Nondestructive Measurement of Conductivity of Doped GaAs Using Compact Microwave Instrument

Yang Ju, Linsheng Liu
Department of Mechanical Science and Engineering, Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
Email: ju@mech.nagoya-u.ac.jp

Abstract

Doped GaAs is the most important material in semiconductor industry. In this paper, we demonstrated a nondestructive method to measure the conductivity of GaAs wafers using a compact microwave instrument. In the experiment, 8 different GaAs wafers with thickness larger than 350 μm, and with resistivities in the range of 1.33×10^{-3} Ω·cm to 10.4×10^{-3} Ω·cm were measured. By using the intersection points of the evaluation curves obtained from known-resistivity wafer samples and the detected voltages for unknown-resistivity wafers, a nondestructive measurement method to determine the conductivity of GaAs wafer was realized. The measurement results are in agreement well with that obtained by using Hall effect measurement method.

Introduction

Doped GaAs has lots of superiorities such as in band width, conductivity, thermal transport properties, phonon properties and so on [1]-[4], it is widely used in semiconductor, chemical industry, electronics, communication, etc. Nowadays it has become the most important material in semiconductor industry. To control the quality of GaAs wafers either in the process of wafer manufacturing or during device fabrication, it is very important to measure the electrical conductivity of the wafers. Four-point-probe method is the conventional technique to measure the conductivity of semiconductor wafers. However, due to the Schottky barrier at the metal/GaAs interface, it can not be used for GaAs wafers. Commonly, conductivity of GaAs wafer was measured by using Hall effect measurement method [5] [6]. In that case, a square sample should be machined from the wafer, and a special soldering should be carried out in order to ensure good ohmic contacts on the sample.

In our research, we demonstrated a nondestructive method to measure the conductivity of GaAs wafers using a compact microwave instrument. Microwaves have an advantage that the response of a sample is directly related to electrical properties of the material. Therefore, they have widely been used in the study of electrical characterization of semiconductor materials.

Since the thickness of the wafer is large enough, the effect of wafer thickness to the measured microwave signal can be ignored. Therefore, a measurement independent of wafer thickness can be realized [7] [8]. By measuring the reflected microwave signal, the output voltage, which is varying with the conductivity of the wafer, was obtained. By using the intersection points of the curve fitting results obtained from known-resistivity wafer samples and the voltages of wafers whose conductivities are expected to be determined, a nondestructive method to determine conductivity of GaAs wafers is achieved.

Experimental Approach

The experimental instrument is made having a similar cost as the four-point-probe equipment, where microwave signal works at the frequency of 96 GHz, and the power of microwave signal is set to be 10 dBm.

Fig.1 is the flow chart of the measurement instrument, and Fig.2 is the photograph of the instrument.

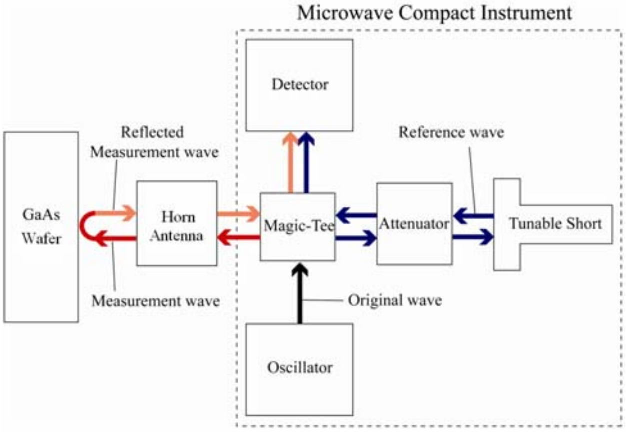

Fig. 1 The flow chart of the experimental instrument

The detection instrument is composed of a microwave compact instrument (which is composed of an oscillator, a magic-tee, a detector, an attenuator, and a tunable short) and a horn antenna.

