Morphology of Thin Aluminum Film Grown by DC Magnetron Sputtering onto SiO_2 on Si(100) Substrate

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Abstract. The morphology and grown mechanism of aluminum films from 3nm to 30nm in thickness onto thermal SiO_2 on Si(100) substrates have been studied by atomic force microscopy and TCR measurement. The thin films prepared by dc magnetron sputtering at 450°C is composed of islands of aluminum. The island density, distribution of island size, height, and shape are studied.

1. Introduction

During the last decade, nanostructured materials and nano scale composites are receiving increased attention, from the viewpoint of both application and of theory [1]. Interest arises from the possible usefulness of the unique electrical [2], mechanical [3], and optical [4] properties.

In the early stage of metal film formation on amorphous substrates, nucleation occurs at many sites on the substrate surface Small clusters of material develop, and the area and height of these "islands" increases until a network and finally a continuous film is formed. As long as the average film thickness is less than a critical value, generally the film structure is a random array of discrete metallic islands. In this discontinuous stage the electrical conduction is non-metallic with a very high sheet resistance and a negative temperature coefficient of resistance. Surface/interface morphology plays important roles in modifying the physical properties of the films. For example, based on the tunneling conduction model, the size of the island and the gap determine the film resistivity and temperature coefficient of resistance.

Extensive works have been done in understanding the growth mechanism of different metallic film on various substrates using different deposition processes [5-7]. Film structure is normally observed directly by transmission electron microscopy, but first the film must be removed from the substrate. The problem with this technique is that the structure observed may not be the same as that on the original substrate. Also it is almost impossible to obtain the film structure in the contact region which has been suggested that plays a major role in determining film properties. Most of the studies on discontinuous metal films in the literature were on films deposited by evaporation technique and very rare data on films deposited by sputtering.

In this paper we studied the growth of Al discontinuous films onto SiO_2 on Si (100) substrates. We present the morphology data, island density, Al island size, gap between the island, island height, and their statistical distribution of the Al films from 2nm to 30 nm in thickness. The electrical characteristics, such as temperature coefficient of resistance, of these films are presented as a verification of the island structure, also correlated with their physical nature. Specifically a non-linear I-V characteristic was observed.

2. Experimental procedure

Aluminum films were deposited at 450°C substrate temperature by a magnetron DC sputtering technique using an aluminum (99.9999%) target in an argon plasma at a gas pressure of 2.7 mTorr. The deposition was performed at 300 V and 1.69 A. Before starting the deposition on the sample wafers, the target was pre-sputtered for ~5 min. 450nm silicon oxide was thermally growth on Si (100) substrates in dry oxygen ambient at 1150°C in a horizontal furnace. The substrates were cleaned in acetone in an ultrasonic bath. Then the substrates were subjected to vapor degreasing in isopropyl alcohol and were dried in a hot atmosphere of it. The substrates were degassed in a load lock chamber at 400°C for 2 min before transferred into the sputtering chamber. Thick aluminum electrodes were predeposited on the substrates. The sputtering chamber was evacuated to a base pressure of approximately 4×10^{-9} torr by a cryopump. The residual gases in sputtering chamber were monitored by a RGA. And the main residual gases were N_2 and H_2O. For sputtering, pure argon gas (99.999%) was introduced into the sputtering chamber through a mass flow controller. The aluminum (99.9999%) target, 305 mm in diameter was placed at a distance of 50 mm from the substrate. Al films were grown for different duration of deposition. The deposition rate is ~0.7nm/second. All the cleaning and deposition operations were performed in a class 100 clean room environment.

Atomic force microscopy (AFM) studies were performed by scanning probe microscope (Dimension 3100, Digital Instruments) in ambient conditions. The scan was taken using silicon tip (radius of curvature ~5 nm) in a tapping mode. Initially the film quality was checked by performing large area scans. The dc electrical resistance of the films was measured from 300 to 400 K using a HP 4156B. The measurements were made by sweeping a voltage from –5 volts to +5 volts across two electrodes and plotting the current. Predeposited (sputtered) aluminum contacts on Si substrates were used for the resistance measurements.

3. Results and discussion

3.1 Microstructural study

The aluminum films were deposited at 450°C for different duration of deposition as indicated in Table 1. AFM images in different length scales have been taken to study the film surface morphology at different stages of film growth. Four such images of a small area scan are shown in figure 1. The scan size is 500nm × 250nm. The deposition times for these four films are 3, 7, 9, and 15 seconds.

Table 1

Values of island density (n), island size (d), island height (h), and inter-island distances (s) for aluminum films deposited at 450°C at 2 mTorr.

