Thickness and Conductivity Analysis of Molybdenum Thin Film in CIGS Solar Cells Using a Resonant Electromagnetic Testing Method

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Abstract — This paper presents a analysis method that combines the nondestructive resonant electromagnetic testing and the mathematical model to analyze the thickness and conductivity of molybdenum (Mo) thin film in copper indium gallium selenide (CIGS) solar cells. Induced eddy currents (EC) in the Mo thin film produce a variation of EC probe impedance in the quasi-static magnetic field. As anticipated, the proposed method shows that the coil impedance largely depends on the electrical properties and the thickness of the Mo film. The experimental and analytical results for gold and aluminum films with different thicknesses are shown and discussed. The Mo films with two kinds of manufacturing process are also examined and analyzed. We demonstrate that the proposed method is appropriate for estimating the conductivity and thickness of Mo films. Larger output signals from the coil probe can also be obtained by a resonant exciting source.

I. Introduction

Characterization of the electrical parameters is one of the primary processes for performance of semiconductor wafers, especially in photovoltaic (PV) applications. The measurement of the conductivity, the mobility, and the carrier concentration is frequently used in PV industry. The conventional method is to contact the specimen using four-point probe or other technologies, which damage the surface completeness of the solar cells to bring about the measurement difficulty of the cell properties. Furthermore, several studies have presented about measuring the electrical properties of semiconductor and thin metal films with the nondestructive methods, such as microwave [1]–[2] and infrared image [3] methods. However, few studies have been performed to investigate the effect of thickness and conductivity of Mo film on CIGS solar cells using the electromagnetic testing method, which lead to insufficient data for analytical modeling the detection method.

Eddy current testing (ECT) has been applied for the measurement of conductivity, permeability, and the estimation of the thickness of the coating for decades [4]–[7]. In addition, the ECT method has an advantage in the simple analytical modeling and performing. Therefore, we present how the proposed analysis method combined the ECT method with a resonant exciting source and the mathematical model can be used to analyze the thickness and conductivity of Mo film of CIGS solar cells in this paper.

II. Nondestructive Resonant Electromagnetic Testing

Figure 1 illustrates the physical principles of nondestructive resonant electromagnetic testing. The EC probe with a cylindrical air cored coil is placed in close proximity to a Mo thin film supported on an insulated glass substrate and excited with ac currents at the desired resonant frequency. When a time varying current flows through the coil, a primary magnetic field is perpendicularly produced to the plane of the coil. An eddy current, inducing on the Mo film due to the effect of primary magnetic field, flows in the opposite direction to the excited currents. A secondary magnetic field, opposed to the primary magnetic field, is produced by the induced eddy currents, which in turn, induces a change in the impedance of the probe. The conductivity and thickness of the Mo film is estimated by the variation of coil impedance.

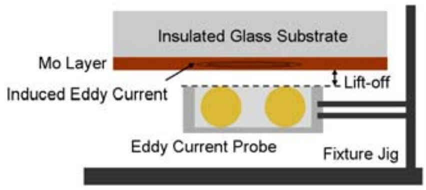

Fig 1. Schematic diagram of nondestructive resonant electromagnetic measurement for the Mo thin film of CIGS solar cell.

In the mathematical analysis of electromagnetic field, the dependent variable in this application mode is the azimuthal component of the magnetic vector potential, **A**, which conforms to the following relation:

$$(j\omega\sigma - \omega^2\varepsilon)\mathbf{A} + \nabla \times (\mu^{-1}\nabla \times \mathbf{A}) = \mathbf{J}_{coil} \quad (1)$$

where ω, σ, μ, and ε are the angular frequency (rad/s), conductivity, permeability, and permittivity, respectively. $\mathbf{J}_{coil}$ is the excited current density applied to the coil probe. According to the constitutive relation (C.R.), the changed current density (A/m^2) of coil probe, $\mathbf{J}^e$, can be calculated as follows:

$$\mathbf{J}^e = \sigma\mathbf{E} = -\sigma(\nabla V + \frac{\partial \mathbf{A}}{\partial t}) \quad (2)$$

where **E** is the electric field intensity (V/m). The electric potential (V), *V*, is obtained from Faraday's law. The defining equation for magnetic vector potential **A** is a direct consequence of Gauss' law for magnetism. Ohm's law is finally used for calculating the impedance (Ohm), **Z**, of the coil probe with the radius (m), *r*.

