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Electrodeless thin film conductance measurements using the Sommer–Tanner method

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A method to determine the electrical conductance of thin films such as *a*-Si:H that does not require contacting electrodes is presented. This method, introduced by Sommer and Tanner, is based on measuring the phase shift of a capacitive transmission line. The lower detection limit for the geometry used here is $10^{-11} \Omega^{-1}$, which makes it suitable to determine the photoconductivity of *a*-Si:H thin films. The method shows reasonable agreement with classical conductance measurements using sputtered electrodes. © 1996 American Institute of Physics. [S0034-6748(96)04710-7]

I. INTRODUCTION

When producing thin film amorphous hydrogenated silicon (*a*-Si:H) for use in, for instance, thin film transistors or photovoltaic cells, it is important to monitor the film conductance. Usually this is done by a straightforward two-point resistance measurement using deposited coplanar electrodes; the disadvantage is that it is an *ex situ* technique that renders the film unsuitable for further use.¹

Sommer and Tanner (ST) developed a method to measure the conductivity of a two-dimensional electron gas (2DEG) on a liquid helium surface.² Since thin films might also be considered two-dimensional electron gases, we will apply the ST method on these, thus enabling an electrodeless, in-line measurement of the conductance. In this article, we will determine the conductance of expanding thermal plasma (ETP) deposited³ *a*-Si:H thin films deposited on high resistivity Corning 7059 glass.

II. SOMMER–TANNER METHOD

Figure 1 shows the setup, consisting of a three-electrode system above which the film is placed at a distance d to form a transmission line. An ac voltage is applied to the first electrode. Using a lock-in amplifier, the current at the third electrode is measured phase sensitively. The second electrode is grounded in order to shield the measurement electrode from the driven one. Assuming the thin film can be considered a 2DEG, the current, measured at the third electrode, is given by⁴

$$I^* = \frac{I}{I_0} = (1+j) \frac{W \delta_0}{2w_1^2} \frac{\sinh^2(jk_0 w_1)}{\sinh(jk_0 W)}, \quad (1)$$

where

$$I_0 = \omega C' w_1^2 (L/W) V_0, \quad (2)$$

$$k_0 = \frac{1-j}{\delta_0}, \quad (3)$$

$$\delta_0 = \sqrt{\frac{2\sigma_0}{\omega C'}}, \quad (4)$$

$$C' = \frac{\epsilon_0 \epsilon_r}{d}, \quad (5)$$

with I_0 the normalization current, d the gap distance between the electrodes and the film, V_0 the amplitude, and ω the angular frequency of the applied ac voltage. σ_0 is the conductance and C' the capacity of the system per unit area. w_1 is the width of the first and the third electrodes, $W(>2w_1)$ the width of the total electrode system, including the middle ground electrode, and L the length of the conducting film. The relations presented here are only valid provided the electrode width w_1 is much larger than the gap distance d in order to approximate an ideal capacitor that in turn must be much larger than the film thickness τ to guarantee a 2DEG: $w_1 \gg d \gg \tau$. For a given electrode geometry, the normalized current I^* depends, according to Eq. (1), only on the so-called two-dimensional skin depth δ_0 , which represents the length scale over which the ac wave will propagate, and on the current I_0 .

The in-phase and 90° phase-shifted current can be depicted by evaluating Eq. (1) in its real and imaginary parts (seen in Fig. 2), these parts are plotted versus δ_0 for two electrode geometries: the geometry that has been actually used (the numerical values are listed in Table I together with typical values of the measured signals) is indicated by the solid curves, whereas the dashed curves represent a geometry with a larger middle electrode ($W=20$ mm); note the peak in the in-phase current at $\delta_0 \approx W/2$.

If the frequency and capacity are assumed fixed, it follows from Eq. (4) that the left part of the plot is the high, and the right part the low conductance region. Exactly the same curves can be obtained by keeping the capacitance and the conductance constant and changing the frequency. Since the capacitance of the air gap between the electrodes and the film is known, the latter method enables determination of the film conductance σ_0 of a sample by fitting the measured 0° and 90° phase-shifted currents as a function of frequency. With the geometry stated in Table I, resistances in the range of 10^3 – $10^{11} \Omega$ can be measured. As can be seen from Fig. 3, the

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FIG. 1. Sommer-Tanner conductivity measurement setup: (a) side view; (b) top view.

low resistance (high conductance) region lies at higher excitation frequencies where it is advantageous to use a commercial lock-in amplifier to measure the current. To detect low frequency signals, i.e., when measuring low conductances, a current amplifier, a PC with two analog inputs and a simple Fourier analysis algorithm will suffice.

It can be deduced that the amplitude I_0 of the detection signal is inversely proportional to the total width W (see the Appendix), where the other geometry parameters w_1 and d have to scale with W to fulfill the set requirements. Scaling down can improve the detection amplitude and the detection limit for low conductivities by an order of magnitude if it is

FIG. 2. In-phase and out-of-phase parts of the current vs inverse skin depth for two different electrode geometries. The solid curves indicate the geometry actually used (the electrode widths are 5, 2, and 5 mm), whereas the dashed curves indicate a hypothetical geometry with a larger middle ground electrode (5, 10, and 5 mm).

