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A Contactless Method for Measuring the Bulk Resistance of II-VI Compound Semiconductors

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A radio frequency measurement technique for measuring the bulk resistivity of II–VI compound semiconductors is described. Wafers of *n*-type CdS are used to demonstrate the technique. An equivalent circuit model is introduced which predicts a frequency dependence for the CdS wafer impedance which agrees well with the experiment. The model assumes a broad distribution of relaxation times associated with the polarization. The radio frequency method gives values for the resistivity within 15% of four point probe measurements for the lower resistivity wafers, and within 5% for the higher resistivity wafers. © *1994 American Institute of Physics.*

I. INTRODUCTION

In measuring the resistivity of a II–VI compound semiconductor using standard techniques such as van der Pauw or the four point probe, it is frequently necessary to deposit a metal layer in order to obtain accurate results. For wide band-gap *p*-type materials these methods can give inaccurate results even when a metal layer is deposited.[1] High frequency techniques exist[2] that are less sensitive to the surface contact and do not require surface metallization. In 1946, Roberts and von Hippel[3] reported a technique for measuring the complex permittivity of a material uniformly filling a hollow waveguide based on the reflection coefficient. Later, Benedict and Shockley[4] reported a technique utilizing the transmission coefficient. The methods above can be used to measure the complex permittivity of a semiconductor, but the measurements can depend strongly on the waveguide-semiconductor interface. Significant errors result if the interface is not treated properly.[5] In other work, Miyamoto and Nishizawa[6] and Bryant and Gunn[7] have used capacitive coupling to probe bulk charge carriers. Methods utilizing capacitive coupling can eliminate the need for an ohmic contact since, at high frequencies, the capacitance offers a low impedance path for probing the resistivity of the bulk material. Haase *et al.*[8] have recently utilized capacitive coupling to help electrically characterize *p*-type ZnSe. In another approach, Miller *et al.*[9] describe an inductive coupling technique which has been extended by Yablonovitch *et al.*[10] to accurately measure resistivity, as well as other material properties. In this method, the resistivity is determined by using the power absorbed by the charge carriers which is shown theoretically to be proportional to the conductivity of the material.

The work described herein is a rf measurement technique which employs reflection measurements from a vector network analyzer to extract the resistivity of a semiconductor wafer. In order to demonstrate the method, *n*-type CdS wafers are employed. Four point probe measurements are employed for comparison with the rf measurement technique.

In the rf method, the reflection coefficient of a semiconductor wafer in a special test fixture is measured as a function of frequency. An equivalent circuit model for the wafer impedance is developed that results in a frequency dependence which agrees well with the measurements for CdS wafers. The resistivity extracted from the model is within 15% of values obtained from four point probe measurements.

II. EXPERIMENT

A brass conical-coaxial test fixture, shown in Fig. 1, was constructed to hold the CdS wafers during the measurement procedures. It is constructed to have a characteristic impedance of 50 Ω (±5%). An air dielectric is used, and nylon spacers in the test fixture provide mechanical support to the inner conductor.

Standard calibration procedures employing open and short circuits, as well as a 50 Ω load are used to determine calibration coefficients for error correction of the vector network analyzer. Next, the test fixture is connected to the coaxial line leading to the network analyzer. The measurement plane is then moved to the CdS wafer by the electrical delay capability of the network analyzer. Subsequent measurements on the short circuited test fixture indicate that this calibration procedure is not adequate for frequencies above 300 MHz. For this reason, only frequencies below 300 MHz were used in the experiment.

Impedance measurements were made at 1.35 MHz intervals between 30 and 300 MHz. The real part of the measured wafer impedance was typically about 100 Ω at 30 MHz and decreased to between a few ohms and a few tens of ohms at 300 MHz dependent on the bulk resistivity. The imaginary part of the impedance typically decreased from several hundred ohms at 30 MHz to about 100 Ω at 300 MHz. At the frequencies used in this experiment, the 2.8 mm stub on the endcap of the test fixture can be modeled as an inductance in series with the wafer impedance. The maximum impedance of this inductance can be calculated and is less than 1 Ω. This impedance is less than 1% of the imaginary part of the wafer impedance and is neglected in the model developed below.

