ISSN 1063-7826, Semiconductors, 2012, Vol. 46, No. 11, pp. 1407–1410. © Pleiades Publishing, Ltd., 2012.
Original Russian Text © A.N. Yablonskiy, B.A. Andreev, D.I. Kryzhkov, V.P. Kuznetsov, D.V. Shengurov, Z.F. Krasilnik, 2012, published in Fizika i Tekhnika Poluprovodnikov, 2012, Vol. 46, No. 11, pp. 1435–1439.

XVI SYMPOSIUM
"NANOPHYSICS AND NANOELECTRONICS",
NIZHNI NOVGOROD, MARCH 12–16, 2012

Mechanism of the Subband Excitation of Photoluminescence from Erbium Ions in Silicon under High-Intensity Optical Pumping

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Submitted April 25, 2012; accepted for publication, April 25, 2012

Abstract—The photoluminescence (PL) excitation spectra of erbium and band-to-band silicon in Si:Er/Si epitaxial structures under high-intensity pulsed optical excitation are studied. It is shown that the nonmonotonic dependence of the PL intensity on the excitation wavelength λ_{ex} near the absorption edge of silicon is due to inhomogeneity in the optical excitation of the Si:Er active layer. The sharp rise in the erbium PL intensity in the spectral range λ_{ex} = 980–1030 nm is due to an increase in the excited part of the Si:Er emitting layer on passing to subband light pumping ($\lambda_{ex} > 980$ nm) with a low absorption coefficient in silicon because of the effective propagation of the excitation light in the bulk of the structures under study. It is shown that, under the subband optical pumping of Si:Er/Si structures, as also in the case of interband pumping, the exciton mechanism of erbium ion excitation is operative. Excitons are generated under the specified conditions as a result of a two-stage absorption process involving impurity states in the band gap of silicon.

DOI: 10.1134/S1063782612110231

1. INTRODUCTION

Erbium-doped silicon has attracted considerable attention because the wavelength of the radiative transition $^4I_{13/2} \longrightarrow {}^4I_{15/2}$ in the 4*f*-shell of the Er^{3+} ion ($\lambda \approx$ 1.54 μm) is the optimal for light propagation in both silicon and quartz fiber-optic transmission lines. Despite extensive studies [1, 2], the mechanisms of the excitation of erbium ions via the electron subsystem of silicon and de-excitation of erbium photoluminescence (PL) in Si:Er/Si structures still remain insufficiently understood. The achievement of a practically important gain and lasing in erbium-doped silicon structures at the wavelength of 1.54 μm requires the creation of population inversion for the radiative transition of the erbium ion. Of particular importance in this regard is investigation of the optical properties of Si:Er structures under high-intensity optical excitation necessary for providing population inversion. The goal of our study was to examine the PL excitation spectra of erbium and the band-to-band PL excitation spectra of silicon in Si:Er/Si and Si:Er/SOI (SOI means silicon-on-insulator) structures and to refine, on the basis of the experimental data obtained, the model of PL excitation from erbium ions in silicon.

2. EXPERIMENTAL

The Si:Er/Si and Si:Er/SOI structures were grown by sublimation molecular-beam epitaxy (SMBE) [3–5] on *p*-type Si structures (resistivity of 4.5 and 18 Ω cm, respectively). The growth temperature of the structures was 500–600°C, and the thickness of the Si:Er epitaxial layer was 1–5 μm. The structures were excited with pulsed light from a Spectra-Physics MOPO-SL parametric light generator pumped by an Nd:YAG pulsed laser. In studies of the PL excitation spectra, the wavelength of the excitation light was varied within a wide spectral range (λ_{ex} = 800–1500 nm). The PL signal was measured with an Acton grating monochromator 2300i, a Hamamatsu InP/InGaAs photoelectron multiplier (sensitivity range 930–1700 nm, response time ~2 ns) and a LeCroy digital oscilloscope. The erbium PL was recorded at a wavelength of 1535 nm, which corresponds to the main radiative transition of the erbium ion, $^4I_{13/2} \longrightarrow {}^4I_{15/2}$. The temporal resolution of the system, determined by the pulse width of the excitation laser light, was ~5 ns. The PL was studied at liquid-nitrogen temperature ($T = 77$ K).

