Open Journal of Applied Sciences, 2022, 12, 1944-1953
https://www.scirp.org/journal/ojapps
ISSN Online: 2165-3925
ISSN Print: 2165-3917

Study of Copper Thin Films Resistivity by Using Van der Pauw Method at Low Frequencies

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How to cite this paper: Allassem, D., Mahamat, B.M., Kriga, A., Dari, Y.D., Béchir, M.H., Taha, M.A., Nimir, Y.N., Chatelon, J.P. and Rousseau, J.-J. (2022) Study of Copper Thin Films Resistivity by Using Van der Pauw Method at Low Frequencies. *Open Journal of Applied Sciences*, **12**, 1944-1953.
https://doi.org/10.4236/ojapps.2022.1211135

Received: October 26, 2022
Accepted: November 26, 2022
Published: November 29, 2022

Abstract

The objective of this work research is the use of four-point measurements and so-called Van Der Pauw methods in measuring the resistivity of copper thin films widely used in the manufacture of planar components such as inductor and others. Aligned configuration and square configuration are commonly used to measure thin films resistivity before use. But differences in values between the two configurations according to frequency and thickness were observed according to the authors. Measurements with both configurations on the same thin films must make it possible to know measurements evolution as a function of frequency and thickness. The observation of measuring frequency ranges of each configuration and the minimum thicknesses to have solid copper resistivity are the main contributions of the paper. This electrical characterization is carried out on copper thin films deposited on alumina substrates (50 mm × 20 mm × 635 μm) using RF sputtering technique. Copper thin films with various thicknesses (3.3 μm, 3.6 μm and 5.2 μm) were characterized. Low-frequency electrical characterization of these thin films was performed by four-point measurement method and using an HP 4284A type LCRmeter over the frequency range of 20 Hz to 1 MHz. Van der Pauw's method was used to calculate resistivity. These studies allowed us to know influence of measurement configurations and influence of parameters such as frequency and thickness of the copper thin films on resistivity.

Keywords

Thin Film, Characterization, Van der Pauw, Resistivity, Thickness, LCRmeter

1. Introduction

In microelectronics, thin films are widely used for the manufacture of planar components such as inductor and transformers and to protect these components against corrosion, galvanize and insulate them electrically. Copper thin films are particularly used because of the good conductivity of copper and its relatively low production cost. After the realization of thin films, they are subjected to a series of characterizations highlighting their various properties (physical, electrical, magnetic, mechanical, etc.). Electrical characterization is the subject of this research work.

The few studies that focus on measuring copper thin films resistivity by using four-point measurements are limited. The measurement of the conductivity of thin copper films over a few frequencies and for a thickness value is proposed in [1]. The choice of frequencies and thickness are not justified. This work is continued in [2] but thin films resistivity is measured according to radiofrequency sputtering deposition parameters. The correction coefficient used to calculate resistivity by the Van der Pauw method has been studied in [3]. And the problematic of choice between configurations was presented in [4] but the answers provided cannot justify a choice.

The overall objective of this study is the electrical characterization (indirect determination of resistivity) of copper thin films in low frequencies (20 Hz to 1 MHz). This work should highlight the best accuracy between the measurements made with the four-point aligned method and the four-square-point method known as Van der Pauw methods. This characterization work is done on copper thin films deposited on alumina substrates. The prototypes are made at the Hubert Curien Laboratory using magnetron RF sputtering technique. The copper is deposited on a rectangular alumina mechanical support (20 mm × 50 mm × 635 μm). The characterization of these thin copper films of various thicknesses is done at the research laboratory of the National Institute of Science and Technology of Abeche.

The research work presented in this paper provides an answer to the problem of knowledge and therefore choice of aligned or square configuration during four-point measurements of the thin copper films resistivity. The parameters study is frequency and thickness. The paper allows knowing frequency ranges for a good concordance and minimum thicknesses to obtain a resistivity comparable to the solid copper resistivity.

2. Materials and Methods

The following sections present the devices and measurement methods.

