Final Scientific Report

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Executive Summary

The response of dielectric material to electromagnetic waves in the millimeter wavelength range (30 to 300 GHz) has received relatively little study and the processes that give rise to absorption in this region are often poorly understood. Understanding the origin of absorption at these wavelengths has basic significance for solid state physics as well as importance for development of technology in this region of the RF spectrum. This project has provided high-quality data on the temperature dependence of the dielectric loss in high-purity, semi-insulating silicon carbide (HPSI SiC), a material that holds much promise for application, especially in devices that must operate in the high power and high frequency regime. Comparison of this experimental data with theoretical predictions for various loss processes provides convincing evidence that the loss in HPSI SiC arises almost entirely from intrinsic lattice loss (ILL) as described by Garin⁽¹⁾. Fitting the data to this model yields an accurate value for the Debye temperature that characterizes crystalline SiC. In addition, our results refute a previous study⁽²⁾ which reported much higher loss, attributed to the presence of free charge.

The quality of the data acquired in this project is clear evidence for the value of the experimental technique that was employed here. This technique combines the excitation of a high-quality open resonator by a phase-locked backward wave oscillator (BWO) with use of a spectrum analyzer to measure the change in the resonator response curve when the sample is inserted. This system has demonstrated consistent results for very challenging measurements and does not suffer from the artifacts that often arise when using other techniques that rely on thermal sources.

The low absorption loss found in HPSI SiC, when combined with its other outstanding material properties, e.g. high thermal conductivity, high tensile strength, and high carrier mobility, should provide incentive for designers to utilize this material to solve the challenging problems that are encountered as devices are pushed to operate at higher frequencies and higher power levels. In particular, for the fusion energy program, it may provide an economical alternative to CVD diamond for certain gyrotron and beam line applications. In addition, the value obtained for the Debye temperature provides an important datum for modeling the crystalline structure of SiC. Clearly SiC is a unique material with few competitors and should see wider utilization.

Comparison of Actual Accomplishments With Goals and Objectives

The primary scientific goal of this project was to acquire the necessary, high-quality, experimental data to allow comparison of alternate loss models and thereby distinguish the predominate loss mechanism in high-gap semiconductors, especially CVD diamond and HPSI-SiC. The major accomplishment of this project was the successful completion of this goal for HPSI-SiC. This was done by upgrading our experimental apparatus to enable loss measurements over the temperature range from 200K to 800K. As noted above, the temperature dependence of loss was found to be sufficient to identify intrinsic lattice loss as the primary mechanism of loss in HPSI-SiC. Additional DLTS measurements on SiC, as originally proposed, were found not to be needed as the defects previously seen with this technique do not contribute significantly to the

loss. Additional, high-quality, room temperature measurements were obtained on samples of CVD diamond, sapphire, and quartz. Comparison of these results with those from the Microwave Diagnostic Laboratory of the Institute of Applied Physics of the Russian Academy of Sciences⁽³⁾ provided confirmation of our data's accuracy. Regrettably, we were not able to measure samples of other wide-gap semiconductors as originally proposed. This was due in part to a lack of promising samples and in part to an equipment failure that delayed operation.

An additional goal of this project was to provide opportunities for students, especially minority students, to participate in challenging experimental research. Several students have participated during this project period and two of these students used this activity to complete their Masters thesis.

Project Summary

For an ideal crystalline dielectric, basic theoretical considerations predict that absorption in the millimeter-wave spectral region can be attributed to intrinsic lattice loss (ILL) arising from multi-phonon absorption processes. Substantially higher losses may be introduced by the presence of lattice disorder, defects, impurities, etc. For each loss process, theoretical models can be used to predict the dependence of loss on temperature and frequency. Acquiring experimental data on the variation of loss with these parameters will enable one to identify the loss processes present in a material. If losses other than ILL are found to be present, there is potential to improve the material by identifying and reducing the defects or impurities producing the additional loss. However, if ILL predominates, no further reduction of loss is possible. ILL is strongly dependent on the phonon population hence it is can be identified by its temperature dependence.

The very low level of loss to be measured ($\tan\delta \sim 10^{-5}$) required the use of a high Q, open resonator to obtain reliable values. The quasi-optical, experimental apparatus developed for this purpose is described in detail elsewhere⁽⁴⁾ and is shown schematically in Figure 1. The major components are an open resonator with a Q of $\sim 10^6$, a backward wave oscillator (BWO) to excite the resonator, and a spectrum analyzer (SA) with external mixers for detection at millimeter waves. An ancillary system, that phase locks the BWO frequency to the SA local oscillator, is crucial for rapid and accurate data collection. To accomplish measurements with this system, the sample must be held on center in the resonator with a clear aperture sufficient to avoid lowering the resonator Q. Varying the sample temperature over a wide temperature range under these conditions presented an experimental challenge. This was met by fabricating a heating cell that utilized edge heating and a cooling cell that employed a combination of edge cooling and flow of a cooling gas over the surface. The large thermal conductivity of SiC helped to reduce temperature variations over the sample.

Figure 2 summarizes the data obtained for loss as a function of temperature in HPSI SiC. This data was fit to a model for temperature dependence proposed by Garin⁽¹⁾ in the case of two-phonon absorption where an optical phonon is created and an acoustic phonon annihilated. The

functional form of this model is: $\tan\delta = Cf^2T^{-1} \left[\sinh(-T_D/2T) \right]^{-2}$ where f is the frequency, T is the absolute temperature, C is a scaling constant and T_D is the Debye temperature. A non-linear least squares fit of the data to this model is shown by the solid line in Figure 2. From the fitting parameters, the value of the Debye temperature is found to be; $T_D = 1071 \pm 24\text{K}$. There is no evidence for the presence of any loss mechanism other than that described by this model. The other possible two-phonon process, one that involves only acoustic phonons and would have a T^3 temperature dependence, appears to be absent. Further theoretical studies may explain this absence. Significant absorption due to the presence of free charges is ruled out by these results.

Figure 1

Figure 2

References

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Publications and Presentations

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