EFFECT OF PULSED LASER ANNEALING ON OPTICAL PROPERTIES OF SILICON IMPLANTED WITH SELENIUM AND MANGANESE

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Different fluences of Mn^+ and Se^+ ions were implanted in silicon, followed by pulsed laser annealing. Studies carried out by RBS and Raman spectroscopy analysis show a significant redistribution of impurities in depth and to the Si surface. In the case of Mn^+ implantation, during the cooling stage of the Si melted state, the most of Se impurity atoms move to the near-surface region. The laser annealing of Se^+ implanted up to 10^{16} ions/cm^2 results in in-depth redistribution. After annealing, the IR absorption of Se implanted and laser annealed sample sharply increased by 50 times. The measured Raman spectra indicate on different levels of the modified Si-crystallinity perfection depending on impurity type and concentration.

Keywords: ion implantation; pulsed laser annealing; selenium; manganese; RBS.

Introduction

Silicon is the main material of microelectronics. However, the structure of silicon atoms restricts the application of silicon in photodetectors and silicon solar cells. The bandgap of silicon is 1.12 eV (wavelength of 1100 nm), traditional silicon photodetectors are unsuitable for telecommunication wavelengths, which are close to 1300 nm and 1550 nm. For this reason, a lot of work has been done to broaden the detection range to 1300-1500 nm. Among these, bonding an InGaAs detector to a silicon waveguide [1], growing epitaxial Ge or SiGe on a silicon waveguide [2] and using ion implatation with sebsquent plused laser annealing to create an intermediate band in band gap [3]. Compared with the first and second methods, the third method is compatible with standard CMOS processes.

Se ion implantation is used instead of Si ion implantation to obtain deep level impurities that are more stable than the defects caused by Si implantation under high temperature processes. Currently, it is established that single-crystal silicon oversaturated with chalcogen atoms (S, Se and Te) exhibits the highest absorption coefficient (~10^4 cm-1) of light in the IR spectral range at room temperature.

Semiconducting transition-metal silicides have been studied extensively, since they could play an important role in the Si-based technology. Among them, $MnSi_x$ (x = 1.67–1.75), the so-called higher manganese silicides (HMS) are promising materials for applications in optoelectronics, spintronics, and thermoelectrics due to their interesting physical and chemical properties, e.g., the direct band gap in the infrared region, ferromagnetism with relatively large magnetic moment, large Seebeck coefficient, and high resistance to oxidation at high temperatures [4].

The present work is devoted to Se and Mn- hyperdoped silicon layers fabricated by ion implantation followed by pulsed laser annealing. Our investigation on the whole focuses on the effect of ion type and fluence on the structural and optical properties of Se-supersaturated silicon layers.

Materials and methods

Silicon (111) p-type double side polished wafers were separately implanted with 200 keV Se^+ ions to the fluence of 1×10^{16} and 1×10^{15} ions/cm^2, with 95 keV Mn^+ ions to the fluence of 1×10^{16} ions/cm^2, with 95 keV Mn^+ ions to the fluence of 1×10^{16} ions/cm^2 and subsequently with 125 keV Se^+ ions to the fluence of 1×10^{16} ions/cm^2.

Pulsed laser irradiation of the implanted samples was carried out under the experimental conditions of optical and pyrometric diagnostics in situ of phase transformations (Fig. 1) initiated by a ruby laser pulse (λ = 694 nm, FWHM = 70 ns) with a uniform pulse energy distribution along the area with a diameter of 4 mm. The energy density W in the laser pulse was set as 2 J/cm^2.