TABLE I. Sommer-Tanner system geometry and parameter values.

Parameter	Value
V_0	10 V
I_0	10^{-9} – 10^{-7} A
σ_0	10^{-11} – 10^{-2} Ω^{-1}
ω	50–5000 Hz
C'	1.77×10^{-14} F/mm
d	0.5 mm
w_1	5 mm
W	12 mm
L	25 mm
τ	0.5–3 μm

possible to position a striplike 1.2-mm-wide electrode system at a distance of 50 μm from the film.

III. RESULTS

In Fig. 3, a Sommer-Tanner spectrum of the photoconductivity of a plasma-enhanced chemical vapor deposition (PECVD) device quality *a*-Si:H film is shown. Shown are the in-phase and 90° phase shifted measured currents, respectively. The solid curves are best fits to theory, whereas the dotted and dashed curves indicate the currents that would have been measured at a 30% lower and 30% higher conductance, respectively. The calculated conductance is $\sigma_0 = (2.3 \pm 0.1) \times 10^{-9}$ Ω^{-1} . Given a film thickness of 1 μm , this means the conductivity is $\sigma = (2.3 \pm 0.1) \times 10^{-5}$ ($\Omega \text{ cm}$) $^{-1}$. The measured conductivity using deposited electrodes was $\sigma = 1.5 \times 10^{-5}$ ($\Omega \text{ cm}$) $^{-1}$. A comparison between the two methods for measuring photoconductivity was also made for ETP deposited layers. The results of this comparison are shown in Fig. 4. The error bars shown in the ST data are the uncertainties given by the fit procedure. We see from this graph that the conductivities measured by the ST method are a factor of 1.4 ± 0.3 higher than the ones measured with the electrode technique, consistent with the factor of 1.5 found for the PECVD layer. The apparent discrepancy between the two methods originates from a difference in light

FIG. 3. Sommer-Tanner spectrum of a device quality film. The squares and circles are the in-phase and 90° phase-shifted measured currents, respectively. The solid curves correspond to a conductance of 2.3×10^{-9} Ω^{-1} , the dotted curves to 1.6×10^{-9} Ω^{-1} , and the dashed curves to 3.0×10^{-9} Ω^{-1} .

FIG. 4. Comparison of the measured photoconductivity using the Sommer-Tanner technique and the conventional coplanar electrode method.

absorption in the photoconducting thin film. In the ST method light is incident on the glass substrate and in the electrode method it is incident on the film. Due to the anti-reflection behavior of the low refractive index glass substrate ($n \approx 1.5$) in front of the high refractive index a -Si:H film ($n \approx 4$), light absorption under the former condition is about 25% higher than under the latter which will increase the measured conductivity by roughly the same amount.

By measuring sample transmission, reflection, and the absolute light intensity of the light source, the data in Fig. 4 are corrected for differences in absorption and the result is shown in Fig. 5. As can be seen, the ST method results in a small overestimation of film conductivity, but the general trend is clear.

We therefore conclude that with the Sommer-Tanner method it is possible to measure the conductance of thin films with a conductance higher than $10^{11} \Omega^{-1}$ without the use of contacting electrodes. The results are in good agreement with conventional conductivity measurements using deposited silver electrodes.

FIG. 5. Comparison of the two techniques after correction for differences in light absorption.

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APPENDIX

When choosing an electrode geometry, the following should be kept in mind.

(1) The width of an electrode must be significantly larger than the gap distance: $w_1 = \alpha d$ where $\alpha \gg 1$ (typically $\alpha \approx 10$).

(2) The total width is given by $W = \beta w_1$ where $\beta > 2$ to accommodate the middle grounding electrode (typically $\beta = 2.5$).

(3) For a meaningful fit, it is essential that the peak in the in-phase current is measured. This implies that at some point, the skin depth δ_0 reaches a value of about $W/2$ (see Fig. 2); this can also be written as $\delta_0 \approx \alpha \beta d/2$. Using Eqs. (4) and (5), the typical value for the angular frequency ω can be expressed in d :

$$\omega_{\text{peak}} \approx \frac{8\sigma_0}{\alpha^2 \beta^2 \epsilon_0 \epsilon_r d}. \quad (\text{A1})$$

(4) Substitution of Eq. (A1) in Eq. (2) yields for the normalization current I_0 :

$$I_0 \approx \frac{8\sigma_0 L V_0}{\beta^2 W}. \quad (\text{A2})$$

The detection signal is therefore proportional to the film conductance σ_0 , the electrode length L , and the amplitude of the input voltage V_0 , and inversely proportional to the total electrode width W . Since both β and W increase with an increase of the width of the middle grounding electrode, one should try to keep the electrode small.

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