Thin Solid Films 517 (2008) 289–292

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Single swift heavy ion-induced trail of discontinuous nanostructures on SiO_2 surface under grazing incidence

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ARTICLE INFO

Available online 24 August 2008

Keywords:
Silicon dioxide
Silicon
Heavy ion irradiation
Nanostructures
Electronic excitations
Atomic Force Microscopy
Tapping mode
Contact mode

ABSTRACT

Some recent results concerning swift heavy ion irradiation of thin SiO_2 layers on Si under normal incidence irradiation leading to the formation of nanodots at the interface between the SiO_2 film and the Si substrate or at the SiO_2 surface are summarized. Moreover, we report observation of discontinuous and elongated tracks at the SiO_2 surface after grazing incidence irradiation of SiO_2–Si structures with fast heavy ion. A characterization of these nanostructures by means of Atomic Force Microscopy (AFM) has been performed. The present results are of major importance with regard to the development of emerging nanoelectronic devices and systems.

1. Introduction

The generation and development of surface features by heavy ion bombardment is of prime interest for various and novel applications in Nanotechnology fields, because of their exotic properties and interesting physical aspects [1,2]. High fluence (about 10^{17} cm^{-2}) and low energy (a few 100 keV) ion implantation combined with subsequent thermal processes is a well known technique for achieving nanostructured materials. To date, energetic heavy ions play a crucial role in the synthesis and modification of materials [3–7]. Unlike in the more conventional lithographic techniques based on ion, electron, UV or X-rays beam irradiation at low energies and high fluences, a single swift heavy ion is sufficient to induce a track in the material. Irradiation with fast heavy ions allows therefore structuring materials with a very good efficiency closed to one. Furthermore, many studies have been devoted, for some decades, to irradiation effects on Silicon (Si) and Silicon dioxide (SiO_2) because of their manifold applications and their paramount role in Microelectronics and Optoelectronics. Experimental results have shown that a single swift heavy ion can induce a morphological modification in SiO_2 [6–11].

The aim of this study serves a double purpose. On the one hand, some recent results concerning individual swift heavy ion-induced nanostructures in SiO_2–Si samples at normal incidence in the electronic excitation regime are summarized. At the SiO_2 surface, the production of craters or hillocks with irradiation efficiency generally inferior to one has been reported [12–14]. Unlike, at the interface between the thin SiO_2 layer and the Si substrate, where fast heavy ion led to the production of nanodots with experimental efficiency equal to one [15–18]. On the other hand, we report direct observation of intermittent surface tracks after irradiation at grazing angle of incidence in the electronic stopping regime. In this respect, we account for morphological modifications at the SiO_2 surface with experimental efficiency equal to one. For such experiment, irradiated samples were characterized by means of Atomic Force Microscopy (AFM).

2. Observation of surface modifications on SiO_2–Si samples irradiated at normal incidence

A fast heavy ion penetrating into a solid, deposits a large amount of energy along its trajectory, leading to local melting and subsequent disturbance of the target material. The extremely high local energy deposition along the ion path leads to a material transformation within a narrow cylinder of about 10 nm wide [8,19]. The structural modifications of the stopping medium increases with the energy transfer [7–9,19].

Track formation induced by swift heavy ion irradiations in Si or SiO_2 structures at normal incidence have been reported by many authors. Depending on the irradiation conditions, craters or hillocks can be formed at the surface or in the bulk of the target medium. In the results described in the literature, a quasi-systematic chemical etching has been performed subsequently to the irradiation to reveal the ion tracks at the surface or in the bulk of the target material [8–9,19]. Since

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doi:10.1016/j.tsf.2008.08.148

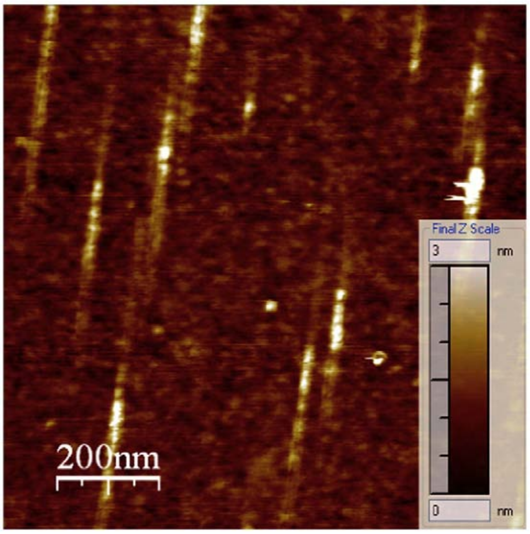

Fig. 1. Two dimensional view of tapping mode AFM topographical measurements of 0.63 MeV $^{208}Pb^{32+}$ ion tracks in 11.8 nm SiO_2 layer on Si crystals irradiated at 5×10^{10} Pb/cm^2 under 1° of inclination angle with respect to the SiO_2 surface. Ions traversed from bottom to top. Image size is 1 μm^2.

radiation tracks were not easy to detect, chemical etching was proved to be a very efficient technique to reveal cylindrical track induced at the surface or in the bulk of materials by ion irradiation. Since the pioneer results of D.A. Young concerning the first fission fragment individual track chemically revealed on LiF substrates [20], this technique has been of widespread use in Solid State Detectors [21–23] and continues to do so in the study of radiation defects production in solids [23–25]. However, that is a destructive technique which does not act only through the ion wake, but enlarges towards the surrounding material of the ion path.

