Sheet Resistance Measurement of Non-Standard Cleanroom Materials Using Suspended Greek Cross Test Structures

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Abstract—This paper presents work on the development, fabrication and characterization of a suspended Greek cross measurement platform that can be used to determine the sheet resistance of materials that would contaminate Complementary Metal Oxide Semiconductor (CMOS) processing lines. The arms of the test structures are made of polysilicon/silicon nitride (Si3N4) to provide a carrier for the film to be evaluated and thick aluminum (Al) probe pads for multiple probing. The film to be evaluated is simply blanket deposited onto the structures and because of its design automatically forms a Greek cross structure with (Al) probe pads. To demonstrate its use, 1) gold (Au), 2) copper (Cu), and 3) silver (Ag) loaded chalcogenide glass Agx(Ge30S20Se70)1−x have been blanket evaporated in various thicknesses onto the platform in the last processing step and autopatterned by the predefined shape of the Greek crosses. The suspension of the platform ensured electrical isolation between the test structure and the surrounding silicon (Si) substrate. The extracted effective resistivity for Au (5.1 × 10−8 Ω·m), Cu (1.8–2.5 × 10−8 Ω·m) and Agx(Ge30S20Se70)1−x (2.27 × 10−8 Ω·m – 1.88 Ω·m) agree with values found in articles in the Journal of Applied Physics (1963), the Journal of Physics D: Applied Physics (1976), and the Journal of Non-Crystalline Solids (2003). These results demonstrate that the proposed Greek cross platform is fully capable to measure the sheet resistance of low (Au, Cu) and high Agx(Ge30S20Se70)1−x resistive materials.

Index Terms—Critical dimension metrology, Greek cross, non-standard cleanroom materials, self patterning, sheet resistance, test structure, Van der Pauw.

I. INTRODUCTION

GREEK cross type structures are widely used in the semiconductor industry for the measurement of sheet resistance [1], [2]. A typical Greek cross structure used for sheet resistance measurements is shown in Fig. 1. The sheet resistance is extracted at the heart of the cross and an accuracy of better than 0.1% can be achieved [3]. The sheet resistance is determined by forcing a current from pad A to B and measuring the potential difference across D and C. After that the current is reversed and the potential $V_{DC}$ is measured and the resistance extracted [4]:

$$R_{00} = \frac{V_{DC} - V_{CD}}{I_{AB} - I_{BA}}$$

(1)

The current is then forced between B and C and the process repeated.

$$R_{00} = \frac{V_{AD} - V_{DA}}{I_{BC} - I_{CB}}$$

(2)

Note that $I_{BA}$, $I_{CB}$, $V_{CD}$ and $V_{DA}$ are negative quantities [4]. The average resistance of these two measurements is then calculated as

$$R = \frac{R_{00} + R_{00}'}{2}$$

(3)

and the sheet resistance is derived as

$$R_s = f \left( \frac{\pi R}{\ln(2)} \right) \left[ \Omega/\square \right]$$

(4)

where $f$ is a correction factor related to the geometrical asymmetry of the sheet resistor. All layers considered in this paper were assumed to be homogeneous in composition and uniform in film thickness, setting $f$ to 1.

Other test structures such as bridges can be also used to determine the sheet resistance as shown in Fig. 2. In this case, the sheet resistance is measured by forcing a current between pad C and D and measuring the voltage difference $V_{BA}$. The sheet resistance in case of bridges was determined by using the following relation [5]

$$R_{sb} = \frac{V_{BA} W}{I_{CD} L} \left[ \Omega/\square \right]$$

(5)
The parameters $W$ and $L$ are the width and length of the bar structure, respectively. Unlike the Greek cross these dimensions need to be known if the sheet resistance is to be extracted. Note, that (5) assumes that the measured track is both homogeneous and any sidewall effects are negligible. If there are any sidewall effects present then the Greek cross minimizes any influence.

Knowing the sheet resistance $R_s$ and thickness $t$ of the evaluated and assumed homogeneous film, one can then derive the resistivity $\rho$ using the relation:

$$\rho = R_s \cdot t \cdot \frac{1000}{W \cdot L},$$  

(6)

As technology moves forward and new applications are developed materials need to be evaluated which may not be compatible with silicon fabrication lines (for example both Gold (Au) and silver (Ag) are not allowed in CMOS processing areas). Greek cross test structure fabricated in the standard manner can therefore not be used as they will contaminate the line. It is of course possible to pattern such materials using float-off techniques but this requires good adhesion to the underlying material and, if the layer is very thin, there can then be probing problems. Contamination is only critical during Front End of Line (FEOL) processing, since contamination has easy access to the silicon surface. Back End of Line (BEOL) processes are far less affected by these contaminations, since barrier layers above the CMOS features are used to isolate these regions from contamination on the upper layers. However, any contamination of the processing equipment will automatically have an effect on CMOS devices when fabricated in these areas.

