CONDENSED MATTER PHYSICS

Conference materials
UDC 537.534
DOI: https://doi.org/10.18721/JPM.153.301

Influence of the initial surface state on the ripple formation induced by O_2^+ sputtering of Si

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Abstract. Influence of the initial Si surface state on the rate of ripple nucleation under bombardment with low-energy O_2^+ ions was investigated. It was found that the creation of a defect area in the Si near-surface layer or the creation of the initial surface relief by ion bombardment with a focused Ga^+ ion beam facilitates a significant acceleration of the ripple nucleation on the Si surface during subsequent irradiation with an O_2^+ ion beam.

Keywords: ripple formation, sputtering, nanostructuring, silicon, ion beam.

Funding: This study was funded by the Ministry of Education and Science of the Russian Federation within the framework of the state assignment of the P.G. Demidov Yaroslavl State University of topic no. 0856-2020-0006.

Citation: Smirnova M. A., Bachurin V. I., Churilov A. B., Influence of the initial surface state on the ripple formation induced by O_2^+ sputtering of Si, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 15 (3.3) (2022) 8–12. DOI: https://doi.org/10.18721/JPM.153.301

Материалы конференции
УДК 537.534
DOI: https://doi.org/10.18721/JPM.153.301

Влияние начального рельефа поверхности Si на формирование рипплов при облучении ионами O_2^+

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Аннотация. Исследовано влияние предварительно сформированного рельефа поверхности Si, облученного ионным пучком Ga^+ с энергией 30 keV на скорость зарождения рипплов при бомбардировке ионами O_2^+. Установлено, что начальный рельеф поверхности способствует существенному ускорению процесса зарождения рипплов на поверхности Si.

Ключевые слова: формирование рипплов, распыление, наноструктурирование, кремний, ионный пучок.

Финансирование: Работа выполнена в рамках Государственного задания ЯрГУ им. П. Г. Демидова Минобрнауки РФ по теме 0856-2020-0006.

Ссылка при цитировании: Смирнова М. А., Бачурин В. И., Чурилов А. Б. Влияние начального рельефа поверхности Si на формирование рипплов при облучении ионами O_2^+ // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2022. Т. 15. № 3.3. С. 8–12. DOI: https://doi.org/10.18721/ JPM.153.301

Introduction

Ion beam sputtering is a powerful method for micro- and nanostructures formation on the surface of various materials. The main advantages of this method are the fairly short processing time of large areas and the possibility of metals, semiconductors, insulators nanostructuring. Moreover, the adjustment of irradiation parameters, such as angle of incidence, fluence, kinetic energy and ion beam diameter, allows generating a sized-controllable structure. Recently, a large number of works is devoted to the study of a periodic wavelike nanostructures (ripples) formation on the metal and semiconductor surfaces [1].

According to experiments, ripple nucleation on the Si surface occurs at a certain (critical) fluence, which depends on the energy and type of ions and the ion beam incidence angle [2-5]. At the moment, there is a small number of works [6, 7] which demonstrate that the creation of initial topographic inhomogeneity's on the Si surface leads to a marked reduction of the critical fluence required for the sputter ripple nucleation.

In the present work, we have studied an influence of the initial Si surface state on the process of ripple nucleation and evolution under bombardment with low-energy O_2^+ ions. Initial surface is defined as the Si surface irradiated by 30 keV Ga^+ ion beam.

Materials and Methods

Experiments on the formation of ripples on the Si (100) surface were carried out on the Cameca IMS 4f machine. All the samples were bombarded by separated 12,5 keV O_2^+ ion beam at an angle of 38° with respect to the surface normal.

Fig. 1 *a*) shows the geometry of the conducting experiments. At the moment of ripple nucleation, which are perpendicular to the plane of the ion beam incidence, oxygen enrichment occurs on the wave slopes facing to the incidence ion beam. The concentration of this enrichment is corresponding to SiO_2 [9]. This leads to increasing of the current of secondary Si^+ ions (Fig. 1*b*). Reaching the plateau of the I(t) dependence indicates the completion of the ripple formation process with a constant wavelength. Two series of samples were prepared. In the first series, the surface bombardment was stopped at the moment of ripple nucleation; in the second series it was stopped after final ripple formation.

