Erbium doped silicon single- and multilayer structures for light-emitting device and laser applications

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The paper is a brief retrospective review of our contribution to the Si:Er problem in the last decade. It contains a description of the experimental facilities, results of the light-emitting media (Si:Er and $Si_{1-x}Ge_x$:Er) research, and device applications.

I. INTRODUCTION

The idea to use silicon as the host matrix for electrical and optical excitation of Er^{3+} ions embedded into it[1,2] proved rather fruitful in terms of solving the problems involved in silicon optoelectronics. The use of silicon as an intermediate medium transferring the excitation induced by the current or optical pumping to Er^{3+} ions has allowed a substantial increase of the excitation cross section (up to 3×10^{-15} cm^2),[3] i.e., by 5–6 orders as compared with direct optical excitation of Er^{3+} embedded into a dielectric matrix (8×10^{-21} cm^2).[4]

The progress in the development of Si:Er-based light-emitting devices with a higher power yield and quantum efficiency is associated with the improvement of the optically active media (increase of optically active Er^{3+} concentration, formation of optically active Er-containing complexes with higher excitation cross-section, and minimization of Er^{3+} nonradiative relaxation processes) and optimization of the light-emitting device design. In this contribution, we focus on both approaches: (i) We report a new optically active Er-containing complex radiating at 1.54 μm, a novel mechanism of sub-band-gap photo-excitation of erbium in silicon. (ii) We show possibilities for enhancing the power yield of electroluminescent light emitting devices (LEDs) including LEDs radiating at room temperature at reverse and forward bias of the *p-n* junction. We also demonstrate a novel long-term optical memory effect on the basis of Si:Er light emitting structure with the active Si:Er layer placed within the depletion region and discuss the perspectives and progress in the development of laser-type structures on Si:Er basis. (iii) We describe an original sublimation variant of the molecular beam epitaxy (MBE) technique (SMBE) and demonstrate its capabilities for realizing light-emitting devices effectively radiating up to room temperature.

II. STRUCTURE GROWTH AND CHARACTERIZATION

The light-emitting structures and devices considered in this contribution were grown using an original SMBE technique that is basically a modification of the standard MBE in which fluxes of Si and doping impurities (Er in this case) are produced by sublimation of a Si crystal intentionally doped with these impurities.[5] The SMBE technique successfully combines a fairly high growth

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rate (up to 5 μm/h) with a high crystalline quality of epitaxial layers and precise control of the impurity profiles (including the possibility for delta doping). Its merits have been experimentally demonstrated in the last decade through realization of a variety of Si:Er-based light-emitting structures and devices, such as thick uniformly doped Si:Er layers (up to 3–5 μm); periodic multilayer . . . Si/Si:Er/Si/Si:Er/Si . . . structures (Si and Si:Er layers thickness down to 10–20 Å, the number of periods up to 400) with quantum efficiency of more than 10% at 4.2 K and pump power of 10 μW; and LEDs radiating at reverse bias under the *p-n* junction breakdown (from tunnel through mixed to avalanche regimes) at room temperature.[6–9]

Most Si:Er-based light-emitting structures and devices were grown on *p*- and *n*-type Si (100) substrates with the resistivity of 10–20 Ω cm. The growth temperature (T_{gr}) was varied from 430 to 700 °C. The Er and O concentrations in Si:Er layers were of about (3–5) × 10^{18} and (1–10) × 10^{19} cm^{-3}, respectively. The number and types of simultaneously sublimating sources were varied depending on the desired features of growing layers. SMBE allows growth of epitaxial structures with the layer thickness and carrier concentration continuously varying along the substrate length. This eventually makes it possible to produce series of LEDs with smoothly varying parameters in a single growth cycle, which is essential in new LED design engineering. SMBE allows separate control of the erbium and donor concentrations in Si:Er layers, which makes it easier to control the breakdown regime of LEDs.

To characterize the Si:Er and SiGe:Er layers, we use the standard methods of secondary-ion mass spectrometry (SIMS), Rutherford backscattering spectrometry (RBS), x-ray diffraction, capacitance-voltage (C-V) measurements, admittance spectroscopy, deep level transient spectroscopy (DLTS), and the Hall effect. The major part of the photoluminescence (PL) and electroluminescence (EL) studies was carried out using the high-resolution BOMEM DA3 Fourier spectrometer (Quebec, Canada) and the grating monochromator MDR-23 (St. Petersburg, Russia). The PL spectra were excited with an Ar^{+}-ion laser, and the EL spectra with a pulse or continuous drive current. Liquid nitrogen cooled Ge and InGaAs detectors were used for detection of the luminescence signal. Mesa-like LEDs were formed using the conventional mesa technique. The fabricated diodes had the radiating area of up to 2.5 mm^2, 70% of which was free of the metal cover.

