Study of ripple formation on Si surface under Ga ion beam bombardment

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Abstract. The process of microrelief formation on Si (100) surface under 30 keV Ga\(^+\) ion beam bombardment with doses \(2 \times 10^{17} - 4 \times 10^{18}\) ion/cm\(^2\) at incident angles \(\theta = 0\) - 50° was studied. It was found that wave-like structures form on the surface at \(\theta = 25°\) - 35° and doses \(6 \times 10^{17} - 2 \times 10^{18}\) ion/cm\(^2\). The nice ripple formed at \(\theta = 30\pm2°\) incident angles and irradiation dose \(10^{18}\) ion/cm\(^2\).

1. Introduction

Irradiation of the surface of a solid body by ion bombardment leads to the formation of various types of micro – and nanostructures on the surface. Depending on the type of substrate, ion energy and type of ions, it is possible to form a certain morphology on the surface. The formation of micro- and nanostructures on the surface of semiconductor materials by ion bombardment has recently attracted interest. In particular, a large number of works is devoted to the formation of periodic wavelike structures on a nanometer scale called ripples. The reviews [1, 2] present the main results, devoted to the experimental and theoretical study of the formation of such structures on the surface of various materials irradiated with ions of inert and chemically active gases. The main regularities of the parameters of the forming structures were experimentally established. Thus, ion bombardment may have different effects on the surface, depending on many factors such as incident ion energy, type of ions, angle of incidence, sputtered substrate temperature and material composition and etc. There are differences between using inert and chemically active ion beams in the process of ripple formation. The irradiation dose, which the ripple formation begins with is one of the distinguishing features. In case of using chemically active ions this dose is orders of magnitude less than in case of using inert ions.

This article presents the results of an experimental study of the processes of microrelief formation on the Si surface irradiated by ion beam Ga\(^+\) with a 30 keV. This type of ions is neutral in relation to Si, since the implanted ions don’t form chemical compounds with silicon atoms in contradistinction to N\(_2^+\) and O\(_2^+\) ions. The implanted ions of Ga are present in the surface layer in the form of precipitates. The deposition depth of precipitates is comparable to a projectile range [3, 4]. This behavior of embedded ions differs from classical rare-gas atoms. At the moment, there is a small number of works devoted to the formation of the microrelief by Ga ion beams on the Si surface [5, 6], on the glass surface [7], on the crystal diamond surface [8]. It should be noted that focused Ga\(^+\) ion beams are a widespread experimental tool in the formation of nanostructures on various surfaces, under different irradiation conditions (angle of incidence, irradiation dose, etc.). Formation of the relief can lead to a
change of the sputtering rate [9] and the reproducibility of the experimental results, especially in the case of formation the structures with high aspect ratio [10].

2. Experimental

The irradiation experiments of Si (100) with a 30 keV Ga⁺ ion beam were carried out on a Quanta 3D 200i. Beams with a diameter of 4 μm and 300 nm were used at various irradiation parameters (percentage of overlap, delay time, scanning mode). Three series of experiments were carried out.

In the first one the angles of incidence of the ion beam were Θ = 25°, 30°, 35°, 40°, irradiation doses were D = 2·10¹⁷, 4·10¹⁷, 6·10¹⁷, 8·10¹⁷, 10¹⁸, 2·10¹⁸, 4·10¹⁸ ion/cm², the ion beam current was 5 nA. In the second - the angles of incidence of the ion beam were Θ = 0°, 20°, 30°, 40°, 50°, the irradiation doses were D = 10¹⁸ ion/cm², the ion beam current was 5 nA. The surface topography was explored by using a Quanta 3D 200i. In the third – preliminarily some samples were created at the fixed angle of incidence of ion beam Θ = 30°, irradiation doses were D = 2·10¹⁷, 4·10¹⁷, 6·10¹⁷, 8·10¹⁷, 10¹⁸, 2·10¹⁸, 4·10¹⁸ ion/cm², ion beam current 5 nA. Under certain experimental conditions of irradiation of the Si surface with Ga⁺ ions, a wavelike structure (ripples) was formed on the surface. This structure, which is formed on the Si surface at these parameters, is characterized by a high reproducibility of the result. A platinum band was applied perpendicular to the direction of propagation of the ripples on the surface of each sample for more accurate determination of the parameters of the relief. It was made to protect the wavelike structure from the further exposure of the incident ions. Further, the cross-section along the platinum band was made by ion etching. The formation of samples and the cross-section line was carried out on a Quanta 3D 200i (in-situ). The surface topography of all samples was explored ex situ by Supra 40 electron microscope in detail.

3. Results and discussions

It was found that at irradiation doses and angles of incidence more than 40° the formation of a relief on the surface does not occur. At angles of incidence of the ion beam less than 25° and irradiation doses exceeding 4·10¹⁷ ion/cm², a granular structure is formed on the surface and it becomes reticulated (characteristic size about 100 nm) with the irradiation dose increasing. At angles of incidence in the range from Θ = 25° to 35° and irradiation doses higher than 4·10¹⁷ ion/cm², a wavy relief appears. A well reproducible periodic relief (ripples) is formed near the angle of incidence of the ion beam Θ = 30°. This is consistent with the results of the work [6]. However, in contrast to the results presented in [6], the generation of ripples was observed in this work at more then twice irradiation dose (> 2·10¹⁷ ion/cm²). Perhaps it is due to the fact that in [6] the relief parameters were determined by using the AFM method, which is sensitive to the exploration of relief inhomogeneities.

