THE COMPLEX PERMITTIVITY OF ALUMINIUM NITRIDE SUBSTRATES

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Abstract The complex permittivities of aluminium nitride substrates manufactured by several companies have been measured and found to be significantly different. The facility used for the measurements is described. Results of measurements of the thermal conductivities of the materials will also be reported.

Introduction Because of its good thermal conductivity, aluminium nitride is considered to be a suitable replacement for beryllia, which is highly toxic, as a substrate material for high power and high density microwave integrated circuits. The thermal conductivity of pure, single crystal, aluminium nitride at room temperature is greater than 300 W/mK. This is greater than that of pure metallic aluminium.

The permittivity of aluminium nitride is similar to that of alumina, which is used extensively as a MIC substrate. The specified loss tangent, approximately 10^{-3}, of commercially available aluminium nitride substrates is however greater than that of high purity alumina, which is of the order of 10^{-4}. Recent measurements, [1], of the losses of microstrip lines on aluminium nitride and alumina substrates indicate that the performance of the aluminium nitride substrate might not be prohibitively worse than that of alumina. A facility for the measurement of the complex permittivity of unmetallised substrates has been developed and used to demonstrate the effect of the production process on the performance of aluminium nitride substrate materials. It is expected that the loss tangent of material would be reduced by improvements in its preparation. To date attention has been focussed on establishing a production process by which the thermal conductivity is optimised.

The thermal conductivity of aluminium nitride substrate materials is also to be measured.

Measurement Technique It was considered desirable to measure the materials in substrate form to avoid the need to machine samples to fit a test fixture geometry. The technique described by Bhartia and Hamid, [2], for the measurement of the dielectric properties of sheet materials has therefore been adopted. The substrate is placed against the broad wall of a section of rectangular waveguide to form a partially dielectric loaded structure, as shown in Fig.1.

Modes propagating on this partially dielectric loaded waveguide structure have a longitudinal section magnetic (LSM) field distribution. The LSM_{10} mode is the fundamental mode excited by an incident rectangular waveguide TE_{10} mode. Propagation parameters of the LSM_{10} mode are defined by the following characteristic equation, [3]:

$$\epsilon h \tan(hd) = -l \tan(lt)$$

where

$$\gamma^2 - \left(\frac{\pi}{a}\right)^2 = h^2 - k_0^2 = l^2 - \epsilon k_0^2$$

γ being the axial component of the propagation constant

k_0 being the free space wavenumber,

and ϵ the relative permittivity of the dielectric.

If the axial component of the propagation constant is known, this equation is readily solved for the permittivity of the dielectric using standard numerical techniques. The axial component of the propagation constant can be determined from the measured reflection/transmission scattering parameters of the section of partially loaded waveguide using closed form expressions, such as those given by Weir, [4].

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Measurement Procedure A fixture of cross-sectional dimensions 25.4mm x 10.16mm has been used, enabling standard 1" x 1" substrates to be accommodated, whilst allowing the use of WG16 waveguide components to interface with measurement instrumentation, without too severe a mismatch being incurred at the H-plane discontinuity. The single mode operating bandwidth of WG16 is 8GHz to 12.4GHz.

An HP8510B network analyser was used to measure the fixture scattering parameters. The TRL calibration procedure, employing WG16 standards, was used to establish a measurement reference plane at the interface between the waveguide components and the fixture.

Scattering parameter measurement errors were estimated by assessing the reproducibility of the measurements. The error in the linear magnitude of the scattering parameters was found to be approximately 0.002, and in the phase approximately 1 degree. These errors are almost entirely due to the misalignment of the calibration standards and measurement fixture at the interface with the WG16 components. An analysis of simulated measurement data indicates that errors of this magnitude should give rise to an uncertainty of less than 1% in the computed relative dielectric constant of the substrate sample, and of the order of 10^{-3} in its loss tangent.