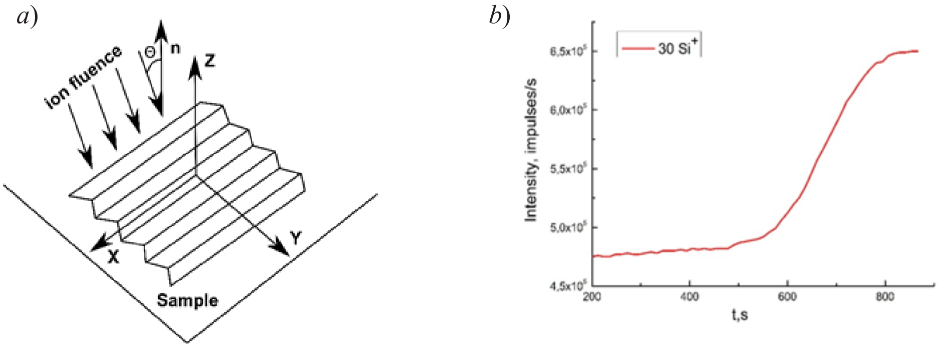

Fig. 1. Ripple formation scheme (*a*). The dependence of the secondary ion current output on the irradiation time (in this case, ion implantation of Si were carried out under $\Theta = 0°$, $\Phi = 10^{17}$ cm^{-2}) (*b*)

The process of ripple nucleation was determined by an increasing the current of secondary Si^+ ions [8], which detected during ion bombardment of the surface. The depth of the sputtering crater where ripples nucleated was determined on a Talystep profilometer. The samples were pretreated by ion implantation of Si(100) surface with a 30 keV Ga^+ ion beam on a Quanta 3D 200i. Beams with a diameter of 4 μm were used. The dimensions of the irradiated area were 200×200 μm^2. An angles of incidence of the ion beam were $\Theta = 0°, 30°$, ion fluences were $\Phi = 10^{17}, 2{\cdot}10^{17}, 4{\cdot}10^{17}$ cm^{-2}. A more detailed analysis of the surface topography was carried out ex-situ using a scanning electron microscope Supra 40.

Results and Discussion

Silicon samples irradiated with a Ga^+ ions were examined by the SEM method. It was found that at a fluences of $2{\cdot}10^{17}$, $4{\cdot}10^{17}$ cm^{-2} a noticeable surface relief in the form of grid-like structure and ripples occurs and $\Theta = 0°$, $30°$ respectively. As the fluence increases, the surface rms rougness increases up to 30 nm at $\Theta = 30°$ and $\Phi = 4{\cdot}10^{17}$ cm^{-2}. At a fluence of $\Phi = 10^{17}$ cm^{-2}, an irradiated surface stays smooth at normal incidence and a small perturbations are observed at $\Theta = 30°$.

Fig. 2 demonstrates the Si surface relief before (left column) and after (right column) irradiation with an O_2^+ ion beam. In Fig. 2, *a*) there is an experiment with initial smooth Si surface, Fig. 2, *b*) shows an experiments where the initial surfaces were pretreated with a gallium ions at different ion fluences.

