Advanced Materials & Powders Handbook

Aluminium Nitride (AlN)

The existence of AlN was discovered in 1862 by F. Briegler and A. Geuther and the first synthesis was realized by J.W. Mallets in 1877. For more than a hundred years AlN was merely of academic interest for its chemistry. AlN ceramic technology evolved quickly since 1984 but the products in the beginning are best described as inconsistent. This was due to poor-quality powders and inexperience with commercial-scale fabrication technologies. Materials, both powders and parts, were poorly characterized. Thus, results were often not reproducible, particularly in the metallization of substrates. During the period 1985-88, the following concerns arose about the use of AlN in microelectronic packaging: oxidative stability, hydrolytic stability, surface finish/chemistry, metallization paste systems, cofiring and brazing, thermal conductivity, cost. High-Quality AlN substrates and packaging emerged in the early 1990s. The consistency of AlN products has increased dramatically and processing technologies have been developed to the point that AlN ceramics are now in use worldwide in commercial packages. Metallization systems as consistent and strong as the oxide metallization systems have been developed for nitrides. In addition, co-fired, multilayer AlN packaging has been developed and offers an alternative for power applications. More than 20 companies worldwide are developing AlN technology.

In comparison to other electrically insulating ceramic materials only AlN and beryllium oxide (BeO) offer high thermal conductivities. BeO shows higher values than AlN but has been banned by numerous manufacturers because of its toxicity. Thus, the nontoxic AlN continues to replace BeO for most applications.

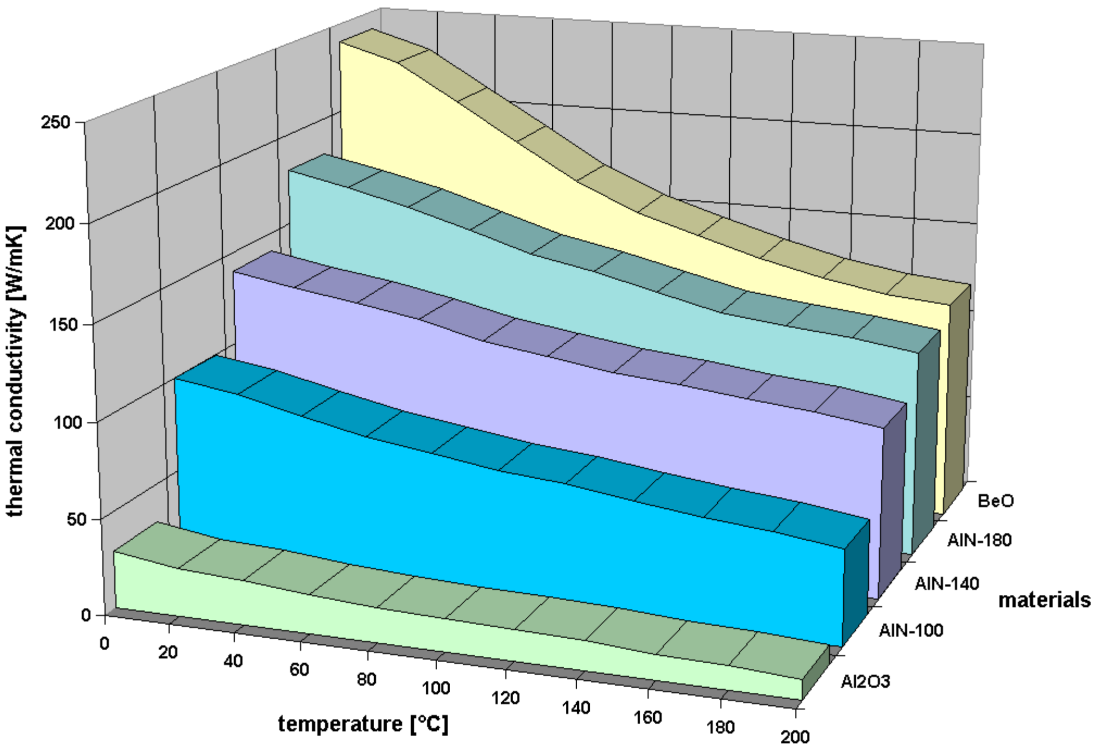

Fig. 1: Thermal conductivity of different AlN qualities and other ceramic materials

Aluminium Nitride (AlN)

AlN is the only stable compound in the binary system Al - N and exists in only one crystal structure (wurtzite, hexagonal). Pure AlN has a density of 3.26 g/cm^3 and dissociates under atmospheric pressure above 2500 °C. Pure AlN is colorless and translucent but is easily colored by dopants or impurities. Thus, carbon impurities cause the typical light gray color of AlN powder. AlN powder is susceptible to hydrolysis by water and humidity. This is the reason for its characteristic ammonia smell.