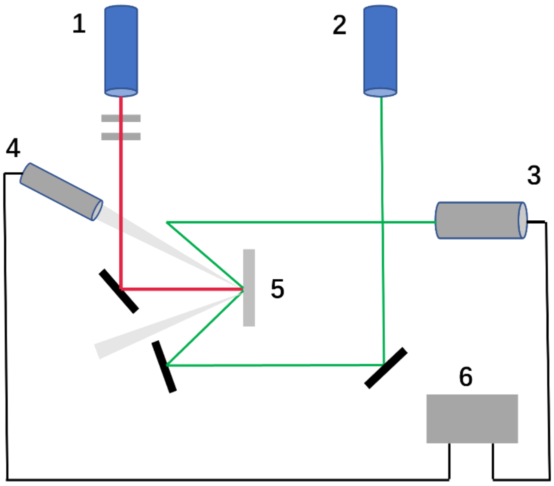

Fig. 1. Schematic of the experimental setup for the ns-laser annealing: 1 - ruby laser, 2 - assisting Nd-laser, 3 - photodetector (FD-256 photodiode) of probe radiation, 4- pyrometric detector of IR radiation (PR sensor), 5 - sample holder, 6- digital oscilloscope, 7 - weakening neutral light filters

Analysis of depth distribution of impurity atoms, the fraction of selenium and manganese atoms at silicon lattice sites, and the degree of crystallinity of implanted layers was carried out by obtaining spectra of Rutherford back scattering (RBS) of He$^+$ ions with energy of 1.5 MeV in the regime of channeling along the 100 direction and without it (random) in acceleration complex HVE2500 with a registration angle of 170°. Information on depth distribution of concentration of selenium atoms was obtained by processing the RBS spectra using the HEAD software package. The RBS spectra were simulated using this software stepwise until complete overlap with the experimental spectra was achieved.

The Raman spectroscope (Ramanor U1000) was used to investigate the Raman spectra with a 532 nm solid-state Nd laser as excitation source.

Transmission and specular reflection spectra were taken in the range of 190-2500 nm (Lambda 1050, Perkin Elmer).

Results and discussion

The distribution of ions in silicon firstly simulated with SRIM. As we can see from the Fig. 2, the simulation result of SRIM basically similar to the as-implanted one.

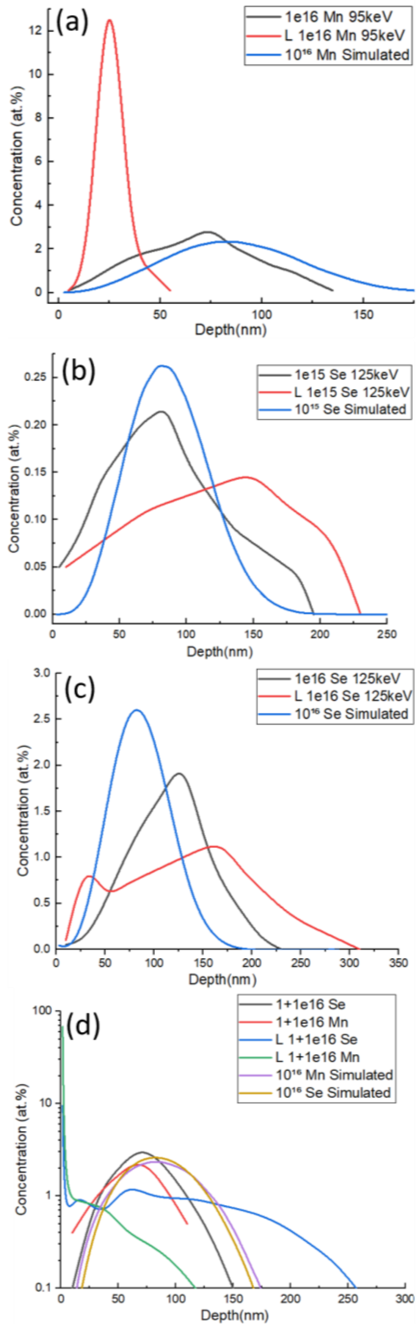

Fig. 2. Distribution of Se and Mn in silicon. The implatation concentration: (a)Mn$^+$ 10^{16} ions/cm^2 (b) Se$^+$ 10^{15} ions/cm^2 (c) Se$^+$ 10^{16} ions/cm^2 (d) Mn$^+$ 10^{16} ions/cm^2 + Se$^+$ 10^{16} ions/cm^2