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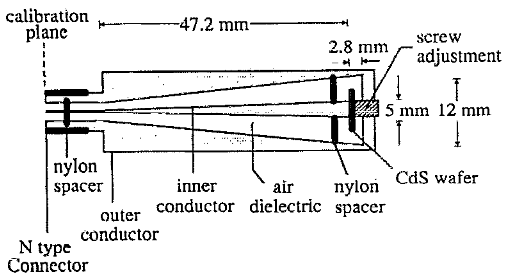

FIG. 1. Conical-coaxial test fixture detail.

The impedance of five wafers with resistivities between 2.9 and 39 Ω cm were measured. Four of the wafers were approximately 0.9 mm thick with one being 2.42 mm thick. The surfaces of the test fixture which contact the wafer were machined very flat so that the variations in the air gap between the wafer and the test fixture surfaces were minimized. The CdS wafers were oriented along the c axis. The wafer surfaces were polished with 1/4 μm diamond and then etched to remove surface damage due to the polish.

III. THEORY

An equivalent circuit model of the impedance of the CdS wafer in the test fixture is shown in Fig. 2. The impedance of the air gap between the semiconductor wafer and the test fixture surfaces is modeled as the capacitance C_g. Since a low resistance ohmic contact is not made to the wafer for the rf measurement, the surface region of the wafer is expected to be depleted of free-charge carriers and can be modeled as a lossy dielectric. The impedance of the lossy dielectric at the semiconductor surface is then modeled by a capacitance C_s with a resistance R_s in parallel. The impedance of bulk region is modeled as the resistance R_b.

Because the metal-semiconductor contact in this experiment is not ohmic, the conduction current across the semiconductor surface is small. Above some frequency, the displacement current across the surface will be much greater than the small conduction current. This implies that the impedance of R_s is much larger than that of C_s. For the wafers used in this experiment, this was true at frequencies greater than a few MHz. Using this approximation, the impedance is

$$\mathbf{Z} \cong R_b + 1/(\omega^2 R_s C_s^2) - \frac{j}{\omega}(1/C_g + 1/C_s), \tag{1}$$

where ω is the angular frequency. The bulk resistance R_b can be extracted from the measurement of Re(**Z**) as a function of frequency. However, the possibility that R_s and C_s may have some frequency dependence must first be considered.

The surface resistance R_s is associated with the dielectric conduction which has been shown to be proportional to the frequency.[11] Thus,

$$R_s \propto 1/\sigma = 1/\omega\epsilon_2, \tag{2}$$

where σ is the dielectric conductivity and ϵ_2 is the imaginary part of the dielectric constant. Also, the surface capacitance C_s is proportional to the real part of the dielectric constant of the surface region. Since both the surface capacitance C_s and the surface resistance R_s depend on the dielectric constant, it is necessary to know what frequency dependence can be expected of the polarization. For many polar materials the dielectric properties can be modeled theoretically by assuming a broad distribution in relaxation times associated with the polarization due to dipole alignment.[12] A distribution in relaxation times results in the imaginary part of the dielectric constant being relatively constant and the real part slowly decreasing with frequency.

For a real part of the dielectric constant decreasing slowly with frequency, C_s should also slowly decrease with frequency. The measured value for the capacitance of the series combination of C_g and C_s can be determined from the imaginary part of the impedance as seen in Eq. (1). For each wafer, the measured capacitance does decrease slowly with frequency. It smoothly decreases in value by about 10% as the frequency ranges from 30 to 300 MHz. The capacitance was a few pF for each sample. Since C_g depends upon the dielectric constant of air and can be considered to be independent of frequency over the measurement range, this slow decrease is consistent with the expectation of C_s slowly decreasing with frequency. With regard to the real part of the wafer impedance, it is important to note that since ϵ_2 is relatively constant with frequency, R_s varies as ω^{-1}. It is assumed that the slight frequency dependence of C_s can be neglected with respect to this frequency dependence of R_s. The resulting form for the wafer impedance is then

$$\mathbf{Z} = R_b + K/\omega - \frac{j}{\omega}\left(\frac{1}{C_g} + \frac{1}{C_s}\right), \tag{3}$$

where $K \equiv 1/\omega R_s C_s^2$ is a constant.