This paper presents a novel method to overcome these problems by using suspended Greek cross test structures (see Fig. 3) to determine the sheet resistance of blanket deposited layers. The suspended test structures are made from polysilicon with a silicon nitride cap, which automatically patterns the device and at the same time serves as the carrier for the film to be characterized. This approach can be applied to electrically characterize any conducting film and the design, fabrication and characterization of this technique will be described in this paper using 1) Au, 2) copper (Cu), and 3) Ag$_9$(Ge$_{30}$Se$_{70}$)$_{1-\gamma}$, as examples.

Au and Cu, with their well known material properties, are used to demonstrate the performance of the proposed measurement platform. The sheet resistance of the high resistive chalcogenide glass film with 20–nm (Ag$_{0.4}$(Ge$_{30}$Se$_{70}$)$_{1-\gamma}$) and 80–nm (Ag$_{0.4}$(Ge$_{30}$Se$_{70}$)$_{1-\gamma}$) thickness have also been measured. This has been used to extract the effective chalcogenide glass resistivity for both thicknesses as a demonstration of how materials with migration can be characterized using this structure. These ternary materials are solid electrolytes and as such may be used to transfer metal mass in ionic form from an oxidizable source to a location where reduction/electrodeposition can take place. Metal transport in these solid ion conductors has been used to alter the mass distribution in microelectromechanical resonators to trim their resonant frequency [6]. The effective resistivity of the films must be measured as it is an important factor in modeling the electrodeposition process. In addition, since effective resistivity is related to the amount of Ag dissolved in the Ge–Se glass, this parameter may be used to approximate the level of Ag doping without having to resort to complex material analysis.

II. MATERIALS AND METHODS

One of the major attractions of this technique is that structures can be prepared in batches to provide the measurement platform. The material to be measured is then simply laid down and autopatterned by the predefined structure of the measurement platform. Test structures are removed from the deposition equipment and can then be immediately probed. In addition the aluminum (Al) pads make probing very simple and repeatable for the conductive film being measured. Structures can be stored for later depositions and sheet resistance measurements.

Greek crosses as opposed to bridge test structures have the advantage that sheet resistance is measured in the heart of the cross and not along the entire structure. This advantage is important when films with possible diffusion/ion migration at contact pads are being electrically evaluated. In bridges a change in sheet resistance with time would be immediate when ions start to migrate at pads, because the sheet resistance is measured across the whole structure. In Greek crosses, changes in extracted resistance would only occur if the ion concentration changes at the heart of the cross due to migration or reduction. Therefore, Greek crosses can also be used to measure the sheet resistance of these films before diffusion alters the film composition in the heart of the test structure. To demonstrate this capability, bridges along with Greek test structures were used to extract the effective resistivity of the different chalcogenide glass films.

The following describes the fabrication of the platform test chip (Fig. 4), which incorporates Greek cross and bridge test structures. Greek crosses have arm lengths of 120 $\mu$m
a 0.1-μm LPCVD Si$_3$N$_4$ layer is then deposited at nominal 800 °C. These two layers are then patterned using a combination of Reactive Ion Etching (RIE) and Deep Reactive Ion Etching (DRIE) to form the arms of the test structures and the probe areas. A 1.5-μm-thick aluminum (Al) layer is then deposited with 2-kW power using a Balzers sputter system and patterned employing wet chemical etch using phosphoric acid at 45 °C to form contact pads for probing on the Si$_3$N$_4$-polysilicon probe areas. The test structures are then released from the Si-substrate by removing SiO$_2$ under the arms of the crosses and bridges and around the probe areas using a NH$_4$F : CH$_3$COOH solution and subsequent supercritical carbon dioxide point drying.

Fig. 6 shows a Greek cross test structure with Al pads after the release etch step. The observed upward deflection of the test structure arms was due to the slight stress mismatch between the compressive polysilicon and tensile Si$_3$N$_4$ layers.

As a precaution the sidewalls of the arms of the test structures were covered with a 5-nm-thick polymer to reduce the risk of surface currents using the polysilicon as a parasitic path. The polymer ($C_4F_8$) deposition was carried using the passivation cycle of a Bosch process in a STS DRIE etcher at 300 W for 12 s. The polymer on top of the test structures was removed by argon milling in a Balzers sputter system in 15 minutes.

