Technical Physics Letters, 2023, Vol. 49, No. 11

07.3

Planar (lateral) light-emitting diodes with Ge(Si) nanoislands embedded in a photonic crystal

© V.B. Shmagin[1], A.V. Novikov[1,2], A.N. Yablonskiy[1], M.V. Stepikhova[1], D.V. Yurasov[1], A.N. Mikhailov[2], D.I. Tetelbaum[2], E.E. Rodyakina[3,4], E.E. Morozova[1], D.V. Shengurov[1], S.A. Kraev[1], P.A. Yunin[1], M.V. Shaleev[1], A.I. Belov[2]

[1] Institute of Physics of Microstructures, Russian Academy of Sciences, Nizhny Novgorod, Russia
[2] Lobachevsky State University, Nizhny Novgorod, Russia
[3] Rzhanov Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
[4] Novosibirsk State University, Novosibirsk, Russia
E-mail: shm@ipmras.ru

Received August 29, 2023
Revised August 29, 2023
Accepted September 25, 2023

Lateral $p-i-n$-LEDs were fabricated on structures with Ge(Si) self-assembled islands using local ion implantation. The use of preliminary amorphization and solid-phase recrystallization of the implanted areas allowed to decrease the impurity activation temperature down to 600°C, which significantly reduced the detrimental effect of post-implantation annealing on the luminescence signal of Ge(Si) islands at room temperature in the range of 1.3−1.55 microns. The electroluminescence signal from Ge(Si) islands was increased by more than an order of magnitude due to the embedding of photonic crystals in the i-region of diodes.

Keywords: silicon, light emitting diodes, Ge(Si) islands, photonic crystals, implantation.

DOI: 10.61011/TPL.2023.11.57199.19713

The lack of a radiation source operating in the 1.3−1.55 μm spectral range and compatible with silicon IC technology is one of the hurdles on the path of development of modern silicon optoelectronics. Various light-emitting group IV heterostructures are considered as candidate sources of this type. Structures with self-assembled Ge(Si) nanoislands are especially notable for the following reasons. First, they produce a luminescence signal at room temperature in the indicated spectral range [1]. Second, the procedure of formation of structures with Ge(Si) islands does not involve thick buffer layers; such structures may be grown directly on silicon-on-insulator substrates [2], simplifying considerably the task of their integration with silicon planar waveguides.

However, owing to the fact that Si and Ge are indirect-bandgap materials, the efficiency of radiative recombination in structures with Ge(Si) nanoislands is low. The use of various cavities (two-dimensional photonic crystals (PhCs) included) has been proposed as a way to raise this efficiency [3–5]. It was demonstrated that the interaction of Ge(Si) nanoislands with PhC modes provides an opportunity to enhance the luminescence signal intensity of islands by several orders of magnitude under optical pumping [5]. However, electrical pumping of PhCs formed on structures with Ge(Si) nanoislands is needed for practical applications. It is also preferable for these structures to have a thickness comparable with the thickness of a planar silicon waveguide (220−250 nm). Planar $p-i-n$-diodes with PhCs with a microcavity embedded into their i-region have been proposed as a solution to this problem [6]. Local implantation of impurities was used to form doped regions of diodes [6]. However, the use of high ($\geqslant$ 1000°C) temperatures of post-implantation annealing in [6] led to diffusion spreading of Ge(Si) islands, a reduction in the intensity of their luminescence signal at room temperature, and a shift of this signal into the spectral region of Si luminescence [6]. In addition, the use of PhCs with a microcavity limited the emitting structure volume and, consequently, the power of fabricated light-emitting diodes [6].

In the present study, the formation of planar (lateral) light-emitting p^+-i-n^+-diodes with Ge(Si) nanoislands and PhCs without a microcavity embedded into their i-region is reported. The use of these PhCs contributes to a substantial increase in the emitting volume, and the interaction of islands with PhC modes results in a considerable enhancement of their electroluminescence (EL) intensity at room temperature. Owing to preliminary amorphization and subsequent solid-phase recrystallization, the temperature of post-implantation annealing of contact regions of diodes was reduced to 600°C. This provided an opportunity to mitigate the negative influence of technological processes of diode fabrication on the emissive properties of Ge(Si) islands and produce light-emitting diodes operating at room temperature within the 1.3−1.55 μm wavelength range.