3. RESULTS AND DISCUSSION

We have previously found [6–8] that the PL signal from erbium ions is observed in Si:Er/Si epitaxial structures and also in Si:Er/SOI and SiGe:Er/Si

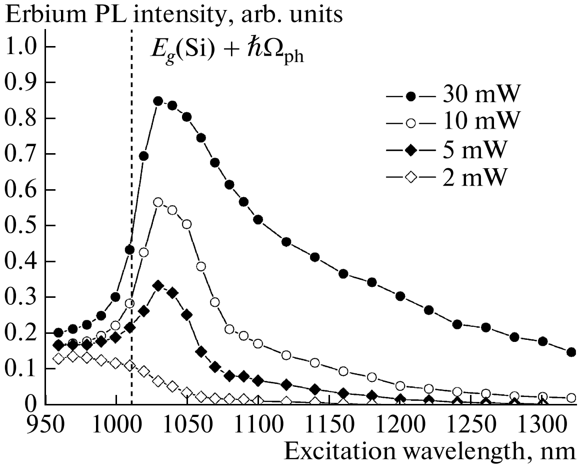

Fig. 1. PL excitation spectra of erbium in a Si:Er/Si structure at varied optical pumping powers. T = 77 K. The dashed vertical line denotes the silicon absorption edge. $\hbar\Omega_{ph}$ is the optical phonon energy.

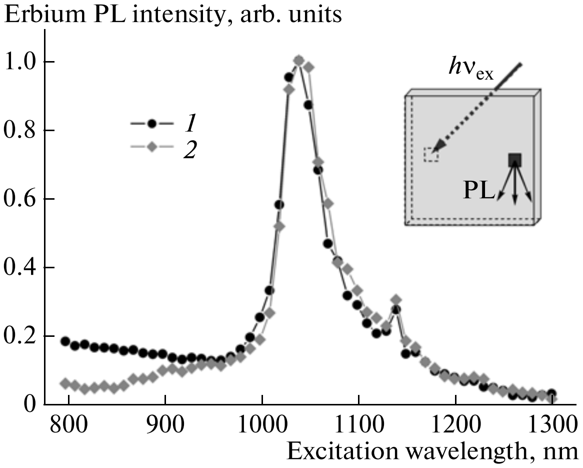

Fig. 2. PL excitation spectra of erbium in a Si:Er/Si structure, obtained in a scheme with two apertures under excitation from the side of (*1*) the Si:Er active layer and (*2*) the Si substrate. T = 77 K. The inset shows the scheme of the experiment.

structures under high-intensity pulsed optical excitation both in the case of interband pumping and in the excitation of structures with light whose photon energies are substantially lower than the band gap of silicon, E_g (Si) (subband excitation). In the case of the high power density of optical pumping in the spectral range corresponding to the optical absorption edge of silicon (980–1030 nm), the erbium PL intensity sharply increased as the excitation wavelength became longer and a peak with a maximum at a wavelength λ_{ex} = 1030 nm appeared in the PL excitation spectra (Fig. 1). We previously attributed the fact that the given peak is observed in the PL excitation spectra of erbium to a sharp rise in the intensity of the nonradiative de-excitation of erbium ions with increasing free-carrier concentration [7, 8] and to a decrease in the efficiency of the exciton mechanism of erbium ion excitation due to the generation of electron-hole plasma [9] on passing from subband optical excitation to that of the band-to-band type. To explain this effect, other authors have suggested models based on resonance excitation of the erbium ion via excitons bound to a deep donor level [10] or nonresonant excitation via a virtual Auger process [11]. However, the suggested hypotheses regarding the nature of the appearing peak disagreed with a number of experimental results, which made further studies necessary.

