Effect of Thickness on Properties of Copper Thin Films Growth on Glass by DC Planar Magnetron Sputtering

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Abstract
Copper thin films with nano-scale structure have numerous applications in modern technology. In this work, Cu thin films with different thicknesses from 50–220 nm have been deposited on glass substrate by DC magnetron sputtering technique at room temperature in pure Ar gas. The sputtering time was considered in 4, 8, 12 and 16 min, respectively. The thickness effect on the structural, morphological and electrical properties were studied by X-ray diffraction (XRD), atomic force microscope (AFM) and four point probe (FPP) measurements, respectively. The results show that by increasing thickness, the copper films crystallinity in (111) direction increases. Also by varying the films thickness the significant changes were observed in the films surface morphology due to the mechanism of films growth. Finally, the relationship between film resistivity and Cu film thickness are investigated in this paper.

1. Introduction
In recent years, variety of practical and industrial applications of thin films is considered the importance of technological developments of thin films. Nowadays scientists and researchers are focused on film formation processes in order to obtain the insight into mechanisms leading to special structural properties. Many parameters can influence on the thin films structure such as time, Ar gas pressure, kind of substrate and also the thickness, which determines the physical properties of the thin films.

Cu thin films with nanostructural dimensions have widely applications in electronic devices because of both high electromigration resistance
and high electrical conductivity [1, 2]. Due to these
caracteristics; Cu thin films are widely used for
many applications alike diodes [3], solar cells [4]
and high-speed integrated circuits (IC) [5, 6]. The
Cu thin films usually fabricated by different
technique, including Reactive Pulsed Laser
Deposition (RPLD) [7], DC magnetron sputtering
[8], RF magnetron sputtering [9], ion beam assisted
DC magnetron reactive sputtering [10] and
molecular beam epitaxy (MBE) [11]. We choose
the DC magnetron sputtering method because it
has many advantages, such as high growth rate, the
possibility of large area deposition, and low cost
[12].

A lot of papers have been reported on the Cu
thin film; however, most of them were using si
substrates to deposit the films, while few reports
treated the glass substrates [13]. In this study, the
copper thin films have been prepared on glass
substrates by DC planar magnetron sputtering at
different time depositions. Then by using X-ray
diffraction (XRD) (Philips pw 3710) analyses in
the θ/2θ mode using Cu Kα X-rays, atomic force
microscopy (AFM) and conventional four-point-
probe (FPP5000) resistivity measurements,
investigated the microstructural, surface
morphology and electrical properties of Cu films.
The effect of thickness on the structure and
resistivity of the film will be briefly discussed.

2. Experimental procedure

In this work, Cu thin films with different
thicknesses have been deposited on glass substrate
by DC magnetron sputtering technique. The
substrate was fixed directly above the Cu target
(99.9% in purity) of 870 mm in diameter with a
target-to-substrate distance of 7 cm. The sputtering
deposition was carried out in a pure argon (Ar) gas
(99.999%) at a pressure from 6 × 10⁻⁵ to 8 × 10⁻² torr
and the sputtering power at 30 W which led to a
deposition rate of approximately 12.5 nm/min. The
size of glass substrates are 2 cm × 3.5 cm and were
cleaned ultrasonically in acetone and alcohol each
for 15 min and blown dry in N₂ gas before they
were introduced into the chamber. To illustrate the
effect of the thin film thickness, four copper thin
film samples with thicknesses at around 50–220
nm were prepared at room temperature. Film
thickness was controlled by a quartz crystal mass
monitor in the chamber. The deposition conditions
of the Cu thin films are showed in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Deposition condition for the Cu thin films.</th>
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<tbody>
<tr>
<td>Target</td>
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<tr>
<td>Substrate</td>
</tr>
<tr>
<td>Target-substrate distance (cm)</td>
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<tr>
<td>Base pressure (mTorr)</td>
</tr>
<tr>
<td>Deposition pressure (mTorr)</td>
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<tr>
<td>Voltage (V)</td>
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<tr>
<td>Current (mA)</td>
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<tr>
<td>Sputtering power (W)</td>
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<tr>
<td>Deposition rate (nm/min)</td>
</tr>
<tr>
<td>Deposition time (min)</td>
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<tr>
<td>Film thickness (nm)</td>
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</table>

3. Results and discussion

Fig. 1 reveals that the thickness of Cu thin films
as a function of sputtering deposition time. By
increasing the deposition time for 4 min to 16 min
the films thickness linearly increases and the
deposition rate is approximately 12.5 nm/min. The
influence of the thickness on XRD pattern of Cu
thin films deposited on glass substrates are shown
in Fig. 2a-d. In all figures (2a-d), a diffraction peak
attributed to the Cu (111) phase is observed at
2θ = 43°, which the diffraction patterns of all the
samples were similar except the variation of the
peak intensities due to the differences in thickness.
Also, the film thickness was considered to have no
remarkable effect on the preferred (200)
orientation because Cu has the face centered cubic
(FCC) crystal structure and for this structure (111) face has the lowest surface energy [14].

