ULTRASMOOTH, CONDUCTING MULTILAYER FILMS FOR ADVANCED APPLICATIONS

D. G. Stearns, S. Baker and M. Wall
Lawrence Livermore National Laboratory, P.O. Box 808, Livermore CA

The incorporation of three-dimensional thin film structures in advanced applications such as magnetic recording is presenting ever-increasing demands on the control of the microstructure and physical properties of the thin films. As an example, in certain electrically active devices it is necessary to have a contact layer on the bottom of the device. The contact layer must have low resistance and be very smooth, since it serves as the underlayer to a thin film stack. Our previous experience with x-ray reflectance coatings has lead us to investigate Mo/Si multilayer (ML) structures as a promising candidate for such a contact layer. In this paper we demonstrate that Mo/Si ML films can be grown relatively thick (0.5 μm) with virtually no accumulation of roughness and, with the proper choice of structural parameters, can exhibit low resistivity.

A series of Mo/Si ML structures was grown to study the dependence of the film properties on the individual Mo and Si layer thicknesses. Films having a total thickness of ~0.5 μm were grown by depositing alternating Mo and Si layers onto high resistivity (> 1000 Ω-cm), superpolished Si wafers using dc magnetron sputter deposition. The individual layer thicknesses were varied from sample to sample, with values of 2.5, 5.0 or 10.0 nm for Mo, and 1.0, 2.0 or 5.0 nm for Si. In addition, a single 0.5-um-thick Mo film was grown. Deposition conditions were chosen that have been shown to yield smooth polycrystalline Mo and amorphous Si layers with thin (~1 nm), asymmetric interlayers of mixed composition[1] . The microstructure of the ML films was characterized using x-ray diffraction and transmission electron microscopy (TEM). The surface roughness was characterized using atomic force microscopy and the resistivity was measured using a four-point probe technique.

The surface roughness (σ^2) of the film, as defined as the integral of the power spectral density (PSD) over the frequency range of 10^{-3} - 10^{-1} nm^{-1}, is found to scale linearly with the Mo layer thickness and is fairly independent of the Si layer thickness. Cross-sectional TEM images show that the roughness originates from polycrystalline texture of the Mo layers. The film resistivity increases with decreasing Mo thickness in good agreement with Sondheimer-Fuchs theory of electron scattering at the multilayer boundaries. Modeling of our results yields a value of ~20 nm for the electron mean-free-path in the Mo layers at room temperature.

The opposing dependency of the resistivity and surface roughness of the ML films on the Mo layer thickness allows us to identify optimum structural parameters for achieving an ultrasmooth, conducting film. The Si layers should be just thick enough to disrupt the Mo crystallite growth; 1 nm is found to be sufficient. An Mo layer thickness of 2.5 nm produces a surface roughness of $\sigma < 0.2$ nm with a resistivity of ~ 60 uΩ-cm. The resistivity can be decreased at the expense of greater surface roughness.

The PSDs of the surface roughness of the films exhibit qualitatively the behavior predicted by a simple, stochastic model of thin film growth with relaxation via surface diffusion[2] . However, quantitative modeling shows that the fundamental growth parameters change with the Mo layer thickness. In particular, the growth unit volume Ω increases approximately linearly with the Mo layer thickness. This is likely due to the increasing size of the Mo crystallites with layer thickness, consistent with a picture of columnar, competitive growth cones[3] .

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[1] D. G. Stearns, R. S. Rosen and S. P. Vernon, Appl. Opt. **32**, 6952 (1993).
[2] D. G. Stearns, Appl. Phys. Lett. **62**, 1745 (1993).
[3] R. Messier and J. E. Yehoda, J. Appl. Phys. **58**, 3739 (1985).

I. Motivation

a) 3D thin film structures require control of microstructure and physical properties. In electrically active structures, it is sometimes required to have a contact layer on the bottom, which should be low resistivity and very smooth.

b) Our experience with Mo/Si ML structures, from our work with x-ray reflective coatings, suggests that these could be grown relatively thick (~1 um) with virtually no accumulation of roughness, and could be made low resistivity. Our goal is to find the optimum structural parameters.

II. Description of experiment

a) A series of ML structures was grown to study dependence on Mo and Si layer thicknesses. (Describe sample matrix).

1) Fabrication by magnetron sputtering on superpolished Si substrates having $\rho >$ 1000 Ω-cm. Deposition conditions used were known to yield smoothest layering and abrupt interlayers. Discuss interlayer formation.

b) Structural characterization by XRD and TEM used to measure layer thicknesses and study growth morphology.

c) Surface roughness characterized using AFM.

d) Resistivity measured using four point probe technique.

III. Results

a) Roughness (σ) scales with Mo thickness ($t^{1/2}$) and is fairly independent of Si thickness (AFM). Roughness originates from polycrystalline texture of Mo layers (TEM).

b) Resistivity (ρ) increases with decreasing Mo thickness in good agreement with Sondheimer-Fuchs theory and RT mfp of 230 A.

c) PSD of ML roughness does not follow a simple growth model based on a growth unit Ω and relaxation parameter ν via surface diffusion. Instead, both Ω and ν wary with the Mo layer thickness.

IV. Discussion

a) The counteracting dependencies of the resistivity and surface roughness of the ML films on the Mo layer thickness provides for a well-defined optimum structure. The Si layers should be just thick enough to disrupt the Mo crystallite growth; 10 A is sufficient. Mo layer thickness of 25 A produces $\sigma < 2$ A and $\rho \sim 60$ uΩ-cm. Hence it is feasible to grow conducting films that remain ultrasmooth (ie. as smooth as the substrate) having total thickness of at least 0.5 um.

b) The failure of the simple growth model to describe the roughening of the ML is not unexpected, since it does not include kinetics of crystalline growth, ie. effects of columnar growth. By fitting the PSDs to the simple model, it appears that both the growth unit and relaxation parameter increase with Mo layer thickness, which is probably due to the increasing size of the Mo crystallites with thickness. Indeed, in the picture of growth by competing columns, the surface would be composed of single-crystal caps that are randomly located in the film plane, with an average diameter that would increase with film thickness. This would look like a surface with an increasing growth unit size.

D. G. Stearns, S. Baker, M. Wall, F. Weber and M. Carey
Lawrence Livermore National Laboratory
P.O. Box 808, MS L-395
Livermore CA 94551
(510) 423-4938
(510) 422-8761 Fax
E-mail: stearns1@llnl.gov