COMPLEX PERMITTIVITY MEASUREMENTS OF GALLIUM-ARSENIDE USING A HIGH-PRECISION RESONANT CAVITY

Eric J. Vanzura, Claude M. Weil and Dylan F. Williams
Electromagnetic Fields Division
National Institute of Standards and Technology,
325 Broadway, Boulder, CO 80303-3328, USA

Abstract

Data are presented on the complex permittivity of gallium arsenide, as measured at room temperature in the 8-12 GHz frequency range. The measurements were performed using a mode-filtered cylindrical cavity resonator with helically wound walls. The estimated accuracies at 10 GHz are ± 0.4% in relative permittivity and ± 5% in loss tangent.

Introduction

As part of a program to develop some primary monolithic microwave integrated circuit (MMIC) standards for the United States, the National Institute of Standards and Technology (NIST) has been fabricating both coplanar and microstrip transmission line standards that may be used for calibrating wafer-probing equipment commonly used in MMIC development. Such standards require the use of gallium arsenide (GaAs) as a substrate material. Accurately predicting the impedance of such standards requires an accurate knowledge of the complex permittivity for GaAs in the frequency range for which MMIC standards are intended to function.

This requirement was the motivation to initiate a task at NIST to measure the microwave properties of high-resistivity GaAs using a resonant cavity technique. The accuracies currently available for such measurements have recently been greatly improved through the use of sophisticated correction algorithms. Three 2 mm thick disc samples were cut from the middle and near both ends of a 76.2 mm (3 in) diameter boule of GaAs. The discs were subsequently reduced in diameter in order that they fit into the 60 mm diameter NIST cavity resonator.

Experimental Technique

The NIST cylindrical cavity resonator is a 2-port, mode-filtered type, operating in the TE_{01p} mode at X-band (8-12 GHz) [1,2]. The TE_{01} mode contains fields that are parallel to the plane of the disk and azimuthally constant. This means that the material parameters can only be measured in this plane. The NIST cavity is capable of performing very accurate measurements of the relative complex permittivity of low-loss, nonmagnetic materials at room temperature [3,4]. The mode-filtering, which represents a principal advantage of this type of cavity, is accomplished through the use of helically wound walls that effectively suppress the axial cavity currents; non-TE_{01p} modes are attenuated by a minimum of 20 dB.

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RF energy is coupled into and out of the cavity using two narrow slots in the upper end plate; the cavity is very under-coupled (approx -26 dB), giving an empty Q factor of about 80 000 at 10 GHz. The samples to be measured need to be precisely machined to the resonator's diameter and then placed on the moveable lower end plate. A material measurement basically involves noting the change in resonant mode parameters (frequency and Q factor) of the empty cavity versus that when a sample is present. This change is measured using either the fixed length method or the fixed frequency method; in the former, the shift in resonant frequency is noted whereas in the latter, the change in cavity length needed to retune the cavity to the same resonant frequency is noted instead.

Traditionally, the resonant frequency and bandwidth, from which the Q factor is derived, have been estimated directly from the resonance curve. Such techniques are of limited accuracy. Furthermore, the measurement yields a value for the loaded Q, that is the reduced Q created by the loading of the input and output coupling ports. Determination of the material loss tangent requires a knowledge of the unloaded Q which, as a first approximation, is related to the loaded Q through the two iris-coupling factors.

There have been two major efforts at NIST to significantly improve the accuracy of material parameter measurements using the cavity technique. Both have sought to exploit the major improvements in data acquisition created by the use of the automatic network analyzer. In the technique developed by Estin [3], the input scattering parameters S_{11} and S_{22} are measured, as well as the transfer parameter, S_{12}, following a full 2-port TRL calibration. The unknown coupling coefficients are derived from the Q circle fit of the S_{11} and S_{22} data in the complex S-parameter plane using a linear least squares fit and an approximate circuit model. An estimate for the loaded Q is derived from a linear fit to the S_{12} data from which the unloaded Q is obtained. In the technique developed by Vanzura [4], only the input scattering parameters, S_{11} and S_{22} are measured, thereby eliminating the need for transfer parameter measurements. A nonlinear regression fit to the circle data is performed using a more rigorous circuit model. From this, direct estimates for eight unknown circuit parameters are derived, including the two coupling coefficients, the resonant frequency, the unloaded Q, and the complex impedance of the two coupling irises. It has been shown that the two different techniques yield results that are very comparable for all parameters other than unloaded Q; for this, the Vanzura technique consistently yielded lower estimates than that of the Estin method.

