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Characterization of silicon surfaces implanted with silver ions at low energy using spectroscopic ellipsometry

V.V. Bazarov*, V.I. Nuzhdin, V.F. Valeev, A.L. Stepanov

Kazan Physical - Technical Institute, Sibirsky Tract, 10/7, 420029, Kazan, Russia

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An amorphous silicon (α-*Si*) layers formed on the surface of single-crystal substrate (*c-Si*) by low-dose implantation with silver ions were studied by spectroscopic ellipsometry. Ion implantation of *c-Si* was carried out with energy of 30 keV, current density varied from 0.1 to 5 $\mu A/cm^2$ and with doses in the range of $6.24 \cdot 10^{12}$–$1.3 \cdot 10^{16}$ ion/cm^2. The effect of non-linear increase in the generation rate of radiation defects with a grow of current density was observed and discussed.

1. Introduction

Recently, it was found that one of promising methods for a formation of porous Si with inclusions of metal nanoparticles is the low-energy high-dose ion implantation [1,2]. It was demonstrated that the processes of nucleation and growth of pores in *c-Si* during irradiation is accompanied with an amorphization of Si, which starts almost immediately after the beginning of implantation. As it was also early shown by examples with *c-Si* implanted by a set of various ions with different energies ([3–8] and references there), a spectroscopic ellipsometry (SE) is an informative technique for studying of partially amorphized semiconductor layers. This method is very effective because there is a quite large difference between the optical constants for α-*Si* and *c-Si* materials.

The interest to low-energy implantation of *c-Si* by heavy ions (with a mass exceeding mass of Si atom) is caused by possibilities for formation of structural radiation defects by accumulation of collision cascades with densities much higher than in the case of light ions. For a defect description introduced by ion implantation and an estimation of their depth distribution in samples the Rutherford Backscattering Spectroscopy (RBS) technique is usually applied [9,10]. However, for heavy ions a penetration path is usually very short and so the RBS using for a characterization of thin implanted layer is not possible (with the exception of high-resolution RBS [11,12], but such specific technique is some exception). It is known that the process of *c-Si* amorphization during ion implantation depends both on substrate temperatures and on dose rates. These phenomena have been studied since 1970s [13,14] and are still of interest to researchers [10]. However, there are no data in a literature on low-energy 30 keV Ag-ions implantation of *c-Si*. Therefore, in the present work SE approach is suggested and tested for observation and explanation of *c-Si* amorphization during implantation by heavy Ag-ions with low-energy of 30 keV for various dose, ion current densities and substrate temperatures.

2. Experiment

The objects for SE experiments were single-crystal *c-Si* wafers of (100) orientation implanted by $^{108}Ag^+$ ions with energy $E = 30$ keV in dose range $D = 6.24 \cdot 10^{12}$–$1.25 \cdot 10^{16}$ ion/cm^2 and current density J from 0.1 to 5 $\mu A/cm^2$ Implantation was carried out on the ion accelerate ILU-3 at residual vacuum of 10^{-5} Torr.

Optical analysis of the implanted *Si* layers was carried out with an ES-2 spectroscopic ellipsometer with binary modulation of polarization at wavelengths of 380–820 nm, a spectral resolution of 6 nm, a step size of 10 nm during measurements, and an angle of incidence of light beam $\varphi = 70°$. The features of the ellipsometer ES-2 are briefly described in Ref. [15].

In present study, an optical model of an isotropic heterogeneous film consisting of a mixture of crystalline and amorphous Si phases on a *c-Si* substrate was chosen. Variable parameters in the framework of this model were the thickness of the implanted layer (d),

* Corresponding author.
E-mail address: vbazarov1@gmail.com (V.V. Bazarov).

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the filling factor (f) of α-Si in c-Si, and the thickness of the natural layer of SiO_2 on the sample surface (d_{SiO2}). The optical constants - refractive and absorption indexes n and k of implanted layer were calculated depending on the content of the α-Si phase in accordance with the effective medium approximation, Bruggeman's model. The calculated spectral dependences of ellipsometric angles $\psi_{th}(\lambda)$ and $\Delta_{th}(\lambda)$ obtained by varying of d, d_{SiO2} and f, were compared with the experimental spectral data of $\psi_{exp}(\lambda)$ and $\Delta_{exp}(\lambda)$ to get the best match (Fig. 1).

It was found that the value of d_{SiO2} is order of 1–4 nm for all implanted c-Si samples. The results for d and f are presented in following section.

3. Results and discussion

For initial evaluation of the thickness of implanted layer were used the computer modeling program SRIM-2011 [16]. Simulation show that during the initial period of irradiation, Ag atoms accumulated near the Si surface with a maximum of a statistical Gaussian concentration distribution at the depth of R_p ~23.4 nm with deviation of ΔR_p ~7.1 nm. These values give the calculated thickness of layer with separated Ag atoms which could be estimated as $d_{SRIM} = R_p + 2\Delta R_p$ ~38 nm.

The mass of the $^{108}Ag^+$ ion exceeds remarkably the one for ^{28}Si atom. The number of Si atoms displaced from their equilibrium positions in the volume of substrate crystal lattice per incident single 30 keV Ag^+ ion could be calculated by the Kinchin–Pease model [17], which for displacement threshold equal to 13 eV gives a value of ~1100. Therefore, the formation of the α-Si structure proceeds by a heterogeneous mechanism in which an amorphous layer is developed as a result of an overlapping of many local disordered regions formed by an arrival of individual Ag^+ ions.