Because AlN is a covalent compound, limited atomic mobility prevents complete densification of pure AlN. Thus, relatively high pressures or sintering aids are required to assist densification. Typical sintering additives are rare-earth or alkaline-earth oxides. To achieve high thermal conductivities mostly yttrium compounds are used. The formation and microstructural distribution of yttrium aluminium garnet controls both densification and thermal properties. The sintering temperatures highly depend on the additives and range from 1600 to 1900 °C.

Aluminium Nitride	**AlN 140**	**AlN 180**
r $_{th}$ Density (theoretical) (g/cm^3)	3,26	3,32
r $_{m}$ Density (as measured) (g/cm^3)	3,24	3,31
s $_{B}$ Flexural strength (MPa)	350	> 300
s $_{D}$ Compressive strength (GPa)	2,1	> 2,0
K_{IC} Fracture toughness (MPa m$^{1/2}$)	3,35 ± 0,2	3,35 ± 0,2
E Young's modulus (GPa)	310	310
l Thermal conductivity (W/mK)	140 ± 10	180 ± 10
a Coeff. of thermal expansion (10^{-6} K^{-1}) RT - 100 °C RT - 300 °C RT - 500 °C RT - 1000 °C	 3,6 4,6 5,2 5,6	 3,6 4,6 5,2 5,6
c_P Specific heat (J/kgK)	738 ± 20	738 ± 20
Volume resistivity (W cm)	> 10^{12}	> 5 x 10^{12}

Aluminium Nitride	AlN 140	AlN 180
Dielelectric strength (kV/mm)	³ 25	> 20
e $_r$ Dielectric constant (at 1 Mhz)	8,6	8,6
tan d Loss tangent (at 1 MHz)	0,5 x 10^{-3}	0,5 x 10^{-3}
Resistance to thermal shock	excellent	excellent
a - radiation (Imp/cm^{2}h)	£ 0,07	
a + b - radiation (Imp/cm^{2}h)	£ 0,5	

Table 1: Physical properties of two standard AlN-ceramics

AlN exhibits a very good resistance to a wide variety of materials. It is wet by molten Al but does not react with it. Most metals, including Cu, Li, U, ferrous alloys and some superalloys do not attack AlN. AlN is also stable against molten salts, such as carbonates, eutectic mixtures, chlorides and cryolite.

Corrosion studies showed that acids attack the secondary phases in the grain boundaries whereas strong alkaline media dissolve the AlN base material. AlN withstands distilled water and sea water and is stable in a pH-range from 3 to 11. Yttria containing samples revealed a better corrosion resistance in acids than AlN with calcia additions.

Contrary to expectations in the early 1990s the use of AlN ceramics has been restricted to a few products only. AlN ceramic has always been compared with alumina, the typical ceramic package material. Today, the consumption of AlN ceramic packages are affected by their ratio of performance and reliability and cost. Although the price of AlN ceramic packages has decreased over the past few years the cost reduction is generally considered to still be inadequate. Advantages of material characteristics do not compensate for the cost differential in the current cost-oriented climate. The lack of a world-scale AlN powder plant kept AlN raw material prices high, while the lack of a large market has precluded the construction of a world-scale plant. There is only a small number of companies which can produce AlN powder in larger volumes and there have been quite some changes in the list of suppliers over the past 10 years. Currently the main vendors for AlN powders are: Advanced Refractory Technologies Inc. (USA); H.C. Starck and Elf Atochem (Europe); Toyo Aluminium and Tokuyama Soda (Japan).