III. NEW OPTICALLY ACTIVE Er-1 CENTER IN SMBE-GROWN Si:Er/Si STRUCTURES

Depending on the T_{gr}, the PL intensity and excitation efficiency of SMBE grown Si:Er structures are governed by different types of optically active Er centers. At a relatively low T_{gr} of about 430 °C, a series of low symmetry Er centers identified earlier in highly O and Er implanted Si[10] dominates in the PL spectrum (lower curve in Fig. 1). Most pronounced at this temperature is the axial symmetry Er complex with oxygen, the well-known center Er-O1 (marked by arrows in Fig. 1). With an increasing T_{gr}, a fairly broad spectral band [full width at half-maximum (FWHM) = 20 to 30 cm^{-1}] is seen to develop. It was interpreted as pertaining to Er^{3+} ion in SiO_2-like precipitates.[10] At the T_{gr} of 560 °C, the PL spectrum, together with the dominance of the SiO_2-precipitate type Er centers, exhibits formation of a new Er-related center, the center Er-1 (marked by arrows in Fig. 1). In our previous publications, we distinguished the center Er-1 as specific and one of the most optically efficient among the variety of Er-related centers discovered in SMBE structures.[6,11] Besides being formed at an elevated T_{gr}, it emerges also as a result of the transformation of erbium-oxygen complexes during the 800 °C

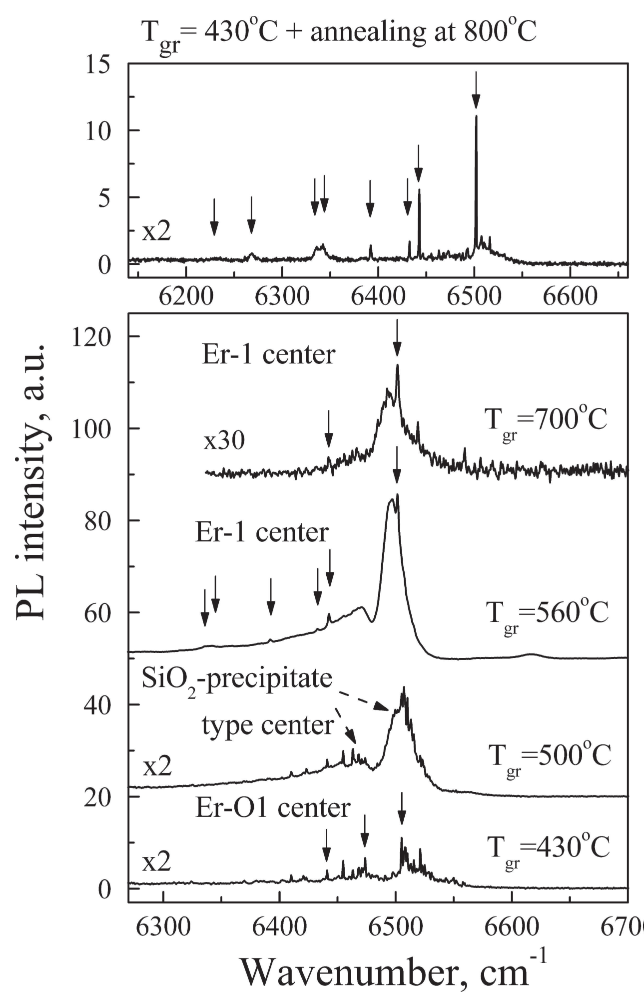


FIG. 1. PL spectra of the uniformly doped SMBE layers grown at different temperatures. The upper curve represents the spectrum of Si:Er layer grown at 430 °C after subsequent annealing at 800 °C for 30 min in hydrogen atmosphere.

annealing of Si:Er layers grown at 430 °C. In the last case, the luminescent response of Si:Er samples is governed mainly by this isolated center Er-1 with the characteristic spectral line pattern consisting of eight very well resolved PL lines (see Fig. 2 and the upper curve in Fig. 1).

The ultra small line widths and high intensity of the Er-1 PL spectrum made possible a successful observation of the Zeeman effect.[12] A detailed analysis of the magnetic field induced splitting[13] confirmed that, indeed, the Er-1 PL emission is related to a particular type of Er center dominant in the structure under study. Based on the analysis of the magnetic field induced angular dependent splitting of the PL lines, we identify the orthorhombic-*I* symmetry of the Er-1 center and find *g*-tensors for several lower-lying levels of the $^4I_{15/2}$ ground and the lowest excited $^4I_{13/2}$ state multiplets. In particular, we identify the original Γ_6 and Γ_7 characters for the lowest crystal-field split levels of the ground and the excited states, respectively. Given this analysis, we suggest that the microscopic structure of the Er-1 center comprises a single Er^{3+} ion at a distorted interstitial T_d site with multiple oxygen atoms in its direct vicinity.

Realization of preferential generation of only one type of optically active Er-related centers, which is feasible by appropriate annealing of the SMBE grown Si:Er/Si multinanolayer structure, is a major step forward to Si photonics based on Er doping. As can be seen from Fig. 2, the width of this PL line is extremely small, $\Delta E \leqslant 0.08\ \mathrm{cm}^{-1}$ (10 μeV). To the best of our knowledge, this is among the lowest values ever measured for any emission band of rare-earth (RE) ions in a semiconductor matrix. We have established that the spectral characteristics of emission related to the Er-1 center (intensity and linewidth) indicate a feasibility of a 10^3 higher value of the absorption cross section, as compared to the implanted