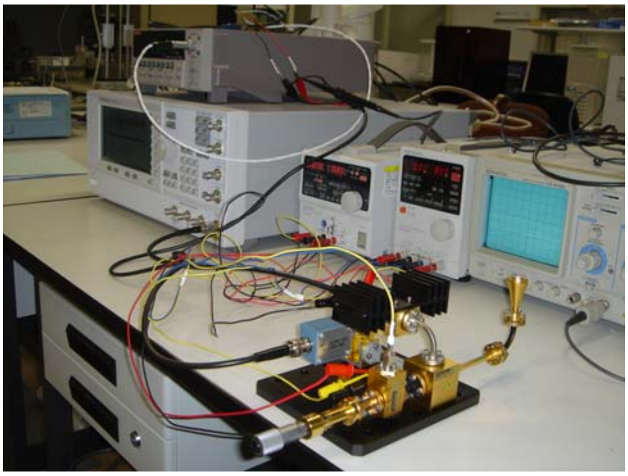

Fig. 2 The photograph of the experimental instrument

When the wafer is in experiment, the reflected signal is received and the reflected voltage is displayed on the oscilloscope.

Figure 3 shows the view of the measurement where the wafer is set on the antenna in a contact fashion. A contact-less fashion having a constant stand off distance between the wafer and the antenna can also be realized.

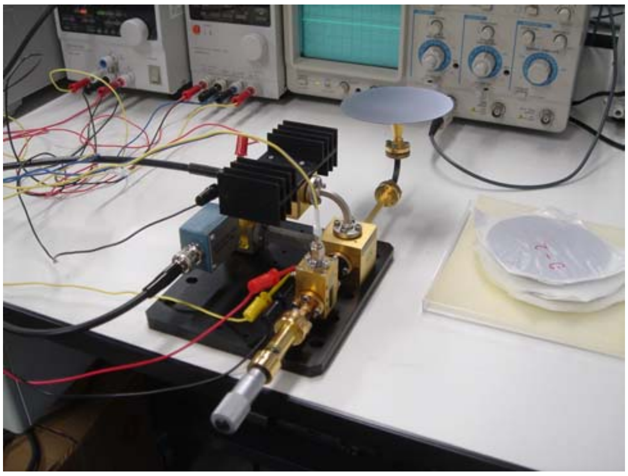

Fig. 3 The photograph of the experimental instrument with a measured GaAs wafer

In the experiment, 5 GaAs wafers with known-resistivity are used as the reference samples to form the evaluation curve, some of their characteristics are shown in Table 1. Another 3 GaAs wafers with unknown resistivities for measurement are shown in Table 2.

From the comparison of Table 1 and Table 2, we can find that all the wafers have similar diameters of about 8 cm, which are a quite ordinary dimension for normal use. The thicknesses of the wafers are from 350 μm to 700 μm.

Table 1 Characteristics of the reference wafer samples

Wafer No.	Resistivity (Ω·cm)	Diameter (mm)	Thickness (μm)
1	3.42×10^{-3}	84.04	690
2	2.74×10^{-3}	83.98	700
3	2.11×10^{-3}	83.98	550
4	1.67×10^{-3}	84.00	560
5	1.33×10^{-3}	84.02	510

According to our former researches [8], if the values of the wafer's thickness and its conductivity are large enough, the effect of the wafer thickness on the measured microwave signal can be ignored (i.e. the measurement result is independent of wafer thickness). Here, we also consider the round trip attenuation of the microwave signals in the wafer to be larger than 99%, the minimum available thickness to satisfy such condition can be obtained from [8]

$$d = \frac{4.61}{\sqrt{2\omega\mu_0\left(\sqrt{\omega^2\varepsilon^2+\sigma^2}-\omega\varepsilon\right)}} \tag{1}$$

where ω is the angular frequency of the microwave; μ_0 and ε_0 are permeability and permittivity of free space; ε and σ are permittivity and conductivity of the wafer ($\varepsilon = 13.1\varepsilon_0$).

