Formation of Si:Er Light Emitting Layers by Continuous and Pulsed Ion Beams[1]

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Abstract – In this work the formation of Si:Er solid solutions and erbium silicide layers by means of high-fluence ion implantation and pulsed ion-beam treatment (PIBT) was investigated. The dependence of Er atoms redistribution in Si and also the microstructure and phase composition of Si:Er layers on implanted fluence and regimes of PIBT was established. It is shown that Si:Er layers obtained using pulsed and thermal treatments have photoluminescent properties in the near infrared region at 77 K. These properties are manifested by the intensive signals at λ = 1.13 and 1.54 μm.

1. Introduction

Doping of Si by rare earth Er ions is one of the prospective approaches to produce Si-based structures emitting light in the 1.5–1.6 μm communication range. The method of ion implantation is widely applied for the formation of thin film Si:Er solid solutions [1]. The significant disadvantage of this method is severe damage of Si matrix during implantation by heavy Er ions. In order to eliminate the radiation-induced damage the high-temperature annealing ($T > 900$ °C) is usually carried out.

However, the elimination of simple kinds of defects is accompanied by the creation of extended defects (dislocations, dislocation loops) [3] and erbium ion clusters which result in quenching of Er photo- and electroluminescence with temperature increasing.

Pulsed treatments of the implanted layers by nanosecond laser, ion and electron beams can be alternative to traditional thermal annealing. Pulsed nanosecond treatments allow one to localize heating of the amorphous material for its area and depth. Moreover, due to high velocities of heating, melting and crystallization defect-free epitaxial Si layers can be formed as a result of pulsed treatments [4].

In this work the structural and luminescent properties of Er-implanted Si layers annealed by pulsed ion beams were studied.

2. Experiment

In order to form Si:Er solid solutions and erbium silicide layers the implantation of *n*-Si (100) wafers was carried out at room temperature with Er^+ ions with energy $E = 100$ keV and fluencies $\Phi = 10^{16}$ and 10^{17} cm^{-2}. To eliminate radiation defects and to synthesize erbium silicides, Si samples were subjected to pulsed ion-beam treatment (PIBT). Pulsed accelerator has generated high-energy ($E = 300$ keV) carbon ion beams with nanosecond duration ($\tau = 50$ ns). Total fluence of carbon ions implanted into Si sample during one nanosecond pulse does not exceed $\Phi \sim 10^{13}$ cm^{-2}. During PIBT energy density ($W = 1.4$–2 J/cm^2) and number of pulses ($N = 1$–10) were varied.

The distribution of implanted Er ions in Si after ion implantation and PIBT was studied by Rutherford backscattering spectrometry (RBS). The microstructure and phase composition of Si:Er layers were investigated by transmission electron microscopy (TEM). Photoluminescence (PL) of Si:Er layers was studied in the near infrared region ($\lambda = 1$–1.7 μm) at temperature $T = 77$ K. In order to excite the PL signal Si samples were irradiated by Ar^+ laser ($\lambda = 514.5$ nm, $P = 200$ mW). Registration of PL was performed by BOMEM Fourier-spectrometer equipped with liquid nitrogen cooled Ge photodetector.

3. Results and discussion

RBS spectra of Si samples measured after ion implantation show that due to low energy ($E = 100$ keV) Er atoms are located in the narrow peak near the surface with thickness of 80 nm. PIBT of a Si layer implanted with the fluence $\Phi = 10^{16}$ cm^{-2} leads to the epitaxial recrystallization of amorphous layer that was seen by channeling of helium ions within the implanted layer and also to redistribution of some part of Er atoms closer to the surface (segregation) and into Si crystal. Segregation effect of Er atoms is due to low solubility of Er in Si and trapping of impurity by front of liquid

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phase crystallization. Compared to Si the channeling in Er peak is absent that indicate interstitial position of Er atoms in Si lattice.

In the case of high-fluence implantation ($\Phi = 10^{17}$ cm^{-2}) PIBT results in to significant suppression of Er segregation due to achieving of high Er concentration in the implanted layer ($N \sim 10^{22}$ cm^{-3}). At such fluence, Er profile expands into Si crystal up to depth of 0.15–0.2 μm depending on the number of pulses. Similar redistribution of the implanted atoms in Si during PIBT was observed for Fe impurity [4].

Figure 1 shows the bright-field TEM image of a Si layer implanted with fluence $\Phi = 10^{16}$ cm^{-2} and subjected to PIBT.