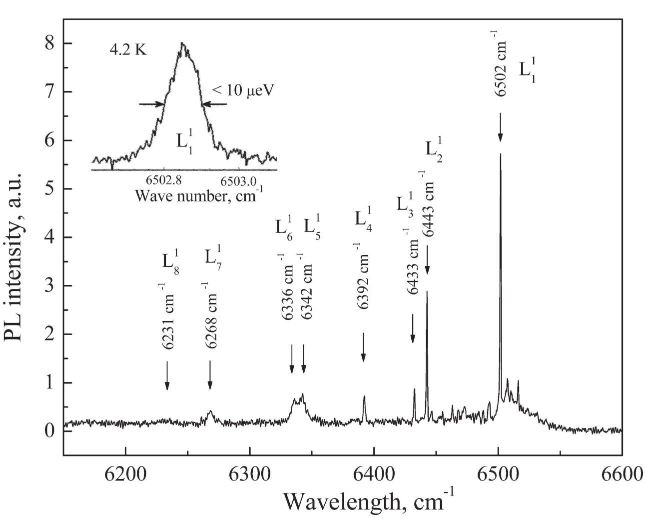


FIG. 2. PL spectrum of SMBE grown multilayer Si:Er/Si structure with predominant Er-1 center. The inset shows a high-resolution spectrum of the highest-intensity L^1 line in the Er-1 series.

Si:Er materials used so far. Therefore, the Er-1 center emerges as a plausible candidate for realization of the optical gain in Si:Er.

IV. SUB-BAND-GAP PHOTOEXCITATION OF ERBIUM IN SILICON

The excitation spectra of erbium PL in SMBE-grown Si:Er structures have been taken using Nd:YAG-pumped optical parametric oscillator in a wide range of excitation wavelengths (λ_{ex} = 780 to 1500 nm).[14] It has been shown that a considerable signal of erbium PL can be obtained with the excitation photon energies lower than the band gap of Si (λ_{ex} > 1060 nm; Fig. 3). Moreover, at a high pumping power a rapid increase of the Er luminescence intensity has been observed in the range λ_{ex} = 1000 to 1030 nm, which corresponds to the edge of light absorption in bulk silicon. At the same time, a strong decrease of the band-to-band PL intensity took place in this wavelength range. As could be expected, no noticeable signal of the band-to-band PL was observed at excitation photon energies below the Si band gap. This drop in the exciton PL intensity is associated with the decrease in the absorption coefficient of silicon in the wavelength region in question and, as a consequence, the decrease in the intensity of electron-hole pair generation. On the other hand, this result evidently indicates that under conditions of sub-band-gap pumping excitation of the erbium ions must proceed without participation of excitons.

From the obtained experimental data and, in particular, from the high efficiency of Er PL, we can conclude that for $h\nu_{ex} < E_g$ the absorption occurs in the epitaxial erbium-doped layers. The observation of sub-band-gap excitation of erbium PL can be explained assuming that the Er-related impurity levels in the silicon band gap are formed in the epitaxial layers. Indeed, erbium-doped silicon layers are known to demonstrate, as a rule, the *n*-type conductivity. In such a case, the absorption of a photon of energy $h\nu_{ex} < E_g$ could promote electrons from the valence band directly to the donor levels associated with erbium. Subsequent nonradiative recombination of these electrons with holes in the valence band could deliver energy necessary for excitation of Er ions. The proposed mechanism is schematically depicted in Fig. 3.

The proposed mechanism of erbium ion excitation can also account for the increase in the erbium PL intensity at longer excitation wavelengths, as experimentally observed in the range λ_{ex} = 1000 to 1030 nm. The band-to-band pumping of Si:Er structures generates a large number of electron-hole pairs, which gives rise to the onset of intense, free-carrier-mediated nonradiative Auger de-excitation of Er ions, thus substantially lowering the efficiency of erbium PL. As the pump photon energy decreases, the light absorption coefficient in bulk silicon

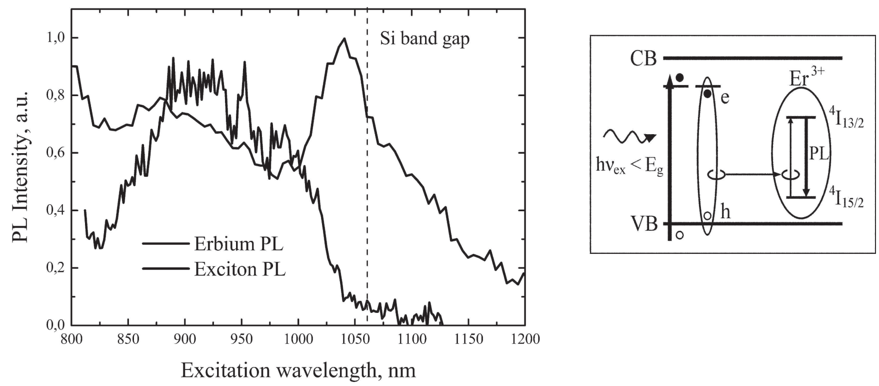


FIG. 3. Erbium- and exciton-related PL excitation spectra of SMBE Si:Er structure and a possible mechanism of sub-band-gap excitation ($h\nu_{ex} < E_g$) of erbium in silicon.

drops sharply in the vicinity of E_g, which leads to a sharp drop in the number of free carriers created in the structure. Therefore, the Auger de-excitation efficiency decreases strongly, thereby increasing the erbium PL signal.

