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Microwave measurement of the conductivity of conducting thin films

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Abstract: A new method to measure the conductivity of conducting thin films in a contactless fashion was demonstrated. A microwave compact equipment working at 94 GHz was used to measure the amplitude of the reflection coefficient of the microwave signal. Indium Tin Oxide films having conductivity of $8.20\times10^{4}\sim8.02\times10^{5}$ S/m on the glass substrates were used as the samples. An evaluation equation was built to determine the conductivity from the measured amplitude of the reflection coefficient. The evaluated conductivity of conducting thin films agrees well with their actual value.

Key words: conductivity; conducting film; microwave; contactless; compact equipment
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1　Introduction

With the development of information technology and the requirement of environmental protection, thin conducting film has become more and more important. It has been widely used as a transparent electrode, and a heat_reflecting glass. In order to control the quality of thin conducting film in the process of manufacturing, a commercial method to measure its electrical conductivity quantitatively is required. Four point probe method is the conventional technique for conductivity measurement of thin conducting film[1-2]. However, the mechanical contact of the probe with a sample may damage the sample and is not suitable for on_line measurement. Coil method can measure the conductivity of thin conducting film in a contactless fashion[3-4]. However, the close proximity of the inductive coil to the sample also cannot satisfy the requirement of on_line testing. In this paper, we demonstrate a new microwave method by which the conductivity of thin conducting film can be measured.

On the other hand, usually, a network analyzer is used as the equipment for microwave nondestructive testing. It has a large size and high price, and is difficult to be used in the industrial environment. To overcome these problems, we have developed a compact equipment working at 94 GHz by which the conductivity of thin conducting film is determined successfully.

2　Description of the equipment

A microwave compact equipment was designed

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and fabricated for microwave NDT5. Figure 1 shows the schematic depiction of the microwave measurement system. This system is composed of microwave compact equipment, computer and x_y_z stage. A Gunn_diode oscillator supplies a continuous microwave signal having a fixed frequency of 94 GHz. A coupler divides the microwave signal into a measurement signal and a reference signal with the power ratio of 9: 1. During the measurement, the reference signal is constant and used as a standard signal to be compared with the measurement signal. The measurement signal is applied to the sample through a sensor. After interacting with the sample, the reflected wave is received by the same sensor. Then both the measurement signal and the reference signal are guided to a 4_path detecting circuit. By detecting the two signals in the circuit, the amplitude ratio of the reflected signal to the reference signal and phase difference between the two signals are measured. The compact equipment is 370 mm long, 480 mm wide and 145 mm high.

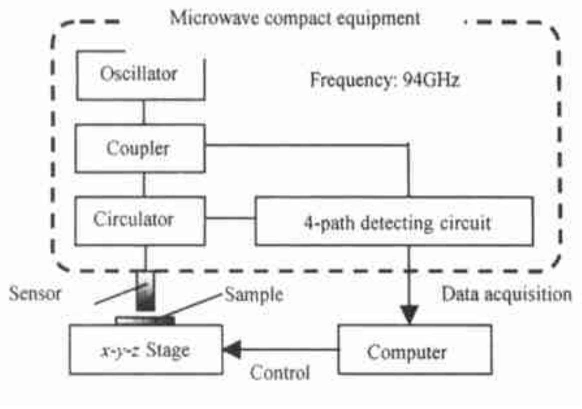

Fig. 1 Schematic depiction of microwave measurement system.

