrate with through-holes slits is possible. To achieve this, various ingenious measures have been taken in the forming, dewaxing and firing processes.

3 Types of Metallized Substrates

Metallizing methods for AlN substrates include, like those for alumina substrates, the thick-film printing method, copper sheet bonding method, refractory metallization method, and thin-film forming method (physical vapor deposition or plating). Compared with other types of substrates, developing the metallizing techniques for the AlN substrate has been delayed; hence, the practical use of AlN substrates is later than was originally foreseen. However, progress in these metallizing techniques has enabled the practical use of the AlN substrate, in particular for power modules, to develop rapidly. Kawasaki Steel has perfected these metallizing techniques and is proceeding with the commercialization of metallized AlN substrates.

3.1 Copper-Bonded Substrate

The Kawasaki Steel copper-bonded AlN substrate is manufactured by bonding with an Ag-Cu brazing material to which active metal is added. The major properties of this product are shown in **Table 2**. As the bare substrate, an AlN type with high thermal conductivity and high strength made by Kawasaki Steel has been used, and the development of the ideal brazing material composition and its manufacturing process has realized high heat radiation, high electric insulation, high bonding strength, and outstanding wire bonding ability.

The market for the copper-bonded substrate is rapidly expanding, particularly for power transistor modules and insulated gate bipolar transistor (IGBT) modules.

Table 2 Characteristics of Cu-bonded AlN substrate

Number of thermal cycling without cracking (−65～+150°C)		100～300
Thermal shock resistance (RT～400°C)		>5 cycle
Circuit pattern	Cu thickness	max 0.3 mm
	Width of Cu pattern	min 0.5 mm
	Gap in Cu pattern	min 0.5 mm
	Allowance	±0.25 mm
Eelectrical properties	Cu electrical resistivity	<2.0 μΩ·mm
	Electrical resistivity (DC 500 V)	$>1\times10^{11}$ Ω
	Breakdown voltage	>1.7 kV/mm
	Humidity resistance	85°C, 85%RH
Peeling strength		>49 Pa/m (5 kgf/cm)
Thermal expansion coeffiecient of Cu (300°C)		7.6×10^{-6}/°C
Solderability		>95%
Warping		<0.1/50 mm

3.2 Thick-Film-Printed Substrate

The paste system for a thick-film hybrid IC using an alumina substrate has nearly reached perfection, but such a system for AlN with satisfactory properties has not yet been developed. Kawasaki Steel has jointly developed with a paste maker the Ag-Pd-based conductive

Table 3 Characteristics of thick film conductor and resistor fired on AlN substrate

Conductor	Firing condition (in air)	800～900°C × 10 min
	Sheet resistivity	180 m$\Omega/\square$
	Sheet wet	>98%
	Solder leach	260°C, 60 Sn/40 Pb, 10 s × 4 cycle
	Adhesion strength	
	Initial	3.7 ± 0.8 kgf/4 mm^2
	After aging (48 h)	2.2 ± 0.6 kgf/4 mm^2
	After aging (300 h)	2.5 ± 0.7 kgf/4 mm^2
Resistor	Firing condition (in air)	850°C × min
	Sheet resistivity	10, 100, 1 000, 10 000 ($\Omega/\square$)
	TCR*1)	
	100, 1 000 ($\Omega/\square$)	< ±100 ppm/°C
	10, 10 000 ($\Omega/\square$)	< ±200 ppm/°C

*1) Temperature coefficient of resistivity

paste shown in **Table 3**, and has good prospects for developing a conductor of even lower resistance. For the resistive paste, one already marketed that conforms well with the above-mentioned conductor can be used within a range of 10 Ω to 10 k$\Omega/\square$. The Kawasaki Steel AlN substrate is not only very compatible with these paste systems, but is particularly suitable for hybrid IC use because its as-fired surface is smooth and flat. The application of this AlN substrate to hybrid ICs has begun for high-frequency use, and its application to high-frequency dummy loads and many other products is being examined.

3.3 Other Metallized Products

Besides the above-mentioned copper-bonded and thick-film printed AlN substrates, Kawasaki Steel has developed a W-metallized substrate by the thick-film printing method, as well as Cu, Au, and other thin-film metallized substrates by the plating method, thereby being able to respond to diverse market needs.