2.1. Thin Film Deposition

Copper thin films are deposited using magnetron radiofrequency sputtering technique. RF sputtering technique is the process by which particles are torn from a target bombarded by energetic ions and projected onto a substrate placed on their paths. The ions used for bombing are created from argon, and the plasma is created by applying a high-frequency electrical voltage between target and substrate.

The deposition process is maintained by argon flow and improved by placing magnets behind the target to increase electrons opportunity to ionize argon atoms [5] [6] [7].

The following **Table 1** contains RF sputtering technique parameters.

Thin film thicknesses are measured using a profilometer. **Table 2** contains measured values.

2.2. Van der Pauw's Four-Point Measurement Method

The measurement method used is four-point method: two probes are used to inject current and two others to measure the potential difference as close as possible to Device Under Test (DUT) terminals. This method is used to overcome cables and contacts resistances with the DUT that can affect measurement results. Resistivity is then obtained using Van der Pauw's method which consists of two configurations: square configuration and aligned configuration [1] [2] [3] [4].

2.2.1. Aligned Four-Point Configuration

In this configuration, the four points are aligned at equal distance on surface of rectangular structure of length *a*, width *d* and equidistance *s* as shown in the following **Figure 1** according to an arrangement $I_{Hcu} V_{Hpot} V_{Lpot} I_{Lcu}$ [1] [2] [3] [4] [6]-[14].

Injected currents and measured voltage allow to calculate resistivity according to following formula [1] [2] [3] [6] [8]:

$$\rho = \frac{V}{I} * C\left(\frac{d}{s}; \frac{a}{d}\right) * e \tag{1}$$

Table 1. RF sputtering technique parameters

Code	Substrate heating	Substrate polarization	Interval target-Substrate (cm)	Pre-sputtring (min)	Plim (mbar)	Pdép (mbar)	Power FWDP (W)	Ar (sccm)	duration (min)
MRT33	None	Connected to the enclosure	6.7	6	$5.4.10^{-7}$	2.10^{-2}	300	20	20
MRT34	"	"	"	"	"	"	"	"	"
MRT35	None	Connected to the enclosure	6.7	6	2.10^{-6}	$1.8.10^{-2}$	300	20	30
MRT36	"	"	"	"	"	"	"	"	"

Table 2. Measured thin film thicknesses

Code	Edge thickness (µm)	Other edge thickness (µm)	Center Estimated thickness (µm)	Final thickness (µm)
MRT33	3.1	2.9	3.335	3.3
MRT34	3.1	3.2	3.565	3.6
MRT35	4.5	4.7	5.175	5.2
MRT36	4.5	4.6	5.175	5.2

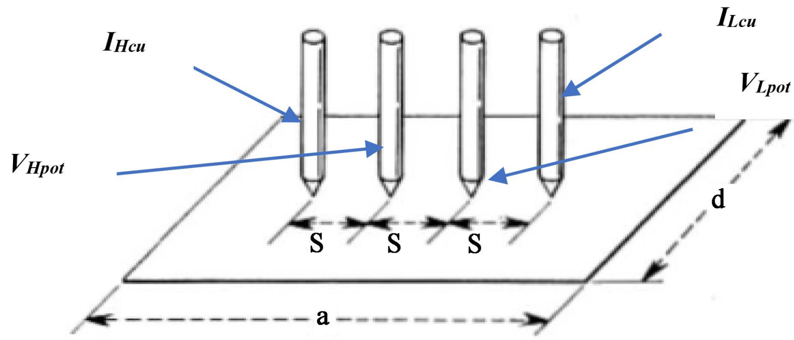

Figure 1. Aligned Van der Pauw configuration [4] [6] [8] [10].

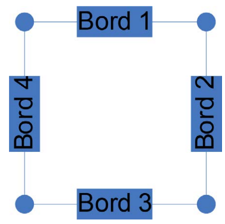

Figure 2. Van der Pauw square configuration [7].

With ρ resistivity, V measured voltage, I injected current and C correction coefficient which is a function of ratio between width d of sample and distance between pointes (probes) s on the one hand and ratio between length a and width d on the other hand and e copper thin film thickness. C is chosen from Van der Pauw's table based on values of d, a and s.

