Nondestructive measurement and high-precision evaluation of the electrical conductivity of doped GaAs wafers using microwaves

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A nondestructive method for measuring the electrical conductivity of doped GaAs wafers using a compact microwave instrument is presented. Based on the characteristics of the microwave detector and the fact that the microwave measurement is independent of the thickness of the wafer, the analytical and explicit expressions to evaluate the electrical conductivity of the wafer are derived. Using this method, only the voltages of the reflected signals for two wafer samples whose conductivities are known are required to calibrate the two undetermined constants in the equation. Then, the conductivity of any other wafer can be evaluated by substituting the measured voltage of the reflected signal into the explicit expressions. Seven different doped GaAs wafers with thickness larger than 350 μm and conductivities in the range of $1.3 \times 10^4$ S/m to $7.6 \times 10^4$ S/m are measured in the experiment, two of which are used for calibration. The evaluated results agree well with those obtained by the conventional Hall effect measurement method, with an evaluation error less than ±4.5%. The proposed method is potentially useful for the contactless and nondestructive evaluation of the electrical conductivity of any kind of semiconductor wafer. © 2010 American Institute of Physics.

I. INTRODUCTION

Doped GaAs is one of the most important materials in the semiconductor industry due to its important advantages over silicon, such as a wide band gap and superior conductivity, thermal transport properties, and phonon properties. It is widely used to manufacture devices, such as microwave frequency integrated circuits (ICs), monolithic microwave ICs, infrared light-emitting diodes, laser diodes, solar cells, and optical windows. To control the quality of doped GaAs wafers either in the process of wafer manufacturing or device fabrication, it is important to know the electrical conductivities of the wafers. The four-point-probe method is the conventional technique used to measure the conductivities of semiconductor wafers; however, due to the Schottky barrier at the metal-GaAs interface, it cannot be used to measure GaAs wafers. Recently, the eddy-current method, which measures small impedance changes of an inductive coil placed in close proximity to a sample, has been used as a contactless method for determining the conductivity of semiconductor wafers. However, the sensitivity of this method is still low, and it is necessary to know the thickness of the wafer. Typically, the Hall effect measurement (HEM) method is used to measure the conductivity of GaAs wafers. However, due to the Schottky effect, this method cannot be used in a contactless and nondestructive way for the measurement of GaAs wafers. When using the HEM method to measure the conductivity of a doped GaAs wafer, good ohmic contacts on the wafer are needed, for which a square sample should be machined from the wafer and a special soldering or evaporating should be carried out. However, the fabrication of good quality metalized contacts to III–V semiconductors is one of the most challenging problems in GaAs and InP integrated technology, which makes the aforementioned methods more difficult to implement. At present, there is still no method available for measuring the conductivity nondestructively to characterize and control the quality of doped GaAs wafers during manufacturing or even the finished wafer products.

Microwaves have the advantage that the response of a sample is directly related to the electrical properties of its composing materials. Therefore, microwaves are widely used in the study of the electrical characterization of semiconductor materials. In addition, microwaves can propagate easily in free space, which makes them suitable for contactless measurements. Moreover, it is possible to obtain the measurement independent of the thickness of the wafers. The electrical conductivity of Si wafers has been measured by microwaves in our previous research, where the evaluation equation was obtained by a polynomial fitting using four reference samples. In this paper, analytical and explicit expressions of conductivity derived by microwave theory are used instead of the polynomial fitting routine, and only two reference samples are needed for calibration. The evaluated results agree well with those obtained by the conventional HEM method, with an error less than ±4.5%.

II. THEORETICAL ANALYSIS

When a microwave irradiates a doped GaAs wafer, a reflection occurs at both the top and bottom surfaces of the wafer due to the discontinuity of the medium. The microwave signal reflected from the wafer will be the sum of the reflections from both the top and bottom surfaces. Therefore, the
measured reflection coefficient depends on the electromagnetic parameters and the thickness of the wafer.

According to our former research, the values of the thickness and the conductivity of a wafer are both large enough, the reflection from the bottom surface will be much smaller than that from the top surface; therefore, the measurement result will be independent of the thickness of the wafer. The minimum thickness that satisfies this condition has been described in detail in our previous work.

