MAPPING THE THICKNESS OF CONDUCTING LAYERS BY A MM-WAVE NEAR-FIELD MICROSCOPE

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ABSTRACT

We describe a quantitative contactless technique of mapping resistivity of conducting films using a 80 GHz near-field scanning probe. We report (i) a capacitive method of maintaining a constant probe-sample separation; (ii) a quantitative measurements of near-field mm-wave reflectivity of conducting films.

INTRODUCTION

An evaluation of the thickness of thin conducting layers is an important task in semiconducting industry. This may be conveniently done through the measurement of sheet resistance *R*, using the relation $d=\rho/R$ where d is the thickness and ρ is the known specific resistivity of the layer. The sheet resistance is usually measured either by the four-point technique or by the eddy-current probe. Both these methods have serious limitations in the determination of the thickness of thin metal coatings on semiconducting wafers. While the four-point method requires electrical contact which may damage the sample; the penetration depth of the standard eddy-current probe is too big, so it senses both the substrate and the coating. Microwave reflectivity [1] is more advantageous for thickness monitoring of submicron thick conducting layers since the penetration depth of microwaves for majority of metals is below 1 µm. Early applications of microwave reflectivity for the determination of the thickness of conducting layers were limited either by insufficient spatial resolution or by insufficient sensitivity. A recent rise of interest in the scanning probe microscopy has resulted in several advanced microwave near-field probes based on sharp tip that have overcome these limitations [2-4]. However, these techniques cannot be directly applied to thickness monitoring of conducting layers since they either requires a mechanical contact with the sample [3] or do not have enough sensitivity [2] to probe highly conducting metallic layers common in semiconducting industry (Al, Cr, W, Ti, etc) Microwave near-field scanning techniques based on waveguide probes [5-7] are more promising for this task.

We have recently developed a near-field contactless resistivity microscope which operates at 80 GHz and has a spatial resolution of 10-30 µm [5]. Here, we describe the application of our technique for local measurements of resistivity and thickness of conducting layers with a sheet resistance of 0.2-10•. This has become possible through the careful control of the probe-sample separation which is a prerequisite for quantitative resistivity mapping.

PROBE DESIGN

Figure 1 demonstrates our scanning probe which is a thin slit cut in the convex endplate of a rectangular waveguide [5]. This

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slit is a transmitting/receiving mm-wave antenna. The same endplate also serves as one plate of rf-capacitor, while the sample serves as another plate. This is achieved through electrical isolation of a short waveguide section containing the probe from the rest of the mm-wave circuit by a thin mylar sheet (Fig. 1). While the mylar sheet is transparent for the mm-wave, it preserves a good electrical isolation for lower frequencies. An rf-oscillator is connected to the waveguide section with the probe, while the ground of the oscillator is connected to the rest of the mm-wave tract and, if possible, to the conducting sample. The rf resonant circuit includes the probe-sample capacitance which strongly depends on the probe-sample separation. By tracking the resonant frequency of the oscillator, we measure the probe-sample capacitance, and thus, the probe-sample separation.

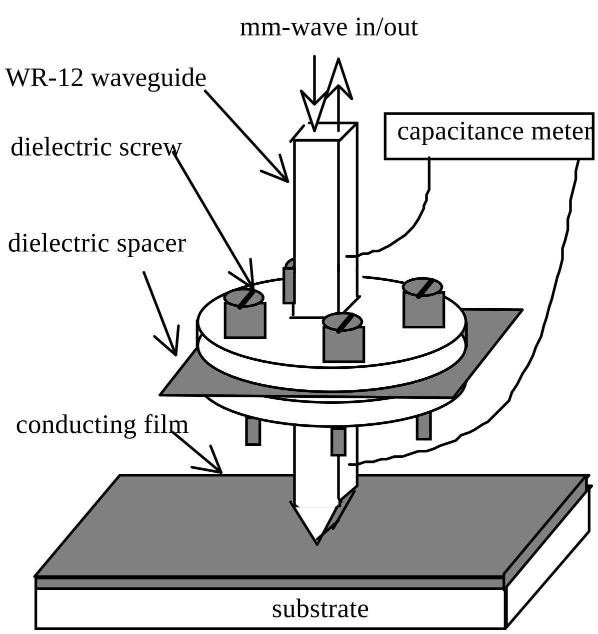

Fig.1. Design of a mm-wave near-field probe with a capacitance distance control. The probe is a thin slit cut in the convex endplate of a rectangular waveguide. Probe-sample separation is determined from the measurement of probe-sample capacitance at 6 MHz while the information on the film thickness is achieved through the mm-wave reflectivity at 80 GHz.