2.2.2. Square Four-Point Configuration

In square configuration, the four points are arranged and form a square on thin film surface and the sides are numbered from 1 to 4 as shown in following **Figure 2**.

Current is injected on the two points of edge 1 (bord 1) and voltage is measured at the opposite edge 3 (bord 3). Current is then injected into edge 4 (bord 4) and voltage on edge 2 (bord 2) is measured.

Ohm's law is then applied to calculate the two resistances $R_{12,34}$ and $R_{14,23}$. Resistivity ρ is the solution to the so-called Van der Pauw equation [1] [2] [3] [4] [6]-[13]:

$$\exp\left(\frac{-\pi \cdot e}{\rho} R_{12,34}\right) + \exp\left(\frac{-\pi \cdot e}{\rho} R_{14,23}\right) = 1 \tag{2}$$

In square configuration, $R_{12,34} = R_{14,23} = R$ and Van der Pauw's equation is simplified and gives:

$$\exp\left(\frac{-\pi \cdot e}{\rho} R_{12,34}\right) = \frac{1}{2} \tag{3}$$

Resistivity is then deduced:

$$\rho = \frac{\pi e}{\ln 2} R = \frac{\pi e}{\ln 2} \frac{V}{I} \tag{4}$$

2.3. Measuring Equipment and Principle

To perform measurements according to above configurations, LCRmeter HP 4284A combined with a four-point tester was used. An LCRmeter is an impedance bridge that measures impedance (phase and modulus) of a DUT and converts it into secondary parameters such as resistance, inductance, etc. Four-point tester is used to inject current and measure voltage drop at DUT terminals. The measurements were made in serial RL mode with a SHORT correction to eliminate residual impedances that can be added in series to DUT impedance [6] [7]. The results will be presented in the results and discussion section. **Figure 3** shows the LCRmeter and the four-point tester.

3. Results and Discussions

From material and methods presented above, several measurements were made. The results are presented in this part of the work.

3.1. Aligned Four-Point Configuration

Figure 4 below shows resistivity evolution as function of frequency for four samples with various thicknesses (MRT33 = 3.3 µm, MRT34 = 3.6 µm, MRT35 =

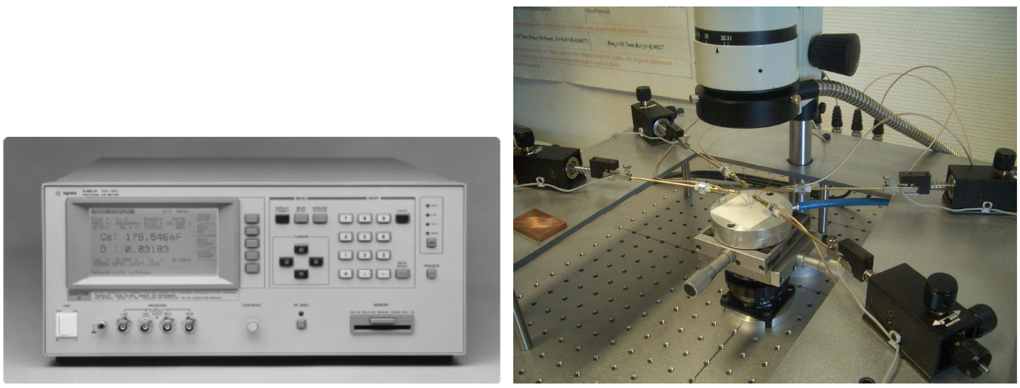

Figure 3. Low frequency measuring equipment: LCRmeter and Four-point tester [7].