To ensure that the computed loss tangent of the substrate sample is not an overestimate because of the conductor loss contribution to the measured scattering parameters of the fixture, an estimate of the attenuation component due to conductor losses is subtracted from the propagation constant of the LSM_{10} mode propagating on the partially loaded measurement fixture. An estimate of the measurement fixture loss has been determined from the measured quality factor of the resonant cavity formed by placing small coupling apertures at the ports of the empty fixture. This estimate of the conductor loss corresponds to the field distribution of the TE_{10} mode propagating on the empty fixture, and differs slightly from that when the propagating mode field distribution is perturbed by the presence of the dielectric substrate.

Experimental Results To illustrate the effect of the production process on the dielectric properties, the complex permittivities of samples of aluminium nitride substrates manufactured by five different companies have been measured. To the naked eye four of the materials seem to be similar. The fifth material, that designated Mat.K in Figs.2 and 3, has a visibly discernible reddish tinge. The relative dielectric constants and loss tangents of the substrates are plotted in Figs. 2 and 3, respectively. The permittivities of the materials are significantly different. The relative dielectric constants lie between 7.7 and 9.5. That of the material designated Mat.K is noticeably larger than those of the other materials, which cover a narrower range of values. The loss tangents lie between approximately 5×10^{-3} and 1.5×10^{-2}. Both the relative dielectric constants and the loss tangents of each of the materials exhibit some degree of variation with frequency over the measurement frequency band. This range of permittivities is similar to that of measured values already reported in the literature, [5],[6].

The obvious discontinuities in the measured permittivities correspond to resonant fixture lengths, at which levels of uncertainty increase rapidly as the magnitude of the measured reflection from the fixture tends to zero.

Thermal Conductivity Measurement The thermal conductivities at ambient temperature of the substrate materials are to be measured using the thermal flash technique, [7].

Discussion A facility for the accurate measurement of the complex permittivity of unmetallised substrates over waveguide bandwidths has been developed. It has been used to measure the permittivities of aluminium nitride substrate materials manufactured by several different companies. The measured loss tangents may be acceptable for some applications where a heatsinking substrate is required. The differences between the loss tangents of the materials manufactured by the different companies indicates that the production process does have a significant effect on the loss of the material. The loss tangent of aluminium nitride substrate materials might therefore be reduced by further improvement of the production process.

References

1 P.Wright and L.E.Davis, Measured Properties of Aluminium Nitride Microstrip Substrates, Elec.Lett.,vol.29,pp13-15,1993.

2 P.Bhartia and M.A.K.Hamid, Dielectric Measurements of Sheet Materials IEEE Trns.Ins.&Mea.,vol.IM-22,1974.

3 R.E.Collin,
Field Theory of Guided Waves,
McGraw Hill, New York, 1960.

4 W.B.Weir
Automatic Measurement of Complex Dielectric Constant and Permeability at Microwave Frequencies.
Proc.IEEE, vol.62, pp33-36, 1974.

5 S.G.Konosowski, *et al*,
Evaluation of Advanced Ceramics for High Power and Microwave Circuitry - Part II
Int.J.Hyb.Mic.,vol.10,pp13-18,1987.

6 G.Angenieux
Broadband Dielectric Characterisation of Aluminium Nitride
Microwave Journal,pp91-98,Oct,1990.

7 W.J.Parker *et al*,
Flash Method of Determining Thermal Diffusivity, Heat Capacity and Thermal Conductivity,
J.Appl.Phys.,vol.32,1961.

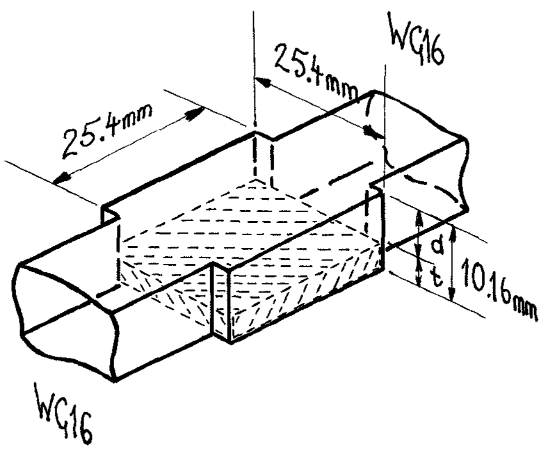

Fig.1 Partially Dielectric Loaded Waveguide Permittivity Measurement Fixture.

