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Luminescent response of photonic crystals with embedded Ge nanoislands with different hole etching depths

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Two-dimensional Si-based photonic crystals with embedded Ge nanoislands were studied. In particular, dependences of the steady-state and time-resolved photoluminescence response on the depth of the air-holes which form the photonic crystal itself were investigated. It was shown that the maximum luminescence intensity was observed not for the fully-etched photonic crystals but for the intermediately etched ones. The possible origin of such a behavior is discussed.

Keywords: SiGe heterostructures, Ge islands, Photonic crystals, Photoluminescence, non-radiative recombination.

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Modern microelectronics has progressed to a point where it is facing more and more difficulties, since it is virtually impossible to reduce the characteristic sizes of elements, which have reached the level of several nanometers, further. In view of this, extensive studies into data transfer with optical signals used instead of electrical ones have been initiated, and many components of optoelectronic circuits (waveguides, detectors, modulators, etc.) have already been fabricated [1]. However, engineers still need to construct one of the key optoelectronic components: an efficient Si-compatible light-emitting device operating at wavelengths corresponding to minimum losses in fiber ($1.3-1.55\,\mu$m). Light emitters based on group IV elements (SiGe and SiGeSn) appear to be promising in the context of integration with silicon technology [2]. Structures with self-assembled Ge islands are one of the types of light emitters of this kind with their emission spectrum falling into the required wavelength interval. However, their efficiency is low due to the fact that both Si and Ge are indirect-gap semiconductors with a band offset of an unfavorable shape (type II heterojunction).

It is known that the emissive properties of materials may be adjusted by altering their environment (specifically, by creating cavities). Photonic crystals (PhCs) are one of the types of (dielectric) microcavities that are being studied extensively at present. PhCs are often produced by etching an array of holes in a semiconductor layer that induce a periodic variation of the refraction index (n) in the growth plane, while a jump of n at the interface of two media is normally formed in the growth direction. The key parameters specifying the properties of PhCs are the symmetry of positioning of holes, their period, and their diameter [3]. The hole etching depth also exerts a considerable influence on the characteristics of a PhC [4]. Different operating modes of a PhC may be implemented depending on the etching depth [4]. In the present study, we report the results of examination of the influence of hole etching depth in PhC produced on structures with self-assembled Ge islands on their spectra and photoluminescence (PL) kinetics.

All the studied structures were grown by molecular-beam epitaxy on silicon-on-insulator (SOI) substrates with a top Si layer 70 nm in thickness and a buried oxide layer with a thickness of $2\,\mu$m. Five layers of Ge islands separated by Si layers with a thickness of ~ 17 nm served as the active medium. The growth temperature of the structure was $\sim 600^\circ$C, and the amount of deposited Ge was ~ 1 nm. These values were chosen based on the results of earlier studies, where the intensity of the PL signal from islands at 300 K was found to be maximized with such parameters [5]. The grown structure was cut into chips, and identical PhC arrays with a hexagonal lattice were formed on them. PhCs were fabricated by electron lithography with subsequent plasmachemical etching in a mixture of SF_6/CHF_3 gases. PhCs with holes positioned with period $a = 550$ and 600 nm and ratio $r/a = 0.2$ and 0.25 of the hole radius to the period were formed on each chip. The PhC size was $100 \times 100\,\mu$m. Different PhC hole etching depths were set for different chips by varying the etching time.

A test structure with several PhC $50 \times 250\,\mu$m in size was formed for each chip so that the PhC could be cleaved after etching to determine the hole etching depth by scanning electron microscopy (SEM). Schematics of the studied structures and typical SEM images of PhC are