Take the resistivity $R \in (1,\ 15)\times10^{-3}$ Ω·cm, then the conductivity $\sigma \in (0.67,\ 10)\times10^{4}$ $S\cdot m^{-1}$, and consider the applied frequency to be 96 GHz, $d_{\min} \in (11.84,\ 46.10)$ μm can be derived from Eq. (1). The maximum value of $d_{\min}$ is still less than 1/7 of the thickness of wafers shown in Table 1 and Table 2. It means that the measurement independent of wafer thickness can be realized.

Table 2 Characteristics of the wafers used for detection

Wafer No.	Resistivity (Ω·cm)	Diameter (mm)	Thickness (μm)
6	$3\text{~}5\times10^{-3}$	76.02	350
7	$5\text{~}10\times10^{-3}$	75.96	400
8	$10\text{~}15\times10^{-3}$	76.00	430

With setting the output voltage without any wafer to be zero as a calibration, output voltages of the measured microwave signals were recorded and shown in Table 3.

Table 3 Output voltages of GaAs wafers

Wafer No.	Output voltage (V)	Wafer No.	Output voltage (V)
1	-0.3731	5	-0.3766
2	-0.3740	6	-0.3719
3	-0.3750	7	-0.3693
4	-0.3758	8	-0.3651

Results and Discussion

The measured voltages versus the resistivities of the reference samples are shown in Fig.4. Quadratic polynomial fitting (QPF) result of the 5 experimental points is also shown in this figure. The relationship between the resistivity and voltage is

$$R = 59.5420*V^2 + 45.2364*V + 8.5927 \tag{2}$$

Taking the measured voltages of the 3 unknown-resistivity wafers into account, the evaluated results are shown in Fig. 5. In Fig. 5, the curve is the same as that shown in Fig. 4, and the resistivity-coordinate values of the intersection points of the fitting curve and the voltage lines are the resistivities of the wafers to be detected.

