Heat Dissipating Transmission Lines

Aluminum nitride (AlN) is an attractive substrate material for microwave packages because of its high thermal conductivity and low loss dielectric property. However, what was not well known was how the behavior of AlN might change with moisture. The chemical reactions with water are described in this paper.

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Aluminum nitride (AlN) is an attractive substrate material for microwave packages because of its high thermal conductivity and low loss dielectric property. The thermal conductivity of AlN is 160-225 W/mK[1], over five times that of the more commonly used alumina (Al2O3) at 28 W/mK or LTCC material at 2.8 W/mK. Furthermore, AlN is a low loss dielectric with a dielectric loss tangent of only 0.003 at 10 GHz. However, what was not well known was how the behavior of AlN might change with moisture. The possible chemical reactions with water are described later with the test data.

For this reason we conducted a study to determine the electrical (insertion loss) and environmental performance (water reactivity) of Aluminum Nitride. The study used material from several vendors to determine the general maturity of the material processes, the impact upon manufacturing if an alternate vendor was utilized, and the dependence of insertion loss upon thermal conductivity. Test data is presented for each of the three vendor's material and comparisons are made.

In addition, a few samples of AlN from one of the vendors was soaked and boiled in water to determine the effect of water reactivity on insertion loss.

Thermal management is a major consideration in the selection of packaging technology, particularly for high power dissipation chips. Multilayer substrate materials with low thermal conductivity such as LTCC (2.8 W/mK), take up valuable routing real-estate by requiring cutouts in the substrate to allow direct die attach to a metal base, or the use of thermal vias. Actually, this often results in larger, more expensive packages.

The high thermal conductivity of AlN accommodates the mounting of high thermal dissipation chips directly to the substrate. In multilayer substrate applications, this allows for routing of nets in the buried layers under the chip, an advantage in high density packages.

AlN also has good material properties for both microwave and high speed digital packages. Table 1 compares several materials, from which it is seen that, in addition to high thermal conductivity, AlN has a coefficient of thermal expansion (CTE) which is intermediate between that of silicon (Si) and gallium arsenide (GaAs) semiconductors. This close thermal expansion match with common semiconductors is especially desirable, since most microwave packages contain Si for control functions and GaAs for microwave functions.

Material	Coefficient of Thermal Expansion ppm/K	Thermal Conductivity W/mK (at room temp)
Si	4.1	150
GaAs	5.9	45
AlN	4.7	190
Alumina	7.9	28

Table 1. The thermal conductivity and thermal expansion are critical material parameters.

Transmission Line Design

Three transmission line types were used in the tests. Microstrip is a transmission line configuration most common for interconnecting microwave chips, as illustrated in Figure 1a. Coplanar waveguide (CPW), not as commonly employed, is illustrated in Figure 1b. CPW has several advantages when compared to microstrip, such as lower dispersion, ease of shunt connections, and lower radiation.

Conductor backed CPW (CBCPW), often used in the CPW implementation, is illustrated in Figure 1c. Grounding vias are required for CBCPW to insure that the top and bottom grounds are at the same potential[2].

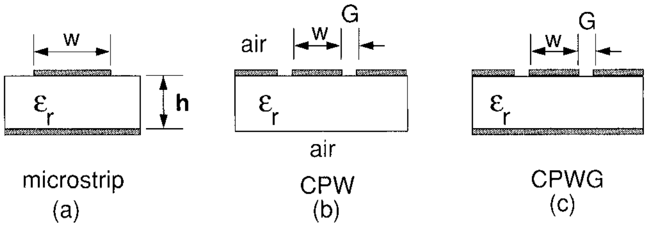


Figure 1. Transmission line types evaluated in the tests.

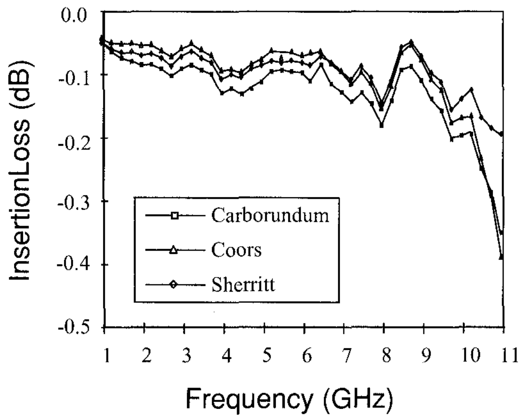
Transmission Line Test Data

AlN substrate samples were obtained from three separate suppliers, (Table 2). The substrates were processed using standard thick film processing, employing Electro-Science Laboratories D-8835-1D gold paste. X-ray fluorescence tests were conducted from which it was determined that the thickness of the gold was about 11 microns for all of the samples tested.

Vendor Name and Location	Lot Number	Thermal Conductivity W/mK⊥
The Carborundum Company Phoenix, AZ, USA	CBO Lot #1169-4	160
Coors Electronic Packaging Company Chatanooga, TN, USA	Plate #17443-34-2	171.9
Sherrit Technology Fort Saskatchewan Alberta, Canada	Lot # T174BR190 AlN	190

Table 2. Vendor lot numbers for the samples of AlN. (⊥Vendor specification sheet.)

Five different line lengths of both microstrip and CPW transmission line were fabricated from each of the substrate samples. Several samples of each line length from each manufacturer were tested. Typical results are shown in Figure 2. It is noteworthy that the insertion loss measured for samples from the three different substrate vendors is substantially the same, suggesting that the AIN material is inherently reproducible in its electrical characteristics, an important production consideration. Furthermore, the results also demonstrate that the insertion loss and thermal conductivity are independent of each other, since the thermal conductivities of the samples did differ among vendors.



