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Contactless measurement of electrical conductivity of semiconductor wafers using the reflection of millimeter waves

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We present a method for quantitative measurement of electrical conductivity of semiconductor wafers in a contactless fashion by using millimeter waves. A focusing sensor was developed to focus a 110 GHz millimeter wave beam on the surface of a silicon wafer. The amplitude and the phase of the reflection coefficient of the millimeter wave signal were measured by which electrical conductivity of the wafer was determined quantitatively, independent of the permittivity and thickness of the wafers. The conductivity obtained by this method agrees well with that measured by the conventional four-point-probe method. *© 2002 American Institute of Physics.* [DOI: 10.1063/1.1520339]

Conductivity is one of the important electrical properties of semiconductors, just as carrier concentration, carrier mobility, and the lifetime of excess carriers. It is very important to measure the electrical conductivity of semiconductor wafers in order to control their quality, either in the process of wafer manufacturing or during device fabrication. The four-point-probe method is the conventional technique for conductivity measurement of semiconductor wafers and it is still widely used today due to its cost effectiveness.[1,2] However, the sample might be damaged or contaminated by the mechanical contact of the probe. In addition, in order to determine the conductivity quantitatively, a thickness calibration is required. A contactless method to measure the conductivity of semiconductor wafers is the coil method, which measures small impedance changes of an inductive coil placed in close proximity to a sample.[3–5] Although the conductance of the sample affects the magnitude of induced eddy currents and thus the effective impedance of the coil, to determine the conductivity of the sample, the thickness of the sample has to be measured by another technique. In this letter, we demonstrate a contactless measurement method using millimeter waves for determining conductivity of semiconductor wafers quantitatively.

Microwaves (including millimeter waves) have the advantage that the sample's response is directly related to electrical properties of materials; therefore, they have been widely used in the study of electrical characterization of semiconductor wafers. By combining with laser techniques, microwaves have been used for determining minority-carrier lifetimes of silicon wafers,[6] and for mapping photoconductivity of GaAs wafers.[7] On the other hand, microwaves have been used for measuring the sheet resistance of conducting films in different configurations.[8–10] However, the measurement of electrical conductivity (or resistivity) of semiconductor wafers, using microwaves, has not been successful as yet.

In this experiment, a high-frequency millimeter wave was used in order to ensure the transmitted millimeter wave attenuated rapidly inside the wafer, so that the reflection from the bottom surface of the wafer can be neglected. Thereby, it becomes possible to consider the reflection only on the top surface of the wafer, thus, the millimeter wave response signal is not affected by the thickness of the wafer. In addition, in the experiment, both the amplitude and phase of the reflection coefficient are measured. By using these two parameters, it is possible to determine the conductivity independent of the permittivity of the semiconductor wafers. Moreover, to increase the sensitivity of the measurement, the millimeter wave was focused on the wafer surface with a larger standoff distance between the sensor and the sample, which was thought to satisfy an important requirement for on-line application. Furthermore, a higher spatial resolution was obtained that allows the technique to map out the distribution of the conductivity of semiconductor wafers.

The principle of the technique described here is based on the interaction of the millimeter wave with the semiconductor wafer. When a millimeter wave signal irradiates a semiconductor wafer, reflections occur at both the top and bottom surfaces of the wafer due to the discontinuity of medium. The millimeter wave signal reflected from the wafer will be the sum of the two components reflected from the top and bottom surfaces. Since the reflected component from the bottom surface varies with the thickness of the wafer, generally this thickness will affect the measurement results. However, since the attenuation of the millimeter wave increases rapidly inside the wafer with increasing operating frequency, the reflected component from the bottom surface can be decreased to a negligible value by using a high operating frequency. Therefore, the measured reflection coefficient of the millimeter wave signal can be expressed by considering the reflection only from the top surface as

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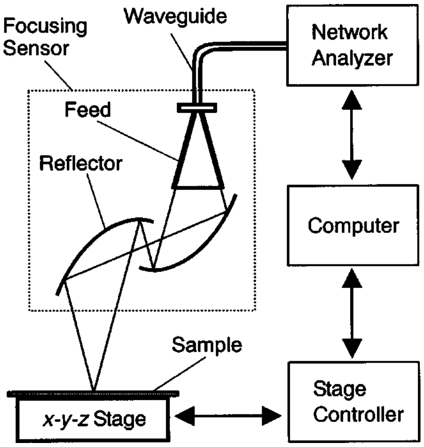

FIG. 1. Configuration of the millimeter wave measurement system.

$$\Gamma=\frac{\eta-\eta_0}{\eta+\eta_0}, \tag{1}$$

where

$$\eta=\sqrt{\frac{\mu}{\epsilon-j\frac{\sigma}{\omega}}} \tag{2}$$

and

$$\eta_0=\sqrt{\frac{\mu_0}{\epsilon_0}}. \tag{3}$$

In the above equations, Γ represents the reflection coefficient, and η and η_0 are intrinsic impedance of the semiconductor wafer and free space, respectively; σ, μ, and ϵ are the conductivity, permeability, and permittivity of the semiconductor wafer, and μ_0 and ϵ_0 are the permeability and permittivity of free space, respectively; ω denotes the angular frequency, and $j=\sqrt{-1}$.