Planar p^+-i-n^+-diodes with PhCs embedded into the i-region were formed on a structure with Ge(Si) nanoislands that was grown by molecular-beam epitaxy on a silicon-on-insulator substrate. The grown structure featured buffer and coating Si layers with a sequence of five layers of Ge(Si) nanoislands, which were separated by Si layers 15 nm in

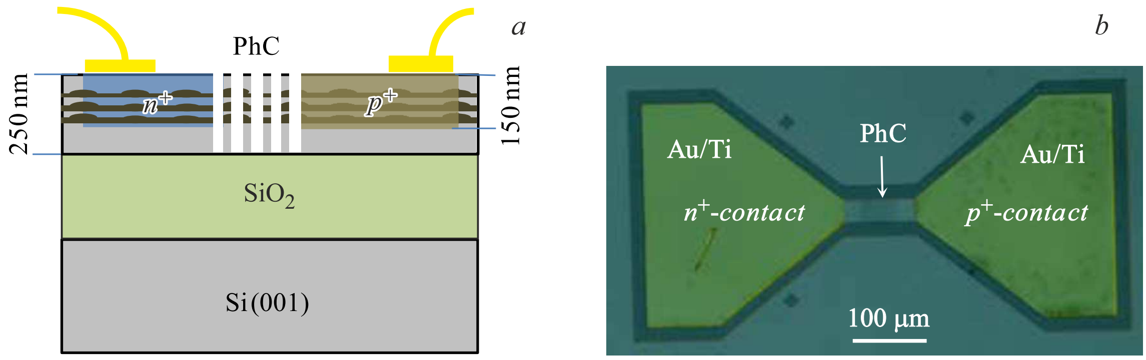

Figure 1. *a* — Schematic diagram of the formed planar diodes. The overall thickness of the structure above the oxide layer and the amorphized layer thickness are indicated. *b* — Scanning election microscope image of diodes with a PhC embedded into the *i*-region.

thickness, between them. This structure was synthesized at a temperature of 600°C that is the optimum one for maximizing the intensity of luminescence of Ge(Si) islands at room temperature [1]. The overall thickness of the structure above the oxide layer was 250 nm (Fig. 1, *a*).

Local n^+- and p^+-regions for Ohmic contacts to planar diodes were formed by implantation of phosphorus and boron ions, respectively, through a photoresist mask. The energy and dose of P^+ ions $(15\,\mathrm{keV}/4 \cdot 10^{14}\,\mathrm{cm}^{-2} + 60\,\mathrm{keV}/1.5 \cdot 10^{15}\,\mathrm{cm}^{-2})$ for the formation of n^+-regions were chosen so that the thickness of the amorphized near-surface structure layer was ~ 150 nm after implantation (Fig. 1, *a*). When p^+-regions were formed, preliminary implantation of fluorine F^+ $(35\,\mathrm{keV}/3 \cdot 10^{15}\,\mathrm{cm}^{-2})$ ions, which ensured amorphization of the p^+-region to the same depth, was carried out prior to the implantation of B^+ ions $(20\,\mathrm{keV}/1.5 \cdot 10^{15}\,\mathrm{cm}^{-2})$. A crystalline layer ~ 100 nm in thickness, which remained after implantation at the boundary between the structure and buried oxide (Fig. 1, *a*), acted as a seed one in the course of solid-phase recrystallization during post-implantation annealing [7]. According to the results of X-ray diffraction and electrophysical measurements, the use of solid-phase recrystallization provided an opportunity to reduce the temperature of restoration of the crystalline quality of implanted regions and activation of the introduced impurity from the level of 800–1100°C, which is typical of Si technology, to 600°C (the growth temperature of Ge(Si) islands).

Metallic contacts to implanted regions were formed after thermal annealing via lift-off lithography and Au/Ti layer deposition. The sheet resistance of p^+- and n^+-regions in diodes annealed at 600°C was 100–150 and 40–45 $\Omega/\square$, respectively. When the annealing temperature was increased to 1000°C, the resistance of p^+-regions decreased by a factor of ~ 1.5, while the resistance of n^+-regions remained unchanged. PhCs were formed after the deposition of contacts by electron lithography and plasma-chemical etching in *i*-regions of certain diodes. The PhC parameters (period a and aperture radius r) were chosen so that several PhC modes fell into the spectral range of luminescence of Ge(Si) islands [5]. Since the size of PhCs $(50 \times 50\,\mu\mathrm{m})$ exceeded the size of the *i*-region of diodes $(20 \times 30\,\mu\mathrm{m})$, a PhC occupied the entire *i*-region and parts of n^+- and p^+-regions. At the final stage, mesa grooves, which bounded the current flow region (Fig. 1, *b*), were etched along the perimeter of diodes throughout the entire structure (down to the SiO_2 layer). EL spectra of diodes were recorded in the DC current mode with the use of a 10× optical objective, a Fourier spectrometer, and a cooled Ge detector.

The current–voltage curves of fabricated diodes measured both before and after PhC formation have a typical diode shape (Fig. 2, *a*). It was found that the PhC formation is accompanied by a significant (up to an order of magnitude) reduction in forward current through a diode under the same voltage applied to it (Fig. 2, *a*). This current suppression is attributed to narrowing of the cross section of the *i*-region (due to PhC formation) and to additional recombination of carriers on a developed PhC surface. The application of positive bias to the substrate (relative to p^+- and n^+-regions of a diode) resulted in a considerable increase in current flowing through the diode (Fig. 2, *a*).