For a given wafer, the applicable frequencies for the thickness-independent measurement can be estimated by considering the range of the wafer’s thickness and conductivity. Higher frequencies are preferred when measuring thinner and lower-conductivity wafers. The electrical conductivities of the doped GaAs wafers tested in our experiment are in the range of $1.3 \times 10^4 \text{ S/m}$ to $7.6 \times 10^4 \text{ S/m}$, and the minimum thickness of the wafers is $350 \pm 25 \mu\text{m}$. The compact microwave instrument used in our experiment can generate microwave signals at 96 GHz, so the independence of the measurement from the wafer thickness is safely guaranteed. In general, the doped GaAs wafers used in the semiconductor industry are thicker than $50 \mu\text{m}$ due to the brittleness and fragility of the wafers, and their conductivities are in the range of $(1 \sim 10) \times 10^4 \text{ S/m}$. Even for the minimum $50 \mu\text{m}$ thickness of doped GaAs wafers, this instrument and the evaluation method independent of wafer thickness are still applicable if the conductivities are higher than $0.568 \times 10^4 \text{ S/m}$, which is smaller than the aforementioned range.

A diode detector is used in the compact microwave instrument. Because the diode detector works in a small signal range, it can be considered as a square-law detector. Therefore, while keeping the standoff distance between the sample and the horn antenna constant in the experiment, the output reflected voltage $V$, which varies with the conductivity of the wafer, has a relationship with the squared absolute value of the total reflection coefficient, $|\Gamma|^2$, as

$$V = k_0 |\Gamma|^2 + b_0,$$

where the two undetermined constants $k_0$ and $b_0$ can be calibrated with two wafer samples whose conductivities are known.

If the measurement is independent of the thickness of the wafer, $|\Gamma|$ can be replaced with $|\Gamma_y|$, which is the absolute value of the top surface reflection coefficient. Thus, the output voltage $V$ can be expressed by $|\Gamma_y|^2$ as

$$V = k_0 |\Gamma_y|^2 + b_0.$$  

From Eq. (2), the absolute value of the surface reflection coefficient can be calculated from the output voltage as

$$|\Gamma_y| = \sqrt{(V - b_0)/k_0},$$

On the other hand, according to microwave theory, $|\Gamma_y|$ can be expressed as

$$|\Gamma_y| = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1},$$  

where $\eta_1 = \eta_0/\sqrt{\varepsilon_\tau}$ and $\eta_2 = \sqrt{\mu/\varepsilon_\tau}/\sqrt{1 - j\sigma/(\omega\varepsilon_\tau)}$ are the intrinsic impedance of free space and the doped GaAs wafer, respectively; $\omega$ is the angular frequency of the microwave ($\omega = 2\pi f$); $\varepsilon$, $\mu$, and $\sigma$ represent the permittivity, permeability, and conductivity of the wafer, respectively. Due to the nonmagnetic performance of the doped GaAs wafer, its permeability can be taken as $\mu = \mu_0$, where $\mu_0$ is the permeability of free space. The permittivity of doped GaAs wafers can be expressed approximately as $\varepsilon = \varepsilon_\tau \varepsilon_0$, where $\varepsilon_\tau$ is the relative dielectric constant of the wafer. For the doped GaAs wafers tested in our experiment, $\varepsilon_\tau$ is 13.1.

Based on the aforementioned analysis, the intrinsic impedance of a doped GaAs wafer can be written as

$$\eta_2 = \eta_0/\sqrt{\varepsilon_\tau - j\sigma/(\omega\varepsilon_\tau)}.$$  

From Eqs. (4) and (5), $|\Gamma_y|$ can be expressed as

$$|\Gamma_y| = \frac{1 - \sqrt{\varepsilon_\tau - j\sigma/(\omega\varepsilon_\tau)}}{1 + \sqrt{\varepsilon_\tau - j\sigma/(\omega\varepsilon_\tau)}}.$$  

To evaluate the conductivity of the wafer, the explicit expression of $\sigma$ in the form of $|\Gamma_y|$ or the reflected voltage $V$ is of great importance. By taking $\sqrt{\varepsilon_\tau - j\sigma/(\omega\varepsilon_\tau)} = A + jB$, ($A, B \in \mathbb{R}$), the conductivity $\sigma$ can be solved from Eq. (6) as

$$\sigma = (\omega\varepsilon_\tau)\sqrt{1 - (y\varepsilon_\tau)^2}/y,$$

where

$$y = \frac{(|\Gamma_y|^2 + 1)\sqrt{(2\varepsilon_\tau - 1)(|\Gamma_y|^2 - 1)^2 + 4|\Gamma_y|^2 - 4|\Gamma_y|^2}}{(2\varepsilon_\tau - 1)(|\Gamma_y|^2 + 1)^2 + 4|\Gamma_y|^2}.$$  