Pulsed laser melting leads to a considerable redistribution of the implanted impurity. For Mn$^+$, the most atoms move to the surface of silicon and form a near-surface layer of about 50 nm thick with a concentration of 6×10^{21} cm^{-3}, compared with the as-impanted one of 140 nm with average concentration of 7.5×10^{20} cm^{-3}. Conversely, for Se$^+$, after the laser annealing, the redistribution range of atoms was extended to 250-300 nm in comparison with the initial range of 175-225 nm with maximum concentration of 1.0×10^{20}cm^{-3} ions/cm^2. We can find the explanation of this result based on the work of Tang [5], where Mn in melt and solid state has substantially higher diffusion coefficients than Se.

Absorption was estimated taking into account transmittance (T) and specular reflectance (R) using the formula:

$$A(\%)=100\ \% - T(\%) - R(\%).$$

As can be seen, the PLA results in increase of absorption by about 50 times for Se with implantation concentration of 10^{16} ions/cm^2.

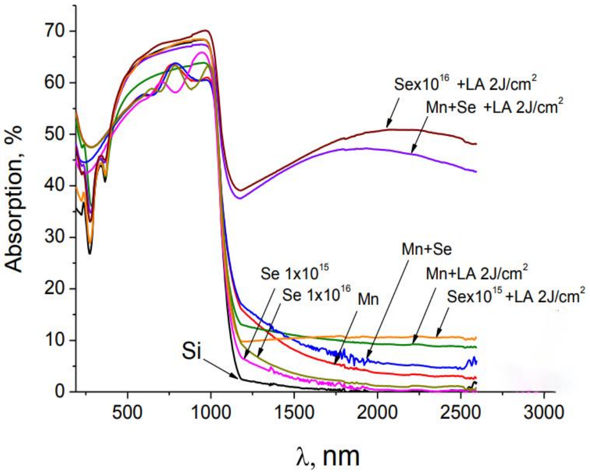

Fig. 3. Absorption spectra of the implanted Si(111) before and after laser annealing

Figure 4 shows that the PLA substantially improves the crystallinity of the as-implanted samples, especially for the lower Se$^+$ ion fluence (10^{15} ions/cm^2), and the incorporation of Mn atoms improves the crystallinity of Si (Se) layer.

Interestingly, the intensity of Si-band in Raman spectra after the laser annealing of silicon with manganese is higher than that of silicon with selenium alone.

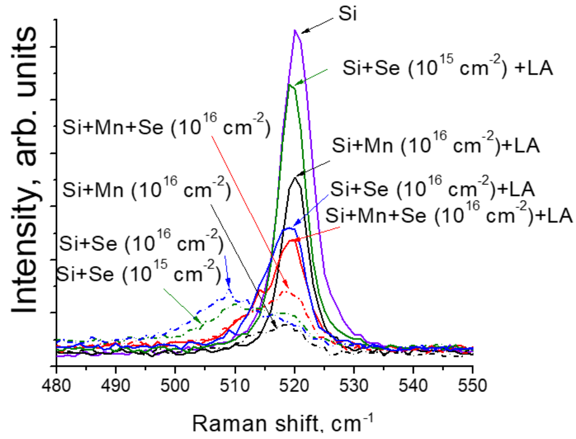

Fig. 4. Raman spectra of the ion implanted and laser-annealed samples

Conclusions

Apparently, the segregation of the Mn atoms to the surface of crystalline silicon, occurs at the cooling stage of the melted silicon layer. As for silicon implanted with Se$^+$ to the fluence of 10^{15} ions/cm^2 corresponds to the better crystal perfection but weaker optical absorptance than 10^{16} ions/cm^2 of Se in the second case.

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