Thin Solid Films 573 (2014) 84–89

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Growth kinetics of ion beam sputtered Al-thin films by dynamic scaling theory

Neha Sharma *, K. Prabakar, S. Dash, A.K. Tyagi

Material Science Group, Indira Gandhi Centre for Atomic Research, Kalpakkam 603102, TN, India

ARTICLE INFO

Article history:
Received 7 February 2014
Received in revised form 21 October 2014
Accepted 29 October 2014
Available online 5 November 2014

Keywords:
Ion beam sputter deposition
Dynamic scaling theory
Growth kinetics
Static and dynamic scaling constant
Scaling phenomenon

ABSTRACT

This paper reports the study of growth kinetics of ion beam sputtered aluminum thin films. Dynamic scaling theory was used to derive the kinetics from atomic force microscopy (AFM) measurements. AFM imaging revealed that surface incorporates distinctly different morphologies. Variation in deposition times resulted in such distinctiveness. The growth governing static (α) as well as dynamic (β) scaling exponents has been determined. The exponent α decreased as the deposition time increased from 3 to 15 min. Consequently, the interfacial width (ξ) also decreased with critical length (L_c), accompanied with an increase in surface roughness. Surface diffusion becomes a major surface roughening phenomenon that occurs during deposition carried out over a short period of 3 min. Extension of deposition time to 15 min brought in bulk diffusion process to dominate which eventually led to smoothening of a continuous film.

1. Introduction

Thin film technology has been evolved as a potential solid state material processing technique. Thus qualitative understanding of thin film growth is essential in case of each deposition technique to optimize film microstructure. Three consecutive steps are encountered in deposition of a thin film. Initially the formation of deposition species (atomic, molecular or ionic species) takes place. This is followed by their transport from source to substrate. The final step points to their condensation onto the substrate and the subsequent film growth. Based on these aspects, three distinct growth mechanisms have been proposed [1]. Volmer–Weber growth (or 3D island growth) of small clusters was nucleating directly on the substrate surface and then growing together to form 3D-islands. These 3D-islands in turn coalesce to form a continuous film. Frank–Vander Merwe growth (2D layer-by-layer growth) causes layers to form and grow on to the substrate. Stranski–Krastanova growth (mixed mode growth) follows layer-by-layer mode to start with and after forming one or two monolayers, layer growth gives way to 3D island mode of growth [1]. Depending upon various growth conditions and materials, different growth mechanisms are encountered. These are specific to deposition techniques and process conditions. In the light of these facts, it is essential to define specific parameters for pin pointing growth mechanisms encountered in varied deposition techniques and process conditions.

A possible and reliable way of assessing the growth mechanism of thin films involves mathematical analysis of surface topography within the frame work of dynamic scaling theory (DST) [2]. This provides a means to acquire the information about the effects of certain surface phenomenon like plastic flow, condensation, evaporation and diffusion on the thin film growth. Therefore the role of such physical processes on the microstructural properties such as roughness and conformality is easily addressed.

In 1985, Family and Vicsek [3] propounded DST to analyze the behavior of growing surfaces by assuming that these are self-affine. According to the conventional DST, the scaling behavior can be represented by the Family–Vicsek scaling relation [3].

$$\xi(L,t) = L^{\alpha} f\left(t/L^{z}\right) \tag{1}$$

where

$$\xi(L,t) \sim t^{\beta} \text{ for } t/L^{z} << 1$$

and

$$\xi(L,t) \sim L^{\alpha} \text{ for } t/L^{z} >> 1.$$

Here, ξ is the interface width, L is the length scale over which the roughness is measured, t is the time of growth. α and β are static and dynamic scaling exponents, respectively. z equals α/β. Such a scaling behavior holds well for thin films synthesized by techniques like

---

* Corresponding author at: Indira Gandhi Centre for Atomic Research, India.
E-mail address: neha@igcar.gov.in (N. Sharma).

http://dx.doi.org/10.1016/j.tsf.2014.10.094
0040-6090/

evaporation [4], sputtering [5], thermal chemical vapor deposition [6] and plasma enhanced chemical vapor deposition [7].

However, the scaling behavior defined by Eq. (1) is not satisfied in other experimental systems [8,9]. There is always an anomalous scaling present in every experimental system which generally causes the appearance of distinct values of the scaling exponents, α and β, which depends upon the scale of measurement [10].

In this work, we are motivated to develop a general understanding of the fundamental processes controlling the growth of the Al-thin film by ion beam sputter deposition (IBSD) system. Al-thin film is a promising candidate for microelectronic device fabrication due to its low resistivity and high compatibility with silicon. For this, we have determined the scaling exponents of Al-thin films deposited on Si(100) by IBSD. The purpose of this study is to understand the growth kinetics of IBSD grown Al-thin films as a function of deposition time and scale of measurement.