The experimentally observed dependence of the peak intensity on the size of the sample and that of the excitation-light spot made it possible to relate the appearance of the peak in the PL excitation spectrum of erbium to an increase in the size of the excited part of the Si:Er active layer at photon energies lower than the band gap of silicon, at which the silicon substrate becomes almost transparent to the excitation light. In this case, the pumping light can effectively propagate in the bulk of the structure under study via multiple reflections from sample boundaries and excite erbium ions in those regions of the Si:Er active layer which lie outside the spot onto which the laser light is focused.

This assumption was verified in the following experiment. The surface of a 10 × 10 mm Si:Er/Si sample under study was covered with aluminum foil on the side of the active layer and on that of the substrate. On both sides of the sample, 1 × 1 mm apertures were made in the foil, laterally spaced by a distance of ~10 mm (see inset of Fig. 2). The excitation-light beam was directed into one of the apertures, and the second aperture served as the exit and for the detection of the PL signal. A specific feature of the measurement scheme described above consists in that the PL signal can only be induced by the excitation light or emission from erbium ions, which propagates within the Si:Er/Si structure under study to distances of ~10 mm. The separation of the "entrance" and "exit" apertures by this distance makes it possible to exclude from consideration the possibility of charge-carrier diffusion from the excited region to that from which the PL signal is recorded. Figure 2 shows how the erbium PL intensity depends on the excitation wavelength (PL excitation spectra) measured under excitation from the side of the Si:Er active layer (configuration *1*) and from the side of the Si substrate (configuration *2*).

Under band-to-band excitation of the structure (λ_{ex} = 800–980 nm), charge-carrier generation and excitation of erbium ions are only possible near the entrance aperture. The fact that a noticeable erbium PL signal is observed under excitation in this spectral range indicates that emission from erbium ions (at a wavelength of 1535 nm) effectively propagates from the excitation region to the exit aperture. It is noteworthy that in configuration *2*, i.e., under excitation from

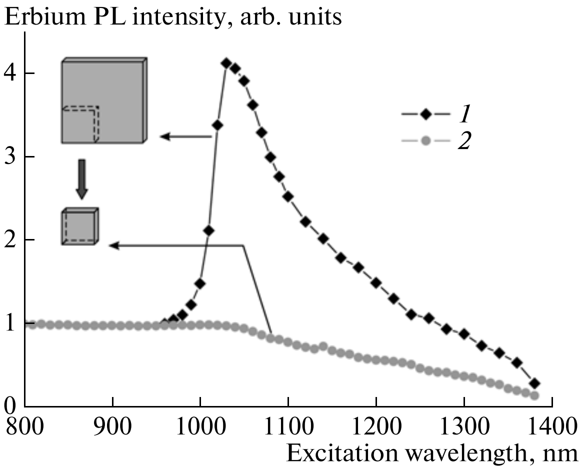

Fig. 3. PL excitation spectra of erbium in a Si:Er/Si structure at a high optical pumping power (30 mW): (*1*) 10 × 10 mm structure, excitation spot size ~2 mm; (*2*) 2 × 2 mm sample, homogeneous excitation over the whole surface of the Si:Er active layer. $T = 77$ K.

the substrate side, erbium ions are excited in the case of interband pumping via charge-carrier diffusion to a distance determined by the thickness of the silicon substrate (~400 μm) and also by the depth of light penetration into the structure. Therefore, a monotonic rise in the erbium PL intensity is observed at 800–980 nm with increasing excitation wavelength (i.e., with increasing penetration depth of the pumped light into the structure).

