High Resolution Subwavelength Inspection Method for Measuring the Uniformity of Conducting Films *

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A microwave adapter was fitted to a wax filled reducing wedge in order to transmit 8–12 GHz microwaves through a sub-wavelength rectangular opening. The configuration produced a 70 dB dynamic range and was found suitable for high resolution inspection of 1 to 10,000 ohm per square conducting films. Network analyzer measurements on 12 conducting films that were reported to be 5 to 1500 ohms per square are compared to the reported values and reconciled with electromagnetic theory.

1. Introduction

Subwavelength microscopy has developed rapidly during the past twenty years [1, 2]. It began with the fabrication of submicron light pipes [3] for use in near-field optical microscopy. Now apertures as small as one namometer [4] diameter have been used with phonon generating materials.

Near-field optical scanning involves viewing samples that are placed near the microscopic aperture. In this case, the limiting factor on resolution is the size of the aperture and not the diffractive properties of electromagnetic radiation. Diffractive properties occur only after waves have traveled a definite distance.

The prospect of utilizing high resolution subwavelength microscopy at microwave frequencies has been investigated at Lockheed Martin. The specific application was to inspect thin conductive films for coating uniformity.

2. Technique

A wax wedge (see Fig. 1) was constructed to reduce a microwave adapter aperture to subwavelength size. The index of refraction of the wax was about 1.5 and aided in the reduction process. The exterior of the double wax reducer wedge was coated with silver paint to eliminate electromagnetic leakage. The geometric size reduction of five-to-one was found to reduce the power throughput by a factor-of-ten.

Time domain measurements made with an HP-8510 Vector Network Analyzer revealed a well defined signal coming from the small aperture. A blocking conductor demonstrated that the throughput was 70 dB above background noise.

It was estimated that the apparatus was satisfactory for measuring the transmissivity of 2 to 10,000 Ω/square conducting films.

3. Theory

A boundary value solution of Maxwell's equations for a one layer conducting film give the following expressions for power (or energy flux) reflection and transmission coefficients:

$$R = |r|^2 = \left| \frac{r_{12}(1 - e^{2\alpha})}{1 - r_{12}^2 e^{2\alpha}} \right|^2, \tag{1}$$

$$T = |t|^2 = \left| \frac{(1 + r_{12})(1 - r_{12}) e^{\alpha - \beta}}{1 - r_{12}^2} \right|^2, \tag{2}$$

where $\alpha = i k_2 d$ and $\beta = i k_0 d$.

The term Z is the so called electromagnetic impedance of the conducting layer and is given (for non-magnetic media) by

$$Z_2 = \sqrt{\frac{K_\mu^*}{K_\varepsilon' - i K_\varepsilon'' - i \sigma/\omega \varepsilon_0}}, \tag{3}$$

where K_μ^* is the complex relative permeability, K_ε' is the real part and K_ε'' the complex part of the permit-

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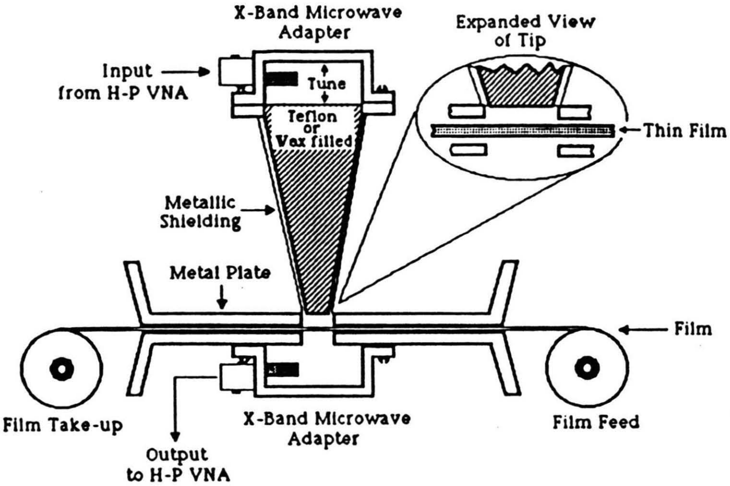

Fig. 1. Diagram of experimental apparatus used to measure subwavelength transmission through thin conducting films.

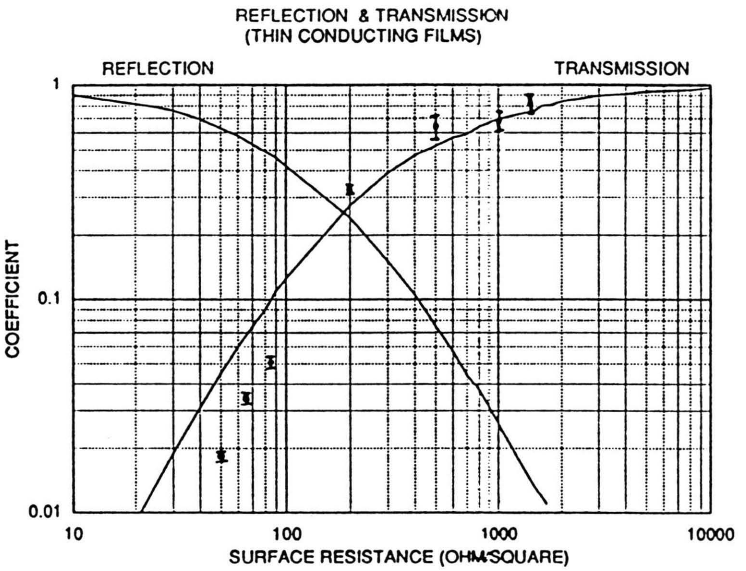

Fig. 2. Plot of theoretical reflection and transmission coefficient vs. surface resistance (ohm/square). [The plotted values indicate the manufacture's values, while the high resolution values are obtained by extrapolating to the transmission curve.]

tivity ($K_\varepsilon^* = K_\varepsilon' - i K_\varepsilon''$), σ, the conductivity of the layer, $\omega = 2\pi f$ the angular frequency, and ε_0 the permittivity of free space.

The expression for the electromagnetic impedance is simplified when the conducting layer is thin compared to the wavelength of the electromagnetic radiation. In this case the term containing σ dominates and (3) reduces to

$$Z_2 = \sqrt{i\,(\Omega/\text{square})\,\omega\,\varepsilon_0\,t}\,. \qquad (4)$$

4. Results

Power reflection and transmission coefficients were computed with (1) and (2). They show (Fig. 2) a cross point at half the impedance of free space ($Z_0/2$) where both coefficients are 0.25 and cover a dynamic range from 10 to 10,000 Ω/square.

Transmission coefficients were measured on 7 unhandled conducting films. The average and standard deviations of six representative measurements on each film are plotted in Fig. 2 at the surface conductivities labeled by the film manufacturer. A preferred film resistivity would be obtained by translating the measured data to the transmission curve of Figure 2.

5. Conclusions

A high resolution subwavelength method has been demonstrated for measuring the surface conductivity of thin conducting films. Measured transmission coefficients can be used to obtain thin film conductivities from Figure 2. Time domain measurements discriminate against electromagnetic noise and have been successfully utilized at frequencies from 8 to 20 GHz. The method is particularly useful in verifying film uniformity and characterizing gradient coatings.

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