Semiconducting nanoparticles embedded in insulating matrices have been the object of continuously increasing interest due to their peculiar physical properties such as strong size-dependent widening of the optical band gaps. One of the main problems for industry is to design a source of light based on these materials. Ion implantation is an effective method of materials properties management for microelectronics, photonics and optoelectronic engineering. Particularly, the implantation of group IV elements in SiO$_2$ layers followed by heat treatments at high temperatures leads to the formation of specific nanostructures exhibiting photoluminescence (PL). The reported intense visible and ultra-violet (UV) PL from Sn-implanted silicon oxides at room temperatures was traditionally associated to oxygen deficiency centers (ODCs) created during the implantation and annealing [1, 2]. The present study is concerned with low-temperature relaxation processes involving photosensitive defects in SiO$_2$-film samples implanted with Sn$^+$-ions.

Time-resolved photoluminescence (PL) spectra in the region of 1.5-6.0 eV, time-resolved PL excitation spectra (3.7-12 eV), and the PL decay kinetics were measured using the selective VUV-excitation at SUPERLUMI station. The primary monochromator with Al-grating had a spectral resolution of 3.2 Å. The PL spectra was measured using a 0.3-m monochromator model ARC Spectra Pro-308i and an R6358P photomultiplier (Hamamatsu) in two time spans $\Delta t_1 = 11.8$ ns (the fast component) and $\Delta t_2 = 92$ ns (the slow component), which were delayed relative to the beginning of the SR-excitation pulse for $\delta t_1 = 2.7$ ns and $\delta t_2 = 60$ ns respectively. The excitation spectra were normalized to the same number of SR-exciting photons using sodium salicylate. The PL spectra were not corrected on spectral sensitivity of optical tract. In order to analyze two fast components of the PL decay kinetics, the convolution method was used. The studied sample was SiO$_2$-film (500 nm) on a silicon substrate irradiated by Sn$^+$-ions ($E = 100$ keV, $F = 5\times10^{16}$ ions/cm$^2$) and annealed at $T = 900$°C during 1 hour.

The PL spectra of the unirradiated films include several ODC bands in regions 2.5-3.5 and 4.3-4.5 eV, usually observed for SiO$_2$ glass and films [3]. After implantation of Sn$^+$-ions and subsequent annealing, the luminescence properties of the samples under study change considerably. The most intensive bands appear at 3.25 eV and 2.5 eV (Figure 1). A couple of lower peaks are located near 1.7 and 4.0 eV. Besides, there is an evidence of additional maximum at 2.1 eV.
The PL excitation spectra (Figure 2) for all emission energies have a complex shape with most noticeable peaks at 5.0-5.5, 10 and 12 eV. These spectra can be divided into three parts, corresponding to low-energy intracenter transitions, excitons and electron-hole pairs formation. Such behavior is similar to silicon-implanted silica films though interference effects [4] are not observed clearly in the present case for Sn+ implanted samples. An interesting feature is that the 11 eV photons excite the whole set of emission bands thus resembling the laser or electron beam excitation effects in photo- and cathodoluminescence, respectively.

The time-resolved luminescence measurements reveal different kinetics of the bands (Figure 1). The luminescence at 4.1 and 2.1 eV decays much faster than the luminescence at 2.1 and 2.6 eV. According to Figure 3, decay curves for both bands are described fairly well by single exponentials placed on the top of constant level of microsecond kinetics. The lifetimes are \( \tau = 4.5 \) ns for \( h\nu_{\text{em}} = 4.0 \) eV and \( \tau = 24 \) ns for \( h\nu_{\text{em}} = 2.1 \) eV. The former value is close to that for 4.2 eV singlet PL band observed for SnODC in tin doped silica [5].

Generally, tin implantation may have several effects on silica matrix, including Sn-nanoparticles formation, silicon substitution and lattice distortions. Subsequent annealing favors the growth of tin nano-sized inclusions and also may yield a portion of SnO\(_2\) nanoclusters. Besides, ion implantation could create an excess of silicon which may further appear as Si quantum dots. All the features described may contribute to photoluminescence. In such a complex case the time-resolved techniques may help to reveal the nature of the bands observed. Particularly the luminescence of silicon nanoparticles is often characterized by long micro- or even millisecond decay kinetics, while the intracenter transitions of point defects may have nanosecond order lifetimes. The 3.2 and 4.1 eV bands in PL spectra can be ascribed by their positions and lifetimes to the triplet-singlet and singlet-singlet transitions of Sn-related variant of the oxygen deficient centers [2, 5]. The 1.7 eV peak coincides with well-known emission band of silicon quantum dots. So the most intriguing contributions there are 2.1 eV and 2.5 eV maxima. Further investigations are required to identify their actual nature.

Thus the main feature of luminescence for samples under study is the appearance of new luminescence centers with complex multiband excitation spectra. The nature of such light emission may be connected both with the nanoclusters and point defects.

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**References**