Sample no.	Deposition time (sec)	Island density (cm^{-2})	Average island size (nm)	Average island height (nm)
1	3	4.824×10^{11}	3.44	1.34
2	4	1.76×10^{11}	5.41	1.62
3	5	9.04×10^{10}	10.93	4.326
4	6	8.24×10^{10}	17.45	5.85
5	7	3.92×10^{10}	25.46	8.874
6	8	3.90×10^{10}	28.58	8.742
7	9	3.12×10^{10}	32.03	10.055
8	15	2.68×10^{10}	36.12	10.513
9	25	8.8×10^{9}	59.45	31.198

Figure 1. AFM images for Al films with different deposition time. (a) 3 seconds, (b) 7 seconds, (c) 15 seconds, and (d) 25 seconds.

The AFM images show that all the films studied are composed of islands. The dependence of the island density, island size, and island height and their distribution ranges, upon the deposition time, is presented for Al films in Fig. 2. It can be noted that the average size of these islands grows from 3.44nm for 3 seconds deposition to 59.45nm for 25 seconds deposition. The average island height grows from 1.34nm for 3 seconds deposition to 31.198nm for 25 seconds deposition. The bars indicate the range of these sizes. From figure 2.(a), and 2.(b), It is observed that the distribution of the island height and diameter spread wider when the nominal film thickness gets thicker. In figure 2.(c) we show the height distribution of two AFM images. We observed that the height distribution to be symmetric at the early stage of the film growth but skew to the greater island height at 25 seconds deposition.

For the development of the island densities, From figure 2.(d), a high island density is already observed at very low coverage. Coalescence sets in at an early stage accompanied by a steady decrease of the island density. Coalescence of islands is predominant as indicated by the decreasing island density and increasing island diameter. Such a behavior strongly points to a very efficient heterogeneous nucleation mechanism.

The AFM images show that the island geometry to be of an oblate spheroid in the early stage of deposition, $t<9$ seconds. For $t > 12$ seconds, many islands have a flat top and regular triangular or hexagonal shape.

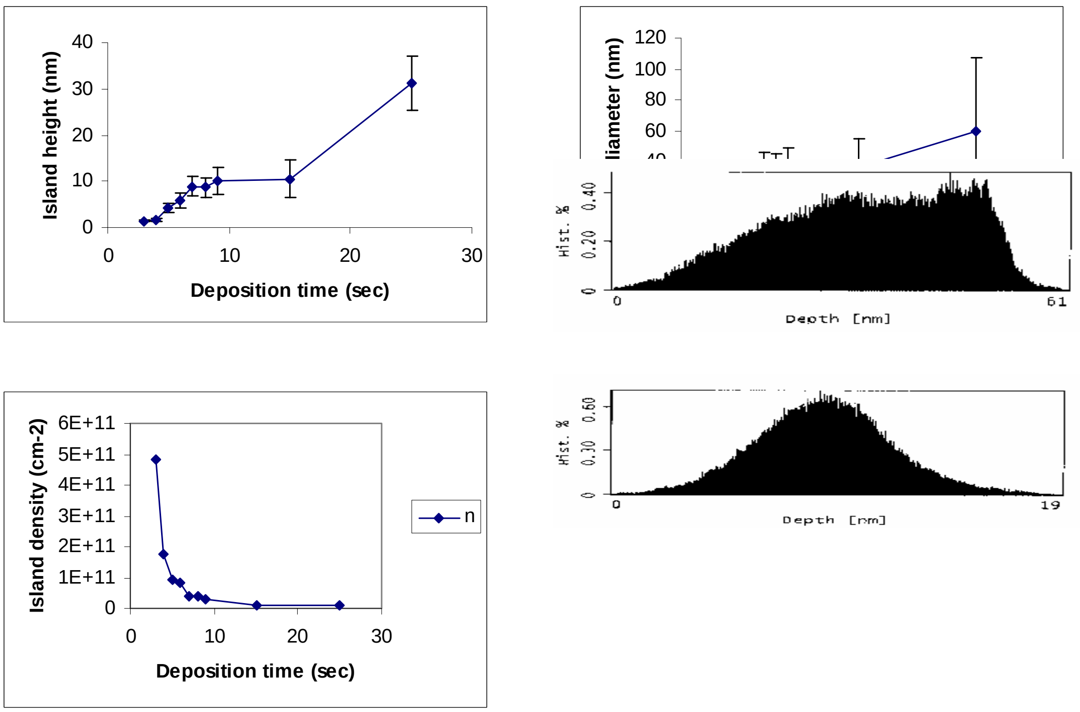


Fig. 2. Plots of (a) the average island height, (b) the average diameter, (c) the island density as a function of deposition time for Al growth at 450°C on Si_2O/Si(100). (d) Island height distributions for Al films with (top) 9 seconds, (bottom) 25 seconds.