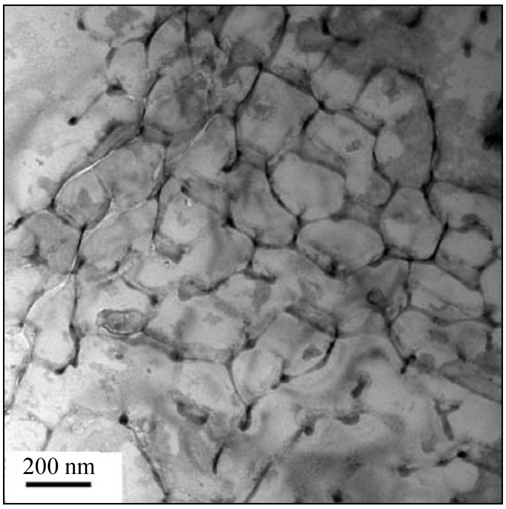

Fig. 1. Bright-field TEM image of Si layer after ion implantation ($\Phi = 10^{16}$ cm^{-2}) and PIBT (W = 2 J/cm^2)

It can be seen that PIBT leads to the formation of cellular structure of the implanted layer characteristic of liquid-phase crystallization. These cellular structures are columns of Si 0.15–0.2 μm in diameter surrounded by walls of erbium silicide precipitates with sizes of 10–20 nm. Electron microdiffraction patterns demonstrated the presence of spot reflexes belonging to Si and ErSi that indicate the formation of single-crystalline Si and ErSi. This result agrees with RBS data which show the channeling of helium ions in the implanted layer after PIBT (450–500 channels).

In the case of high-fluence implantation ($\Phi = 10^{17}$ cm^{-2}) the formation of larger erbium silicide precipitates with sizes of 30–50 nm is observed. Electron microdiffraction pattern showed the presence of large number of rings (up to 20) related to the formation of polycrystalline Si and erbium disilicide ($ErSi_2$). The synthesis of $ErSi_2$ layers correlates with our RBS data which showed decrease of maximum Er concentration from 50 to 25–30% during rapid diffusion of Er atoms in molten Si.

Before low-temperature PL measurements, Si:Er sample prepared by low-fluence ion implantation and PIBT was thermally annealed in quartz tube at the temperature T = 800 °C for 30 min. PL spectrum of this sample (Fig. 2) shows two intensive peaks at 0.807 and 1.1 eV.

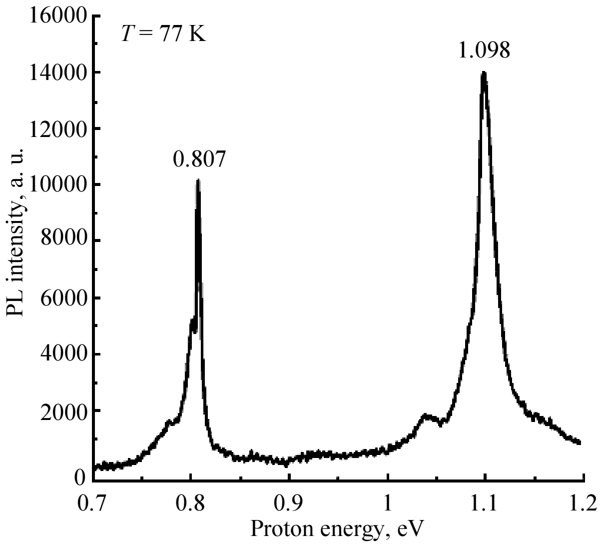

Fig. 2. PL spectrum of Si sample after ion implantation ($\Phi = 10^{16}$ cm^{-2}), PIBT (W = 2 J/cm^2), and additional thermal annealing (T = 800 °C, 30 min)

PL peak at 0.807 eV is related to the optical transitions between energy levels $^4I_{13/2} \rightarrow {}^4I_{15/2}$ of Er^{3+} ion. The main contribution to this peak gives tail regions of Er depth profile. In these regions the concentration of Er atoms significantly lower than that in segregation peak that leads to the formation of light-emitting Si:Er solid solution. The second PL peak at 1.1 eV is due to Si band edge luminescence emitting from the depth of about 1 μm which corresponds to penetration depth of Ar laser radiation. Relatively high intensity and small width of this PL peak is due to low defectivity of Si layer after liquid phase epitaxial recrystallization followed by thermal annealing.

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