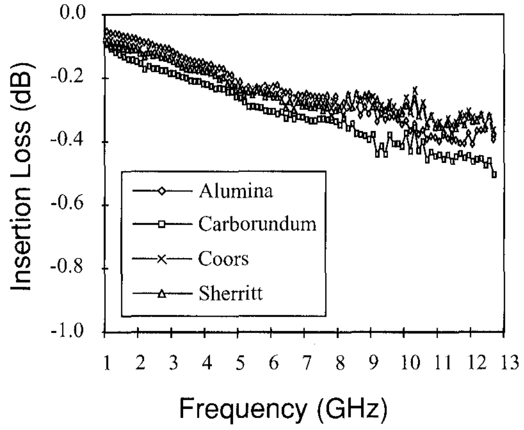


Figure 2. Insertion loss data for the different vendors. (a) Microstrip as the transmission line, h = 160, length = 11.25 millimeter, w = 630 (for AlN). Insertion loss measurements include connector losses, which are the same for all tests. (b) CPW on AlN as the transmission line h = 610, w = 615, G = 168, length = 11.25 millimeter. All dimensions are in microns.

Conductor Loss

The insertion loss tests were conducted on substrates with gold metallization. However, since multilayer AlN substrates are processed at temperatures near 1800°C, their use is restricted to metals with high vapor temperatures such as Tungsten. Unfortunately, tungsten is about 2.5 times more resistive than gold, creating higher microwave loss. However, because of skin depth effects, the loss increase is not proportional to the increase in resistivity. Equation 1 is the commonly used incremental inductance rule for calculating the loss of transmission lines due to conductor loss[3]. From this it is seen that the conductor loss is inversely proportional to the square root of the conductivity. Accordingly, an increase of 2.5 in resistivity causes a factor of 1.58 increase in loss.

$$\alpha = \frac{\sqrt{\varepsilon_{reff}}}{\eta_o L} \sum_{j=1}^{n} R_j \frac{\partial L}{\partial x_j} \quad (1)$$

Where: R_j = surface resistivity $= \sqrt{\frac{\pi \mu f}{\sigma}}$

AlN In Water Tests

There is some concern regarding the effect of water on the performance of AlN[4]. The possible reactions are given in Equations 2 below. AlN and H2O form an acid based reaction. The N2- anion is a very strong basic agent which reacts with water to form aluminum hydroxide and Ammonia. Ammonia and water will also react to form NH4OH which reacts with AlN to form NH3 and Al2+ and OH- ions.

$$\begin{aligned} AlN + 3H_20 &\longrightarrow Al(OH)_3 + NH_3 \\ NH_3 + H_20 &\longrightarrow NH_40H \\ 3NH_40H + AlN &\longrightarrow Al(OH)_3 + 4NH_3 \end{aligned} \quad (2)$$

The effect of the water reactivity upon the microwave performance of AlN was investigated, specifically any tendency for increased microwave insertion loss.

For this investigation CBCPW transmission lines were processed using Carborundum's multilayer processing. The substrates were first tested in the dry state then soaked in 10 megohm deionized water. Retesting of the substrates was performed over a 27 day period.

The substrates were then boiled in water for 8 hours. The results are shown in Figure 3, from which it is seen that there is little effect on the insertion loss after this water exposure.

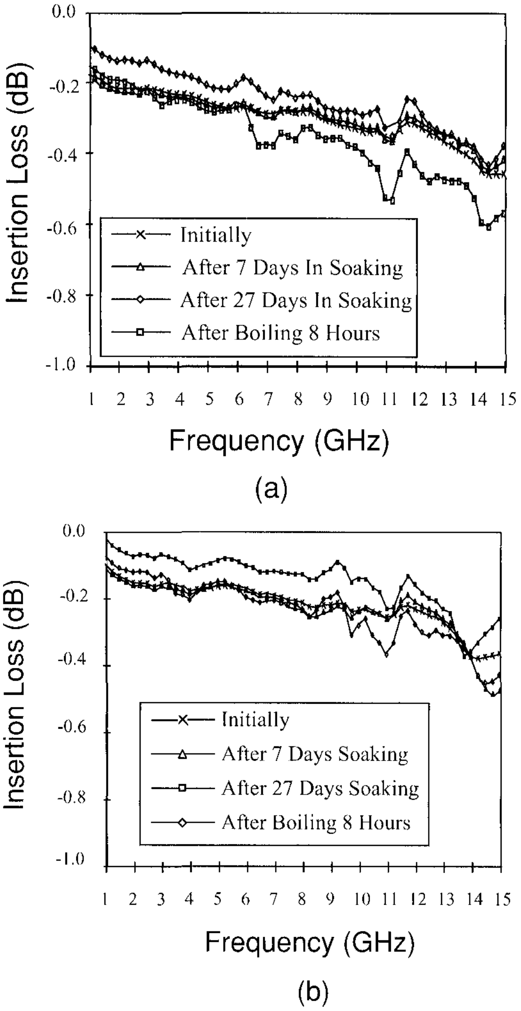


Figure 3. Insertion loss of the CPWG on AlN substrates before and after exposure to water, w = 370, G =163 (a) length = 15.25 millimeter (b) length = 10.16 millimeter. All dimensions in microns.

We feel that the results of this testing indicate that AlN is a suitable packaging and substrate material for microwave applications for several reasons.

First, it is reproducible among different manufacturers.

Second, it undergoes no substantial change with humidity.

Third, it offers thermal conductivity that is at least five times greater than the commonly used alumina material.

Acknowledgments

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