The sharp (by more than an order of magnitude) rise in the intensity of the erbium PL signal under excitation in the range 980–1030 nm, compared with interband pumping, indicates that the pumped light effectively propagates in the Si:Er/Si structure under subband excitation conditions and excites erbium ions both near the "entrance" aperture and in the rest of the Si:Er active layer. A similar effect gives rise to a peak in the PL excitation spectra of erbium in the standard measurement scheme (excitation and recording of the PL signal from the side of the Si:Er active layer) if only a minor part of the structure under study is exposed to the excitation light, especially in cases of a focused beam.

To confirm our conclusion, we cleaved a 2 × 2 mm chip from the Si:Er/Si sample, which made it possible to measure the PL excitation spectrum of erbium under homogeneous illumination of the entire surface of the Si:Er active layer, without reducing the power density P of the excitation light. The resulting excitation spectrum is shown in Fig. 3 (curve *2*). It can be seen that, with excitation of the whole area of the active layer, the erbium PL intensity steadily decreases with increasing excitation wavelength and there is no peak in the PL excitation spectrum. Also, to confirm our hypothesis, we calculated the PL excitation spectra of erbium for the case of homogeneous illumination and exposure of a part of the Si:Er/Si structure. In simulation for the case of inhomogeneous illumination, we assumed that the PL signal is the sum of signals from the excitation spot and from the "dark" unilluminated part of the sample. The second component of the PL signal is excited by the light that passed through the silicon substrate and was reflected from the rear (unilluminated) side of the sample. In this calculation, we used the experimentally measured dependence of the PL signal I on the optical pumping power density and the known dependence of the silicon absorption coefficient on the emission wavelength [12]. Figure 4a shows the excitation spectra calculated for several values of the optical excitation power P. The $I(\lambda_{ex})$ dependences we obtained well describe the appearance of the peak in the PL excitation spectra of erbium near the absorption edge of silicon under inhomogeneous optical excitation of the Si:Er/Si structures. At the same time, similar $I(\lambda_{ex})$ dependences calculated for the case in which the whole surface of

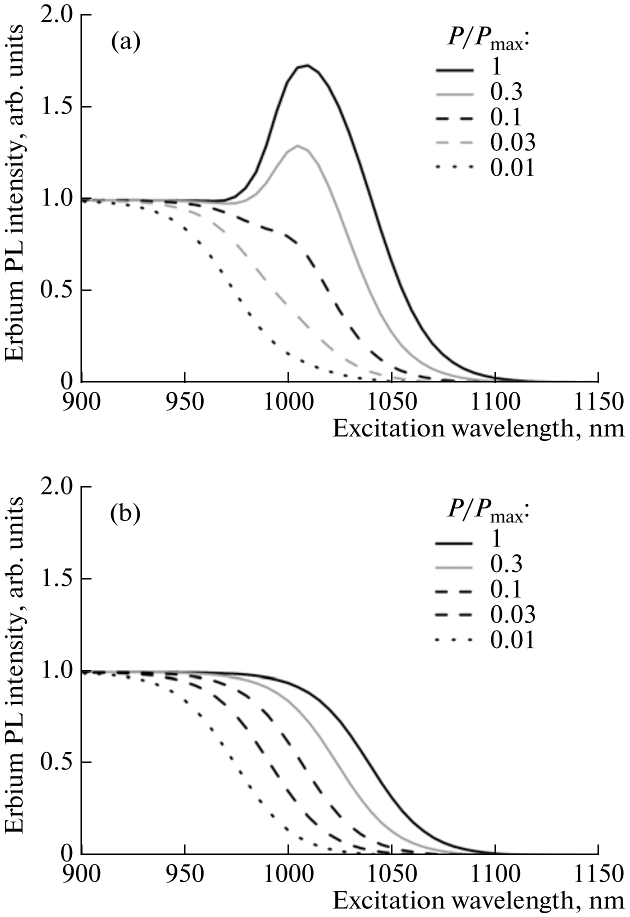

Fig. 4. Calculated PL excitation spectra of erbium in a Si:Er/Si structure at various pump power values (P_{max} is the maximum power): (a) inhomogeneous excitation, sample size 10 mm, 2-mm excitation spot; (b) sample size 2 mm, homogeneous excitation of the surface of the structure.