It was found that post-implantation annealing of diodes at 600°C has an insignificant effect on the luminescence of Ge(Si) islands at room temperature; a broad signal was observed in the EL spectra of such diodes without PhCs within the 1.3–1.7 μm range (Fig. 2, *b*). At the same time, even short-term annealing of diodes at 1000°C resulted in a significant reduction in the intensity of the EL signal of islands and its shift into the short-wavelength spectral region (Fig. 2, *b*). These changes are induced by the diffusion spreading of nanoislands in the course of annealing [8]. Following the formation of PhCs in the *i*-region of diodes, the EL signal intensity of Ge(Si) islands increased significantly (by more than an order of magnitude) at wavelengths corresponding to different PhC modes (Fig. 3). When the post-implantation annealing temperature was reduced from 1000 to 600°C, the intensity of the EL signal of Ge(Si) islands remained high not only in the 1.3 μm region (as in [6]), but also at 1.5 μm (Fig. 3, *a*). The most intense EL lines in diodes with PhCs were found around the maximum of the luminescence band of islands

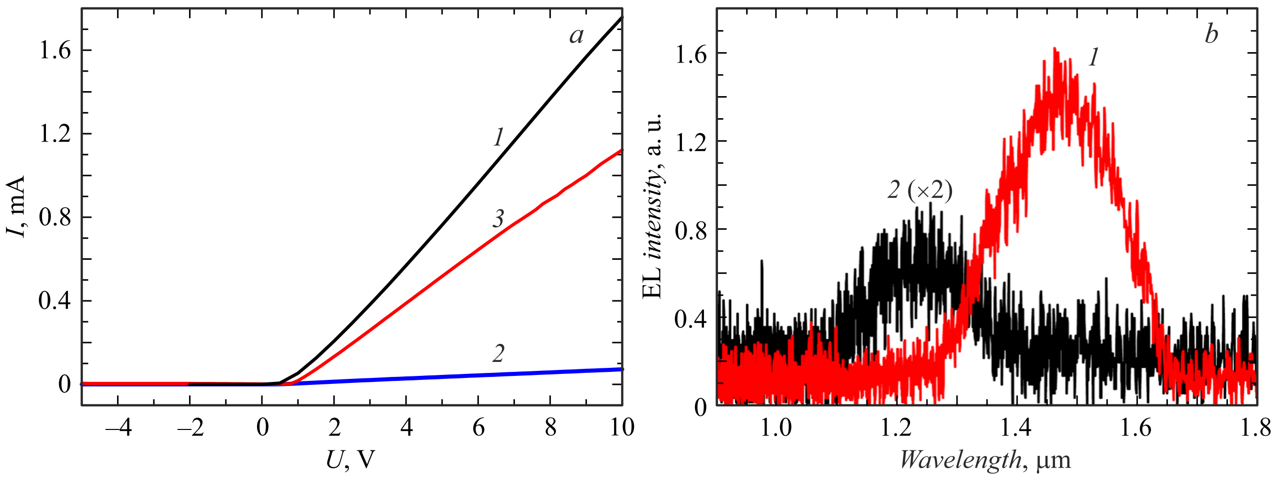

Figure 2. *a* — Current-voltage curves of diodes before (*1*) and after (*2*, *3*) the formation of PhCs under zero substrate bias (*1*, *2*) and with a positive bias of 100 V applied to the substrate (*3*). Diodes were annealed at 600°C. *b* — Micro-EL spectra of diodes without PhCs, which were annealed at 600 (*1*) and 1000°C (*2*), measured at room temperature at a current of 2 mA. The spectrum for a diode annealed at 1000°C was multiplied by 2 for clarity.

