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Ion-induced self-organized dot and ripple patterns on Si surfaces

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Abstract

The evolution of the surface topography during low-energy Ar^+ ion beam erosion of silicon surfaces is studied. Depending on ion-beam parameters, a variety of nanostructured patterns with a very narrow size distribution can be developed on the surface. By rotating the sample, ordered nanodots are formed for ion energies $\geqslant$300 eV at normal and oblique ion incidence angles with respect to the surface normal. Dots evolving at oblique ion incidence of 75° show a very high degree of ordering with a mean dot size $\lambda\sim$30 nm. Without sample rotation at near normal ion incidence angle ($\sim$15°), remarkably ordered ripple structures develop with a wavelength $\lambda\sim$45 nm. The degree of ordering and size homogeneity of these nanostructures increases with erosion time eventually leading to the most ordered self-organized patterns on Si surfaces reported so far.

Keywords: Ion sputtering; Self-organization; Pattern formation

1. Introduction

Low-energy ion bombardment or erosion of solid surfaces is a promising alternative approach for the generation of self-organized nanostructures. In addition to the removal of material from the surface due to sputtering caused by energy and momentum transfer from the incoming ions to target atoms, the interplay between sputter-induced roughening and various surface relaxation mechanisms can lead to a wide range of surface topographies and patterns [1–3]. For example, ordered ripple structures can develop with length scales ranging from some tens to hundreds of nanometers, depending on the sputtering conditions and the target material. Recently, it was observed that self-organized hexagonal or square ordered dot patterns can evolve after low-energy ion sputtering of III/V semiconductor surfaces under normal incidence or oblique incidence and simultaneous sample rotation [4–6]. For the technological most important semiconductor, silicon, ripple as well as dot patterns were found after Ar^+ ion beam erosion. However, ripple patterns are mainly observed at high ion energies or at low ion energies and high temperatures, with length scales above 100 nm and at ion incidence angles (with respect to surface normal) from 40° up to 70° [7–10]. Si dot patterns are formed under normal ion incidence at an ion energy of 1200 eV [11], but the degree of ordering of the nanostructures is much less compared to III/V semiconductors.

In this work, recent results for pattern formation on Si surfaces caused by low energy Ar^+ ion beam erosion ($E_{ion}\leqslant$2000 eV) at normal and oblique ion incidence, with and without sample rotation at room temperature are presented. In particular, it is demonstrated that (i) complex pattern formation processes do arise during erosion of Si surfaces and (ii) remarkably high-ordered dot and ripple patterns with structure sizes below 50 nm can be obtained by choosing appropriate sputtering conditions.

2. Experimental conditions

The samples used in this work were commercially available epi-polished (1 0 0) Si substrates with a root-mean-square (rms) roughness of $\sim$0.2 nm. The samples were mounted on a water-cooled (approximately 285 K) substrate holder with a possibility to revolve about its axis, and the angle of ion-beam incidence, α_{ion} could be varied between 0° and 90° with respect to the surface normal. The low-energy Ar^+ ions were produced in a home-built

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Kaufman-type broad beam ion source equipped with a two-grid ion optical system (beam diameter 200 mm). The operating conditions of the ion source were optimized with respect to well-defined ion energy distributions and ion beam divergences [12,13]. The ion current density j_{ion} was kept constant at about $300\,\mu A\,cm^{-2}$ corresponding to an ion flux of $1.87 \times 10^{15}\,cm^{-2}\,s^{-1}$. The ion fluence was varied from $1.12 \times 10^{17}\,cm^{-2}$ up to $1.35 \times 10^{19}\,cm^{-2}$, corresponding to an erosion time of 60 up to 7200 s, respectively.

The surface topography was analyzed by scanning force microscope (AFM) operating in TappingMode. The measurements were performed in air using silicon cantilevers with a nominal tip radius less than 10 nm. The ordering of patterns was characterized by calculating the Fourier transformation of the height profile. Such profile possesses sharp peaks that correspond to the characteristic orientation and symmetry of the nanostructures in real space. From the Fourier transformation, is possible to deduce the one-dimensional power spectral density (PSD) function by angular averaging [14]. High-resolution transmission electron microscopy (HRTEM) was performed in a 400 keV microscope possessing a point resolution of 0.155 nm to study the shape and structure of dots and ripples in cross-section. Cross-sectional samples were prepared by glueing samples face to face, embedding resulting sandwiches in alumina tubes, wire-saw cutting, plan-parallel grinding, one-sided polishing, other-sided dimpling followed by polishing to a residual thickness of about 15 μm and Ar^+-ion beam etching at 2.8 keV.

