Development of Electrically Conductive Copper Thin Film by using DC Magnetron Sputtering Process

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***Abstract* —In the present research work, a laboratory scale DC magnetron sputtering (DCMS) setup has been designed and fabricated to deposit a highly conductive Cu thin film onto the glass substrate. The setup contained several necessary designed parts like processing chamber made up of glass, water-cooled sputter gun containing neodymium magnets and Cu target, vacuum port and reactive gas inlet etc. The in-house designing, fabrication, and assembly of the parts has resulted in the development of a portable and low-cost magnetron sputtering setup. The sputtering setup was operated by varying the DC input voltage while the sputtering time and standoff distance (SOD) kept constant in order to obtain an optimized thin film of Cu with highest electrical conductivity and lowest surface roughness. Finally, the sputtering time of 5 minutes, SOD of 30 mm and input voltage of 1000 volts were obtained as optimized parameters for the deposition of Cu thin film. The optimized thin film exhibited conductivity of 5.19E-7 s/m and surface roughness of Ra≈30nm.**

Keywords: Magnetron sputtering; copper; thin film; electrical conductivity; surface roughness

I. INTRODUCTION

In many industrial sectors, physical vapour deposition (PVD) technique is used to produce thin film nano-coatings for different purpose such as in displays, solar cells, antistatic coatings, microelectronic industry and infrared reflection and some other applications are: gas turbine bearings, diesel engine piston rings, aerospace components or forming tools, etc. [1].

There are several types of PVD techniques like ion-beam sputtering, reactive sputtering, gas flow sputtering, RF sputtering and DC Magnetron Sputtering, etc.[2,3].The coating produced by sputtering technique has a wide area of applications like in metal industry, bio-medical industry, optical or electrical industries [4]. The demand of thin film coatings produced by PVD techniques is increasing day by day due to its functional properties such as high hardness, wear resistance, corrosion resistance, low friction and specific electrical and optical properties [5, 6].

One of the most popular PVD process is DC magnetron sputtering (DCMS) technique. In the basic sputtering process, a target (or cathode) plate is bombarded by energetic ions produced in the glow discharge plasma present in the processing chamber. The bombardment process results in the ejection, i.e. “sputtering” of target atoms, which gets deposited on the substrate as a thin film as shown in Fig.1 [7].

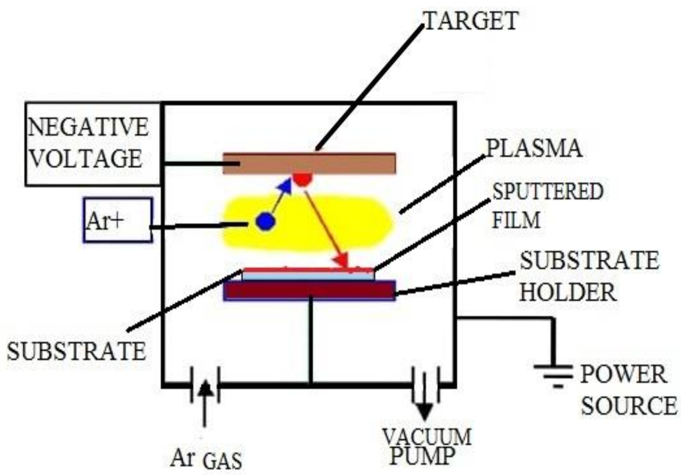

Fig. 1. Schematic representation of DC-Magnetron Sputtering.

Recently, Cu thin films have gained the attention due to its excellent electrical and optical properties. Cu in thin film form is inexpensive and is used in different areas of applications like microelectronic and electronics devices [8], display, solar cell, antistatic coatings [9, 10, 11]. Furthermore, antibacterial thin film of Cu material has also gained much importance in past few years. The use and fabrication of Cu thin film is economical due to its low cost and availability. It has been observed that for most of the applications Cu has proved as a replacement of some costly metals like silver (Ag) and indium (In) as Cu is only 6% less conductive than Ag and 100 times less expensive than Ag and In both[12]. Moreover, desirably the resistivity of Cu thin film is very close to the resistivity of bulk Cu [13]. In many cases, the Cu thin film formed by DCMS technique replaced many other deposition techniques like electro deposition [14], vacuum arc deposition [15], metal organic chemical vapour deposition [16] and chemical vapour deposition [17] etc..

The main aim of present research work was to design and fabricate a low cost DCMS and to deposit the Cu thin film of superior conductivity and lower surface roughness. Different parts of the setup were designed and fabricated, keeping the economy, portability and performance of setup as prime factors. Thereafter, an optimized Cu thin film was deposited by varying the sputtering time, standoff distance (SOD) and input voltage as important DCMS process parameters. Finally, the electrical conductivity and surface roughness of deposited thin film was evaluated and reported.