When the thickness of samples is increased the crystallinity and the mean grain size improved. The average grain size of the films is estimated by scherrer formula [15], given by (Eq.1). The results are presented in Table 2.

\[ D = \frac{0.9\lambda}{\beta \cos \theta} \]  

(1)

![Graph showing copper thin film thickness as a function of deposition time.](image)

**Fig. 1.** Copper thin film thickness as a function of deposition time.

**Table 2.** Mean grain size of Cu thin films deposited on glass substrate.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Time (min)</th>
<th>Thickness (nm)</th>
<th>Grain Size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>4</td>
<td>50</td>
<td>89</td>
</tr>
<tr>
<td>b</td>
<td>8</td>
<td>90</td>
<td>120</td>
</tr>
<tr>
<td>c</td>
<td>12</td>
<td>160</td>
<td>184</td>
</tr>
<tr>
<td>d</td>
<td>16</td>
<td>220</td>
<td>259</td>
</tr>
</tbody>
</table>

![XRD patterns of Cu thin films with different thickness: (a) 50nm, (b) 90nm, (c) 160nm, (d) 220nm.](image)

**Fig. 2.** XRD patterns of Cu thin films with different thickness: (a) 50nm, (b) 90nm, (c) 160nm, (d) 220nm.
Three-dimensional surface morphology of thin films prepared in different thickness is shown in Figs. 3(a-d). AFM (1 µm×1 µm) examination of the Cu samples illustrated clearly that their surface morphologies are strongly affected by thickness. Figure (4) show that the grain size of the films clearly increase as the thickness rises, which is consistent with the XRD results. Investigation of the AFM images revealed that at the beginning of growth, the grain sizes are small (Fig. 3a) and Columnar structures for thin film were observed, which were tiny, dense, and vertical. By increasing thickness, these small grains gradually combine and make bigger grains (Figs. 3b, 3c). Finally, with increasing the thickness to 220 nm, the grains become bigger and at last it can cause to create clusters, which these clusters combine and create big grains which are shown in Fig. 3d. Also surface roughness of Cu films has been studied by AFM. As can be seen from Figure (5) when the film thickness increases from 50 to 220 nm, surface roughness increases from 1.001 to 8.353 nm, which results from an increase of grain size from 89 to 259 nm. It can be considered that the surface roughness of film originates significant from the surface morphology of the glass substrate.
The electrical properties of Cu thin films with different thicknesses from 50 to 220 nm were investigated. Fig. 6 shows the dependence of the Cu film resistivity on thickness. The Cu thin film with 50 nm thickness has the highest resistivity value of 13.7 \( \mu \Omega \)-cm and the resistivity for thicker film of 90 nm is reduced to 5.51 \( \mu \Omega \)-cm. The Cu thin film resistivity further decreases to 3.83 \( \mu \Omega \)-cm as the film thickness increases to 160 nm, after which the resistivity is almost independent of the film thickness and the value varies at approximately 3 \( \mu \Omega \)-cm. The lowest resistivity value is 2.2 \( \mu \Omega \)-cm, obtained for Cu film with thickness 220 nm, which is the thickest film under investigation in the present work. The resistivity of thin films (\( \rho \)) can be expressed as \[ \rho = \rho_p + \rho_m + \rho_f + \rho_i + \rho_s \] where \( \rho_p \), \( \rho_m \), \( \rho_f \), \( \rho_i \) and \( \rho_s \) represents the resistivity caused by photon, impurity, defects, grain boundary and the surface scattering, respectively. The photon can be considered to have the same effects on resistivity. The resistivity caused by impurity and the defects should be the same under the same deposition conditions except varying deposition time. Also, the resistivity due to surface scattering should not play its role in the decreasing resistivity trend in our experiment due to film thicknesses of our Cu films ranging from 50 to 220 nm are much higher than the electron mean free path of Cu (39 nm) [16]. The Cu film resistivity decreases with increasing film thickness to 220 nm, in which the decreasing trend can be attributed to the inverse linear dependence of film resistivity increase on grain size [17].
4. Conclusion
We have investigated the thickness dependence of the structural and electrical properties of Cu thin films deposited on glass by dc planar magnetron sputtering method. The surface morphological study with AFM generally shows the enhanced nanostructure, while the XRD patterns reveal the improve crystalline quality for the thicker films. The RMS roughness was found to increase with increasing film thickness, which is associated with the increase in the crystal size due to surface energy minimization when the film gets thicker. The Cu film resistivity decreases with increasing film thickness to 220 nm, in which the decreasing trend can be attributed to the inverse linear dependence of film resistivity increase on crystal size. For the Cu films with 160 nm thickness and larger, the thickness has no significant effects on the electrical properties, although the crystal size in these Cu films was observed to constantly increase. The phenomenon is attributed to exclusion of grain boundary scattering in limiting the electrical transport of the electrons in the relatively thick film having sufficiently large grains.

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References