All of the GaAs measurements discussed in this paper were processed using the Vanzura technique.

Experimental Results

Measured data, including estimated uncertainty bounds, are shown in Figs 1 and 2 for the three GaAs samples; the designations "start," "middle," and "terminus" refer to the locations on the original boule where the samples were cut. Within the estimated uncertainty bounds, the measured complex permittivity data for the three disks agree well. In Fig. 1, the mean relative permittivity values for the "start" disk appear to be somewhat lower than the other two, which suggests that the boule may be slightly inhomogeneous. Note that in Fig. 2, the measured loss tangent decreases with frequency. This is contrary to the usual trend for semiconductor materials and probably represents an anomalous region of the microwave spectrum where the trend toward increasing loss factor has been reversed. Such behavior has not been previously observed because measuring systems did not possess the needed sensitivity. The two outlying data points in Fig. 2 were caused by the presence of interfering modes and, for purposes of computing a median curve, were ignored.

At 10 GHz, the mean permittivity value for the three disks is 12.94 ± 0.05 (a relative uncertainty of ± 0.39%). The corresponding mean loss tangent value is 0.00059 ± 0.00003 (a relative uncertainty of ± 5.1%). The uncertainty bounds for permittivity increase slightly to ± 0.06 as frequency is reduced to approximately 8 GHz while those for loss tangent increase more rapidly to ± 0.0009 (± 11.3%).

There are statistically significant differences between our data and those reported by other workers. However, the differences are small and probably due to differences in the manner of GaAs manufacture. Champlin and Glover [5] measured the dielectric properties of GaAs at 70 GHz. Their quoted room temperature value is 13.18 ± 0.07, which differs from our value by less than 2%. Our accuracy is slightly higher, however. Strzalkowski et al [6] reported a room temperature value for GaAs of 13.08 ± 0.07 at 1MHz, which is seen to be in even closer agreement with our measurements.

References

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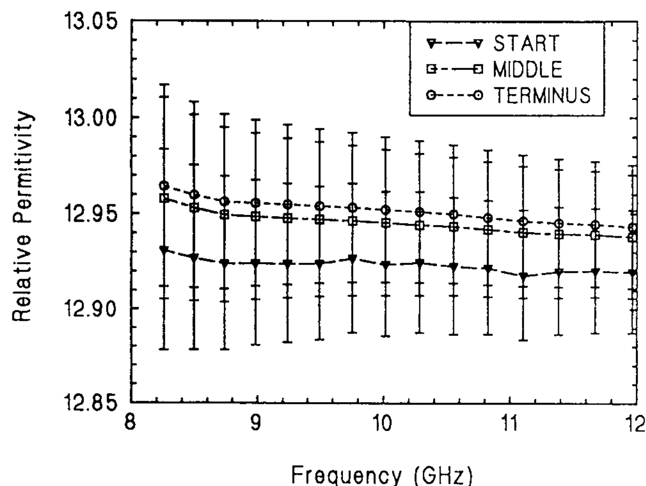

Figure 1: Relative Permittivity data for Three Samples of GaAs at Room Temperature.

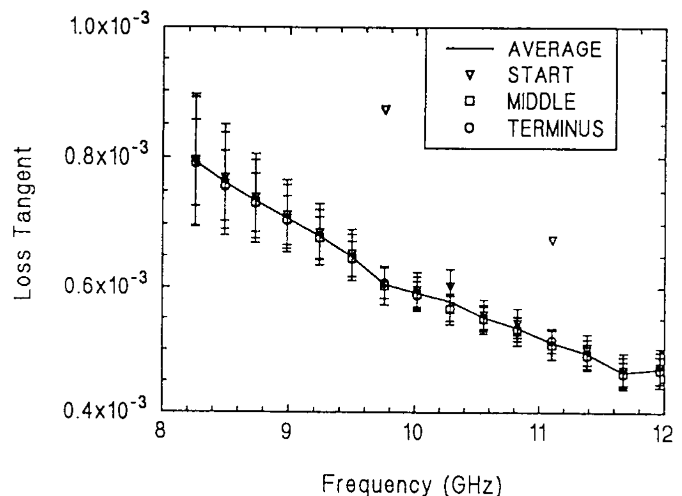

Figure 2: Loss Tangent data for Three Samples of GaAs at Room Temperature.