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Short communication

Highly-ordered ripple structure induced by normal incidence sputtering on monocrystalline GaAs (001): ion energy and flux dependence

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A B S T R A C T

Low energy ion beam sputtering induced nanostructure formation on GaAs (001) surfaces at elevated temperature and at normal ion incidence has been studied for different ion energy and flux of the incident Ar^+. Well-ordered nanoripples are found to develop, whose wave-vector is oriented along ⟨110⟩ crystallographic direction. The ripple structure is found to coarsen with ion energy, while it remains invariant with the ion flux. The evolution of the ripples can be attributed to the biased diffusion of vacancies arising from Ehrlich–Schwoebel barrier.

Ordered surface patterns in nanoscale dimensions on GaAs surface are of particular relevance due to its unique optical and electrical properties and, for semiconductor device applications [1]. To fabricate nanopatterns in large scale and in short time, ion beam sputtering (IBS) is a promising method [2,3]. It is just a single process step, no masking is required and there are no chemical hazards. Unfortunately, major drawback of IBS is the amorphization of upper surface by ion bombardment, which reduces the quality factor in prospective applications. The crystallinity, however, can be retrieved by annealing the sample at or above its re-crystallization temperature. Under this condition, kinetic instability due to the presence of Ehrlich–Schwoebel (ES) barrier [4,5] across step edges develops and the pattern formation is induced by the biased diffusive surface currents.

There is only limited number of studies about IBS induced topography evolution in semiconductors above the re-crystallization temperature [6–9]. Recently, we observed periodic nanoripple formation on GaAs (001) surface by hyperthermal (30 eV) Ar^+ irradiation at elevated temperature, where sputter ejection of target atoms is not important [8]. Subsequently, Ou et al. [9] extended the measurement at high bombarding energy (1 keV Ar^+), i.e. in the presence of sputter-erosion of the surface. In both the cases, the pattern has a strong resemblance with the features developed in homoepitaxy of GaAs (001) [10,11], but bears a higher degree of regularity. Like the elongated mound structure in homoepitaxial growth, the nanogrooves of the ripple structure in ion irradiation tend to orient along $\langle 1\bar{1}0 \rangle$ direction.

Ou et al. [6,9] proposed a vacancy-mediated diffusion model for pattern formation on crystalline semiconductor surface. When ion bombardment is carried out above the recrystallization temperature, ion induced vacancies and interstitials in the bulk are dynamically annealed. But, the adatoms and surface vacancies remain as defects and their kinetics lead to the development of surface patterns. In IBS, vacancy kinetics is expected to dominate because more vacancies are created by the ejection of target atoms. The diffusing vacancies experience an ES energy barrier whenever they try to ascend into the next higher terrace. Thus, there is a preferential accumulation of vacancies at lower terraces, which establishes a net downhill diffusion current in the direction perpendicular to the terrace. This results the formation of vacancy troughs, i.e. negative homoepitaxial growth of vacancy islands, which subsequently coarsen into periodically correlated grooves along a preferred direction determined by the step edge dynamics of the crystalline surface.

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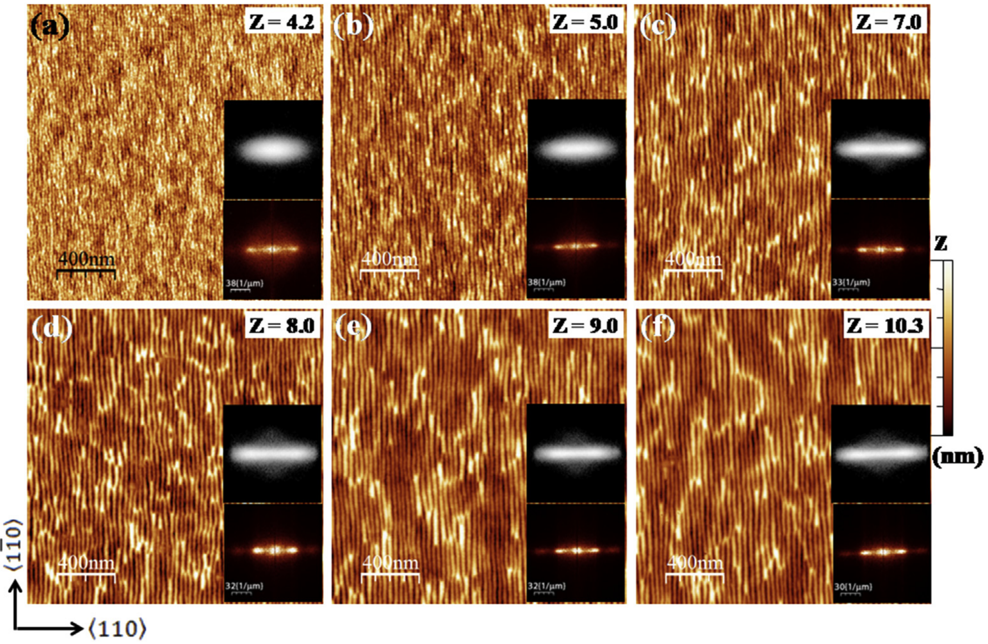

Fig. 1. AFM images of the evolution of GaAs (001) surface topography with respect to ion energy for normal ion incidence $\theta_{ion} = 0°$ and ion flux $j_{ion} = 400$ μA cm^{-2} and $T_g = 450°$ C. (a) $E_{ion} = 100$ eV; (b) $E_{ion} = 200$ eV; (c) $E_{ion} = 300$ eV; (d) $E_{ion} = 400$ eV; (e) $E_{ion} = 500$ eV; (f) $E_{ion} = 600$ eV. All the images were taken after a total fluence of $\phi_{ion} = 1 \times 10^{19}$ ions cm^{-2}. The ⟨110⟩ and ⟨1$\bar{1}$0⟩ crystal directions are marked. In the inset of AFM images the 2D-FFT (lower) and the 2D-slope distribution (upper) are shown. z represents the vertical scale length.