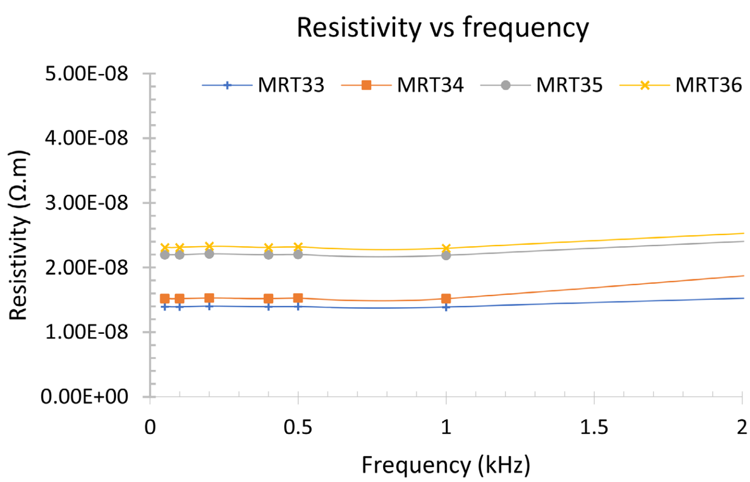

Figure 4. Frequency-dependent resistivity in aligned configuration.

5.2 µm and MRT36 = 5.2 µm) and for 2 mm interval between aligned points.

This figure shows that whatever the thickness, resistivity is constant up to 1 kHz then there is a slight increase due to various causes including, method of measurement, value of injected current, uncertainty on thicknesses measurement and in part, skin and proximity effects [7].

The figure also shows that resistivity value is proportional to thin film thickness. This is Van der Pauw's theory (Equation (1) and Equation (4)). However, MRT35 and MRT36 have the same thickness (5.2 µm) but the resistivities are slightly different. This is explained by uncertainties about thin film thicknesses deposited by RF sputtering technique. Indeed, according to studies conducted at LabHC, thin films thickness deposited by RF sputtering technique is not the same everywhere on substrate surface. Thickness of the deposited film decreases from center to edges of substrate and **Table 2** clearly shows this [6] [7] [15]. But with differences of 5% on resistivity value, these results are totally acceptable.

The figure finally shows that for thicknesses less than or equal to 3.6µm, resistivity is similar but remains lower (1.46×10^{-8} Ω·m) than resistivity of solid copper which is 1.78×10^{-8} Ω·m). This is consistent with Van der Pauw's method which shows that resistivity is proportional to thickness. For thicknesses greater than 5.2 µm, resistivity is slightly higher (2.26×10^{-8} Ω·m) than resistivity of solid copper.

It is important to note that around 3.9 µm of copper deposited by sputtering, copper thin film has the same resistivity as solid copper. This last result will be developed in following parts.

3.2. Square Configuration

Measurements were performed under the same conditions (same samples, distance of 2 µm between points) as aligned configuration but this time points are in square configuration. The results are presented in **Figure 5** below.

Figure 5 shows that whatever the thickness, resistivity is constant up to 40 kHz. Increase in resistivity value is observed only beyond 40 kHz. Compared to

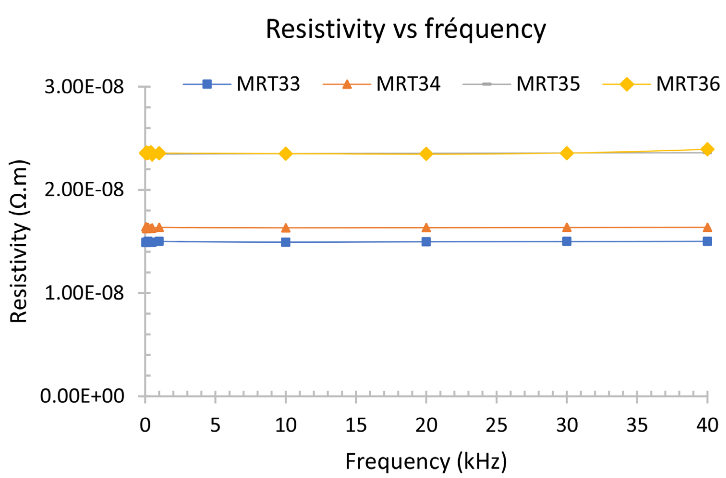

Figure 5. Frequency-dependent resistivity in square configuration.

aligned configuration, validity range of the measurements is wider. The fact that resistivity is constant between 50 Hz and 40 kHz shows that there is a better distribution of current on the conductive film surface and therefore a constant potential difference with frequency. This is possible because points are all close to each other and the thickness uniform. This constant resistivity in this frequency range also shows that skin and proximity effects have no or negligible effect.