The development of high thermal conductivity AlN was pioneered in Japan. Thus, it is not surprising that the largest vendors of powders, substrates and packages are headquartered in Japan. Two primary routes are employed in the production of AlN powders: carbothermal reduction and direct nitridation. With few exceptions, most AlN substrates and packages are manufactured using carbothermal powder. Japanese companies such as Toshiba, Tokuyama Soda, Kyocera, Sumitomo Electric Industries, and Maruwa supply AlN substrates and packages. North American vendors include Carborundum and Coors. In Europe CeramTec and ANCeram have introduced AlN substrates. In Europe the market for AlN parts seems to be developmental, whereas the demand for AlN in the United States has been driven primarily by military applications.

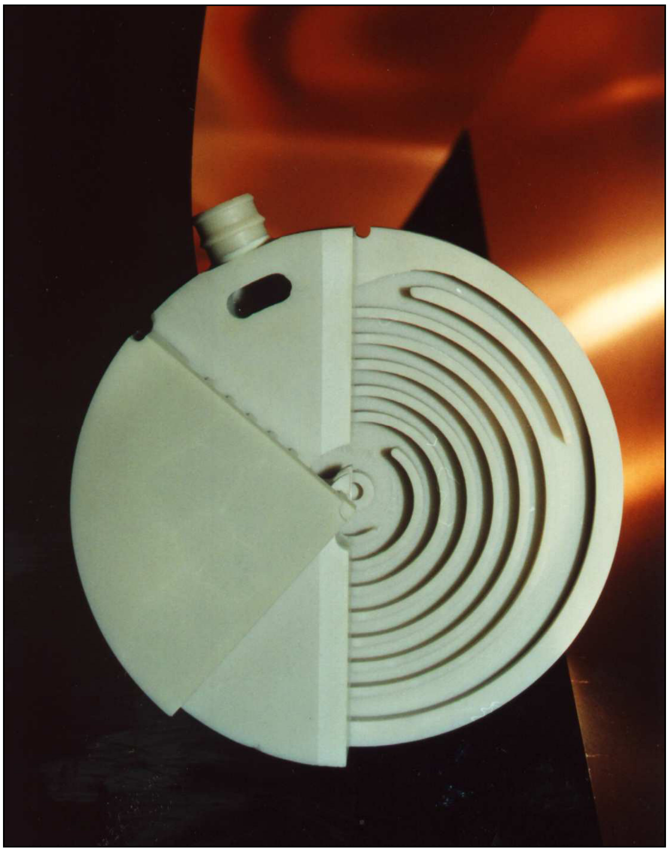

Fig. 2: Circular Aluminium Nitride cooler

AlN AMB (Active Metal Brazing) substrates have now become a cost-effective and reliable alternative to conventional assembly techniques, in particular for laser diode substrates. They can be used instead of classical substrate alternatives, such as high-cost diamond or SiC heat-sinks, and replace metallized Al_2O_3 substrates manufactured using the costly MoMn process.

AlN is the preferred choice for substrates, packages and heat-sinks or coolers, whenever the thermo-mechanical properties or power dissipation capabilities of conventional aluminum oxide materials are insufficient. Typical examples are highly integrated thick-film and thin-film components, water-cooled power converters in rail transport systems, and transmitter and HF diode substrates subjected to thermal cycling in satellite systems.

Conventional metallizing processes for AlN have in recent years been developed to the extent that they are now being increasingly used for volume production. For power electronics in particular, conducting lines able to carry high currents are essential. Copper combines the required low electrical resistance with exceptionally high thermal conductivity.

In summary aluminium nitride components and substrates are used momentarily for various applications:

- power electronics (electrical engines)
- micro electronics (LSI circuits, sensor carriers, high frequency modules)
- naval radio systems, defense systems
- railway systems (inverters for drive systems)

- aeronautical systems (telecommunication and research satellites)
- environmental systems (emission control)

The current world market for AlN powder is estimated to be about 200 t per year. The price of AlN powder ranges between 20 and 180 $/kg. 75 % is consumed within the Japanese market, the remainder shared by the U.S. and European markets. This totals to ca. 250 Million $ for the manufactured AlN end products worldwide. The AlN-market has been growing steadily over the past few years. However, the predicted boom is yet to come.