4 AlN Products with Complicated Shapes and Heaters

4.1 Products with Complicated Shapes

AlN substrates with a thickness of about 1 mm or less can be manufactured by the aforementioned doctor blade method. However, in order to respond to market demands for special shapes, Kawasaki Steel is manufacturing AlN products in different shapes by using various molding methods. Manufacture of products with complicated shapes is made possible not only by the molding methods used, but also by applying raw material processing and firing methods most suitable for their respective manufacture.

For press forming, Kawasaki Steel uses uniaxial pressing and cold isostatic pressing (CIP), and forming up to a maximum size of 300 mm square is possible. By extrusion molding, it is possible to produce a long product with a constant cross section like a pipe. By casting and injection molding, pipes, bobbins, crucibles, and other products with complicated shapes can be manufactured.

4.2 Heaters

Kawasaki Steel has developed ceramic heaters, using an AlN ceramic insulator, which has high thermal conductivity and thermal shock resistance. For the heating element, metallic foil, thick film printed patterns, and resistive windings are used depending upon the purpose. The heaters can be produced in plate, pipe, ring, and various other shapes.

A comparison between the heating characteristics of the AlN heater and a conventional alumina heater is shown in **Fig. 1**. The alumina heater developed thermal stress fracture with a 60 W load, whereas the AlN heater will not break down even with a 120 W load. In addition, it can be seen that the time needed under a low load (15 W) for the AlN heater to reach the required surface temperature is very short. **Figure 2** shows the surface temperature variation in heaters operating at various temperatures. The maximum temperature difference across the surface at 500°C is 25°C for the AlN heater, with a much larger value of 83°C for the alumina heater.

The features of the AlN heater can be summarized as follows:

(1) Rapid heating and cooling are possible, because of

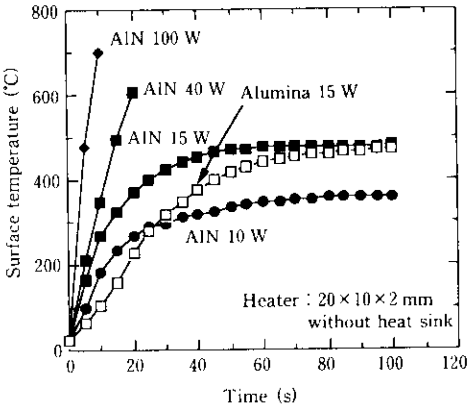

Fig. 1 Surface temperature changes of AlN heater under different loads

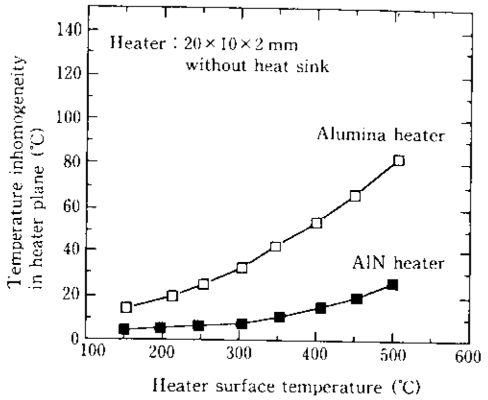

Fig. 2 Changes of temperature inhomogeneity in a heater plane

its high thermal shock resistance.

(2) Preheating the heater is unnecessary, because rapid heating is possible.

(3) A compact size and light weight can be achieved, because a high electric power density can be applied to the AlN heater.

(4) The conventional heat-equalizing plate is unnecessary, because the AlN ceramic material itself acts as a heat equalizer.

5 Concluding Remarks

AlN sintered ceramic and its various metallized products developed by Kawasaki Steel have high thermal conductivity and other excellent characteristics suited for those of IC substrates and ceramic heaters, and are steadily expanding their applications centering around the electronics field.

In the future, the authors intend to achieve quality improvements such as even higher thermal conductivity and enhanced reliability, and to offer a more diverse line-up of metallized products to match market needs. This will enable AlN to be applied in fields that are impossible with such conventional materials as alumina.

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