Statistical characteristics of fluctuation of heights, surface roughness and fractal properties of Cu thin films

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Abstract: To investigate the surface roughness, and get some information about statistical behaviour of Cu thin films and knowledge about morphology and fractal characteristics of them, copper thin films have been deposited on glass substrate by dc magnetron sputtering method. In different deposition rate (0.4-2.5 nm/sec), effect of this parameter on surface roughness has been investigated. By AFM studies interface width ($W$ or surface roughness) and structure function $S_2(l)$ as well as different moment of structure function $S_q(l)$ and correlation length also have been investigated for various experimental conditions. Fractal properties of them have been studied too and height distribution satisfied Gaussian distribution function.

1. Introduction:
Surface roughness or interface width and information about statistical characteristics of thin film surfaces have various application and impact on many phenomena [1, 2]. Since copper (fcc /noble transition metal) has low resistivity and durable electrical properties, it has been used as a contact layer in manufacturing of semiconductor devices. Thus it is vital to control its fine structure in this technology [3-7]. To study the fine structure of thin film, one must investigate: grain size, surface roughness and grain shape against various deposition conditions and coating method [7]. Some works has been done which investigated roughness of Cu thin film on glass or Si substrate, by electro deposition or evaporation method [7-9]. Since sputtering is very clean, fast and more controllable way to deposit thin films[10], this method was used in this work, and some parameters like roughness, statistical characteristics and fractal property of them were investigated under different deposition conditions while all samples had same thickness (250 nm) and only deposition rate was different.

2. Experimental methods:
To produce copper thin films a vacuum system with base pressure of $10^{-7}$ mbar was employed. For plasma formation pure research grade argon with fix pressure (P) (0.02 mbar) was used, and discharge current (i) which is vital to run discharge, was varied from 0.2 to 1 A. Target was made of pure copper (purity %99.99).Substrates were flat circular glasses with diameter of 2.0 cm and thickness of 0.1 mm and just before using them they were cleaned in isopropyl ultrasonic bath. Substrate temperature was monitored by a digital thermocouple which was placed close to substrate, since duration of deposition was relatively short, so substrate temperature was roughly constant (namely 300°K). Distance between copper target and substrate holder was kept fixed at optimum amount (12 cm). A shutter was placed between target and substrate; shutter was there, for two reasons, first to control the period of coating
exactly and second to run pri-sputtering before thin film production to clean the target. Deposition rate and thickness of Cu thin film was measured by a vibrating quartz crystal as well as an exact balance ($10^{-4}$ gr).

The surface topography of Cu thin film samples was obtained using an atomic force microscope (AFM) (Park Scientific Instrument), these images were digitalized in to $256 \times 256$ pixels and their scale ($L$) was $2\mu m \times 2\mu m$. Roughness and other statistical parameters were obtained from these images by using a computer program.

3. Theory:
Since growth of thin film include complicated statistical phenomena, and some parameter depends on dynamic scaling, so one should employ the statistical techniques to investigate film surface. Surface roughness is one of these parameters which is used to describe the fine structure and calculated in form of root mean square (RMS) of height and is obtained by relation (1)

$$W(L,t) = \sqrt{\langle (h(r,t) - \bar{h})^2 \rangle_s}$$  \hspace{1cm} (1)

Were $\langle .. \rangle$ shows statistical average, and $\bar{h}$ is average of heights.

One of the common statistical functions that is used to describe surface is structure function which can be written as;

$$S_2(l) = \langle (h(r,t) - h(r+l,t))^2 \rangle_s$$  \hspace{1cm} (2)

This function is calculated for all points which are in distance $l$ from each other. During growth of thin film, different points on the surface are not independent and height of each point related to height of other points near to it, so up to special distance from a point one can calculate the height of other points, this distance is known as correlation length ($l_0$). If we plot variation of $S_2(l)$ versus $l$ in logarithmic scale, at first $S_2(l)$ increases linearly, and this behavior continues up to a certain value of $l$ (correlation length($l_0$)) then $S_2(l)$ starts to saturate, so for $l < l_0$, we have

$$S_2(l) \approx l^\alpha = l^{2\alpha}$$  \hspace{1cm} (3)

Where $\alpha$ is the roughness exponent.