A least-squares fit to the experimental data for Re(**Z**) is shown in Fig. 3 where Re(**Z**) is plotted as a function of ω^{-1}. It can be seen that the linear response predicted by the model with respect to ω^{-1} agrees well with the measured data. While only a few data points are shown, the data at 1.35 MHz intervals for the Re(**Z**) agrees with the model equally well. The resistivity of the bulk material is obtained by mul-

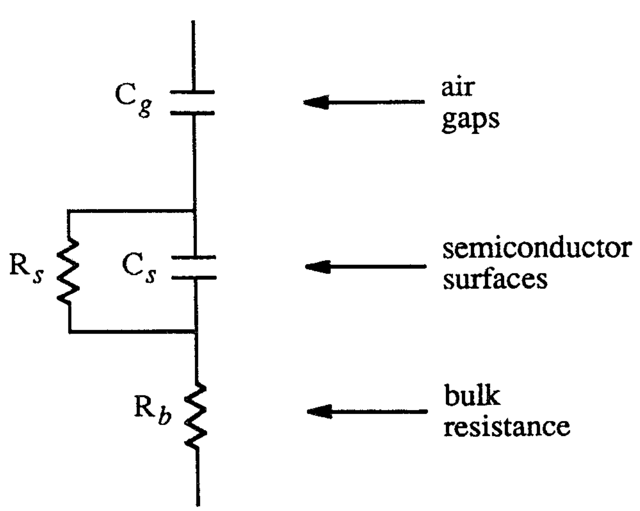

FIG. 2. Wafer impedance circuit model.

