Influence of high-intensity titanium ion beam energy density on dopant accumulation and diffusion in silicon

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Ion-doped layers with a thickness up to 2.6 μm were formed using the method of synergy of high-intensity implantation and simultaneous energy impact of a titanium ion beam with a current density of 1.6 A/cm^2 on the silicon surface. The article presents the results of the regularities of titanium accumulation in silicon from the duration and frequency of pulses, when a power density of the ion beam is fixed $9.6 \cdot 10^4$ W/cm^2. The Auger electron spectroscopy method was used to obtain dopant distributions over the modified layer depth. X-ray phase analysis demonstrated the presence of titanium disilicide $TiSi_2$ and titanium silicide TiSi phases.

Keywords: synergy of high-intensity implantation and energy impact, power density, diffusion, titanium, silicon.

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1. Introduction

Ion implantation methods are unique in that their use makes it possible to control the elemental and phase composition of the ion-alloyed layer, its structure and, consequently, the physico-mechanical properties of metals and alloys, and the electrophysical properties of semiconductor materials [1–3]. Small thickness of ion-modified layers is the main limitation of ion implantation. For example, the average projective range of boron ions in silicon at an energy of 200 keV is 0.53 μm, the average projective range of phosphorus ions is 0.25 μm, the average projective range of titanium ions is 0.186 μm [4,5]. The results of the study in Ref. [6] demonstrate that the implantation of titanium ions with an energy of 45 keV at a fluence of $5 \cdot 10^{15}$ ion/cm^2 allowed obtaining a doped layer with a thickness of 115 nm. The implantation of titanium ions at an energy of 35 keV with an irradiation dose of 10^{15} ion/cm^2 in Ref. [7] led to the formation of an ion-modified layer with a thickness of 200 nm.

In recent years, work has been underway on hyperdoping of silicon with various dopants in order to increase their concentrations and increase the thickness of ion-doped layers to $1-3\,\mu$m [8–10].

The results of numerical modeling of silicon modification by titanium ions using the synergy method of high-intensity ion implantation and simultaneous energy beam action on the surface [12] are presented in Ref. [11]. It is shown that this method provides the possibility of increasing the thickness of the ion-doped layer due to diffusion transfer caused by pulse-frequency heating. The high power density of the ion beam enhances the diffusion of ion-doped impurities to depths exceeding the projective range of ions by several orders of magnitude.

Experimental results of the formation of layers with a thickness from 0.1 to 1 μm using the synergy method of high-intensity implantation of titanium ions into silicon and the energetic action of an ion beam on the surface are presented in Ref. [13].

The results presented in Ref. [14] showed that when titanium ions with an energy of 70 keV are implanted into silicon ion-doped layers with a thickness of up to 1.5 μm are formed, depending on the irradiation time and ion current density.

This paper presents a study of the patterns of titanium accumulation in silicon depending on the duration, pulse frequency, and energy density at a fixed ion beam power density.

2. Experimental procedure

The effect of pulse duration and frequency on the accumulation and diffusion of titanium into silicon was studied at a fixed ion beam power density. Pulse and pulse-periodic beams of titanium ions were shaped using a modified „Raduga 5M“ ion and plasma source [15]. The experiments were carried out for 30 minutes at an arc discharge current of 130 A, pulse durations of 100, 300 and 450 μs, acceleration voltage amplitude of 30 kV and pulse frequency of 18, 6 and 4 pps, respectively. The ion current density reached 1.6 A/cm^2. The power density in the pulse was kept at the level of $9.6 \cdot 10^4$ W/cm^2. The energy density was 9.6 J/cm^2 at pulse durations of 100 μs, and it was 28.8 and 43.2 J/cm^2 at 300 and 450 μs, respectively. The irradiation fluence in the experiments was $\sim 1.4 \cdot 10^{19}$ ion/cm^2. The samples were made of single crystal silicon in the shape of a square with a side of 20 mm and a thickness of 0.38 mm.