At this stage, the platform is ready to characterize: 1) gold (Au), 2) copper (Cu), and 3) high resistive Ag$_x$(Ge$_{1-x}$Se$_{70}$)$_{1-y}$ films. Chromium served as an adhesion layer for both Au and Cu which were evaporated in various thicknesses using an Edwards evaporation system. Fig. 7 shows Greek cross test structures covered with evaporated Au.

For the third layer, chalcogenide glass (Ge$_{30}$Se$_{70}$) was evaporated in two different thicknesses (20 and 80 nm) onto the test structures using an Edwards evaporation system. A 15-nm-thick Ag film evaporated onto and driven into the glass base layer via evaporation and subsequent photodissolution using an Ultra Violet (UV) light power of 3.9 mW cm$^{-2}$ for 20 min on a Karl Suss mask aligner. The dissolution process provided the glass films with Ag ions [8].

### III. RESULTS AND DISCUSSIONS

Electrical measurements on Au and Cu samples were carried out using a HP4062B semiconductor parametric test system, a Solartron 7065 voltmeter and a semiautomatic probe station. High-resistive chalcogenide glass films were electrically characterized utilising a HP4156B semiconductor parameter analyzer and a manual probe station. During all measurements the substrate was allowed to float electrically.

Before sheet resistance measurements were made, the isolation of the measurement platform was tested by attempting to force a dc current of 1 nA with a voltage compliance of 40 V between a probe pad and the surrounding Si substrate. This determined that the Greek crosses and bridges provided sufficient isolation from the measurement currents entering the surrounding substrate from the probe areas. Sheet resistance was determined by forcing a dc current of 10 mA through the Au and Cu and 10 nA through the high-resistive chalcogenide glass layers and calculated using (4). The chalcogenide glass sheet resistance obtained from bridge test structures was quantitative compared to...
The effective resistivity of the evaporated films was calculated using (5) together with the sheet resistance values and the layer thickness.

The thickness of all evaporated films were measured using a Dektak surface profilometer. Measurements were carried out by removing the films on the silicon substrate with a probe needle and scanning over these areas using the profilometer. This involved some uncertainty with the thickness measurement as it was difficult to determine if the Au/Cu films had been completely removed before profiling or whether the underlying Si substrate had been indented which would also compromise the measurement. Hence, the variation in effective resistivity reported in the next section for the Au, Cu, and Ag$_{76}$(Ge$_{32}$Se$_{70}$)$_{1-x}$ may be strongly influenced by the uncertainty in thickness.
Fig. 12. Measured sheet resistance as a function of Greek cross arm width for (a) 20 nm $\text{Ag}_{60.4}(\text{Ge}_{30}\text{Se}_{70})_{1-0.4}$ and (b) 80 nm thick $\text{Ag}_{60.4}(\text{Ge}_{30}\text{Se}_{70})_{1-0.1}$.

Fig. 13. SEM images of 10-$\mu$m-wide Greek crosses with (a,c) 20-nm $\text{Ag}_{60.4}(\text{Ge}_{30}\text{Se}_{70})_{1-0.4}$ and (b,d) 80-nm-thick $\text{Ag}_{60.4}(\text{Ge}_{30}\text{Se}_{70})_{1-0.1}$.

A. Gold

In Fig. 8 the measured sheet resistance is shown as a function of the cross arm width for different Au layer thicknesses. Sheet resistance is independent from the arm width and ranges from 0.1–0.3 $\Omega/\square$ for the deposited film thicknesses. This suggests that the film is homogeneous in its composition with a uniform thickness across the sample.

Fig. 9 presents the sheet resistance as a function of the Au thickness. Including errors from the layer thickness measurements, the sheet resistance is consistent with the $1/R$ relationship as a function of Au thickness. The extracted average effective Au film resistivity of $5.1 \times 10^{-8} \Omega \cdot \text{m}$ is more than 100% higher than the bulk value ($2.44 \times 10^{-8} \Omega \cdot \text{m}$) [7]. Despite the spread in effective resistivity values and the error from the thickness measurements, the extracted effective resistivity agrees with values found in the literature for thin Au films being $3.0–5.0 \times 10^{-8} \Omega \cdot \text{m}$ [9].

B. Copper

The measured sheet resistance is shown as a function of cross arm width for different Cu layer thicknesses in Fig. 10. It can be observed that the sheet resistance ranges from 0.040 to 0.13$\Omega/\square$ and constant over the range of cross arm width available. This indicates that the considered films have a uniform thickness and homogeneous composition.