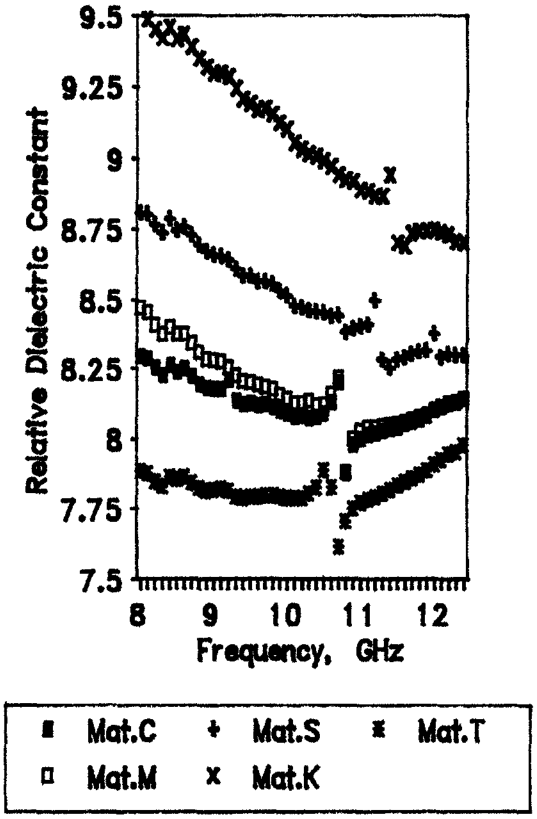

Fig.2 Measured Relative Dielectric Constant of Aluminium Nitride Substrate Materials.

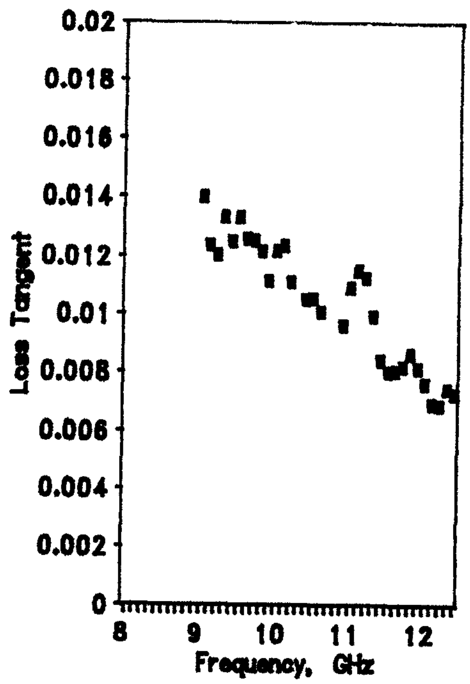

Fig.3a Measured Loss Tangent of Substrate Material Mat.C.

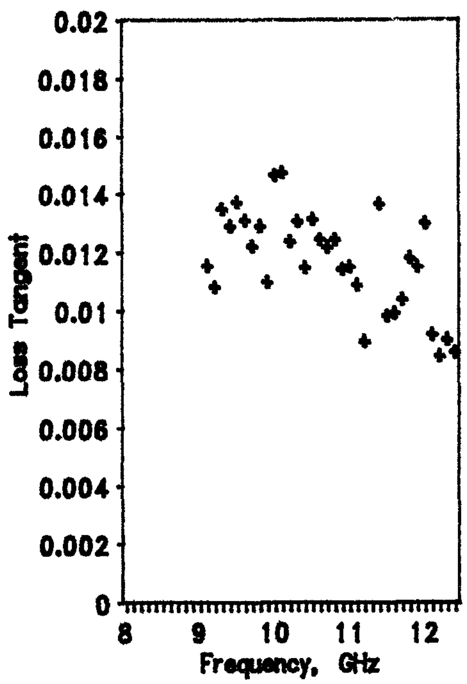

Fig.3b Measured Loss Tangent of Substrate Material Mat.S.