The results of the SE measurements of ion-implanted c-Si are shown in Fig. 2. One can see that in Ag-ion implantation dose range from 6.24 × 10^{12} to 6.24 × 10^{13} ion/cm^2 the content of α-Si in a surface implanted layer with d_{exp} of ~23–25 nm gradually increases to a state of complete amorphization ($f = 1$).

Obtained thickness value is easy to explain, consider energy loss of incident ions during displacement of atom in lattice. Theoretical consideration [16 and references there] has shown that maximum of energy loss distribution and, therefore, the maximum of the initial distribution of point defects is about 0.8 × R_p from the surface.

When the dose D is raised to 6.24 × 10^{15} ion/cm^2 the d_{exp} increases until it reaches ~55 nm. Due to the implantation of recoil Si atoms the thickness of the amorphous layer d_{exp} will be somewhat greater than the calculated thickness d_{SRIM} determined by the profile of the Ag atoms.

For comparison in same Fig. 2, a similar dependence $d_{exp}(D)$ is presented for c-Si implanted by $^{59}Co^+$ ions with energy of 40 keV, taken from the previous work [5]. It can be seen from the dependence that the dose of complete amorphization is about 3 × 10^{13} ion/cm^2 and thickness of the implanted layer is ~20 nm larger in the investigated dose range. These differences are explained by the lower weight of Co-ions and the larger projection range of 40 keV Co-ions in silicon in comparison with the case of Ag-ions.

Fig. 3 shows the dependence of the d_{exp} (D) of the implanted layer for three substrate temperatures of Ag-ion implantation. At the lowest temperature−60 °C, SE characteristics of implanted layers are almost same as for layers fabricated at room temperature of Si substrate. It means that such cooling of substrate not change the defect formation processes compared to conditions of room temperature. At Ag-ion implantation of 300 °C heated samples d_{exp} decreased by 7–9 nm and α-Si filling factors f decreased too for all D. This is due to motion and annealing of some elementary defects occurs during implantation at elevated temperature. An interesting question is what kind of defects do not survive at 300 °C. In Ref. [18] was observe the production and annealing of individual amorphous zones in silicon resulting from impacts of 200-keV Xe ions by *in situ* transmission electron microscopy. It was shown that recrystallization of nanometer-sized amorphous zones is not a singly activated process, but one that takes place over a wide range of

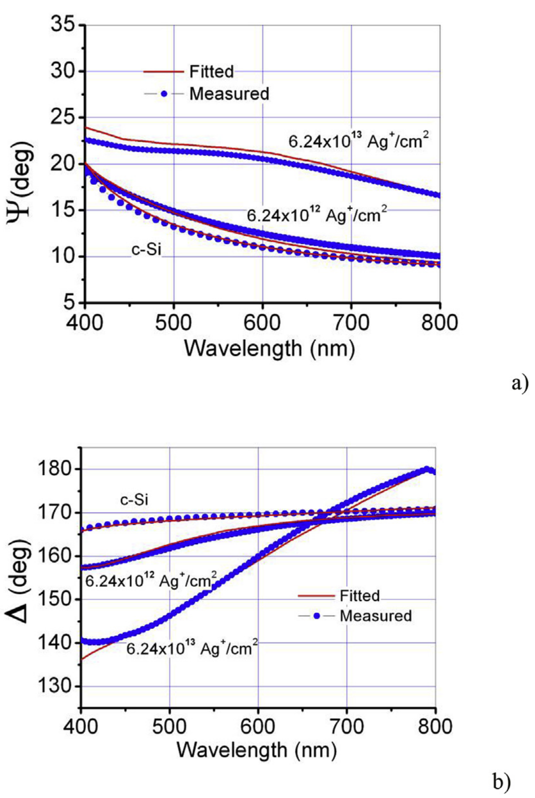

Fig. 1. Measured (•) and fitted (—) ψ (λ) (a) и Δ (λ) (b) spectra for the unimplanted sample c-Si (d_{SiO2} = 3.5 nm) and samples, implanted with doses of 6.24 × 10^{12} Ag^+/cм^2 (d_{SiO2} = 4 nm, f = 0.1), and 6.24 × 10^{13} Ag^+/cм^2 (d_{SiO2} = 1.5 nm, f = 0.9).

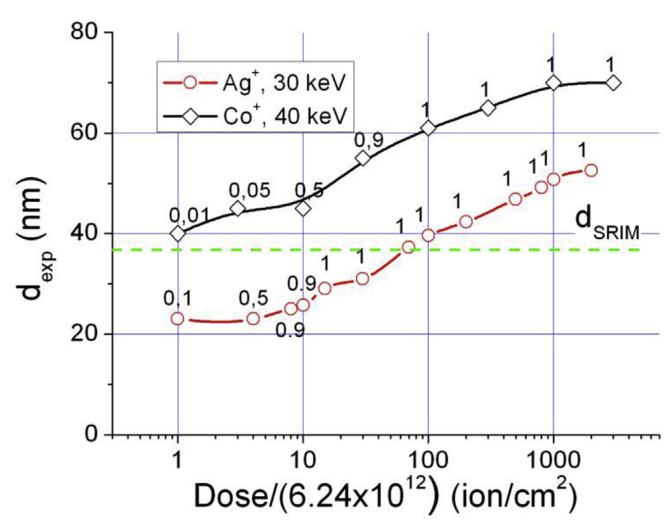

Fig. 2. Dependence of the thickness of the implanted layer d_{exp} on dose values for $^{108}Ag^+$, $^{59}Co^+$ implanted ions collected from the SE data. Near the symbols, the filling factor f of α-Si is indicated. J was about 2 μA/cm^2.