II. EXPERIMENTAL

A. Fabrication of DC Magnetron Sputtering setup

The present DCMS setup has several parts such as processing chamber, upper and lower plates, sample holder, sputter gun, vacuum and reactive gas inlet port as shown in Fig. 2.

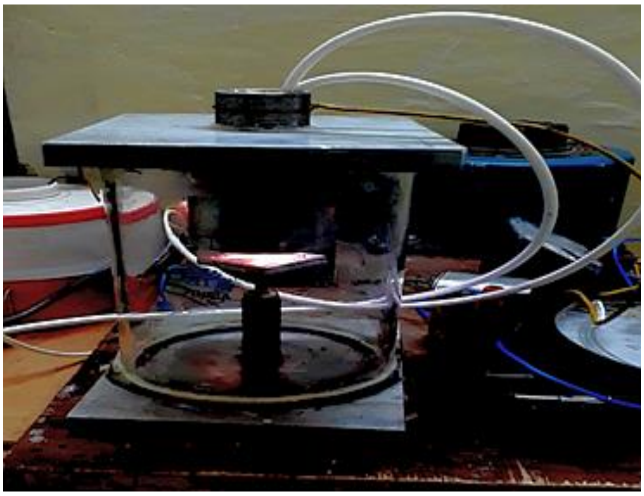

Fig. 2. Fabricated DC magnetron sputtering setup.

The processing chamber is made of transparent, high temperature resistant and toughened borosilicate glass. The chamber is of suitable thickness and cylindrical in shape with both ends open. The upper and lower plates are made up of aluminium material. The upper plate also houses a sputter gun, which is also fabricated from aluminium. The sputter gun is hollow from inside to accommodate concentric magnets and a provision to supply water for cooling effect during the sputtering process. The lower plate accommodates a sample holder having the facility to adjust the SOD between sputter target and the sample. The lower plate is also drilled to make two ports for vacuum and reactive gas.

B. Coating Procedure and Testing

A pure Cu target was selected to deposit the thin film over a glass substrate. This target was firmly placed in the water-cooled sputter gun. The sputter gun assembly housing the target and magnets was mounted on the upper plate. A cleaned glass sample was placed over the sample holder and a specific SOD was maintained between the Cu-target and glass substrate. Both the plates (upper and lower) were placed on the processing chamber and a proper sealing was done by using rubber gaskets and silicone gel to prevent the leakage. Thereafter, the processing chamber was pumped down to a vacuum of approximately 100 µm. The sputtering was performed under different process parameters as shown in Table 1. Finally, the coated specimens were obtained and their resistivity was measured by using Four Point Probe Tester. The surface roughness of the coated specimens was measured by using surface roughness tester (Surfcom Flex 50A, Carl Zeiss). An average of three measurement of each testing is reported.

TABLE 1. DCMS PROCESS PARAMETERS FOR CU THIN FILM

Parameter	Value
Sputtering Target	Pure Cu, Dia. 40mm & 2mm thick
Substrate	Glass, 30mm×20mm×1mm
Stand-off distance (mm)	30
DC sputtering voltage (Volts)	600 – 1200
Sputtering time (mins)	5
Initial Substrate Temperature	30ºC

III.RESULT AND DISCUSSION

A. Resistivity of thin films

In this section, the effect of varying thickness on the resistivity of deposited films has been reported. It is well known that increase of thickness results in decrease of resistivity of films. The resistivity of the Cu (sample) layer is to measure experimentally using a "four point probe". A current is passed through the outer probes, which induces a voltage between the inner probes. The junction between the *n* and *p* -type materials behaves as an insulating layer and the cell must be kept in the dark can be expressed by the following equation

$$\rho_{\square}\left(\frac{\Omega}{\square}\right) = \frac{\pi}{ln\ (2)}\frac{V}{I} \tag{1}$$

Where: $\frac{\pi}{\ln(2)} = 4.532$

The measurement of bulk resistivity is similar to that of the resistivity Cu thin film is reported using the wafer thickness, t:

$$\rho = \frac{\pi}{\ln(2)}\left(\frac{V}{I}\right)t = 4.532\left(\frac{V}{I}\right)t \tag{2}$$

Where t- is the layer/wafer thickness in cm. The simple formula above works for when the wafer thickness less than half the probe spacing (t < s/2). For thicker samples the formula becomes:

$$\rho = \frac{V}{I}\frac{\pi t}{ln\left(\frac{sinh\left(\frac{t}{s}\right)}{sinh\left(\frac{t}{2s}\right)}\right)} \tag{3}$$

The thickness of Cu thin films at a fixed deposition time of 5 min for different input DC voltage was measured. With increasing voltage for the same Ar pressure the probability of collision of Ar+ atoms with electrons coming from copper target increases. It results in the increased deposition rate as shown in Fig. 3.