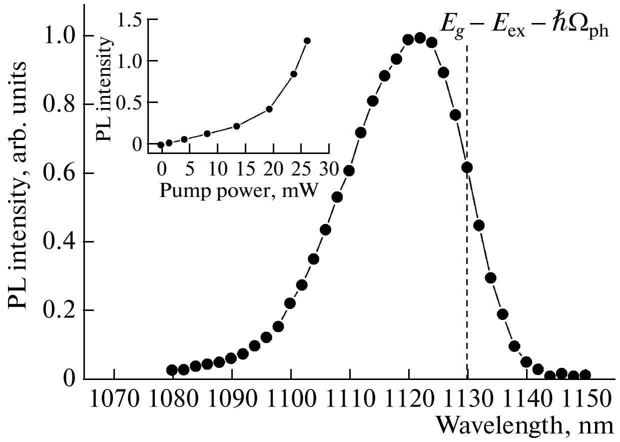

Fig. 5. Spectrum of exciton PL in a Si:Er/Si structure under subband optical excitation conditions ($\lambda_{ex} = 1300$ nm). The inset shows the exciton PL intensity vs. the excitation power. E_{ex} is the exciton binding energy, and $\hbar\Omega_{ph}$ is the phonon energy.

the Si:Er/Si structure is excited (Fig. 4b) show monotonic variation in the intensity with increasing λ_{ex} in the entire spectral range of excitation light.

To determine the mechanism for erbium PL excitation under subband optical pumping, we subjected the excitation spectra of erbium and band-to-band (exciton) PL to a comparative analysis. It was found that, despite the sharp fall in the exciton PL intensity at photon energies $h\nu_{ex} < E_g$, excitons are also generated in Si:Er/Si structures under subband optical excitation. Figure 5 shows the band-to-band PL spectrum of silicon, obtained at an excitation wavelength of $\lambda_{ex} = 1300$ nm, i.e., substantially below the band gap of silicon. This PL spectrum corresponds to the radiative recombination of free excitons in silicon, with the emission of a TO phonon [13]. The erbium and exciton PL intensity ratio, obtained under interband and subband excitation, indicates that the excitation of erbium ions under subband optical pumping occurs, as also in the case of interband excitation, due to the generation of free electron–hole pairs (excitons) in the structures under study. Excitons are presumably generated under these conditions via a double-stage absorption process involving deep impurity states in the energy gap of silicon, which is confirmed by the superlinear dependence of the exciton PL intensity on the excitation power (see inset of Fig. 5).

4. CONCLUSIONS

It was shown that the nonmonotonic dependence of the PL intensity on the excitation wavelength near the silicon absorption edge is due to the inhomogeneity in the optical excitation of the Si:Er active layer. The sharp rise in the erbium PL intensity in the excitation spectral range $\lambda_{ex} = 980$–1030 nm is due to an increase in that part of the Si:Er emitting layer which is excited at photon energies lower than the band gap of silicon because of a substantial decrease in light absorption by the silicon substrate. In this case, the pumped light effectively propagates in the bulk of the structure under study owing to multiple reflections from sample boundaries and excites erbium ions in that part of the Si:Er active layer which lies outside the spot onto which the laser light is focused. It was shown that the exciton mechanism of erbium ion excitation is operative under the subband optical pumping of Si:Er/Si structures, as also in the case of interband pumping. Excitons are generated under these conditions via a double-stage absorption process involving impurity states in the silicon band gap.

ACKNOWLEDGMENTS

The study was supported by grants of the Russian Foundation for Basic Research and by programs of the Russian Academy of Sciences and the Ministry of Education and Science of the Russian Federation (State contract no. 16.518.11.7018).

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Translated by M. Tagirdzhanov