As in the case of aligned configuration, resistivity is proportional to thickness. But the square configuration, the two thin films of the same thickness have the same resistivity. This is very clearly explained by the fact that the two points used to inject current and the two others used to measure voltage are each located in the same area where thickness is almost uniform which is not the case in aligned configuration where the points injecting the current are 6 mm apart. Indeed, by mapping thicknesses of a copper thin film deposited by RF sputtering according to dimensions of substrate, it is observed that thickness varies from center to edges when point move horizontally from center edges as shown in Figure 6 below. For vertical displacement, thicknesses are almost the same given the smaller width of substrate.

As in the case of aligned configuration, it is noted that for thicknesses less than or equal to 3.6 μm, resistivity is comparable but remains lower (1.56×10^{-8} Ω·m) to the resistivity of solid copper which is 1.78×10^{-8} Ω·m). For thicknesses greater than 5.2 μm, the resistivity is slightly higher (2.36×10^{-8} Ω·m). We have in the previous part justified each of these evolutions.

It can therefore be said that the two Van der Pauw configurations contribute to the same results but the square configuration is valid in a wider frequency range because of the thin film deposition technique chosen.

A question that we are entitled to ask ourselves is for what thickness, a copper thin film has the same resistivity as solid copper? This is the purpose of the last part of this work.

3.3. Resistivity and Thin Films Thickness

Thin films resistivity measured by the two Van der Pauw configurations is proportional to thickness (Equation (1) and Equation (4)). But this proportionality is interesting if this thickness allows to have a resistivity less than or equal to the resistivity of solid copper which is 1.78×10^{-8} Ω·m. Beyond this value, thin film is considered more resistive than copper. It is therefore important to determine minimum thin film thickness to obtain the solid copper resistivity. To achieve

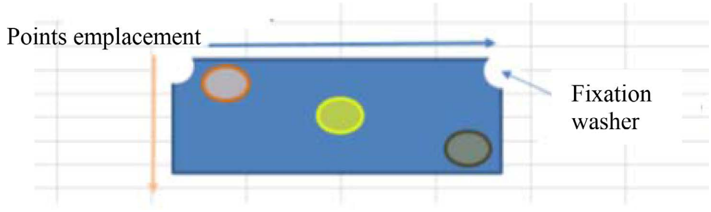

Figure 6. Location of points according to sample dimensions (20 × 50 mm).

this goal, resistivity as a function of thickness was plotted for three frequencies. Figures 7-9 are plotted at 50 Hz, 400 Hz and 1 kHz. The intersection between resistivity curves as a function of thickness and solid copper resistivity value gives this minimum thickness.

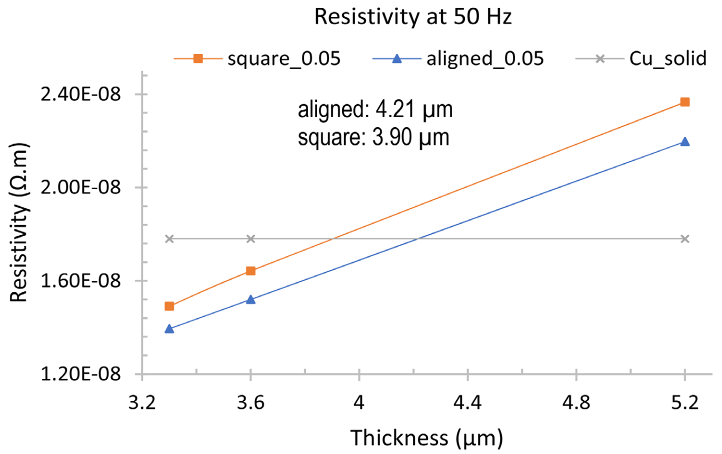

Figure 7. Resistivity as a function of thickness and configurations at 50 Hz.