3. Results and discussion

Fig. 1 shows the AFM images from Si surfaces eroded with Ar^+ ions at room temperature with simultaneous sample rotation for different ion incidence angles α_{ion} and at different ion beam energies E_{ion}. Depending on ion beam parameters, it is possible to generate different topographies on the Si surface. In Fig. 1(a–c), the surface topographies obtained for different ion incidence angles at an ion energy of $E_{ion} = 500$ eV and erosion time 1200 s are depicted. At $\alpha_{ion} = 0°$ (Fig. 1a), hole structures coarsening with time emerge on the surface of Si with no preferred orientation and ordering. By further increasing the incidence angle, the surface roughness decreases until at $\alpha_{ion} = 45°$ (Fig. 1b) there are no characteristic features on the surface. Even after long erosion times the roughness of the surface remains below 0.2 nm, indicating that under certain erosion conditions, direct ion beam erosion can be utilized to smooth surfaces [15]. By increasing the incidence angle to $\alpha_{ion} = 75°$, dot structures are formed with a preferred size but a marginal short range ordering. For $E_{ion} = 1800$ eV, at normal ion incidence dot nanostructures evolve with an isotropic distribution, a mean dot size of ~40 nm (Fig. 1d) and an amplitude of 3 nm, similar to those reported by Gago et al. [11]. These self-organized patterns have short-range hexagonal symmetry and the mean size of dots is almost erosion-time independent. Again, at 45° the surface remains smooth (Fig. 1e) and by further increasing α_{ion}, the surface roughens again (Fig. 1f). From Fig. 1, it is evident

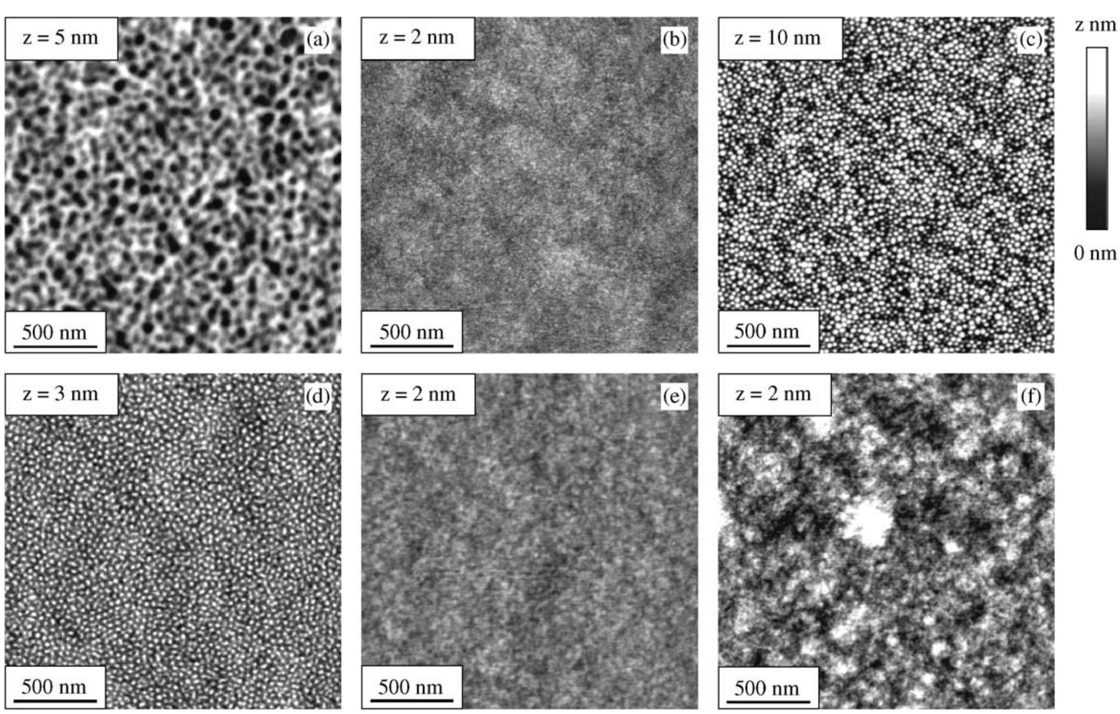

Fig. 1. AFM images of Ar^+ ion beam eroded Si surfaces at different ion incidence angles and ion energies: (a–c) $E_{ion} = 500$ eV, erosion time 1200 s, $\alpha_{ion} = 0°$, 45° and 75°, respectively, (d–f) $E_{ion} = 1800$ eV, erosion time 3600 s, $\alpha_{ion} = 0°$, 45° and 75°, respectively. The image size is $2 \times 2\,\mu m$. Note the different (vertical) z scales.