V. LIGHT EMITTING DIODES RADIATING AT MIXED BREAKDOWN REGIME

Two types of *p-n* junction design were investigated.[9,15] The first type involves dominating p^+-Si/*n*-Si:Er LEDs in which the thickness of the *n*-Si:Er layer exceeds the width of the space charge region (SCR) at any reverse bias including the breakdown voltage U_{br}. In these diodes U_{br} and the breakdown mechanism are determined by the donor concentration N_D in the n-Si:Er layer (left inset in Fig. 4). A decrease of the donor concentration N_D stimulates an increase of U_{br} and transformation of the breakdown mechanism from tunnel ($U_{br}{}^{77} > U_{br}{}^{300}$) through mixed ($U_{br}{}^{77} \approx U_{br}{}^{300}$) to avalanche ($U_{br}{}^{77} < U_{br}{}^{300}$). The second type involves LEDs that are not widely adopted in Si:Er applications. They are p^+-Si/n^--Si:Er/n^+-Si LEDs in which a thin low doped n^--Si:Er layer ($N_D \sim 10^{16}$ cm^{-3}) is placed between the high doped n^+-Si and p^+-Si layers. In these diodes, U_{br} and the breakdown mechanism are determined by the thickness of n^--Si:Er layer (right inset in Fig. 4), which is of great interest in itself as another way to control the

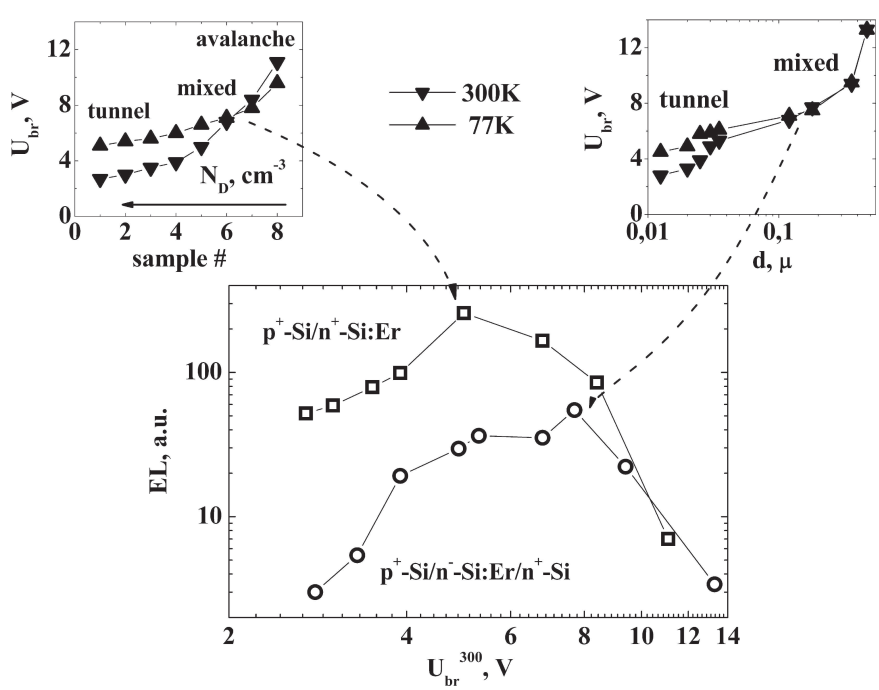


FIG. 4. Er^{3+} EL intensity as a function of U_{br} for various types of LEDs. The insets show a change of the breakdown mechanism with the carrier concentration (left) and n^--Si:Er layer width (right).

breakdown mechanism. It is surprising, but we observed a pronounced tunnel breakdown at $N_D = 1 \times 10^{16}$ cm^{-3} and the width of n^--Si:Er layer $d < 40$ nm. The increase of the n^--Si:Er layer width stimulates, as in the previous case, an increase of U_{br} and transformation of the breakdown mechanism from tunnel to avalanche.

For both types of LEDs, the plot of the erbium EL intensity versus U_{br} looks like an asymmetric bell-shaped curve with the maximum in the region of the mixed breakdown mechanism ($U_{br}^{300} \approx 5$ to 6 V, Fig. 4). EL spectra typical for LEDs with different *p-n* junction breakdown mechanisms are shown in Fig. 5. The Er-related EL is presented by the sharp EL line at 1.54 μm; the broad emission band is associated with the intraband radiating transitions of hot carriers in silicon.[16] We observed a decrease in the Er-related EL intensity in LEDs with both tunnel ($U_{br}^{300} < 5$ V) and avalanche ($U_{br}^{300} >$ 6 to 8 V) breakdown mechanisms, unlike in the mixed LEDs.

The shortcomings of the tunnel diodes, as compared with mixed and avalanche diodes, result from a lower excitation efficiency of Er^{3+} [the product στ characterizing the excitation efficiency decreases from 9.4×10^{-20} cm^{2}s in a mixed diode with $U_{br}^{300} = 5.0$ V down to 1.4×10^{-20} cm^{2}s in a tunnel diode with $U_{br}^{300} = 2.7$ V (Fig. 5), σ and τ are the excitation cross section and the lifetime of an excited Er^{3+} ion] and a smaller SCR width and, therefore, Er^{3+} surface density (only Er ions located in SCR are allowed to relax radiatively, since a strong nonradiative Auger deexcitation of Er^{3+} ions with free electrons occurs outside SCR). The shortcomings of the avalanche diodes are connected with the nonuniform distribution of the drive current density over the *p-n* junction area, which eventually leads finally to the microplasma breakdown. Therefore, we conclude that Si:Er LEDs operating in the mixed breakdown conditions provide an optimum combination of high Er^{3+} EL intensity and excitation efficiency with the uniformity of the *p-n* junction breakdown and seem to be more preferred for reaching maximal Er^{3+} EL intensity at room temperature.