By study another moment of structure function; $S_q(l)$, in range of correlation length, we have relation (4) between $l$ and $S_q(l)$.

$$S_q(l) \approx l^{\xi_q}$$  \hspace{1cm} (4)

If $\xi_q$ is a linear function of $q$ then fluctuation of height is fractal, otherwise surface is multi fractal. $q$ is the scaling view, while slop of plotting $\xi_q$ is a criteria of fluctuation importance. In low $q$ importance of small fluctuation is investigated, while in large amount of $q$ study of bigger fluctuation is vital. Therefore one can say that in fractal surfaces importance of different fluctuation on surface don’t vary, while in multi fractal surface in certain $q$ amount of $\xi_q$ reach saturation, in such surfaces importance of small fluctuation is more that large ones.

Distribution function of heights $P(\bar{h})$ is another statistical function and is calculated when height of points were measured with respect to $\bar{h}$, or $h(r,t) \rightarrow h(r,t) - \bar{h}$.\[1,2,7,9\]

4. Results:
To investigate roughness and fractal properties of Cu surface, copper thin films under various conditions were deposited, information about the produced samples are given in table 1.
Table 1. Information about production of some samples with same thicknesses.

| Sample No. | Current (A) | Rate $\bar{R}(nm/sec)\pm0.1$ | t(sec)  | T(nm)    |
|------------|-------------|-------------------------------|---------|----------|
| 1          | 0.2         | 0.4                           | 555     | 250 ± 30 |
| 2          | 0.4         | 0.8                           | 300     | 250 ± 20 |
| 3          | 0.6         | 1.4                           | 176     | 250 ± 20 |
| 4          | 1           | 2.5                           | 100     | 250 ± 20 |

After AFM analyses of samples, statistical functions of them were calculated. Two dimensional pictures of samples are given in figure 1.

Figure 1. In figure 1 (a)-(d) two dimensional picture of samples 1-4 is given respectively.

At first distribution function were obtained in Gaussian form (relationship (5)) for all samples, figure 2 shows distribution function for one of these samples.

$$p(h) = \frac{1}{W\sqrt{2\pi}} \exp\left(-\frac{h^2}{2W^2}\right) \quad (5)$$
By using equation (1) surface roughness was calculated for samples and it has been seen that with increases of deposition rate, roughness rises and it is due to energy and high speed of atoms during collision with surface.

Structure function of samples were studied too and in figure 3 this function for these samples is shown and it is obvious that amount of structure function for samples which have been produced in higher value of \( R \) is bigger than another. By study \( S_2(l) \) one can calculate correlation length too; this parameter is related directly to coating rate. Value of \( \alpha \) can be obtained by study structure function in range of \( l_0 \). Increase of \( \alpha \) (roughness exponent) with deposition rate shows rise of surface roughness. In table 2 amount of \( W, l_0 \) and \( \alpha \) for all samples is given.

![Figure 2. Distribution function for sample 2; \( p(h) \), which is Gaussian function.](image)

![Figure 3. Structure function for samples.](image)

Fractal properties of these samples in range of \((0.5 < q < 6)\) was studied. In low values of \( R \) surface is fractal, but with increase of discharge current or deposition rate, surface become multi fractal.

With rise in \( R \), slope of plotting \( \xi_q - q \) become larger, which cause increase in \( \alpha \). In range of \((0.5 < q < 3)\) plotting of \( \xi_q - q \) for each sample is linear. These phenomena are shown in figure 4. According to this figure one can conclude that the first three samples surface is fractal, while the last one (number 4) is multi fractal. When current is high, rate of deposition is high too, and each Cu atom collides to surface with very large amount of energy and disturb its neighborhoods so fluctuation of height would increase.

![Figure 4. Variation of \( \xi_q \) versus \( q \) for samples.](image)

5. **Summary:**
Surface roughness directly depends on deposition rate, also \( S_2(l), \alpha \) and \( W \) show increasement.
Surface roughness is a relative quantity parameter, importance of roughness don’t change with respect to scale of view in surface of first three samples (1-3), but importance of small fluctuations in sample 4 is more than larger fluctuations. When deposition rate is low, surface is fractal while in high coating rate multi fractal surface is produced.

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