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Mechanical properties and structure evolution of single-crystalline silicon irradiated by 1 MeV Au^+ and Cu^+ ions

Wei Liang[a,b], Fei Zhu[a], Yunhan Ling[c], Kezhao Liu[d], Yin Hu[d], Qifa Pan[d], Limin Chen[a], Zhengjun Zhang[c,*]

[a] The State Key Laboratory for New Ceramics and Fine Processing, School of Materials Science and Engineering, Tsinghua University, Beijing 100084, China
[b] High-Tech Institute of Beijing, Beijing 100094,China
[c] The Key Laboratory of Advanced Materials (MOE), School of Materials Science and Engineering, Collaborative Innovation Center of Advanced Nuclear Energy Technology, Tsinghua University, Beijing 100084, China
[d] Science and Technology on Surface Physics and Chemistry Laboratory, Mianyang Sichuan 621907, China

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ABSTRACT

Mechanical and structural evolutions of single-crystalline silicon irradiated by a series of doses 1 MeV Au^+ ions and Cu^+ ions are characterized by Surface laser-acoustic wave spectroscopy by (LA wave), Rutherford backscattering spectrometry and channeling (RBS/C) and transmission electron microscopy (TEM). The behavior of implanted Au^+ and Cu^+ ions was also simulated by using Stopping and range of ions in matter (SRIM) software package, respectively. It is demonstrated that LA wave and RBS could be applied for accurate evaluation of the TEM observed amorphous layer's thickness. The modified mechanical properties depend on the species and the dose of implantation. For 1 MeV Au^+ ions, the threshold dose of completely amorphous is 5×10^{14} atoms/cm^2, while the one for Cu^+ ions is 5×10^{15} atoms/cm^2. Upon completely amorphous, the young's modulus and layer density decreased significantly while saturated with the dose increasing sequentially.

1. Introduction

Crystalline silicon has been widely used in semiconductor and electronic technology industry as the principal material candidate in infrared optics and electronic applications for the superior performance [1,2]. Among the unique properties, mechanical property and correlated microstructural changes, as well as the surface/interface properties of silicon have been research focus over the last decades [3–6]. With the development of semiconductor and microelectromechanical systems (MEMS) technology ion implantation of crystalline silicon has been the most widely used technique in semiconductor industry for introducing controllable dopants and lattice damage. Although introducing significant electrical and optical properties modification, the ion implantation process can cause severe damage on crystalline silicon by producing atomic displacements and defects, therefore hinder the applications of Si upon extreme conditions. It is thus of great significance to evaluate the ion irradiation effects on the mechanical properties and structural evolution of crystalline silicon by considering varied implantation conditions while exploring facile characterization techniques. In recent decades, the mechanical properties such as young's modulus and hardness of ion-implanted crystalline silicon have been extensively studied by nanoindentation technique. However, limited by the local measurement nature of nanoindentation, it is difficult to accurately evaluate the overall performance of large size samples. Furthermore, non-destructive test techniques were highly needed to better estimate corresponding properties by excluding possible effects introduced by the interaction between the platform and the analytes. As one of the well-developed non-contact techniques, the laser surface acoustic wave method (LA wave) use forward and reflected acoustic wave to test mechanical properties of material surface and interface, enabling non-destructive measurement over large area with more accurate macroscopic parameter estimations. In recent years, the LA wave method has been proven to be more accurate technique on studying the ion implantation and amorphous process of silicon, while at the same time few studies have been performed to build the relationship between the structural and mechanical properties of irradiated crystalline silicon [7–12].

In this paper, mechanical and structural evolutions of single-crystalline silicon irradiated by Au^+ and Cu^+ ions were extensively studied by means of surface acoustic wave spectroscopy by laser-acoustics (LA wave), Rutherford backscattering spectrometry and channeling RBS/C and transmission electron microscopy (TEM). To better understand the

* Corresponding author.
E-mail address: zjzhang@tsinghua.edu.cn (Z. Zhang).

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interaction mechanism, the Au + /Cu + implantation behavior into silicon were also simulated by SRIM, respectively. It is demonstrated that LA wave and RBS could be used for accurate evaluation of thickness of the damaged surface layer, whose results agree well with the layer thicknesses observed by TEM. Combination of results from different methods revealed that the mechanical property evolution is greatly related to the amorphous process introduced by ion implantation, while the amorphous process is species and dose dependent. Specifically for 1 MeV Au^+ ions, the damage layer reached completely amorphous when the dose is above 5×10^{14} atoms/cm^2, while for Cu^+ ions, the dose is above 5×10^{15} atoms/cm^2. Upon completely amorphous, density and Young's modulus of the damage layer are less dose dependent within the test region.

2. Material and methods

2.1. Preparation of sample and ion implantation

Czochralski-grown (C-Z) n-type silicon wafers of ⟨1 0 0⟩ orientation with the size of 4-inch and thickness of 0.5 mm were used for the experiments. In order to remove the oxide layer on the sample surface, all of the samples were etched in HF solution and washed in ultra-pure water. Au^+ and Cu^+ ions with energy of 1 MeV were implanted at room temperature to investigate damage profiles and modify the mechanical properties of single-crystalline silicon. The pressure in the implantation chamber was about 10^{-6} Torr during implantation. The ion implantation and RBS was performed on NEC 2 × 1.7 MV Tandem Accelerator in Ion Beam Materials Laboratory in Peking University. The size of the beam spot is about 3 mm × 3 mm. The implantation dose of Au^+ ions was varied from 10^{15} atoms/cm^2, 5×10^{14} atoms/cm^2, 1×10^{14} atoms/cm^2, 5×10^{13} atoms/cm^2, to 1×10^{13} atoms/cm^2 respectively and the current density is about 100 nA. The implantation dose of Cu^+ ions was varied from 10^{15} atoms/cm^2, 3×10^{15} atoms/cm^2, 1×10^{15} atoms/cm^2, 5×10^{14} atoms/cm^2, to 1×10^{14} atoms/cm^2 respectively and the current density is about 60nA. The implanted size is about 2.5 cm × 2.0 cm and the homogeneity of the implanted area is better than 2%.