The elemental composition on the surface of the samples was carried out using a HitachiS-3400 N scanning electron microscope equipped with a Bruker XFlash 4010 energy dispersion attachment. The depth distribution of the impurity was studied by electron Auger spectroscopy. The depth of the modified layers was determined by atomic emission spectroscopy using a glow discharge spectrometer Profiler 2. The phase composition of the studied samples was studied by X-ray diffraction analysis (XRD) based on diffractograms obtained using a Shimadzu hbox XRD-7000 diffractometer.

3. Experimental results

The elemental composition was studied on the surface of the samples on an area of $250 \times 350\,\mu m^2$. The method made it possible to obtain an average value of the element content from a depth of up to two micrometers. The admixture of titanium on the surface of the samples in all modes was at the same level and amounted to 38–39 at.%, silicon ~ 60 at.%. Oxygen content of 1–4 at.% was detected.

A detailed study of the accumulation of titanium impurity in depth was carried out using electron Auger spectroscopy (Figures 1–3).

The results of the study showed a uniform distribution of titanium ions at depths up to $1.6\,\mu$m with concentrations reaching 40 at.% with a pulse duration of $100\,\mu$s and a frequency of 18 pps. The titanium concentration decreased to 35–38 at.% with a pulse duration of $300\,\mu$s and a frequency of 6 pps. An increase in the pulse duration to $450\,\mu$s with a pulse frequency of 4 pps led to a decrease in the titanium concentration to 14 at.% at a depth of $1.6\,\mu$m. It can be seen from the figures that changes in the pulse duration and frequency affect not only the impurity content, but also the distribution of elements in a thin near-surface layer up to 50 nm thick. The limitation of the depth of the study is the disadvantage of this method.

Atomic emission spectroscopy was performed to determine the depth of the obtained ion-doped layers. According to the element distribution profile, the thickness of the ion-doped layer at an energy density of 9.6 J/cm^2 was $\sim 2\,\mu$m. The thickness increased to $2.4\,\mu$m as the energy density increased to 28.8 J/cm^2. The maximum layer depth of $2.6\,\mu$m was reached at 43.2 J/cm^2.

A qualitative X-ray diffraction analysis showed that the modified layers contain the following phases in all the samples studied: titanium disilicide $TiSi_2$, titanium silicide TiSi, silicon oxide SiO_2.

Quantitative X-ray diffraction analysis showed that in samples with pulse durations of 100 and $300\,\mu$s, the content of phase $TiSi_2$ is the same and amounts to ~ 88 vol.%. An increase in the pulse duration to $450\,\mu$s led to a slight decrease in the phase concentration $TiSi_2$ to 81 vol.%. The analysis of the TiSi phase content depending on the modification modes showed the opposite picture. The percentage of the phase increased from 5 vol.% to 11 vol.% as the pulse duration increased. The pattern of formation of the SiO_2

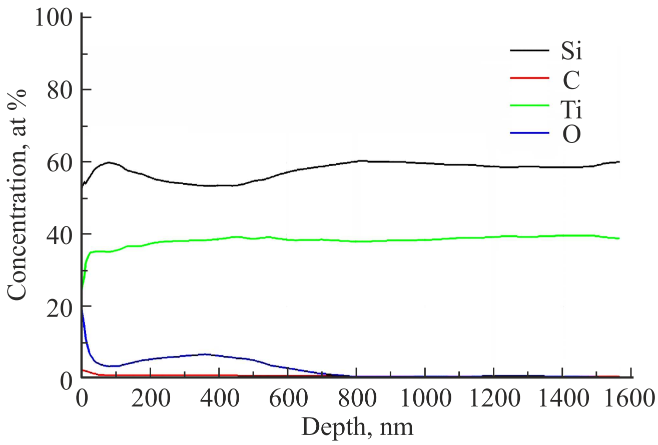

Figure 1. Concentration profiles of the distribution of elements over the depth of the sample obtained at a pulse duration of $100\,\mu$s, a frequency of 18 pps, and an energy density of 9.6 J/cm^2.