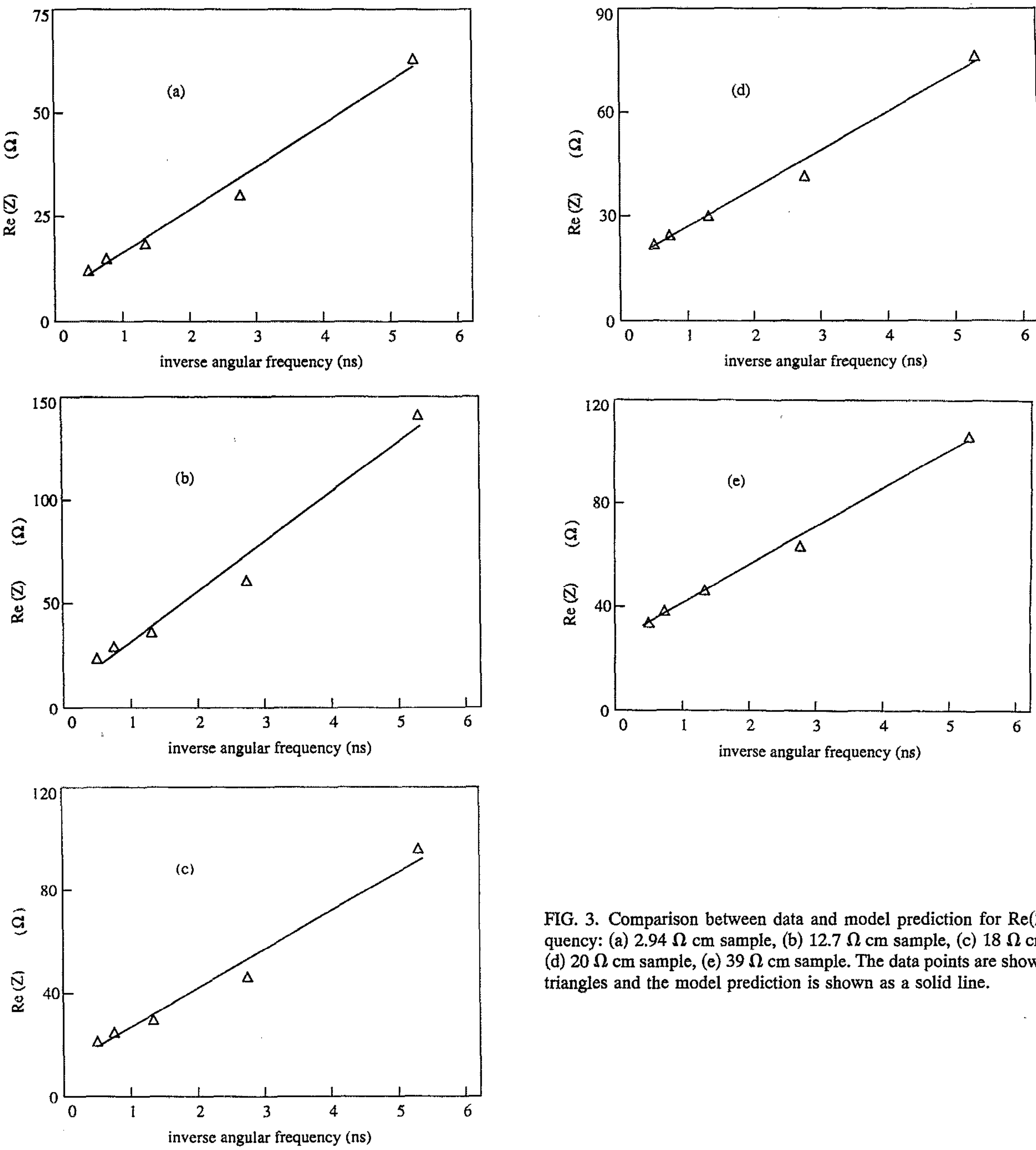

FIG. 3. Comparison between data and model prediction for Re(Z) vs frequency: (a) 2.94 Ω cm sample, (b) 12.7 Ω cm sample, (c) 18 Ω cm sample, (d) 20 Ω cm sample, (e) 39 Ω cm sample. The data points are shown as open triangles and the model prediction is shown as a solid line.

tiplying R_b by the area of the test fixture center conductor and dividing by the wafer thickness. The values of the resistivity for the CdS wafers are compared with four point probe measurements in Table I. The results for the contactless method agree with the value obtained with the four point probe measurements within 15% for material of low resistivity, and within 5% for higher resistivity material.

IV. DISCUSSION

Although further work remains to establish the wafer thickness and resistivity limitations of the technique, it can be seen from Table I that a closer match with four point probe values were obtained for the higher resistivity wafers. This can be partly explained by noting that any experimental errors resulting from small impedance mismatches between the elements of the line connecting the CdS wafer to the network analyzer will cause a larger percentage error in lower resistivity wafers than higher resistivity ones. Improvements in measurement could be made by reducing these mismatches.

The screw adjustment employed to establish contact to the crystal causes surface damage because friction exists between the test fixture surfaces and the crystal as the contact is established. Improvement could be made by replacing the screw adjustment with an adjustment utilizing spring loading. This would significantly reduce the amount of surface damage suffered by the semiconductor wafer during the measurement process.

Since CdS is a wide band-gap II–VI compound semi-

TABLE I. Comparison between resistivities obtained using the high frequency method vs that obtained using the four probe method.

Wafer No.	Thickness (mm)	Four point probe (Ω cm)	High frequency (Ω cm)	% difference
DF 90332-01-06	2.42	2.94	3.33	13
DM 88277-21-13	0.84	12.7	10.9	14
DM 88277-21-03	0.87	18.0	17.0	6
03-04	0.91	20.0	20.8	4
DE 88259-21-06	0.87	39.0	37.9	3

conductor, this technique should be useful in other II–VI compounds such as ZnSe or ZnS.

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