2. Theoretical background

Conventional DST considers development of self-affine surfaces to be associated with scaling relations among surface roughness (defined as root mean square (rms) of surface height H(r) and denoted by "δ"), deposition time (t) and scale of measurement (L). As mentioned earlier, DST proposes that the behavior of the interface width follows the trends propounded by Family–Vicsek relationship [3] given by Eq. (1). This exhibits two distinct asymptotic scaling behaviors for the interface width ξ:

$$\begin{aligned} &\xi(L,t)\sim t^{\beta} \text{ for } t<< \\ \text{and}\quad &\xi(L,t)\sim L^{\alpha} \text{ for } t>>. \end{aligned}$$

Therefore, during initial growth stages, the 'ξ' increases with 't' at a rate of the growth exponent β until a saturation value of ξ_L is reached. After attaining this value, the interface width becomes a function of 'L' through the growth exponent α. At some critical length L_c, the interface width saturates and becomes equal to rms value of roughness 'δ' for all $L > L_c$.

A quantitative representation on the height variation and lateral correlation is provided by the "autocovariance function G(r)" [11]. G(r) at different length scales provides a quantitative description of correlation among heights at different points on a surface as a function of their separation "r". The interface width as a function of length scale is related to this G(|r|) in the following way [12,13]:

$$\xi_L^2 = \left(\frac{1}{L^2}\right)\int_0^L \left[\delta^2 - G(|r|)\right] r\,dr. \tag{2}$$

G(r) for a self-affine surface with spatial scaling exponent α can be approximated as:

$$G(|r|) \approx \begin{cases} \delta^2\left[1-\dfrac{\alpha+1}{2}\left(\dfrac{r}{L_c}\right)^{2\alpha}\right], & \text{for } r \le L_c \\ 0, & \text{for } r > L_c \end{cases}. \tag{3}$$

The Fourier transform of the Eq. (3) yields power spectral density function (PSD) g(q). This is a very useful function as several fundamental aspects of a rough surface can be formulated in terms of PSD. Mathematically PSD is linked to autocovariance function as mentioned below.

$$g(|q|) \;=\; \mathscr{F}[G(|r|)]$$

where $\mathscr{F}$is the two-dimensional Fourier transform operator. The PSD assumes the forms:

$$g(|q|) \approx \begin{cases} \dfrac{\alpha}{\pi}\delta^2 L_c^2 & \text{for} \quad |q| < {}^{1}\!/_{L_c} \\ \dfrac{\alpha}{\pi}\dfrac{\delta^2}{L_c^{2\alpha}} q^{-2(\alpha+d)} & \text{for} \quad |q| \ge {}^{1}\!/_{L_c} \end{cases} \tag{4}$$

where d, in our case, represents line scan direction and equals to '1'.

Thin film growth via a surface-vapor interaction takes place by the stochastic addition or removal of atoms with no lateral transport occurring on the surface. The scaling of growing self-affine surface arises from the competition between roughening and various smoothening mechanisms. By combining the smoothening mechanisms with the stochastic roughening, a kinetic rate expression can be written in reciprocal space to account for surface growth [14]:

$$\frac{\partial h(|q|,t)}{\partial t} \propto -c_n|q|^n h(q,t) + \dot{\eta}\,(|q|,t) \qquad (n = 1,2,3,4). \tag{5}$$

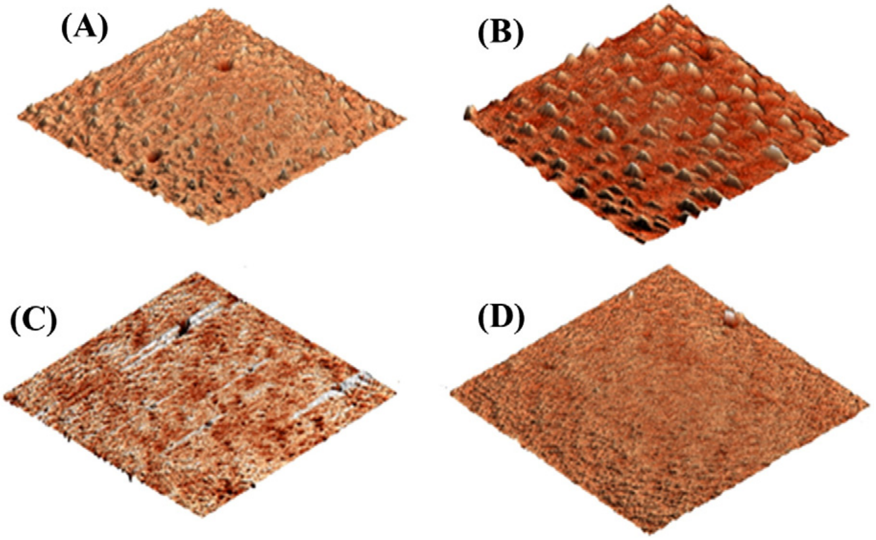

Fig. 1. Representative 3D Atomic Force Microscope (AFM) images (1 × 1 μm^2) of the evolution of surface morphology for the films grown for different deposition times as, (A) 3 min, (B) 5 min, (C) 8 min and (D) 15 min.