Figure 1 demonstrates micrographs of a Si surface irradiated with a Ga⁺ ion beam at an incidence angle 30° and irradiation doses D = 4·10¹⁷, 6·10¹⁷, 10¹⁸, 2·10¹⁸, ion/cm². One can see that the generation of ripples (D = 4·10¹⁷, 6·10¹⁷ ion/cm²) with bright hills (hillocks) are observed on the surface. Those hillocks are Ga drops. It was determined by the analysis of the irradiated surface by the SIMS method on the Cameca IMS 4f. Previously, in [11] it was experimentally established that at irradiation doses of the order of 10¹⁷ ion/cm² and the angle of incidence of the ion beam Θ = 30°, the Ga distribution in the near-surface layer is inhomogeneous and a separate regions enriched in Ga are observed. For cases Θ = 30°, D = 4·10¹⁷, 6·10¹⁷, 10¹⁸ and 2·10¹⁸ ion/cm² the value of wavelength λ was measured by the SEM method, λ ≈ 150 nm and 450 nm respectively for cases D = 4·10¹⁷ and 2·10¹⁸ ion/cm². A similar result was obtained in [5] when the Si surface was irradiated by Ga⁺ ions at an angle of incidence Θ = 30°. At irradiation doses higher than 2·10¹⁸ ion / cm², there is an intersection of waves, the destruction of the wave-like structure, and the increase of the wavelength magnitude. The wavelength λ reaches the value 800 nm at the irradiation dose D = 4·10¹⁸ ion/cm², which is also consistent with the results of work [5].
Figure 1. Micrographs of the Si surface. Irradiation doses: a) 4·10^{17}, b) 6·10^{17}, c) 10^{18} and d) 2·10^{18} ion/cm².

Figure 2 shows electron microscopic images of wave-like structures in a cross-section. These structures were formed on the Si surface by a Ga⁺ ion beam at an angle of incidence Θ = 30°, irradiation doses were 4·10^{17}, 8·10^{17}, 2·10^{18} ion/cm².

Figure 2. Micrographs of ripples cross-section on the Si surface. Irradiation doses: a) 4·10^{17} and b) 2·10^{18} ion/cm².

A platinum band was applied over the wave-like structure as a mask before the formation of the cross-section. Thereby the wave-like was saved from further ionic influence. The values of the ripple amplitude were obtained by the SEM method. For the case shown in Figure 2 (a) the average value of the peak-to-valley amplitude h = 32.5 nm, in Figure 2 (b) – h = 70 nm. Thus, the value of the ripple amplitude increases with the rise of the irradiation dose.

As noted above, behavior of Ga ions in the near-surface layer significantly differs from embedded ions of inert gases, for example Ar. The implanted Ga atoms form precipitates near the surface, which are located at the depth of the ions projective range, as shown in [3, 4]. Apparently, the emergence of such irregularities on the surface in the form of Ga drops is the reason of ripple formation. This ripples are formed at Si surface at irradiation doses by two orders of magnitude less than at inert gas ion bombardment (Ar, Xe) with close energies. The sputtering yields of Ga precipitates and substrate material (Si) is different. This can lead to the appearance of topographic irregularities. The creation of these irregularities with the simultaneous sputtering of Si and the deposition of metals, which form silicides, leads to the ripples generation on the Si surface [12]. The creation of a relief of an arbitrary
shape on the initial Si surface leads to the impetuous formation of ripples with a wavelength, which is specific to the parameters of ion bombardment, as shown in [13, 14]. The absence of relief at angles of incidence of the ion beam more than 35° is due to a sharp drop in the Ga content in the near-surface layer [11]. The sputtering yield almost does not change [11] at angles of incidence less than 25°. The necessary condition for the appearance of a wavy relief on the surface under ion irradiation is not met [1].

4. Conclusions
The process of topography formation on Si surface under irradiation with 30 keV Ga⁺ ion beam bombardment at incident angles \( \theta = 0 - 50° \) was studied. It was found that the process of ripple formation starting with irradiation dose \( 2 \cdot 10^{18} \) ion/cm\(^2\) at angles of incidence nearly 30°. The wavelength and amplitude of the microrelief are increase with grows of the irradiation dose from \( 4 \cdot 10^{17} \) to \( 2 \cdot 10^{18} \) ion/cm\(^2\). The value of the ripple wavelength is increasing from 150 nm to 500 nm. The value of the ripple amplitude is increasing from 30 nm to 70 nm. The existence of an implanted gallium in the near-surface layer in the form of separate precipitates is a possible reason of the early appearance of the wavelike structures. The difference between sputtering yields leads to the appearance of topographic irregularities. These irregularities are initiate the formation of the wavelike relief.

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