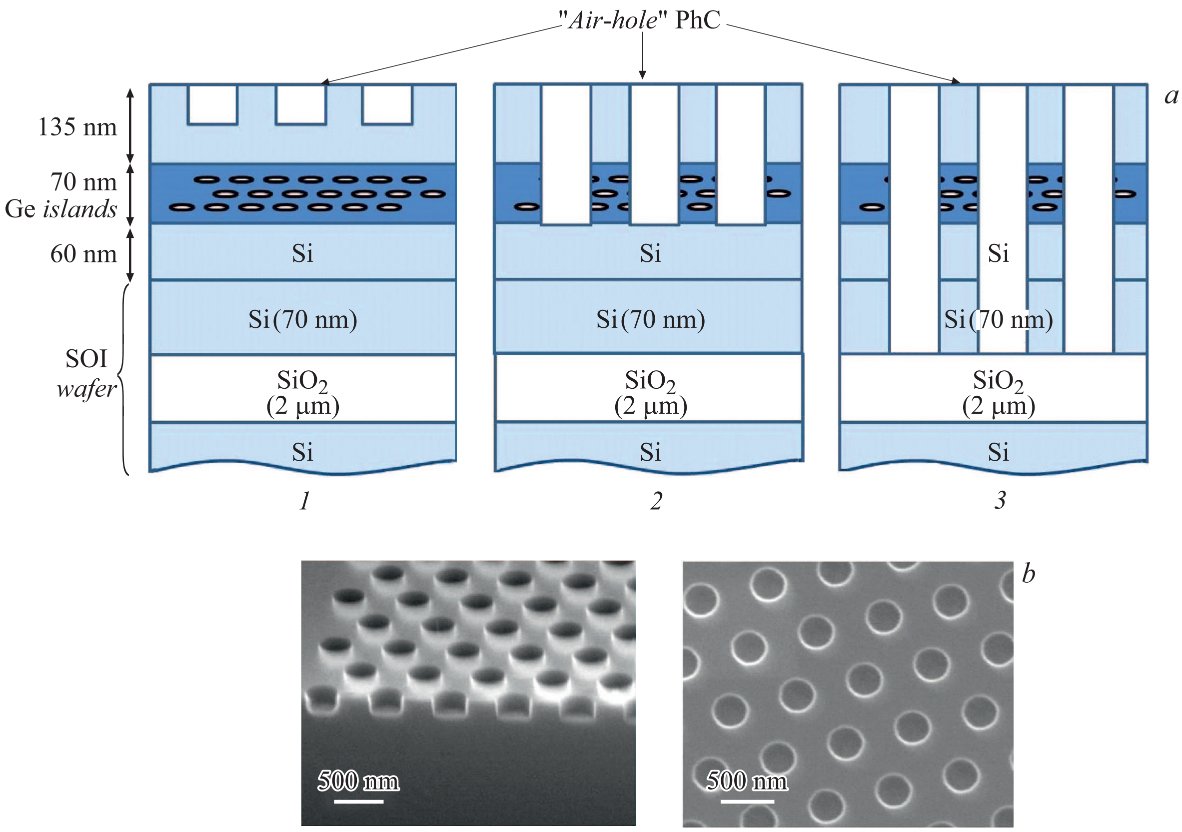

Figure 1. *a* — Schematic of the studied structures with indicated thicknesses of different layers (not to scale). Numbers *1–3* denote three chips with different hole depths. *b* — SEM images of the cleaved surface of one of the test samples used to determine the hole etching depth (left) and one of the PhC formed on the studied structure (right).

presented in Fig. 1. Three chips with hole depths of the order of 80 nm (*1* in Fig. 1), 200 nm (*2* in Fig. 1), and 335 nm (fully etched structure, *3* in Fig. 1) were prepared.

The optical properties of structures were examined by time-resolved micro-PL spectroscopy at 300 K. A pulsed $Nd:YVO_4$ laser („Solar LS") with a wavelength of 532 nm, a pulse duration of ~ 10 ps, and a repetition rate of 1 MHz was used fot PL excitation. Emission was collected by a Mitutoyo Plan Apo NIR 10× objective. The excitation beam was focused with a longer-focus objective (with a focal distance of 30 cm) to a spot $\sim 100\,\mu$m in diameter, which made it possible to perform relatively uniform excitation of carriers over the entire area of the studied PhCs. An Acton 2300i grating monochromator, a system for detection of individual photons based on a superconducting single-photon detector („Skontel"), and a TimeHarp 260 system for time-correlated single photon counting were used to record the spectra and temporal dependences of PL. The spectral resolution of the system was 2 nm, and the time resolution was ~ 100 ps. Dispersion characteristics of PhC modes were calculated using the finite element method in COMSOL Multiphysics.