EXPERIMENTAL RESULTS

We measured mm-wave reflectivity of several e-beam evaporated 2"×2" films of Ag, Al, Au, and Ti on float-glass substrate, calculated their resistance, and compared the data to the dc-resistivity measured by the van-der-Pauw technique. The mm-wave probe is immobile while the samples were mounted on an XYZ stage at a controlled separation beneath the probe. We measured the magnitude and phase of the mm-wave reflectivity S_{11} at 80 GHz and in several points on each film, using an HP 8510C vector network analyzer. We found that the 80GHz signal strongly depends on the probe-sample separation, as well as on the sheet resistance of the film. The capacitance signal at 6 MHz was found to be also strongly dependent on distance, while it was almost insensitive to the sheet resistance. By combination of the mm-wave data and the rf-data we determined the mm-wave near-field reflectivity of our samples.

Figure 2 demonstrates the magnitude and phase of the S_{11} for several thin films of different

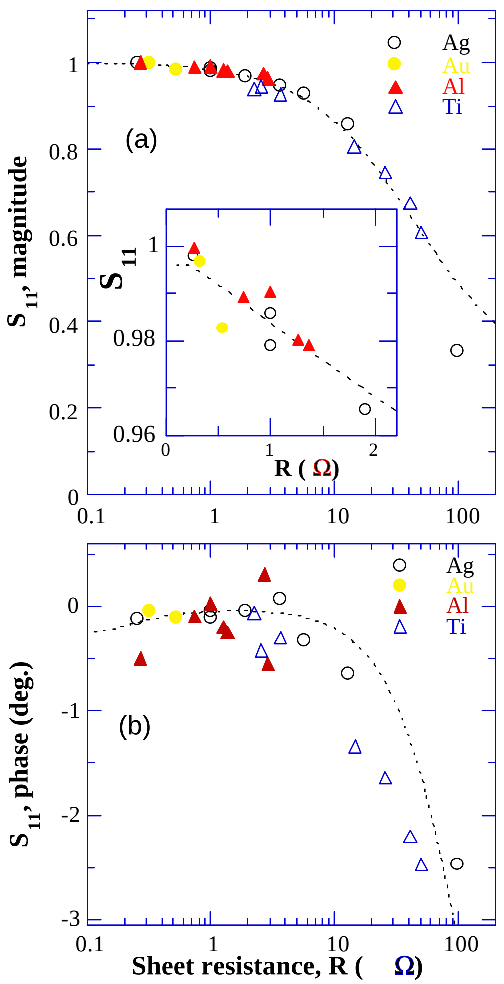

Fig.2 Magnitude (a) and phase (b) of the near-field mm-wave reflectivity S_{11} vs. sheet resistance of thin metallic films (thickness ~80Å to ~1000Å) on glass substrate. The probe is a resonant slit with a width of 10 µm operating at 81 GHz. Probe-sample separation is~5 µm. Dashed lines show model prediction. Linear dependence of the magnitude of S_{11} upon sheet resistance for small sheet resistances (inset) allows thickness control even for films with average sheet resistance of several ohms.

metals. The phase shifts are measured with respect to reflection from bulk Al. Note, that the magnitude of S_{11} for the measured conductors depends only upon their sheet resistance irrespective of their bulk resistivity (1.6 µ•·cm for Ag, 2.4 µ•·cm for Al and 55 µ•·cm for Ti). Hence, the magnitude of S_{11} allows estimate of the film thickness, provided the resistivity is known. To determine resistivity and thickness separately, the phase measurements may provide some help although this is not an easy task.

MODEL

To convert mm-wave reflectivity to film thickness we use a transmission line model which relates reflectivity $\Gamma=(Z_s' - Z_p)/(Z_s' + Z_p)$ to the probe impedance Z_p and to the effective impedance of the sample Z_s' [8]:

$$Z'_s = Z_s \frac{Z_{sub} + iZ_s \tan(k_s d)}{Z_s + iZ_{sub} \tan(k_s d)} \qquad (1)$$

Here d is the film thickness, Z_{sub} is the complex impedance of the substrate, $Z_s=(i\mu_0\omega\rho)^{1/2}$ is the surface impedance of an infinitely thick sample, δ is the skin-depth, and $k_s=(1+i)/\delta$•$2=\mu_0\omega/Z_s$.

(i) In the thick-film limit ($d>>\delta$), the effective impedance equals to surface impedance, Z_s' • Z_s which depends upon the resistivity of material but neither on the film thickness nor on the properties of the substrate.

(ii) In the thin-film limit ($\rho/Z_{sub}<<d<<\delta$) the effective impedance is

$$Z'_s \approx \frac{\rho}{d} + i\frac{\mu_0 \omega d}{3} \qquad (2)$$

It is determined by the film thickness and by the resistivity and does not depend on the impedance of the substrate. The reactive part of Z_s' is much smaller than the resistive part. The magnitude of the reflectivity is determined by the Re (Z_s') while the phase shift is determined by the Im (Z_s').