Taking the errors associated with the layer thickness measurement into account, Fig. 11 exhibits a similar relationship to that shown in Fig. 9. The extracted effective resistivity for copper varies from 1.810–2.5 $\times 10^{-8} \Omega \cdot \text{m}$ and is slightly larger than the bulk value ($1.7241 \times 10^{-8} \Omega \cdot \text{m}$) [7]. However, the effective resistivity agrees with values found in the literature [10] for thin evaporated Cu films being 1.6–2.8 $\times 10^{-8} \Omega \cdot \text{m}$. The observed variation in effective resistivity is suspected due to errors in the thickness measurement.

C. Ag Doped Chalcogenide Glass

Constant Au and Cu sheet resistance values for different test structure arm widths suggest that the proposed measurement platform is working in the expected manner. Fig. 12 indicates that the measured sheet resistance of the two chalcogenide glass films is variable with arm width available and ranges from 1.13 to 1.74 $\Omega/\square$ for 20 nm and from 6.7 to 23.5 $\Omega/\square$ for 80-nm films, respectively. This suggests that the film is not homogeneous in composition and/or nonuniform in thickness across the
test chip. Thinner glass films show a lower sheet resistance than thicker ones (Fig. 12). The difference in sheet resistance is due to the amount of Ag in the glass films. Thin films are more saturated with Ag ions than thicker ones. Because the effective resistivity of these films is a strong function of Ag concentration, thin layer exhibit a better conductivity than thicker ones.

The extracted effective resistivity using Greek cross measurements range from 2.273.48 \times 10^{-5} \ \Omega \cdot \text{m} for thin films and from 0.531.88 \Omega \cdot \text{m} for thick ones. These values agree with the ones published in [11].

SEM images (Fig. 13) of Greek crosses clearly show a difference in film composition between the two samples. The thin Ag saturated electrolyte has a regular grain structure than thicker subsaturated ones which show an irregular grained surface structure with small Ag islands. A regular structure provides better conduction than the small Ag islands formed during the UV photodissolution process. Hence, thin low resistant Ag saturated films are more uniform than thick ones which exhibit a considerable higher sheet resistance.

Bridge measurements (see Fig. 14) could also confirm the difference in sheet resistance between thin (\( \rho = 1.6 \times 10^{-3} \ \Omega \cdot \text{m} \)) and thick (\( \rho = 0.45 \Omega \cdot \text{m} \)) films. However, for both layer thicknesses, the sheet resistance is stable (\( \approx \pm 1\% \)) in cases for Greek crosses over the measurement time of 200 s. Bridge structures however show a strong variation of \( \approx \pm 40\% \) in resistance with time.

In absence of an Ag ion source, e.g., a Ag anode, conduction in these films is electronic. However, local reduction reactions at the cathode (negative charged pad) causes Ag ion migration and subsequent Ag electrodeposition. Ag electrodeposition at the “cathode” pad causes this variability in bridges with time, because sheet resistance is measured along the whole structure. Greek crosses in contrast show little change in effective resistivity for the considered measurement time, since Ag electrodeposition at the pads did not electrically alter the heart of the cross. Greek cross test structures are therefore the better choice to measure sheet resistance compared to bridges where diffusion/ion migration at the contact pads alters the film resistance with time [12].

IV. CONCLUSION

This paper has presented a platform technology to characterize the sheet resistance of any material without risk of contaminating existing process areas and equipment. This is
achieved by using suspended Greek cross test structures that autopattern the deposited layer in the final process step. Test structures can be fabricated in batches and stored for later film deposition and sheet resistance measurements. The methodology has been demonstrated using evaporated Au, Cu, and chalcogenide glass films to provide a conducting layer on the test structure platform.

The extracted effective resistivity of Au and Cu agree with values reported in the literature demonstrating that the proposed platform is suitable for characterising thinner films. The thick aluminum pads provided a reliable contact to the film that facilitates multiple probing. Sheet resistance measurements on $\text{Ag}_{0.4}(\text{Ge}_{30}\text{Se}_{70})_{1-0.4}$ and $\text{Ag}_{0.1}(\text{Ge}_{30}\text{Se}_{70})_{1-0.1}$ films show that they are nonuniform in thickness and composition. The extracted effective resistivity is related to structural composition and Ag ion content of the films and they are comparable with values found in the literature. Sheet resistance measurements from Greek crosses are less affected by possible Ag ion migration/electrodeposition than results obtained from bridge test structures. Therefore, Greek cross test structures can also be employed for the characterization of films with Ag ion migration. Future work will also involve exploring silicon nitride as a mechanical support material for the presented measurement platform.

In conclusion, this platform provides a mechanism to characterize any conductive films that may potentially contaminate otherwise clean process areas. It requires no postprocessing after material deposition and minimizes probing problems by providing thick metal probe pads.

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REFERENCES


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