Therefore, after $k_0$ and $b_0$ in Eq. (2) are calibrated using two reference wafers whose conductivities are known, a wafer’s conductivity can be determined by measuring the output voltage under the same conditions and evaluating equations Eqs. (3), (7), and (8).

III. EXPERIMENTAL APPROACH

A compact microwave instrument is used in our experiment. The instrument is composed of a Gunn oscillator, a magic-Tee, a horn antenna, an attenuator, a tunable short, and a diode detector. The flow chart of the measurement instrument is shown in Fig. 1. The compact microwave instrument can generate microwave signals at 96 GHz (microwaves of

![FIG. 1. (Color online) Schematic diagram of the measurement instrument.](image-url)
this frequency are also referred to as millimeter waves) with power of 10 dBm.

In the experiment, stable microwave signals are generated by the oscillator and then separated into two branches by the magic-Tee. One branch of the signal is sent to the horn antenna to irradiate the wafer, and the reflected signal is received by the antenna. The other branch of the signals is sent to the attenuator then to the tunable-short to form a reference signal with a constant phase difference and a similar amplitude compared with the reflected signal from the wafer. The reference signal is determined by setting the output voltage of the detector to be zero when there is no wafer on the horn antenna, which is done by adjusting the attenuator and the tunable-short. The reflected signal and the reference signal are finally synthesized by the magic-Tee, and the coherent signals are measured by the detector. The detector used in the experiment is a square-law detector, which has an output voltage with a linear relationship with the squared absolute value of the reflection coefficient of the sample.

When the wafer is being measured in the experiment, the reflected signal is received and the reflected voltage is displayed on the oscilloscope. Figure 2 shows the view of the measurement where the wafer is set on the antenna in a contact fashion, i.e., the standoff distance is set to be zero. It is noted that a contactless fashion can also be easily realized by setting the wafers on a ringed support with an unchangeable standoff distance between the wafer and the antenna.

In this paper, two doped GaAs wafers (Nos. 1 and 2) are used as the reference samples to calibrate the two undetermined constants in Eq. (2). Another five wafers (Nos. 3 to 7) are evaluated using the suggested method. The detailed characteristics of the wafers are shown in Table I, and the conductivities shown there are all measured with the HEM method. When the wafers are measured in the experiment, the output voltages are recorded and are also shown in Table I. It is noted that even though the changes in the output voltages for different wafers are comparatively small compared with the values of the measured voltages, the errors of the measured voltages are generally less than ±0.05 mV. Therefore, the ratio of the signal to noise is high enough for a high-precision evaluation.

### IV. RESULTS ANALYSIS AND DISCUSSION

When substituting the known conductivities of wafers Nos. 1 and 2 into Eq. (6), the absolute values of the reflection coefficients are calculated to be 0.9810 and 0.9867, respectively. After substituting the measured output voltages of these two wafers together with their corresponding absolute values of the reflection coefficients into Eq. (2), the two unknown constants are calculated to be $k_0 = -0.2416446$, $b_0 = -0.1405282$.

Using their output voltages shown above, the conductivities of wafers Nos. 3 to 7 are evaluated from Eqs. (3), (7), and (8). The evaluated conductivities are compared with those measured using the HEM method in Fig. 3.