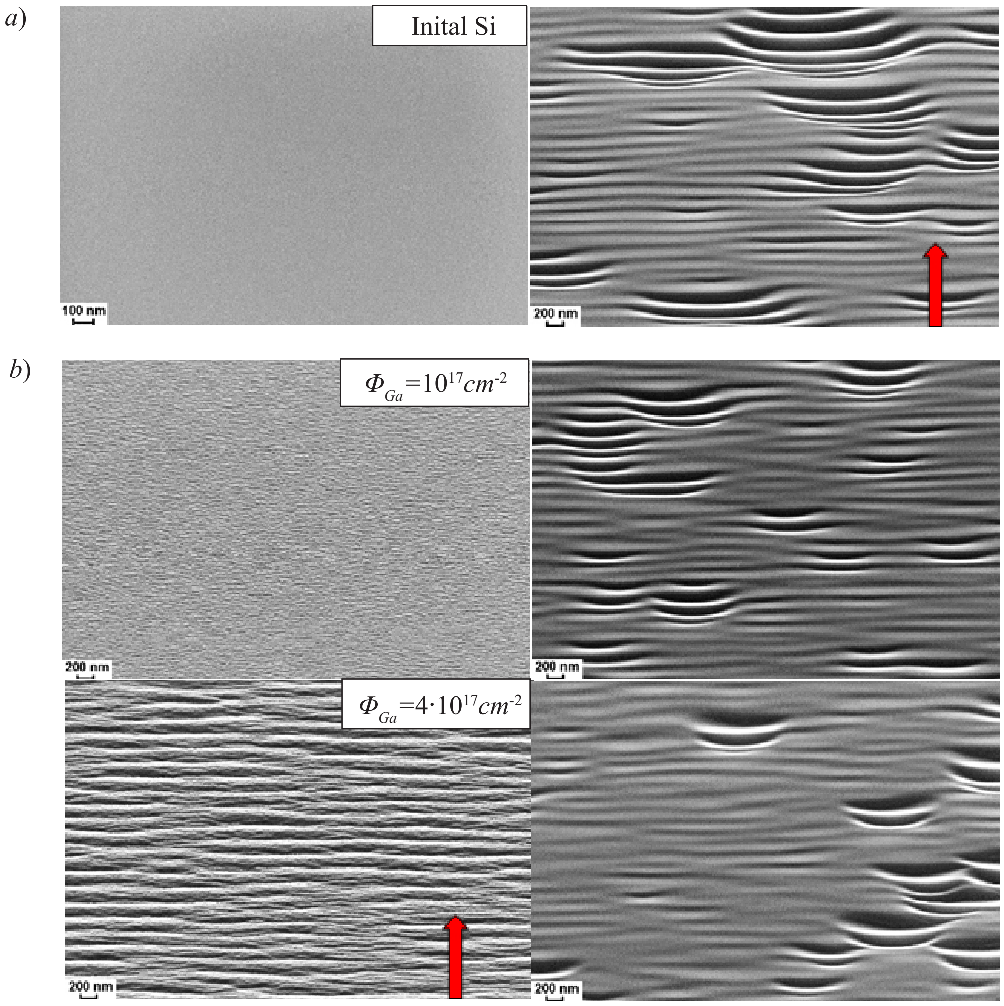

Fig. 2. The surface state before (left column) and after (right column) irradiation with an O_2^+ ion beam in cases of initial smooth (*a*) and pretreated (*b*) Si surface. The arrow indicates the direction of incidence of the ion beam

Irradiation with O_2^+ ion beam of the virgin Si surface leads to the ripple formation at a depth of ~ 6.5 µm with an average wavelength of $\lambda = 460$ nm, which is in good agreement with the data of [8]. The formation of ripples with wavelength $\lambda = 450 \pm 30$ nm was observed on the pretreated Si samples. In this case, the depth of ripple nucleation decreased significantly: practically 1.5 times at a fluence of $\Phi = 10^{17}$ cm^{-2} and more than 2 times at $\Phi = 2{\cdot}10^{17}$ and $4{\cdot}10^{17}$ cm^{-2}, both in the case of pretreated samples with Ga^+ ions at normal and oblique beam incidence (Fig. 3). In the last case, the critical dose for ripple nucleation is lower for all ion fluences, possibly due to the shallower depth of the implanted gallium and the higher amplitude of the relief created by Ga^+ ion bombardment.

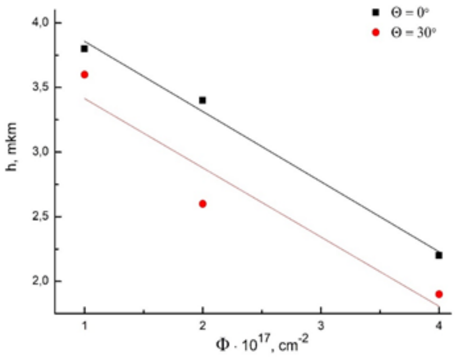

Fig. 3. The dependence of the ripple nucleation depth on the fluence of irradiation of initial Si surface with Ga^+ ions

As noted above, the presence of surface topographic inhomogeneities leads to decrease of the critical fluence required for ripple nucleation on the Si surface under ion bombardment [6, 7]. Present study established that the same effect is triggered by preliminary creation of a defect region in the Si near-surface layer without noticeable changes in the surface topography by implantation with Ga^+ ion beam at $\Phi = 10^{17}$ cm^{-2}. The apparently reason of accelerated ripple nucleation in this case is that the implanted Ga is located in the form of separate nanometer-sized precipitates lying at a depth of 10-20 nm in the Si near-surface layer (at $\Theta = 0°$) [10]. During the sputtering of such samples with O_2^+ ion beam at depths of 10–20 nm a topographic instability may arise due to the difference in sputtering rates of Ga and Si, which will initiate the ripple nucleation process.

One of the first models explaining the formation of ripples [11] combines the effects of sputtering and surface diffusion and is based on the sputtering theory of Sigmund [12]. It relates the rate of atom removal to the energy deposited by incident ion into surface layer. The coefficients in proposed equation [11] are functions of the ion beam parameters and relate the sputtering yield at any point on the surface to the local curvature. Thus, the presence of the original surface local curvature is necessary. Later in the work [13] it is stated, that transition between the flat and rippled states of the surface is not possible. To explain the appearance of the initial surface topography leading to a change of the local angle of ion incidence the term $\eta(x,y,t)$ which accounts the stochastic nature of the current density of incident ions was introduced in the equation of a nonlinear model of ripple formation [14]. From a practical point of view, accounting of this summand seems to be quite difficult. Therefore, in [15] it was suggested to substitute it for an arbitrary initial relief in the modeling of the formation of the wave-like relief. This approach led the authors to the results of modeling structures that quite well consistent with the experimental results.

Thus, it is shown that both the creation of the initial relief on the Si surface and the creation of a defective region in the near-surface layer lead to a significant reduction in the critical dose of irradiation with O_2^+ ions required to initiate the formation of ripples on the Si surface.

Acknowledgments

This study was performed with financial support from the Ministry of Education and Science of the Russian Federation within the framework of the state assignment of the P.G. Demidov Yaroslavl State University of topic no. 0856-2020-0006 and using equipment of the facilities sharing centre “Micro- and Nanostructures Diagnostics”.

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Received 14.07.2022. Approved after reviewing 19.07.2022. Accepted 20.07.2022.