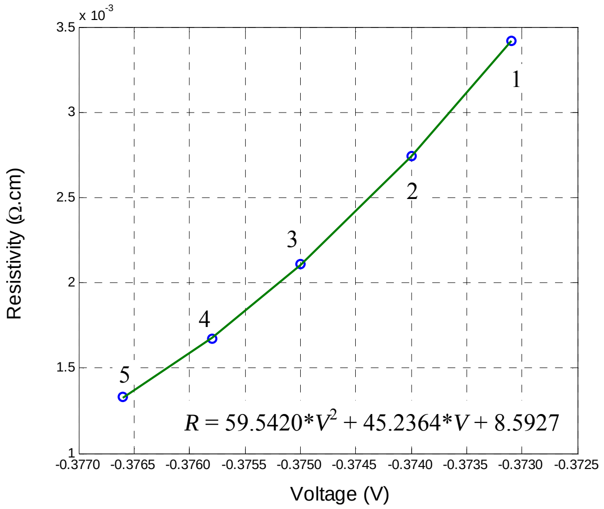

Fig. 4 QPF of the experimental results for the5 known-resistivity samples

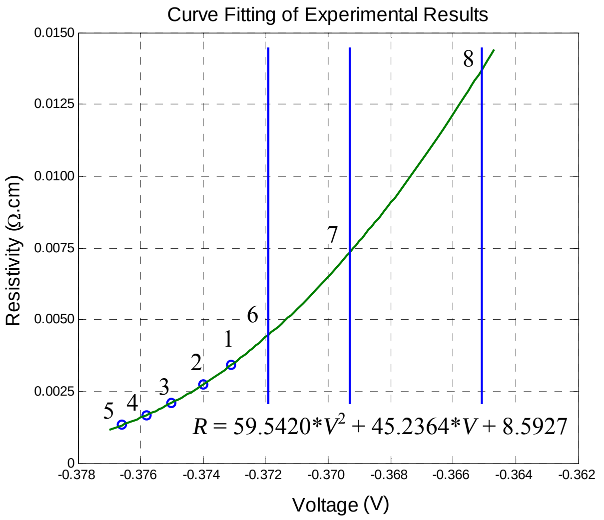

Fig. 5 Resistivity evaluation of the detected wafers using the QPF curve

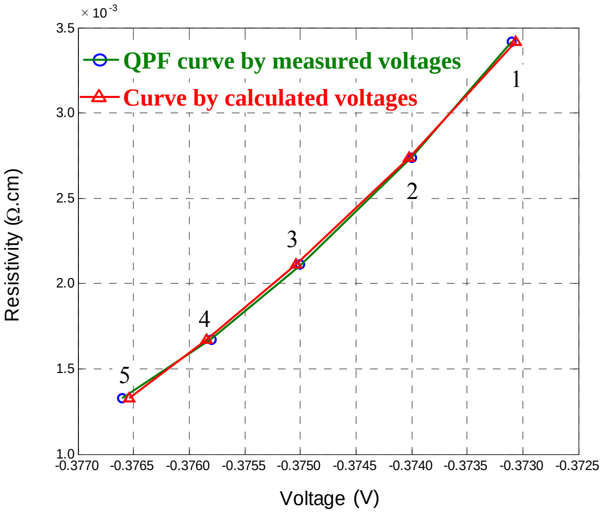

Fig. 6 Evaluation curves obtained by the measured and calculated voltages

Because the voltage lines of the 3 unknown-resistivity wafers are located far from the reference points, the deviation of the evaluated result may be larger in the case of the wafer having a larger resistivity. In practice this issue can be avoided by using reference samples with measured voltages around that of the wafers to be detected.

Figure 6 shows the evaluation curves obtained from the measured voltages and modified by using theoretical calculation [8]

$$|\Gamma_s| = \left|\frac{-\eta_1 + \eta_2}{\eta_1 + \eta_2}\right| \tag{3}$$

where $\eta_1 = \sqrt{\mu_0 / \varepsilon_0}$ is the intrinsic impedance of free space, and $\eta_2 = \sqrt{\mu/\varepsilon}\Big/\sqrt{1 - \mathrm{j}\sigma/(\omega\varepsilon)}$ is the intrinsic impedance of wafer with $\mu = \mu_0$.

In Fig. 6, the voltages calculated from the theoretical reflection coefficients are obtained by using the equation

$$V = k_0 * |\Gamma_s|^2 + b_0 \tag{4}$$

and the k_0=-0.2490 and b_0=-0.1334 are determined by comparing the values of V and $|\Gamma_s|^2$ based on the resistivities of the reference samples.

The resistivities evaluated by the QPF curve obtained from the measured voltages and by the curve obtained from the calculated voltages are shown in Table 4.

Table 4 Resistivity obtained by different measurement method

Wafer No.	Resistivity by Hall effect method (Ω·cm)	Resistivity by measured voltages (Ω·cm)	Resistivity by calculated voltages (Ω·cm)
6	4.34×10^{-3}	4.47×10^{-3}	4.34×10^{-3}
7	7.26×10^{-3}	7.34×10^{-3}	6.79×10^{-3}
8	10.4×10^{-3}	13.6×10^{-3}	11.9×10^{-3}

From the results shown in Fig. 6, it can be found that the shape of the curve obtained from the QPF is almost the same as that obtained from the calculation, but there is a little different in the gradient, i.e., the slope of the QPF curve is a little larger than that of the calculated one. It will also affect the evaluated results.

Conclusions

In this paper, we derived a nondestructive method to measure the conductivity of GaAs wafer by using a compact microwave instrument. In the experiment, the measurement result was independent of wafer thickness. By measuring the reflected microwave signal, the output voltages varying with the conductivities of the wafers were obtained. By using the evaluation curves obtained from the reference samples, the conductivity of GaAs wafers are determined.

With comparing with the results measured by using Hall effect measurement method, good agreement of this nondestructive measurement method is confirmed.

Since the nondestructive measurement is realized and the measurement result is independent of the wafer thickness, this technique could be used to determine conductivity of GaAs wafers not only on as assembly line but also on various other purposes.

Acknowledgments

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