<table>
<thead>
<tr>
<th>Wafer No.</th>
<th>Conductivity (S/m)</th>
<th>Diameter (mm)</th>
<th>Thickness (μm)</th>
<th>Output voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$2.9240 \times 10^4$</td>
<td>$84 \pm 0.05$</td>
<td>$690 \pm 25$</td>
<td>$-0.3731$</td>
</tr>
<tr>
<td>2</td>
<td>$5.9880 \times 10^4$</td>
<td>$84 \pm 0.05$</td>
<td>$560 \pm 25$</td>
<td>$-0.3758$</td>
</tr>
<tr>
<td>3</td>
<td>$3.6496 \times 10^4$</td>
<td>$84 \pm 0.05$</td>
<td>$700 \pm 25$</td>
<td>$-0.3740$</td>
</tr>
<tr>
<td>4</td>
<td>$4.7393 \times 10^4$</td>
<td>$84 \pm 0.05$</td>
<td>$550 \pm 25$</td>
<td>$-0.3750$</td>
</tr>
<tr>
<td>5</td>
<td>$7.5188 \times 10^4$</td>
<td>$84 \pm 0.05$</td>
<td>$510 \pm 25$</td>
<td>$-0.3766$</td>
</tr>
<tr>
<td>6</td>
<td>$1.3774 \times 10^4$</td>
<td>$76 \pm 0.05$</td>
<td>$400 \pm 25$</td>
<td>$-0.3693$</td>
</tr>
<tr>
<td>7</td>
<td>$2.3041 \times 10^4$</td>
<td>$76 \pm 0.05$</td>
<td>$350 \pm 25$</td>
<td>$-0.3719$</td>
</tr>
</tbody>
</table>
From Fig. 3, it is found that the evaluated conductivities match well with the ones measured by the HEM method. The maximum error of evaluation is less than ±4.5% of the conductivity of the wafers. The evaluation method and results are independent of the wafers’ thicknesses. Therefore, a high-precision nondestructive evaluation method has been established.

V. CONCLUSION

In this paper, a nondestructive method for measuring the electrical conductivity of doped GaAs wafers using a compact microwave instrument is demonstrated, and the measurement is independent of wafer thickness. Analytical and explicit expressions for the conductivity are derived with microwave theory, and only two reference samples are needed for calibration. Using the measured output voltages of two reference wafer samples whose conductivities are known for calibrating the two undetermined constants in the evaluation equations and then substituting the output voltage for any other wafer into the evaluation equations, the conductivity of the wafer can be determined. The evaluated results agree well with those obtained with the conventional HEM method, with an error less than ±4.5%.

Moreover, the proposed method could potentially be used for the contactless and nondestructive evaluation of the electrical conductivity of any kind of semiconductor wafer.

ACKNOWLEDGMENTS

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1. Nondestructive measurement and high-precision evaluation of the electrical conductivity of doped GaAs wafers using microwaves


Doped GaAs is one of the most important materials in the semiconductor industry due to its important advantages over silicon, such as a wide band gap and superior conductivity, thermal transport properties, and phonon properties. It is widely used to manufacture devices. To control the quality of doped GaAs wafers either in the process of wafer manufacturing or device fabrication, it is important to know the electrical conductivities of wafers. Four-point-probe method of Hall-effect measurement (HEM) is the conventional technique used to measure the conductivities of semiconductor wafers; however, due to the Schottky barrier at the metal-GaAs interface, this method cannot be used in a contactless and nondestructive way for the measurement of the GaAs wafers. Microwaves have advantage that the response of a sample is directly related to the electrical properties of its composing materials. Therefore, microwaves are widely used in the study of the electrical characterization of semiconductor materials. In addition, microwaves can propagate easily in free space, which makes them suitable for contactless measurements. A nondestructive method for measuring the electrical conductivity of doped GaAs wafers using a compact microwave instrument is presented. Based on the characteristics of the microwave detector and the fact that the microwave measurement is independent of the thickness of the wafer, the analytical and explicit expressions to evaluate the electrical conductivity of the wafer are derived. Using this method, only the voltages of the reflected signals for two wafer samples whose conductivities are known are required to calibrate the two undetermined constants in the equation. Then, the conductivity of any other wafer can be evaluated by substituting the measured voltage of the reflected signal into the explicit expressions. Seven different doped GaAs wafers with thickness larger than 350 µm and conductivities in the range of $1.3 \times 10^4$ S/m to $7.6 \times 10^4$ S/m are measured in the experiment, two of which are used for calibration. Evaluated results agree well with those obtained by the conventional Hall-effect measurement method, with an evaluation error less than ±4.5%. The proposed method is potentially useful for the contactless and nondestructive evaluation of the electrical conductivity of any kind of semiconductor wafer.

![FIG. 1. Schematic diagram of the measurement instrument.](image1)

![FIG. 2. Evaluated conductivities compare with actual values.](image2)