We have made EL kinetic measurements for LEDs radiating at mixed breakdown regime to estimate the excitation cross-section, the lifetime of Er^{3+}, and the internal quantum efficiency. The respective values came to $\sigma \approx 1.4 \times 10^{-16}$ cm^2, $\tau \approx 540$ μs, $\eta \sim 10^{-3}$.[17]

Note that the erbium EL intensity in p^+-Si/n^--Si:Er/n^+-Si structures is noticeably lower than that in p^+-Si/*n*-Si:Er structures. In our opinion, the reason is as follows. An impact excitation of Er^{3+} with hot electrons is most effective, if the electrons energy W is not too high. It should satisfy the condition: $W_{th1} < W < W_{th2}$, where $W_{th1} \approx 0.8$ eV is the Er^{3+} excitation energy (the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition) and $W_{th2} \sim 1.5\ E_G$ (E_G is the band-gap width in silicon) is the energy at which an intense avalanching begins in the SCR. Evaluations show that the flow of electrons with energies in the range $W_{th1} < W < W_{th2}$ forms mainly in that part of SCR where the electric field is rather weak; there is no such region in p^+-Si/n^--Si:Er/n^+-Si diodes but it exists in p^+-Si/*n*-Si:Er diodes. We believe the Er^{3+} impact excitation to be more effective in so-called tunneling transit-time diode structures of the p^+-Si/n^+-Si/n^--Si:Er type. The narrow p^+-Si/n^+-Si junction (the strong-field region) should act as a tunneling injector of hot electrons with energies of $W_{th1} < W < W_{th2}$. The wide enough n^--Si:Er layer (up to 0.5–1 μm) represents a weak-field region, which is needed to excite Er ions and compensate for the energy loss due to scattering by the optical phonons. Our precomputations show that such light emitting structures may prove quite promising for reaching maximal Er-related EL intensity at room temperature.

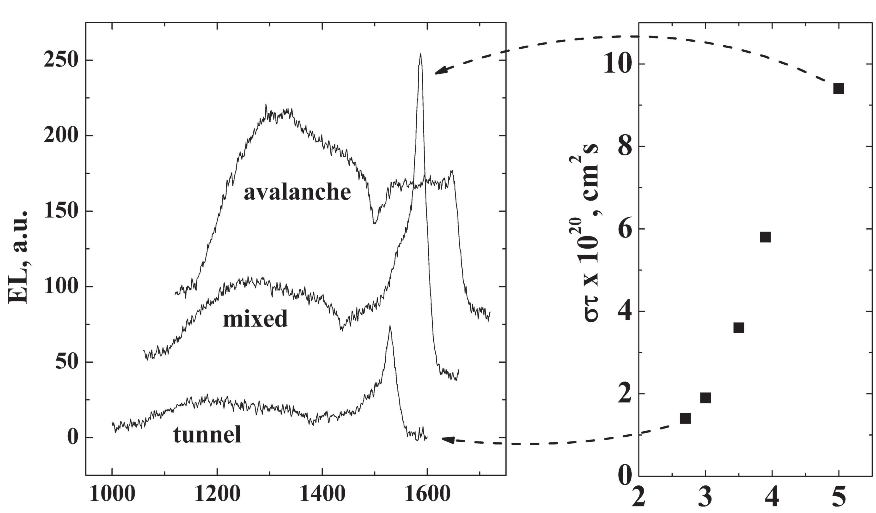


FIG. 5. (a) EL spectrum versus LED breakdown mechanism. For clearness the spectra are moved along the abscissa and ordinate axes. The spectra were taken at 300 K and drive current density of 8 A/cm^2. (b) The dependence of στ production on the breakdown voltage.

VI. LEDS ON THE BASIS OF SELECTIVELY DOPED MULTILAYER STRUCTURES

As we reported, among the advantages of the SMBE method is a capability for growing structures with desired, even δ, doping profiles. Here we show that by a proper design of an impurity distribution profile, one can substantially increase the EL power yield of a Si:Er-based light emitting structure. We examine here two LEDs radiating at 80 K under the forward bias of *p-n* junction. The first one is produced on the basis of a selectively doped Si:Er multilayer structure. Its active region consists of 52 periods of alternating Si:Er and undoped Si layers. The thicknesses of the Si:Er and Si layers are 70 and 120 Å, respectively. The second diode is an ordinary LED with the active region provided by a Si:Er layer with a thickness of 1.6 μm uniformly doped with Er. The Er concentration in Si:Er layers of both LEDs was about (3–5) × 10^{18} cm^{-3} according to RBS and SIMS measurements.