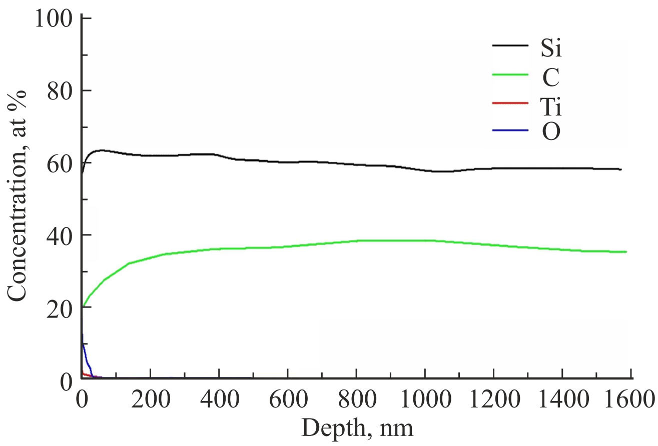

Figure 2. Concentration profiles of the distribution of elements over the depth of the sample obtained at a pulse duration of $300\,\mu$s, frequency 6 pps, energy density 28.8 J/cm^2.

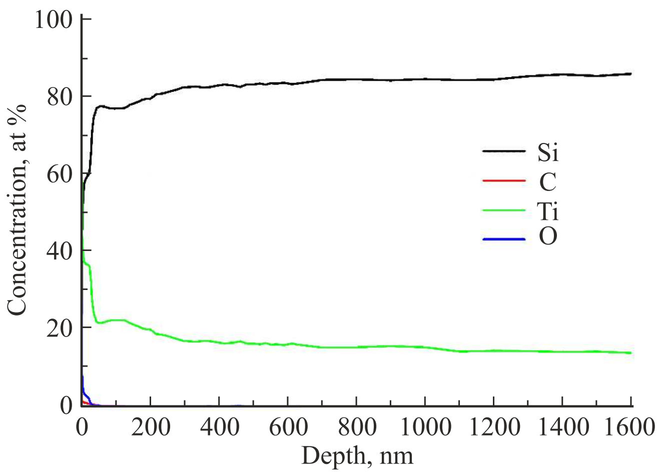

Figure 3. Concentration profiles of the distribution of elements over the depth of the sample obtained at a pulse duration of $450\,\mu$s, frequency of 4 pps, energy density of 43.2 J/cm^2.

phase from high-intensity implantation modes has not been detected, the phase content does not exceed 7 vol.%.

4. Conclusion

Up to 2.6 μm thick ion-doped layers were formed on the silicon surface by the method of synergy of high-intensity implantation and simultaneous energetic action of a beam of titanium ions with a current density of 1.6 A/cm^2 and a power density of $9.6 \cdot 10^4$ W/cm^2. The change in the impurity distribution in the thin near-surface layer to 50 nm and hboxstructural-phase composition is associated with a different energy input to the surface of the samples. It is shown by the method of electronic Auger spectroscopy that the distribution of titanium and silicon over the studied depth is uniform. The titanium content decreases with increasing energy density from 40 to 20 at.%.

X-ray diffraction analysis showed a decrease in the phase content of $TiSi_2$ from 88 to 81 vol.% with an increase in pulse duration and a corresponding decrease in their frequency. The content of TiSi phase was found at the level of 5–11 vol.%, depending on the modification modes, as well as an insignificant content of phase SiO_2.

Analysis of the results showed that deeply doped layers with different depths and structural-phase states are formed on the surface of the irradiated samples at fixed beam parameters, such as current density 1.6 A/cm^2 and power density $9.6 \cdot 10^4$ W/cm^2, with a single ion irradiation fluence $1.4 \cdot 10^{19}$ ion/cm^2 and energy input values of 9.6, 28.8 and 43.2 J/cm^2.

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Conflict of interest

The authors declare that they have no conflict of interest.

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