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Ion beam erosion of amorphous materials: evolution of surface morphology

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Abstract

In this work we present our results concerning the formation of self-organized nanoscale structures during the bombardment with a low-energy defocused Ar ion beam. We studied glass surfaces because of their physical properties, technological interest and cheapness. The evolution of sample surface was studied ex situ by atomic force microscopy. We found, in agreement with Bradley and Harper, a morphology characterized by a regular ripple structure with the wave vector perpendicular or parallel to the ion beam direction. This structure periodicity was found to vary in the range 90–350 nm with a linear time evolution. In order to gain further information about the sputtering process and for comparison with the existing continuum theories of surface erosion, we studied the scaling behaviour of surface roughness.

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1. Introduction and theory

Starting from 1962, when Navez et al. [1] produced by simple ion bombardment a wavelike surface structure (ripples), the attention towards this morphology considerably increased. The formation of periodic modulation on various materials (Si [2,3]; Ge [4]; Cu [5]; Ag [6]; SiO_2 [7]; graphite [8]), obtained by ion sputtering, today represents an active field of research, due to its possible applications in the production of microelectronic devices.

In 1988 Bradley and Harper (BH) [9], starting from the Sigmund's theory of the sputtering, showed that the observed surface instability was a consequence of the dependence of the sputtering

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yield on the local surface curvature. This instability is caused by the different erosion rates for throughs and crests: the former are eroded faster than the latter. Thus sputtering increases exponentially the amplitude of any surface modulation. Bradley and Harper obtained a linear equation describing the surface height evolution, $h(\boldsymbol{r}, t)$, with the balance between erosion and smoothing terms:

$$\frac{\partial h}{\partial t} = \upsilon_x \frac{\partial^2 h}{\partial x^2} + \upsilon_y \frac{\partial^2 h}{\partial y^2} - B\nabla^2\nabla^2 h, \quad (1)$$

where the prefactors $\upsilon_{x,y}$ and B account for the curvature dependent sputtering and surface diffusion effects respectively. This approach gives rise to an observable periodic structure with wavelength $\lambda = 2\pi\sqrt{2B/|\upsilon_i|}$, where $|\upsilon_i|$ is the largest between the two coefficient $|\upsilon_x|$, $|\upsilon_y|$. The BH theory is rather successful in predicting the ripple orientation, however it has some difficulties to estimate the evolution of ripple amplitude and wavelength. For example, the BH theory predicts an unlimited exponential increase in ripple amplitude, in contrast with the linear regime observed in [7]. Similarly, it predicts a time-independent evolution of surface wavelength, while experimental results have shown a monotonic increase of λ with time [10].

In 1994, Cuerno and Barabasi generalized the BH model introducing non-linear terms. Furthermore they accounted for the stochastic arrival of ions by adding to (1) a Gaussian white noise, $\eta(x, y, t)$, with zero mean and variance proportional to the ion flux. In this way equation (1) becomes:

$$\frac{\partial h}{\partial t} = \upsilon_x \frac{\partial^2 h}{\partial x^2} + \upsilon_y \frac{\partial^2 h}{\partial y^2} + \frac{\eta_x}{2}\left(\frac{\partial h}{\partial x}\right)^2 + \frac{\eta_y}{2}\left(\frac{\partial h}{\partial y}\right)^2 - B\nabla^2\nabla^2 h + \eta(x, y, t), \quad (2)$$

which belongs to the class of anisotropic Kadar–Parisi–Zhang (KPZ) equations. A detailed analysis of Eq. (2) predicts surface roughness to scale with time as $w = t^{\beta}$ [11]. This is one of the most important results achieved within the present experimental work.

2. Experimental

Ion beam sputtering is performed in a UHV chamber equipped with a defocused ECR plasma ion source. Prior to insertion into the UHV chamber the glass sample (2×1 cm^2) is cleaned in an ultrasonic acetone bath to eliminate organic contaminants and rinsed in pure water. Within the experiments the ion energy E_{ion} and the ion flux j_{ion} are fixed respectively at 800 eV and about 400 μA cm^{-2}. The sample is bombarded at a temperature of 300 K with Ar ions; the angle of incidence is chosen between 35° and 75° with respect to the substrate normal. To prevent the charging of the sample, a W filament (Th coated) is positioned at the end of the source, ensuring an efficient neutralization of the surface during ion erosion. The surface topography was investigated ex situ by atomic force microscopy (AFM) operating in contact and tapping mode. All measurements were conducted in air using Si-tips with a nominal radius of 20 nm.

3. Results

In Fig. 1 we compare the surface topography before and after Ar-bombardment at an angle of incidence of 35°. The sample clearly shows a regular ripple structure with ridges running perpendicular to the ion beam projection while the wavelength λ and the interface width w (RMS roughness) significantly vary with the sputtering dose (λ = 90–350 nm; w = 1–20 nm).

Fig. 2 shows two different samples sputtered under the same experimental conditions but changing the incidence angle of the ion beam. Ripples oriented perpendicular or parallel to the ion beam projection as predicted by the BH theory are visible in all the AFM topographies. At incidence angles $\vartheta_{\text{ion}} = 35°$ (Fig. 2(a)) the surface is characterized by a regular ripple structure with ridges running perpendicularly to the ion beam projection. The wavelength of the resulting morphology is approximately 160 nm, as determined from the 2D-autocorrelation function. On the contrary, at $\vartheta_{\text{ion}} = 75°$ (Fig. 2(b)) the orientation of the ripples is rotated by 90°: a weakly evolved structure ($\lambda \approx 100$ nm) is now parallel to the ion beam direction.

We studied the evolution of the surface morphology as a function of sputtering time (ion dose)