3.2 Electrical study

Several models have been introduced to explain the electrical characteristics of discontinuous metal films. These include thermonic emission, quantum-mechanical tunneling, tunneling between allowed states, and tunneling via traps and substrates. Investigations have been reported, explaining various electrical behavior according to one or more of these models. For this study, a model, extending the work of Neugebauer and Webb [8], predicts very well the temperature and size effect dependence of these films. The conductivity is given by

$$\sigma = \sigma_0 \exp(-\delta E / kT)$$

Where

This model predicts a linear dependence of lnR on 1/T , which is confirmed by the data from this study, shown in Fig 3(a).

The Neugebauer-Webb model of activated tunneling also predicts that the activation energy, δE, is given by

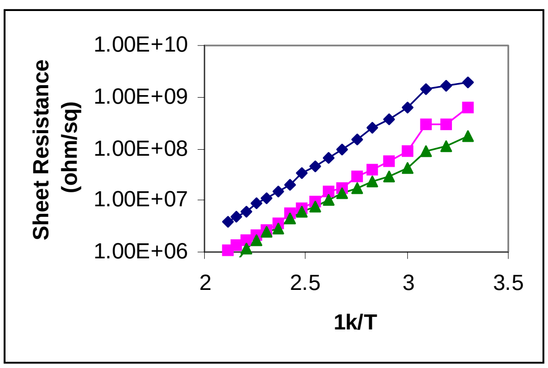
$$\delta E = \frac{e^2}{4\pi\varepsilon}\left(\frac{1}{r} - \frac{1}{2r+s}\right)$$

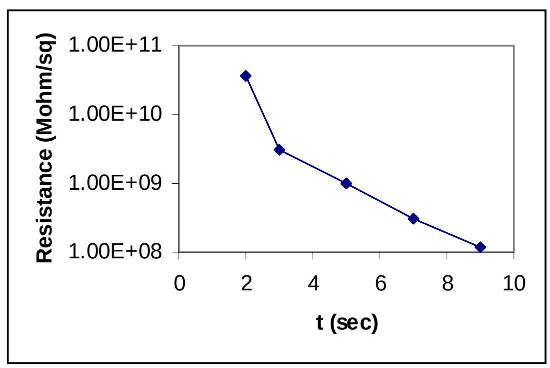
Where r and s are the island size and interisland separation, respectively. ε is an effective dielectric constant of the media between islands.

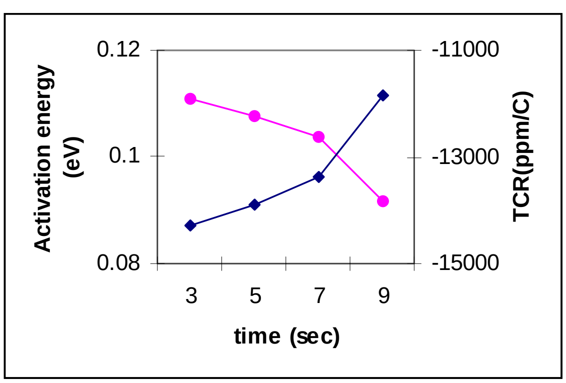
Figure 3(b) shows the measured temperature coefficient of resistance (TCR) of the Al films and the activation energy calculated from the TCR data. The negative TCR data indicate that the electrical conduction in these films is non-metallic so that indirectly confirm that the films are discontinuous.

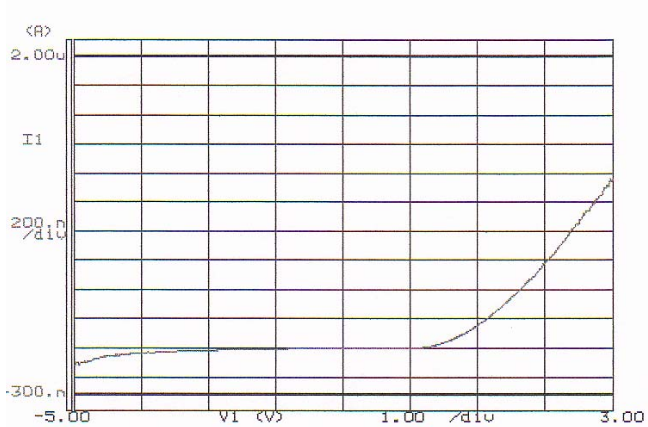
The resistance of the Al films deposited at 450°C and $2.6\times^{10-3}$ Torr as a function of the deposition time is shown in figure 3 (c). It can be seen that the Al films have very high sheet resistance and a rapid drop in resistance is observed during the first 9 seconds of deposition

3.3 Anomalous I-V characteristics









4. Conclusions

The growth of Al thin films on SiO_2 substrate deposited by DC magnetron sputtering technique has been studied by AFM and electrical measurements. Island formation of Al was observed for film of thickness between 1.5nm and 30 nm from AFM images. Predominant coalescence behavior at the early growth stage strongly points to a very efficient heterogeneous nucleation mechanism. All the films show negative TCR and the calculated activation energy are ~0.1 eV. A non-linear I-V characteristic was observed.

Reference

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