2.2. Characterization and evaluation of irradiation effect

Channeled Rutherford backscattering spectrometry was performed for estimating the amount of damage created in silicon. 2-MeV He was used at a backscattering angle of 165°. The mechanical and elastic properties (Young's modulus, density, thickness and Poisson's ratio) in silicon layers that amorphized by ion implantation were measured by laser acoustic wave measurement system (LA wave 29/V5-2) which is made by Fraunhofer IWS in Dresden, Germany. To study the structural changes and evaluate the damage of modification layer induced by ion irradiation, a SRIM-2008 calculation [13], and a cross-sectional Transmission Electron Microscopy (TEM. JEM-2100F, JEOL) were applied to investigate the evolution of the amorphous layer and defect distribution.

3. Results and discussion

3.1. Evolution of amorphous layer induced by ion irradiation

3.1.1. RBS/C measurements

RBS/C spectra of Si samples that irradiated by Au^+ ions and Cu^+ ions are displayed in Figs. 1 and 2, respectively, a random spectrum (Si-r) and a channeling spectrum (Si-c) from a un-implanted virgin sample is illustrated as reference.

Fig. 1 shows spectra from the samples implantation of 1 MeV Au^+ ions. The dechanneling yield increases with increasing ion doses from 10^{13} to 10^{15} atoms/cm^2, indicating an enhancement of the Si sublattice disorder. At the low doses of (1–5) × 10^{13} atoms/cm^2, most crystalline order remains with local damage occurs. With higher dose, more severe damage was introduced. At the dose of 5×10^{14} atoms/cm^2 and 1×10^{15} atoms/cm^2, the spectra are similar to the one from random lattice. This result indicates for 1 MeV Au^+ ions, dose of 5×10^{14} atoms/cm^2 and higher will produce a fully amorphized layer extending from the sample surface, while in smaller doses, the damaged layer near the surface is incompletely amorphous. At greater depths, the RBS yield is reduced again [12,14–16]. The amorphized layer becomes thicker with increasing ion doses from 5×10^{14} atoms/cm^2 to 1×10^{15} atoms/cm^2.

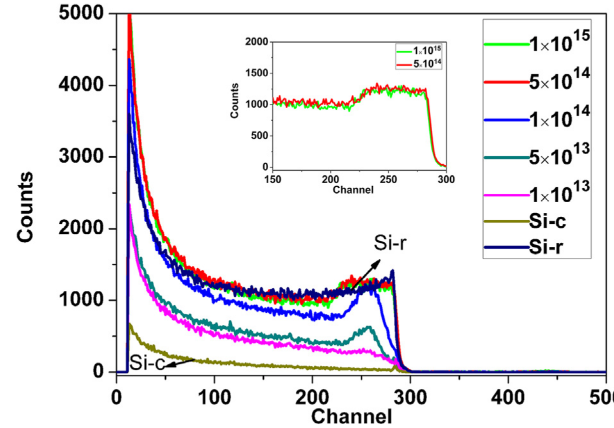

Fig. 1. RBS/C spectra recorded on c-Si before and after irradiation at various doses with 1 MeV Au^+.

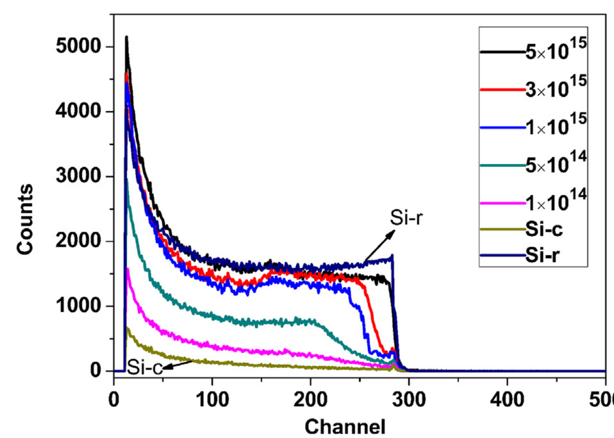

Fig. 2. RBS/C spectra recorded on c-Si before and after irradiation at various doses with 1 MeV Cu^+.

Similarly, for samples irradiated by 1 MeV Cu^+ ions, one can see from Fig. 2 that at the dose of 5×10^{15} atoms/cm^2 the spectrum is similar to the random one. While the dose is below 5×10^{15} atoms/cm^2, the outermost surface cannot reach completely amorphous. Particularly, at the dose of 3×10^{15} atoms/cm^2, the subsurface layer is complete amorphized but the outermost layer is not.

Simulations of RBS/C spectra were performed by using RUMP to determine the thickness of the amorphized layer. The obtained thickness values of the amorphous layer are displayed in Table 1. As for the low doses, c-RBS shows incompletely amorphous, so no thickness values are listed.

3.1.2. TEM measurements

To evaluate the effect of the microstructure evolution and to measure the thickness of the amorphous layer, TEM was utilized and corresponding results were shown in Figs. 3–5.

Figs. 3 and 4 show the TEM images of the amorphous layer formed in single-crystalline silicon surface after 1 MeV Au^+ ions irradiation