As shown in Fig. 6, the EL signal from a multilayer LED saturates weakly with an increasing current density (except for the last few points of curve 1, where the overheating of structure becomes apparent) and at high current densities surpasses the signal obtained in a uniformly doped structure by more than an order of magnitude. Thus, these results clearly show a strong influence of the impurity distribution profile and, in particular, of the presence in the structure of undoped Si layers on Er-related EL efficiency. Roughly, this can be explained by the enhancement of the Er^{3+} excitation efficiency, which is stimulated by the formation in the light emitting structure of undoped Si layers where an intense exciton generation takes place. Note that the same tendency toward an increase in the PL efficiency of multilayer structures as compared to the uniformly doped ones was recorded by us earlier.[6–8] Though the mechanism of this strong increase of luminescence intensity observed in selectively doped multilayer structures needs to be understood in more detail, even now we can expect that the development of LEDs with modified Er impurity profiles will offer new prospects for realization of industrially useful optoelectronic devices.

VII. ELECTRO-OPTICAL STORAGE ELEMENT

In this part, we present the results of the study of EL of n^+-Si/n^--Si/n^--Si:Er/n^--Si/p^+-Si structures in which the Er-doped active layer was positioned relative to the *p-n* junction in the SCR. The structures were grown using the SMBE method on a *p*-Si(100) substrate with the doping level $N_A \approx 10^{17}$ cm^{-3}. Nearest to the substrate, we grew a layer of pure *n*-Si of a thickness to 1 μm and the free-carrier concentration n ≈ 2 × 10^{15} cm^{-3}, then came a thin (about 70 nm) active layer doped with Er^{3+} ions, on which we placed another layer of pure *n*-Si as thick as 10 μm and an n^+ layer with $n \approx 6 \times 10^{18}$ cm^{-3}. The concentration of Er ions in the active layer was ~10^{18} cm^{-3}. The diode structure geometry was chosen such that the Er-doped layer is located within the SCR.

Investigation of the Er^{3+} EL kinetics in a structure with

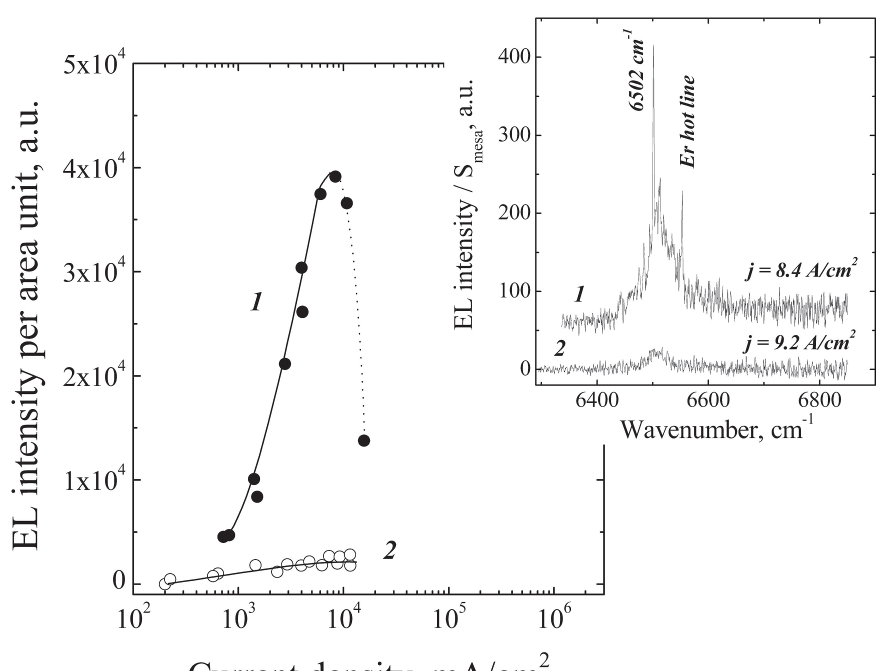


FIG. 6. Dependences of the EL intensity on the drive current density for LEDs with an active region selectively (1) and uniformly (2) doped with Er. The inset shows high-resolution EL spectra ($\Delta\nu = 1$ cm^{-1}) of these diodes taken at 80 K in the forward bias regime.

an active layer positioned in SCR revealed a few interesting peculiarities. The novelty here was observation of the electro-optical conversion with a long-term memory effect of the structure about the current pulse flow through the *p-n* transition at forward bias. A long time after termination of the forward-bias pulse we observed "stored" EL (SEL) of Er^{3+} ions, by application of a reverse bias to the diode structure (Fig. 7). It is important that in all experiments: (i) the voltage of the reverse bias pulses, which excited SEL, U_{rev} ~10 V was below the breakdown voltage, so the SEL effect cannot be explained by the EL signal arising at avalanche breakdown of the reverse-biased *p-n* junction; (ii) SEL of Er^{3+} ions was observed only if the reverse bias pulse was preceded by a forward bias pulse.

The SEL intensity remained stable with an increase of the intervals between the forward-bias and reverse-bias pulses up to the maximal value of 100 ms in our experiments. Dependence of the SEL intensity on the reverse bias pulse parameters shows that with the pulse length decreasing down to the minimal values used in the experiment (~10 μs) the SEL amplitude (intensity) did not change. This effect was observed in our experiments at temperatures up to 120 K.