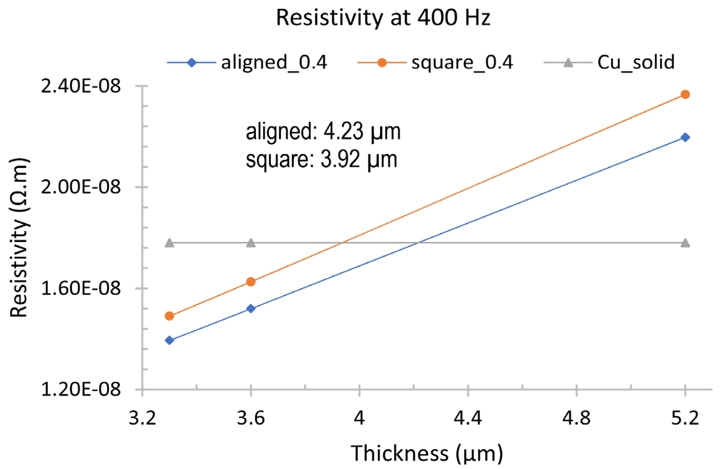

Figure 8. Resistivity as a function of thickness and configurations at 400 Hz.

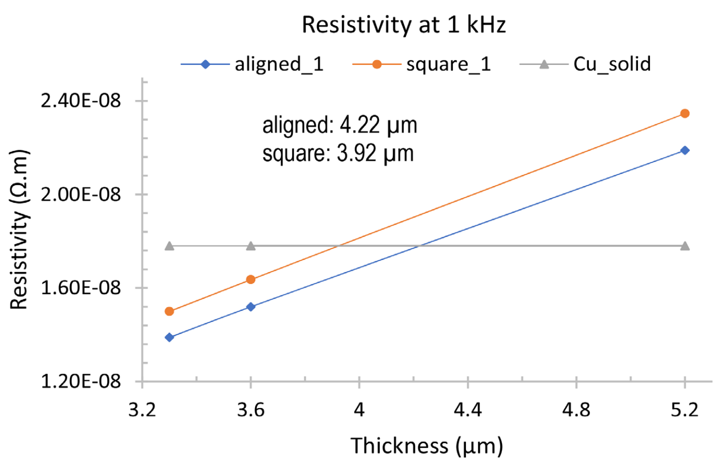

Figure 9. Resistivity as a function of thickness and configurations at 1 kHz.

Table 3. Minimum thin film thicknesses.

Configurations	Thicknesses (μm)		
	50 Hz	400 Hz	1 kHz
Aligned	4.21	4.23	4.22
Square	3.90	3.92	3.92

Table 3 summarizes minimum thickness values to achieve the resistivity of solid copper according to configuration and frequency.

Analysis of the figures and table shows that an average minimum thickness of 4.22 μm is required for aligned configuration and 3.91 μm for square configuration to achieve the resistivity of solid copper. Beyond these thickness values, increasing thickness contributes to making thin films more resistive because of the proportionality between thickness and resistivity.

Finally, there is a gap between the minimum thicknesses in aligned and square configuration. This difference is mainly due to the non-uniformity of thickness from the center to the edges of thin film combined with the position of the points according to configurations detailed in section 3.2.

4. Conclusions

The main objective of this research work is measurements of copper thin films resistivity deposited by radiofrequency magnetron sputtering technique using four-point measurements in an aligned and square configuration called Van der Pauw's method. Thin films of various thicknesses ranging from 3.3 to 5.2 μm were studied.

The study shows that the two configurations (aligned and square) make it possible to measure copper thin film resistivity with good accuracy. The differences observed between values according to the two configurations are mainly due to non-uniformity of thicknesses of deposits from the center to the edges, inherent in the type of deposit technique chosen. However, the square configuration allows for a larger measuring frequency range.

This study also highlighted the proportionality between resistivity and film thickness. To obtain a resistivity comparable to the resistivity of solid copper, a minimum thickness of 4.22 μm in aligned configuration and 3.91 μm in square configuration is required. Thicknesses lower than the minimum thickness give lower resistivities than the resistivity of solid copper which gives the illusion that films are more conductive than copper.

The paper therefore contributes to the choice of four-point measurements configuration according to work frequency and film thickness and the minimum thickness to be deposited to have a thin film that behaves like solid copper.

An in-depth comparison between aligned and square configurations will be proposed in a future paper in order to better understand Van der Pauw's four-point measurements.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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