For better understanding of the underlying physical mechanisms of nanopattern formation on crystalline materials, more experimental data as a function of various ion beam parameters e.g. energy, flux and fluence are useful. The present article describes an experimental study of the topography evolution on monocrystalline GaAs (001) surfaces at elevated temperature under normal-incident ion sputtering in the energy range 100–600 eV Ar$^+$ and ion flux 245–1250 μA cm^{-2}.

Ion beam sputtering was performed in an ion beam system (base pressure 1×10^{-8} mbar) using broad beam from an inductively coupled RF discharge ion source (M/s Roth & Rau Microsystems GmbH, Germany). Commercially available cleaned GaAs (001) wafers with a miscut angle of ±0.5° were exposed to high purity Ar$^+$ beam (99.999%) with normal ion incidence ($\theta_{ion} = 0°$). Within the experiments the ion energy E_{ion} and flux j_{ion} were varied from 100 to 600 eV and between 245 and 1250 μA cm^{-2}, respectively. During sputtering, the substrate temperature T_g was raised to 450° C using a radiation heater from the front side. The sputtered surface topography was investigated by atomic force microscopy (AFM) operating in the tapping mode using a Nanoscope IV multimode SPM.

In Fig. 1, GaAs (001) surfaces sputtered at different energy of Ar$^+$ are shown. For all samples the sputter conditions were: $j_{ion} = 400$ μA cm^{-2} and fluence $\phi_{ion} = 1 \times 10^{19}$ ions cm^{-2}. At energy $E_{ion} = 100$ eV, a ripple pattern with a preferred orientation is developed. The ripple wave vector is along the ⟨110⟩ direction and the length of the ripple runs parallel to ⟨1$\bar{1}$0⟩ direction. For $E_{ion} = 100$ eV, the ripples are not distinctly visible as the amplitude of the ripples (∝ rms roughness) is quite small (0.64 nm), which is a few tenth nm above the rms roughness of the virgin GaAs (001) surface (0.16 nm). The ripple structure is gradually prominent as the sputtering energy becomes higher. The corresponding two-dimensional (2D) fast Fourier transform (FFT) of the AFM images shows the symmetry and order of the ripple structure. They evolve with greater clarity as the bombarding energy is increased. We also evaluated 2D-angle distributions from the AFM images, which exhibit the development of ripple facets. The twofold symmetry of the ripple pattern conforms to the rectangular symmetry of the GaAs (001) surface characterized by two non-equivalent crystallographic directions, ⟨1$\bar{1}$0⟩ and ⟨110⟩ [12].

The wavelength and the rms roughness of the rippled-surface are measured from the height-height correlation function defined as $G(r) = \langle (h_i - h_j)^2 \rangle$, where h_i and h_j are heights of the surface at two locations, i and j, separated by a distance r, and the bracket ⟨⟩ denotes averaging over pairs of points [13]. The height data were extracted from the AFM images (Fig. 1). The log-log plot of $\sqrt{G(r)}$ versus r along the horizontal direction for different ion energies E_{ion} are displayed in Fig. 2, which show a number of oscillations after the linear rising part of the curve. The value of r corresponding to the first minimum is designated as l, the dominant in-plane length scale, which quantifies the wavelength and the value of $\sqrt{G(r)}$ at

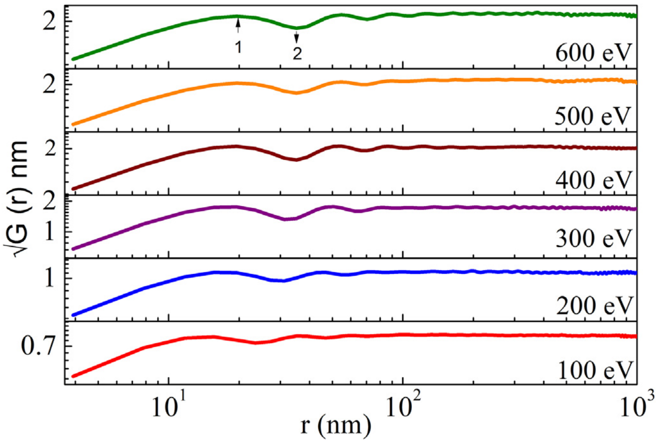

Fig. 2. Square root of the height-height correlation function $\sqrt{G(r)}$ with increasing ion energy E_{ion}. The arrows marked 1 and 2 indicate the surface roughness and the in-plane length scale, respectively.