The results of measurement of micro-PL spectra at 300 K are presented in Figs. 2, *a, b*. It can be seen that a PhC starts forming at a hole etching depth of 80 nm, but the in-plane modulation of n is still relatively weak (the so-called „weak" lattice case). The spectra do not only reveal an increase in PL intensity due to the enhancement of light extraction efficiency, but also contain a set of certain resolved lines corresponding to radiative PhC modes lying above the light cone (this is seen more clearly in Fig. 2, *b*). As the hole etching depth varies from 80 to 200 nm, individual lines in micro-PL spectra associated with these modes become more pronounced and the PL signal intensity increases considerably as compared to the initial structure initial structure.

However, the PL signal intensity enhancement becomes less significant when the hole etching depth increases further from 200 to 335 nm (Fig. 2). The enhancement factor of the peak PL signal intensity (relative to the intensity for the initial structure without a PhC) for a PhC with $a = 550$ nm and $r/a = 0.2$ was ~ 9 at a hole etching depth $h = 80$ nm, increased to ~ 88 at $h = 200$ nm, and decreased to ~ 17 at $h = 335$ nm (Fig. 2, *a*). A similar behavior was observed in the study of another PhC with $a = 600$ nm and $r/a = 0.25$ (Fig. 2, *b*). The integrated PL intensity variation with h was qualitatively similar.

The results of calculation of the dispersion characteristics of modes for a PhC with $a = 550$ nm, $r/a = 0.2$, and $h = 200$ nm are presented in Fig. 2, *c*. It is known [6]

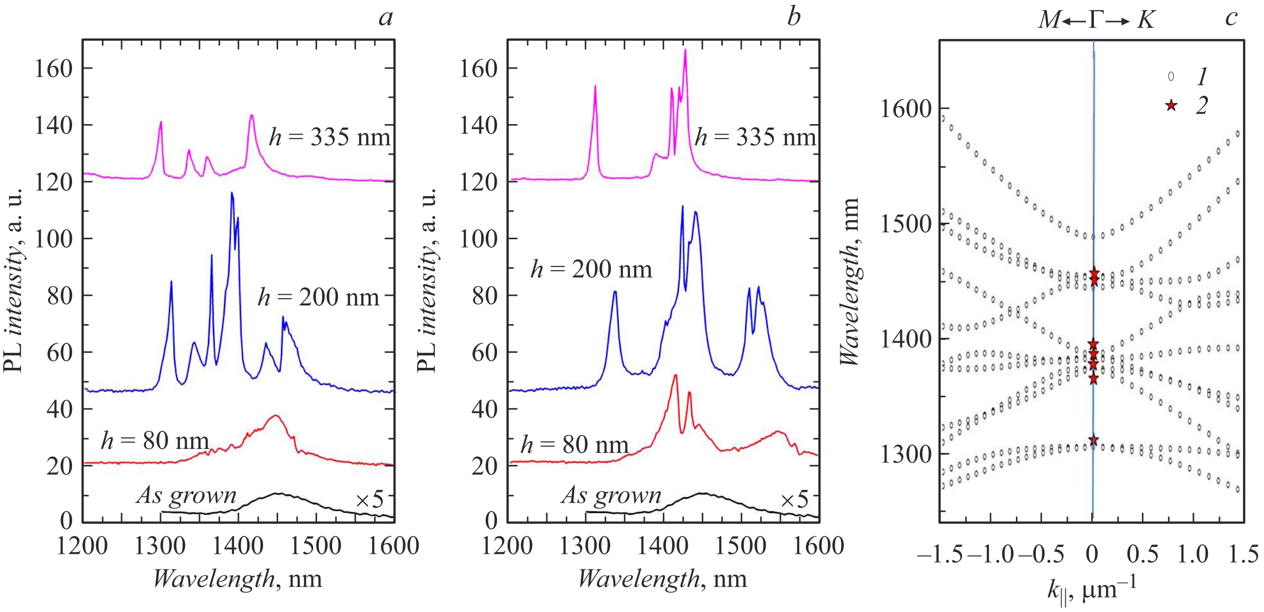

Figure 2. Spectra of steady-state micro-PL from the initial structure (*As grown*) and the formed PhC with $a = 550$ nm and $r/a = 0.2$ (*a*) and PhC with $a = 600$ nm and $r/a = 0.25$ (*b*). Etching depths h are indicated next to the corresponding spectra. *c* — Calculated dispersion characteristics of modes of a PhC (*1*) and experimental positions of lines in its PL spectrum superimposed onto them (*2*). The data correspond to a PhC with $a = 550$ nm, $r/a = 0.2$, and $h = 200$ nm.