$$\mathbf{Z} = 2\pi r \frac{1}{\int_s (\mathbf{J}^e \cdot d\mathbf{s}) / [-(\mathbf{J}^e/\sigma + j\omega\mathbf{A})]} \quad (3)$$

III. ANALYSIS PROCESSING

The experimental instrumentation used to obtain probe impedance signals is the commercial impedance analyzer (Agilent 4294A). The scanning frequency for the EC probe was operated within the range of 1 kHz and 10 MHz. In Fig. 1, the insulated glass is 20 mm in both length and width, and 1.11 mm in depth. Furthermore, the copper coil probe (turns = 900, inner diameter = 2.98 mm, outer diameter = 6.38 mm, and length = 0.76 mm) is placed at 0.43 mm in lift-off distance below the test specimen. The thin conductive films were gold (Au), aluminum (Al), and molybdenum (Mo). In Fig. 2, measurements were made by recording the impedance curve with different samples and then comparing the shift movement and magnitude of the curves between the free-space and other films on the insulated glass. In addition, the resonant frequency of the EC probe was also applied to obtain the enhanced output signal for easily analyzing the conductivity and thickness of the Mo film due to the change of the probe impedance. The commercial mathematical software, MATHCAD, was utilized in solving the electromagnetic mathematical model in this work.

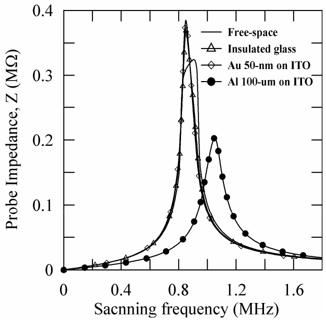

Fig 2. Change in probe impedance curve with different test samples for the resonant electromagnetic measurement.

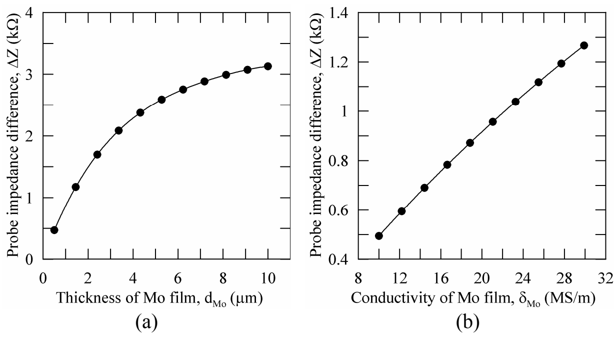

Fig 3. The calculated impedance difference of the EC probe as function of the thickness and conductivity of the Mo film at a 850-kHz resonant frequency.

IV. EXPERIMENTAL RESULTS

The properties of film have a remarkable influence on the value of probe impedance. Figure 2 shows the impedance curve of EC probe for different test samples using the impedance analyzer for the scanning frequency varied from 1 kHz to 1.8 MHz. The film properties cause a remarkable influence on the shift movement and magnitude of the impedance curves when comparing the free-space and other test films on the insulated glass. As the investigation presented in [4], the calculated probe impedance increase with thickness and the curve approaches saturation when the thickness varies from 6 μm to 10 μm as shown in Fig. 3(a). Moreover, figure 3(b) shows that the calculated probe impedance is also directly proportional to the conductivity of the Mo film. Table I shows the measured impedance for different test samples. According the experimental and calculated results, the sample (Mo S-2) has higher conductivity and thicker thickness.

V. CONCLUSION

We have analyzed the properties of the Mo film on the insulated glass substrate by the nondestructive resonant electromagnetic testing and the mathematical modeling. It has been shown that a higher impedance and bigger phase of the induced response can be obtained for a higher conductivity and thicker thickness of the Mo layer. The results indicate a reliable EM method for the analysis of thin film in CIGS solar cells.

TABLE I
PROBE IMPEDANCE DIFFERENCE AND ITS PHASE WITH DIFFERENT FILMS ON THE INSULTED GLASS.

Sample	Measurement	
	Probe impedance difference, $\|\triangle Z\|$ (kΩ)	**Phase of probe impedance difference, θ (Degree)**
Au 25-nm	20.77	-132.45
Au 50-nm	27.64	-132.67
Al 20-um	342.13	159.03
Al 40-um	342.82	159.04
Al 100-um	342.20	158.98
Mo S-1	89.48	-144.75
Mo S-2	94.67	-147.00

VI. REFERENCES

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