Only a few results have been published, however with reference to direct observations of radiation tracks on SiO_2 without any chemical intensification of the tracks. Nevertheless, the efficiency of track formation of those experiments was generally inferior to one. That is the number of tracks observed after irradiation with various techniques was smaller than the number of the incident ions [12–14].

Moreover, recent studies have shown that fast heavy ion irradiation can also induce the formation of nanostructures at the interface between the thin layer of SiO_2 and the Si substrate. For instance, in porous silicon, short-range oxygen diffusion may lead to the formation of nanocrystals of Si grown along the tracks in a matrix of SiO_x [4,5].

Furthermore, after irradiation of SiO_2–Si samples at normal incidence with energetic Gold ions and a gradual subsequent etching with hydrofluoric acid (HF), it has been reported the formation of nanodots at one stage of the chemical etching that became bumps once the oxide layer was totally etched away [15,16]. Besides, the formation of a nanodot in the depths of each hole revealed after HF gradual etching of energetic Lead ions irradiated SiO_2/Si samples has also been recently reported [17, 18].

3. Elongated surface tracks formation at the SiO_2 surface under grazing incidence irradiation in the electronic excitation regime

Heavy ion irradiation of materials at very low angle of incidence permits observing directly the morphological track features by means of near-field microscopic tools [26]. Hence, grazing incidence heavy ion irradiation is a suitable technique to achieve nanostructures on the surface of materials.

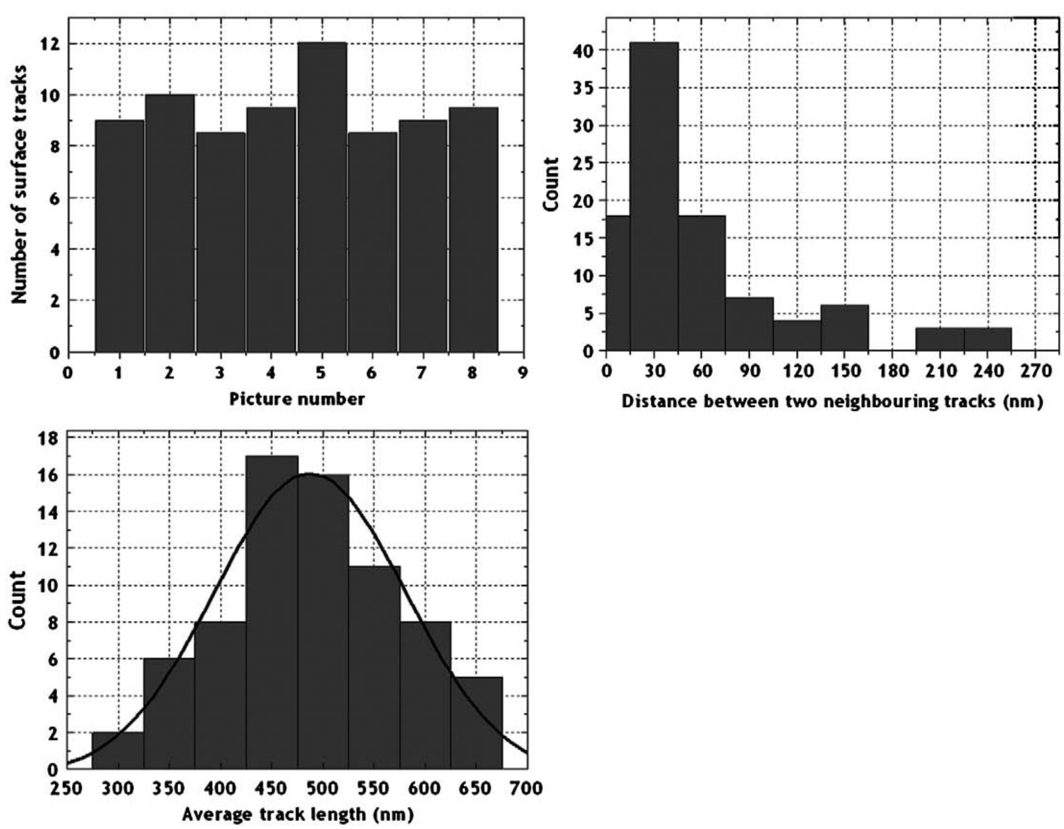

Fig. 2. a) Histogram of the surface tracks density per 1 μm^2 AFM picture of 11.8 nm SiO_2 layer on Si crystals irradiated with 0.63 MeV $^{208}Pb^{32+}$ ions at 5×10^{10} Pb/cm^2 under 1° of inclination angle with respect to the SiO_2 surface. b) Distribution of the distance between two neighbouring tracks. c) Distribution of the surface tracks. A Gaussian fit to the data is indicated by the black curve.