that PhC with a hexagonal lattice support 12 modes: four doublets and four singlets (only 11 modes are shown for clarity in Fig. 2, *c*, since one singlet mode is located at shorter wavelengths than the PL signal of Ge islands). It follows from the comparison of the steady-state micro-PL spectrum (Fig. 2, *a*) with calculated data that the positions of spectral peaks agree fairly well with the calculated positions of various modes at the Γ-point in the Brillouin zone of a PhC (at $k = 0$; see Fig. 2, *c*). A slight discrepancy is attributable to the fact that modes lying within the light cone and having a nonzero $k_{\|}$ value may also produce a certain contribution to the detected micro-PL signal. A qualitative agreement between the micro-PL spectra and the calculated dispersion characteristics was also observed for the other studied PhC.

The determined behavior of the PL signal intensity depending on the PhC hole depth (with a maximum at a certain etching depth) may be formed under the influence of several multidirectional factors acting simultaneously. In the present case, the more pronounced mode structure of a PhC at higher h (increasing depth of in-plane modulation of n) is one of these factors. The interaction of Ge islands with PhC modes lying above the light cone is the process that drives the PL signal intensity growth [6]. Another possible factor is the enhancement of surface area in the course of etching of holes with increasing h. As a result, the contribution of surface non-radiative recombination becomes more significant, and the PL intensity decreases accordingly.

Temporal dependences of the integrated PL intensity for the studied PhC and the initial structure were examined to verify this assumption (Fig. 3). The obtained results demonstrate that the characteristic PL decay time at $h = 80$ nm is close to the one corresponding to the initial structure (approximately 3 ns), while the PL decay time for PhC with $h = 200$ and 335 nm is significantly shorter (0.6 and 0.35 ns, respectively).

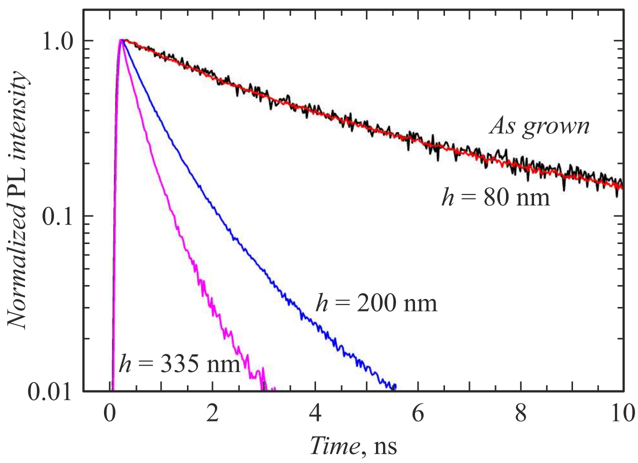

Figure 3. Normalized temporal dependences of the PL intensity of the initial structure (*As grown*) and a PhC with $a = 600$ nm, $r/a = 0.25$, and different hole etching depths h (indicated next to the corresponding curves).

It was found in earlier studies that structures with Ge islands have much longer PL decay times at low temperatures and are characterized by strong temperature quenching of the PL signal at 300 K [7,8]. This suggests that the PL kinetics at 300 K is governed mostly by non-radiative recombination (since radiative recombination times in indirect-gap SiGe heterostructures are much longer than non-radiative recombination times). Therefore, the potential shortening of the radiative recombination time due to the Purcell effect does not manifest itself in the PL kinetics under these conditions.

The shortening of PL decay times in PhC with a greater etching depth (see Fig. 3) provides clear proof that the contribution of surface non-radiative recombination increases with h. A certain optimum depth of PhC hole etching, which in principle depends on the PhC parameters that shape the band diagram of a PhC, may be identified under the influence of two factors mentioned above. Thus, the most commonly used procedure of etching of PhC holes throughout the entire structure may yield non-optimal results. The demonstrated nonmonotonic dependence of the PhC photoluminescence intensity signal on h was plotted based on a minimum set of points; at the same time, it was observed for two PhC with different parameters. In order to obtain more detailed data, these studies should be extended to a larger set of PhC parameters and different measurement temperatures.

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Conflict of interest

The authors declare that they have no conflict of interest.

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