For nonmagnetic materials, considering $\mu=\mu_0$, and using the above equations, the reflection coefficient can finally be written as

$$\Gamma=X+jY=\frac{1-\sqrt{\frac{\epsilon}{\epsilon_0}-j\frac{\sigma}{\omega\epsilon_0}}}{1+\sqrt{\frac{\epsilon}{\epsilon_0}-j\frac{\sigma}{\omega\epsilon_0}}}. \tag{4}$$

By solving the simultaneous equations of the real and imaginary parts of Eq. (4) and eliminating ϵ, the conductivity of semiconductor wafers can be expressed as

$$\sigma=\frac{4\omega\epsilon_0 Y(1-X^2-Y^2)}{[(1+X)^2+Y^2]^2}. \tag{5}$$

Figure 1 shows the configuration of the millimeter wave measurement system. A network analyzer was used to generate a millimeter wave signal fed to a focusing sensor and to measure both the amplitude and phase of the reflection coefficient. A millimeter wave of 110 GHz was used. Under this condition, the reflection from the bottom surface was calculated to be four orders of magnitude smaller than that from the top surface of the wafer for a silicon wafer having a thickness of 500 μm and conductivity of 200 S/m. A computer was used to control the stage and to recode the data measured by the network analyzer. Each experimental point is the average of 200 data points measured in less than 0.05 s. We developed a focusing sensor which consists of a horn feed and two ellipsoidal reflectors and has a size of $58\times54\times66$ mm^3 to obtain a larger standoff distance, higher sensitivity and higher spatial resolution. The focusing sensor acts as the source of the millimeter-wave signal incident on the wafer and also as the receiver of the reflected signals from the surface of the wafer. The diameter of the focused spot is approximately 2 mm and the standoff distance is fixed at 35 mm.

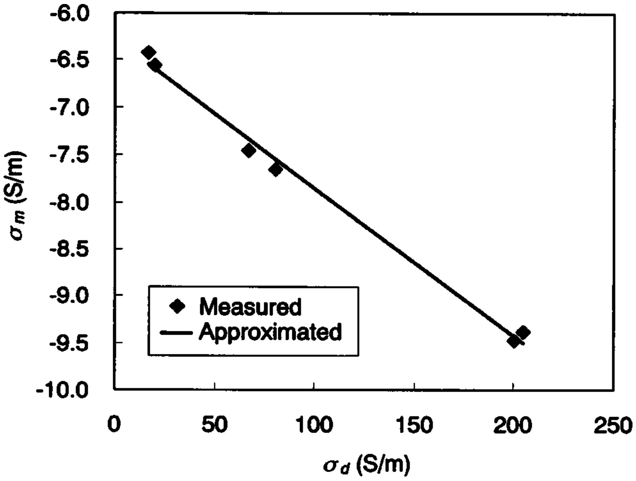

FIG. 2. Relationship between the raw value of the conductivity σ_m, obtained by the millimeter wave measurement and the conductivity σ_d, measured by the four-point-probe method.

Three groups of 30 wafers having conductivities of 9~11, 50~110, and 166~333 S/m were used in our experiment. The samples are *n*-type silicon wafers with planar, (100)-oriented surface, each having a diameter of 100±0.5 mm and a thickness of 525±25 μm. For each wafer, the amplitude A and the phase θ of the reflection coefficient were measured. By using Eq. (6), the real part X_m and imaginary part Y_m of the measured reflection coefficient Γ_m, were obtained.

$$\Gamma_m=X_m+jY_m=10^{A/20}e^{j\theta}. \tag{6}$$

By substituting X_m and Y_m for X and Y in Eq. (5), respectively, the conductivity σ_m was obtained. However, here σ_m is a raw value that is affected by the operating frequency, standoff distance, and an error introduced by nonideal factors of the focusing sensor. Therefore, a calibration is needed in order to obtain σ_l, the low frequency conductivity of the wafer. For this purpose, six wafers were used to generate the calibration equation. Figure 2 shows the relationship between σ_m and the conductivity σ_d, measured by using the four-point-probe method. From Fig. 2, a calibration equation was obtained by replacing σ_d with σ_l as

$$\sigma_l=C_1\sigma_m+C_2, \tag{7}$$

where $C_1=-63.69$ and $C_2=-400.63$ S/m. Using Eq. (7), the conductivities of other 24 wafers were finally determined, as shown in Fig. 3. The conductivities of silicon wafers measured by millimeter waves agree well with those measured by the four-point-probe method.

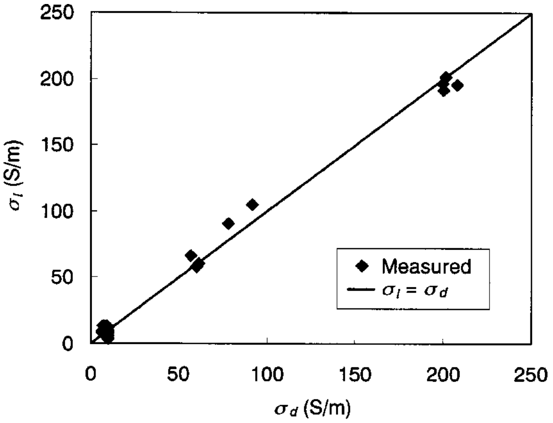

FIG. 3. Comparison of the conductivity at low frequency σ_l, obtained by the millimeter wave method and the conductivity σ_d, measured by the four-point-probe method.

It is noted that if the conditions of the measurement or the kind of wafers is changed, the values of C_1 and C_2 also change. However, by using two reference samples, those values can easily be obtained, and the conductivity of the wafers can be determined. Therefore, for any semiconductor wafer with either carrier type, if the thickness of the wafers is larger than several 100 μm, it is possible to measure its electrical conductivity quantitatively in a contactless fashion by using the method described earlier. However, if the thickness of the wafers is very small, a different measurement setup and a thickness calibration are required. Since the measurement speed is sufficiently high, the technique could be used to measure the conductivity of semiconductor wafers on an assembly line.

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