The experimentally observed peculiarities suggest that the "memory" effect characteristic of the electro-optical conversion is associated with availability in the structure of deep traps for free carriers. During the forward bias pulse, the traps fill up with the carriers. At reverse (negative) bias, the carriers get free from the traps and are able to excite Er ions by impact excitation, if the electric field is high enough.

In Si based optoelectronics of critical importance are memory elements with an optical output. Actually, the structure described in this paper is exactly such a device in which the memory elements are deep traps located in the Si:Er layer. The memory work includes the following stages: (i) at forward-bias pulse the deep traps are filled up with carriers (data writing); (ii) after the pulse terminates the traps can retain their charged state for a long time (data storage); (iii) application of a short pulse of the reverse bias sets the carriers free and they excite EL of the Er^{3+} ion (optical output of data); and (iv) by application of a reverse-bias pulse of a small amplitude the carriers are released from the traps without luminescence (memory erasing).

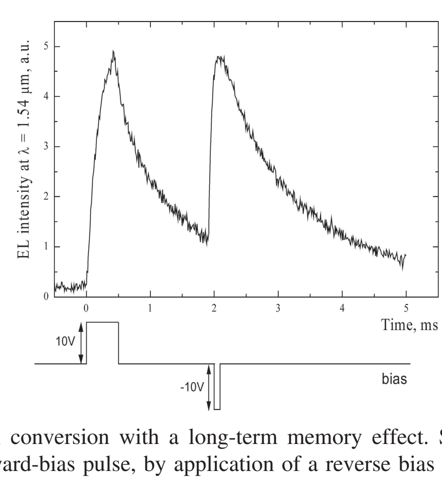
This electro-optical element does not require external sources of radiation; besides, the writing and erasing of information here (filling and depletion of the deep traps) can be effected without exciting the luminescence of an Er ion, which may prove a more convenient option in some applications.

VIII. PROSPECTS OF THE LASER REALIZATION

As mentioned above, Si:Er/Si structures grown by the sublimation MBE exhibit extremely narrow PL lines (Fig. 2). According to our estimations, the optical gain accessible in these structures should reach the value of 3–30 cm^{-1}.[8] This means that the structures of this type emerge as plausible candidates for realizing the population inversion and stimulated emission in Si:Er-based materials.

Laser type structures can be developed on the basis of $Si/Si_{1-x}Ge_x$:Er/Si heterostructures with the active $Si_{1-x}Ge_x$:Er media. The waveguiding effect in this case is achieved through introduction of $Si_{1-x}Ge_x$:Er layers, the refractive index of which depends on the Ge content and can be varied in a wide range. Here we present the results of theoretical simulations and experimental studies, obtained for $Si/Si_{1-x}Ge_x$:Er/Si heterostructures being developed with a view to implementing this idea. The structures in question were grown by a specific method that combines the principles of sublimation MBE with the growth in gas (GeH_4) atmosphere.

Figure 8 shows the results of simulations carried out for the optical mode distribution in $Si/Si_{1-x}Ge_x/Si$ heterostructure and the mode confinement factor (Γ) versus thickness (d) and Ge content (x) of the $Si_{1-x}Ge_x$ layer. As follows from Fig. 8, the maximal confinement factor and, hence, the gain can be achieved in the structures



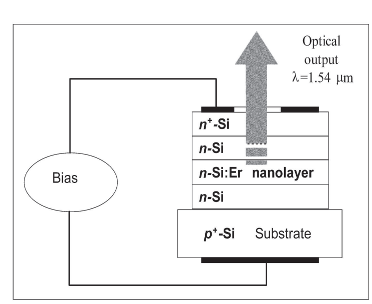


FIG. 7. Electro-optical conversion with a long-term memory effect. SEL of Er^{3+} ions has been observed a long time (up to 100 ms) after termination of the forward-bias pulse, by application of a reverse bias $U < U_{breakdown}$ to the diode structure.

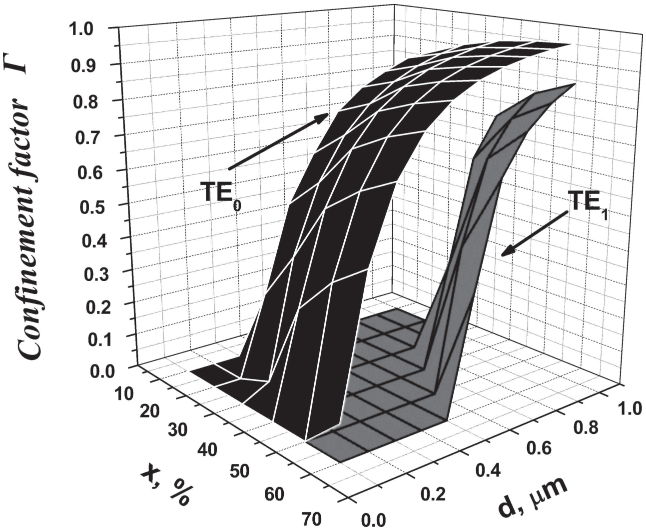


FIG. 8. Dependence of the confinement factor (Γ) simulated for TE_{00} and TE_{01} optical modes in $Si/Si_{1-x}Ge_x$:Er/Si heterostructure on the thickness (d) and Ge content (x) of the $Si_{1-x}Ge_x$:Er layer.