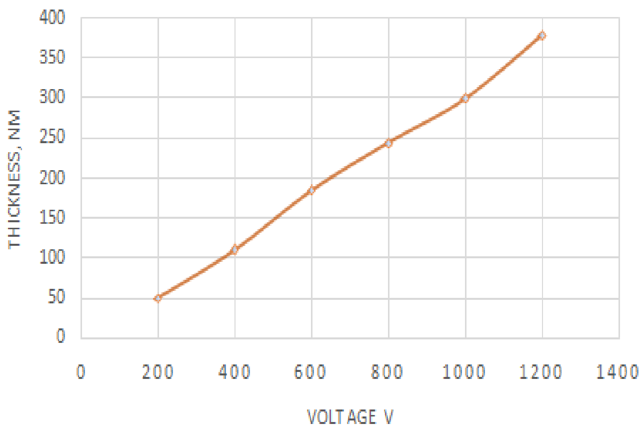

Fig. 3. The effect of input voltage on the thickness of the Cu thin film

The surface roughness of the deposited film was measured by using surface roughness tester (Surfcom Flex 50A. Carl Zeiss). The results of surface roughness measured by the tester are presented in Fig. 4. It can be observed that on increasing the input voltage the surface roughness of the deposited film is decreased. However, on further increase in voltage the change is negligible.

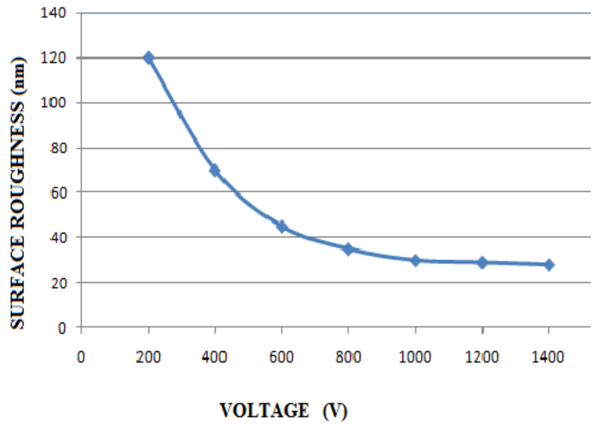

Fig. 4. Roughness of sputtered Cu thin films obtained for different input voltages.

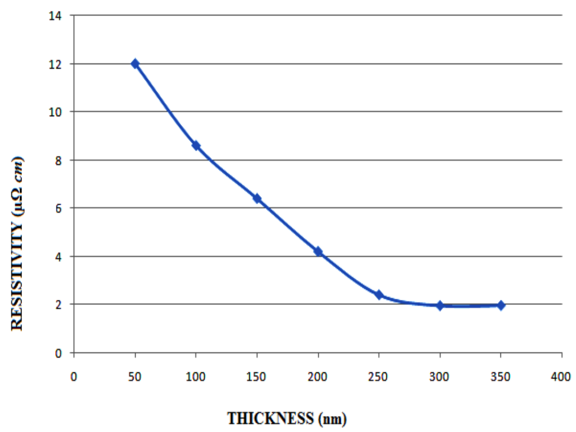

Fig. 5. Effect of film thickness on the resistivity of Cu thin films

Based on eq. (1) the bulk resistivity of sputtered thin films were estimated. For prepared Cu thin films the bulk resistivity ρ=1.95 [μΩ cm] was obtained at 1000 V DC input voltage. According to literature the bulk resistivity for Cu is ρ_0=1.67 [μΩ cm][18]. At 1000 V a maximum thickness of 300 nm was obtained. The electrical resistivity measurements exhibited that for the Cu layer thickness greater than 300 nm the resistivity become nearly constant. Therefore, the deposition of Cu film with a layer thickness higher than 300 nm seems to be unjustified from the economic point of view.

IV.CONCLUSION

This work enabled us to determine the dependence between parameters of deposition process and properties of resulting Cu thin films for contact surface in electronic application. It was observed that the thickness of the deposited film is increased with the increase in input voltage while the surface roughness is decreased. Moreover, with the increase in thickness the resistivity of the thin film gradually drops down. However, the study also exhibited that on further increase in input voltage the change in resistivity is negligible.

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