(iii) The effective impedance in extreme thin-film limit ($d<<\rho/Z_{sub}$) strongly depends on the complex impedance of the substrate:

$$Z'_s \approx Z_{sub}\left(1 - \frac{Z_{sub} d}{\rho}\right) \qquad (3)$$

In this regime, the magnitude of the reflectivity depends on the sheet resistance of the film while the phase shift is determined by the loss tangent and thickness of the substrate, and by the sheet resistance of the film as well. This regime c orresponds to very thin films with R > 20• (which corresponds to film thickness of 100Å for Ag and 300Å for Ti).

Figures 2 and 3 (dashed lines) demonstrate model prediction for several very different conductors common in semiconducting industry. The model predicts that (i) the magnitude of S_{11} for the films with R > 0.5• is determined only by the sheet resistance; (ii) the phase is determined both by resistivity and thickness for R < 2•, while for R > 2• it is

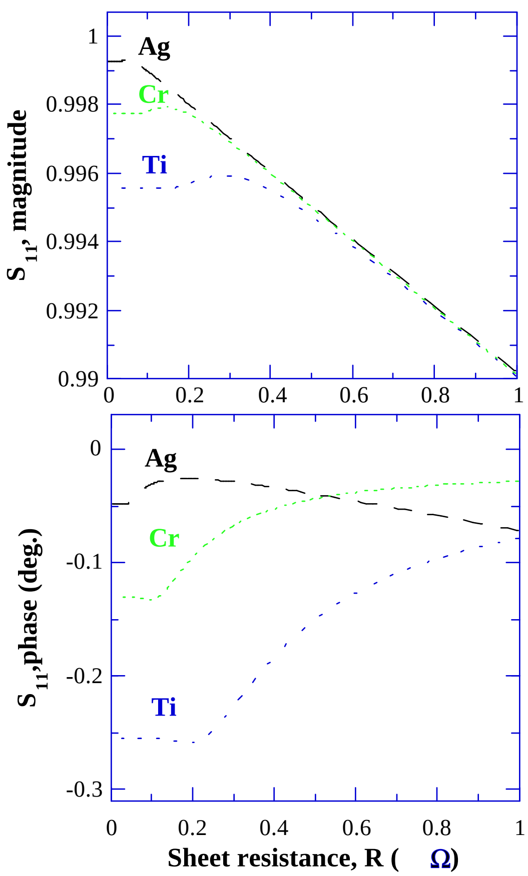

Fig.3 Model prediction for the magnitude and phase of the reflectivity of several conductors of different thickness at 100GHz. The resistivity of each conductor is assumed to be independent on thickness. Model predictions for R>1Ω are demonstrated on Fig.2.

determined by the sheet resistance and by the properties of the substrate as well.

Although the meaning of the probe impedance in the near-field is not clear, we describe our experimental results using above equations, which were developed for the far-field. A good fit to the magnitude of S_{11} (Fig. 2a) is obtained for Z_p • 120•, Z_{sub} = 70+8i and Z_s'=ρ/d. This is consistent with the fact that all our samples are in the thin-film limit.

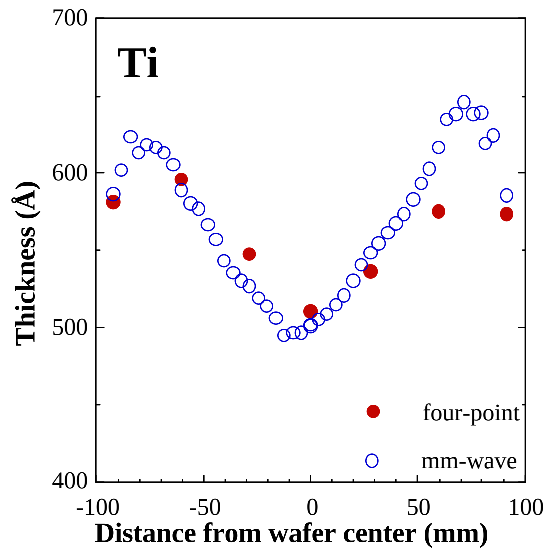

Fig.4 Practical application of the mm-wave near-field probe for the mapping of the thickness of an industrial titanium-coated silicon wafer along its diameter. Open circles show results achieved by our near-field mm-wave probe at 79 GHz. Filled circles show the results taken by the standard four-point resistivity technique approximately at the same points. Note a good correspondence between the two techniques.

CONCLUSIONS

We demonstrate a capacitive method to control the probe-sample separation in the mm-wave near-field imaging. We present local measurements of the mm-wave reflectivity of thin evaporated metal films of Ti, Al, Ag, Au with a thickness of 100Å - 1000Å and demonstrate that the magnitude of the mm-wave reflectivity is directly related to the sheet resistance of the film. We determine the local thickness of a Ti-coating on an industrial silicon wafer and show a clear correlation to the results of the local four-point probing. Since the phase shift upon reflection from thin conducting films is very small, it is not easy to use it for thickness determination at the present stage of research. However, by manipulating with frequency and substrate it may be possible to use the phase information in future for separate determination of the thickness and resistivity of conducting layers.

ACKNOWLEDGMENTS

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