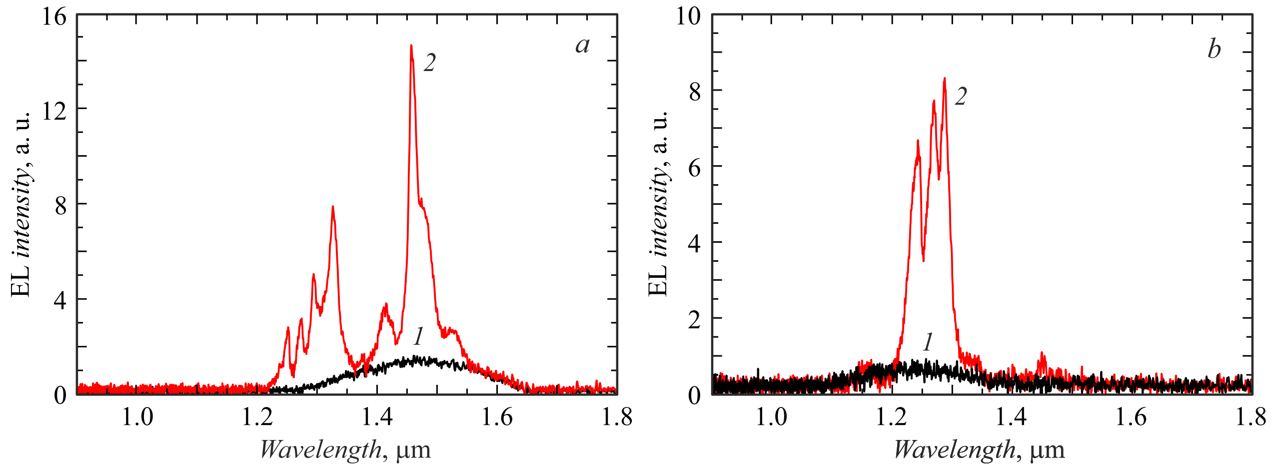

Figure 3. Micro-EL spectra of diodes without (*1*) and with PhCs (*2*) annealed at 600 (*a*) and 1000°C (*b*). Spectra were measured at room temperature and a pumping current of 2 mA. Spectra of diodes with PhCs were measured with a positive bias applied to the substrate. The PhC parameters are as follows: hexagonal lattice, lattice constant $a = 675$ nm, and ratio $r/a = 0.15$ (r is the radius of PhC holes).

in diodes without PhCs (Fig. 3). Owing to the short-wave shift of the EL signal of islands that occurred when the annealing temperature was increased, different PhC lines (modes) had the highest intensity in diodes with identical PhCs annealed at different temperatures. Specifically, the line located at 1.5 μm (Fig. 3, *a*) was the most intense in the diode annealed at 600°C, while shorter-wave PhC lines ($\leqslant 1.3\,\mu$m) were much less intense, since they correspond to the edge of the luminescence band of islands (Fig. 3, *a*). At the same time, these short-wave PhC lines correspond to the maximum of the island EL band (Fig. 3, *b*) in the diode annealed at 1000°C; therefore, they were the most intense, while long-wave ($> 1.3\,\mu$m) PhC lines were almost indiscernible (Fig. 3, *b*). Thus, one may alter the spectral positioning of the EL band of Ge(Si) islands by varying the annealing temperature of structures and, having chosen the right PhC parameters, obtain an intense EL signal corresponding to PhC modes in the practically relevant spectral range of 1.3–1.55 μm.

Funding

This study was carried out under state assignments No. 0030-2021-0019 and FWGW-2022-0007 with the use of equipment provided by common use centers „Physics and Technology of Micro- and Nanostructures“ (Institute for Physics of Microstructures, Russian Academy of Sciences), „Nanostructures“ (Rzhanov Institute of Semiconductor Physics, Siberian Branch of the Russian Academy of Sciences), and „VTAN“ (Novosibirsk State University).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] N.V. Vostokov, Yu.N. Drozdov, Z.F. Krasil'nik, D.N. Lobanov, A.V. Novikov, A.N. Yablonskii, JETP Lett., **76** (6), 365 (2002). DOI: 10.1134/1.1525038.

[2] M. Brehm, M. Grydlik, Nanotechnology, **28**, 392001 (2017). DOI: 10.1088/1361-6528/aa8143

[3] V. Rutckaia, F. Heyroth, A. Novikov, M. Shaleev, M. Petrov, J. Schilling, Nano Lett., **17**, 6886 (2017). DOI: 10.1021/acs.nanolett.7b03248

[4] M. Schatzl, F. Hackl, M. Glaser, P. Rauter, M. Brehm, L. Spindlberger, A. Simbula, M. Galli, Th. Fromherz, F. Schäffler, ACS Photon., **4**, 665 (2017). DOI: 10.1021/acsphotonics.6b01045

[5] S.A. Dyakov, M.V. Stepikhova, A.A. Bogdanov, A.V. Novikov, D.V. Yurasov, M.V. Shaleev, Z.F. Krasilnik, S.G. Tikhodeev, N.A. Gippius, Laser Photon. Rev., **15**, 2000242 (2021). DOI: 10.1002/lpor.202000242

[6] X. Xu, T. Chiba, T. Nakama, T. Maruizumi, Y. Shiraki, Appl. Phys. Express, **5**, 102101 (2012). DOI: 10.1143/APEX.5.102101

[7] L. Pelaz, L.A. Marqués, J. Barbolla, J. Appl. Phys., **96**, 5947 (2004). DOI: 10.1063/1.1808484

[8] G. Capellini, M. De Seta, F. Evangelisti, Appl. Phys. Lett., **78**, 303 (2001). DOI: 10.1063/1.1339263

Translated by D.Safin