3 Theoretical considerations

The principle of the technique described here is based on the interaction of microwave with thin conducting film. When a microwave irradiates a conducting film, a reflection will be generated on the film surface. Since the conductivity of the film is high enough, the reflection coefficient of the microwave, Γ, can be expressed as

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

where

$$\eta = (1+j)\sqrt{\frac{\omega\mu}{2\sigma}}, \quad \eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}, \tag{2}$$

In the above equations, η and η_0 are intrinsic impedance of the conducting film and free space, respectively; σ and μ are conductivity and permeability of the conducting film, where μ_0 and ε_0 are permeability and permittivity of free space, respectively; ω denotes the angular frequency, and $j = \sqrt{-1}$. For nonmagnetic material, we can approximate μ by μ_0. Then, from the above equations, the reflection coefficient can finally be written as

$$\Gamma = \frac{\omega\varepsilon_0 - \sigma + j\sqrt{2\omega\varepsilon_0\sigma}}{\omega\varepsilon_0 + \sigma + \sqrt{2\omega\varepsilon_0\sigma}}, \tag{3}$$

From Eq. (3), the amplitude of the reflection coefficient, $|\Gamma|$, is obtained as

$$|\Gamma| = \frac{\sqrt{\omega^2\varepsilon_0^2 + \sigma^2}}{\omega\varepsilon_0 + \sigma + \sqrt{2\omega\varepsilon_0\sigma}}, \tag{4}$$

In the case of conducting thin films, σ is enough higher than $\omega\varepsilon_0$. Therefore, Eq. (4) can be expressed as

$$\sigma = \frac{2\omega\varepsilon_0 |\Gamma|^2}{(1-|\Gamma|)^2}, \tag{5}$$

4 Experimental procedure and results

In the experiment, 5 Indium Tin Oxide (ITO) films on the glass substrates having conductivity of 8.2× 104(8.2× 105 S/ m were used. Using the microwave compact equipment, the amplitude of the reflection coefficient, $|\Gamma_i|$, was measured for each specimen by an open_ended rectangular waveguide, with a standoff distance of 0.1 mm, where i denotes specimen number. Table 1 shows the conductivity of ITO films used for the experiment and the measured amplitude of the reflection coefficient. Because the measured $|\Gamma_i|$ takes a raw value which is affected by the operating frequency and errors introduced by the equipment, based on Eq. (5), the relationship between σ_i and $|\Gamma_i|$ may be written as

$$\sigma_i = \frac{C_1 |\Gamma_i|^2}{(C_2 - |\Gamma_i|)^2}, \qquad (6)$$

where C_1 and C_2 are constants. Specimens 2 and 4 were used to determine C_1 and C_2. By solving simultaneous equations we obtained $C_1 = 1.414\times 10^4$ S/m and $C_2 = 1.045$. Then, substituting $|\Gamma_i|$ into Eq. (6), the conductivity, σ_i, was obtained for Specimens 1, 3 and 5. Figure 2 shows the relationship between σ_i and the actual conductivity, σ_a. The conductivity of ITO films measured by microwave method agrees well with their actual value.

Table 1　Conductivity of ITO films and measured amplitude of reflection coefficient

Specimen number	Conductivity, σ_a [kS/m]	Amplitude of the reflection coefficient, $\|\Gamma_i\|$
1	82	0.7385
2	206	0.8281
3	608	0.9084
4	673	0.9128
5	802	0.9252

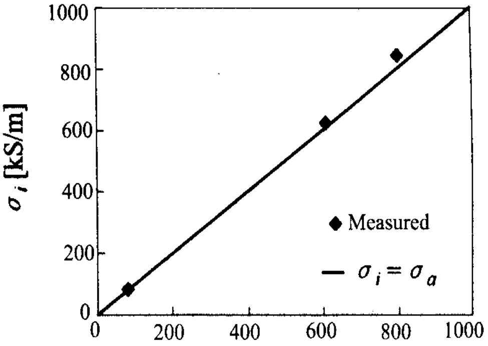

Fig. 2　Relationship between conductivity, σ_i, obtained by microwave measurement and actual conductivity, σ_a.

5　Conclusions

The method for contactless measurement of the conductivity of conducting thin films was demonstrated. By using the microwave compact equipment, the measurement was carried out successfully. The good measurement results show that the proposed technique is a powerful tool for the measurement of the conductivity of conducting thin films.

6　Acknowledgement

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