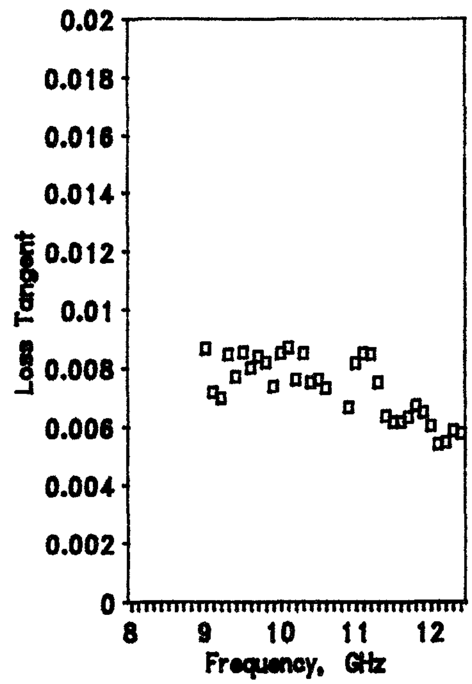

Fig.3d Measured Loss Tangent of Substrate Material Mat.M.

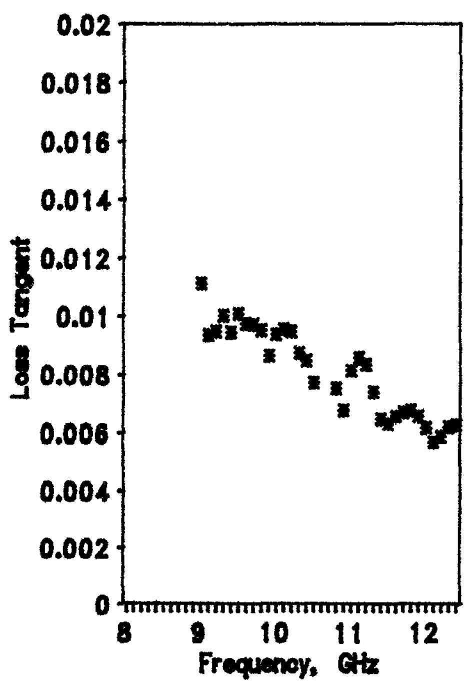

Fig.3c Measured Loss Tangent of Substrate Material Mat.T.

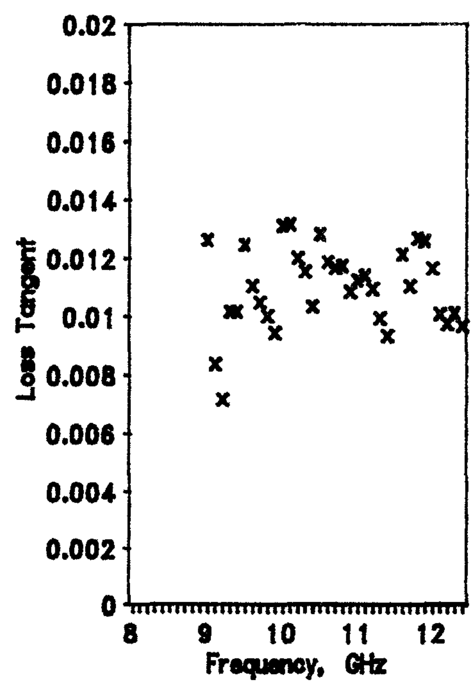

Fig.3e Measured Loss Tangent of Substrate Material Mat.K.