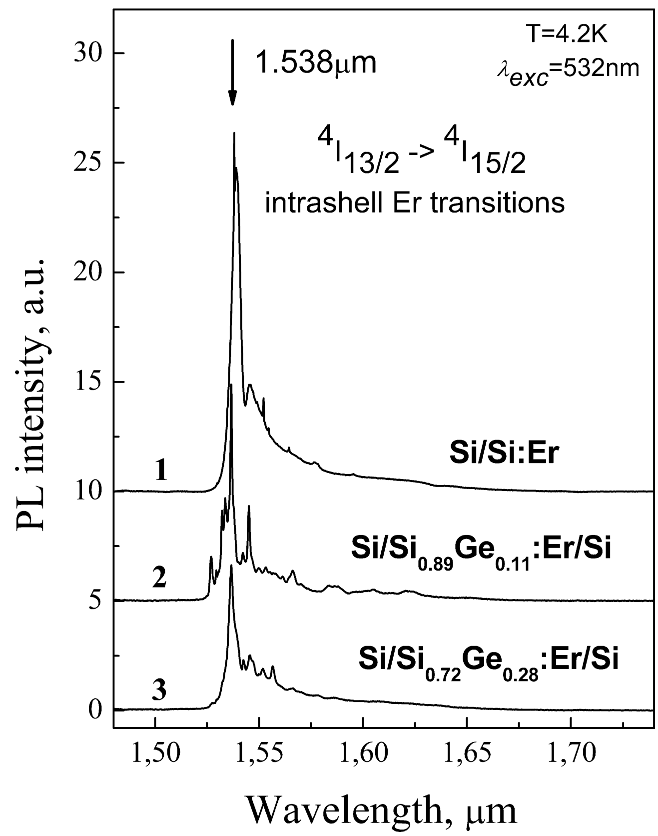


FIG. 9. PL spectra of the Si:Er/Si and $Si/Si_{1-x}Ge_x$:Er/Si structures. Parameters of the structures: (1) $d_{\mathrm{Si:Er}}$ = 1.8 μm; (2) $d_{\mathrm{SiGe:Er}}$ = 0.6 μm, x = 11%; (3) $d_{\mathrm{SiGe:Er}}$ = 1.1 μm, x = 28%.

with sufficiently thick $Si_{1-x}Ge_x$ layers (thicker than 0.5 μm) and high Ge content (more than 30–40%). The Γ factor in this case should reach the value up to 0.98, thus enabling strong localization of the optical modes.

PL studies carried out for $Si/Si_{1-x}Ge_x$:Er/Si hetero-structures clearly demonstrate their high luminescent efficiency, as compared with Si:Er/Si structures. Figure 9 shows the PL spectra taken in the same experimental conditions for some characteristic $Si/Si_{1-x}Ge_x$:Er/Si hetero-structures and for one of the most luminescence-effective Si:Er structures, which has a nearly 0.4% external quantum efficiency at 4.2 K. According to the spectral response, the axial symmetry Er-O1 center is dominating in $Si/Si_{1-x}Ge_x$:Er/Si structures. PL signals at 1.54 μm for both types of structures (Si:Er and $Si/Si_{1-x}Ge_x$:Er/Si) are comparable, which points to their high luminescence efficiency. Note that we did not observe any appreciable influence of the strain relaxation taking place in $Si_{1-x}Ge_x$ layers, especially at high Ge content and thickness, on the intensity of Er-related PL. Even the fully relaxed structures demonstrated efficient Er-related PL (the residual elastic strain coefficient for the structure represented by the spectrum 3 in Fig. 9 amounts to 9 ± 10%).

One can demonstrate a possibility to achieve the population inversion of the Er ion states in these structures under optical pumping.[18] This result has been obtained recently for a $Si/Si_{0.72}Ge_{0.28}$:Er/Si heterostructure with the parameters optimized toward laser realization (Γ factor for TE_{00} mode amounts to 0.94, see also spectrum 3 in Fig. 9). The occurrence of population inversion was determined from the PL transients measurements carried out at 10 K under Cu-laser excitation ($h\upsilon_{ex}$ = 2.1, 2.4 eV). By solving the balance equations, one can show that the relative number of Er ions in the excited ($^4I_{13/2}$) states is directly related with the ratio of the PL rise and decay times measured for the Er signal:

$$N^*/N = 1 - \tau_{\mathrm{rise}}/\tau_{\mathrm{decay}} \quad , \qquad (1)$$

where N^* is the number of Er ions in the excited states, N the total concentration of optically active Er ions, τ_{rise} and τ_{decay} the PL rise and decay times, respectively.

The pump-power dependences of the PL rise and decay times measured for the $Si/Si_{0.72}Ge_{0.28}$:Er/Si structure at the wavelength of Er peak (1.537 μm) are shown in Fig. 10(a). With an increase in the pump power one can see a pronounced decrease of the PL rise times, whereas the decay times of the Er signal remain practically unchanged. At the pump power density of ~1 W/cm^2, the estimations made by using Eq. (1) indicate a high population inversion of the Er^{3+} ion states in this structure [~80% of the total amount of optically active ions are found in the excited states; see Fig. 10(b)]. In fact, this last result provides reliable evidence supporting feasibility of a laser on Si:Er basis in near future.

IX. CONCLUSIONS

A brief review of our contribution to the Si:Er problem in the last decade has been presented. We connect further

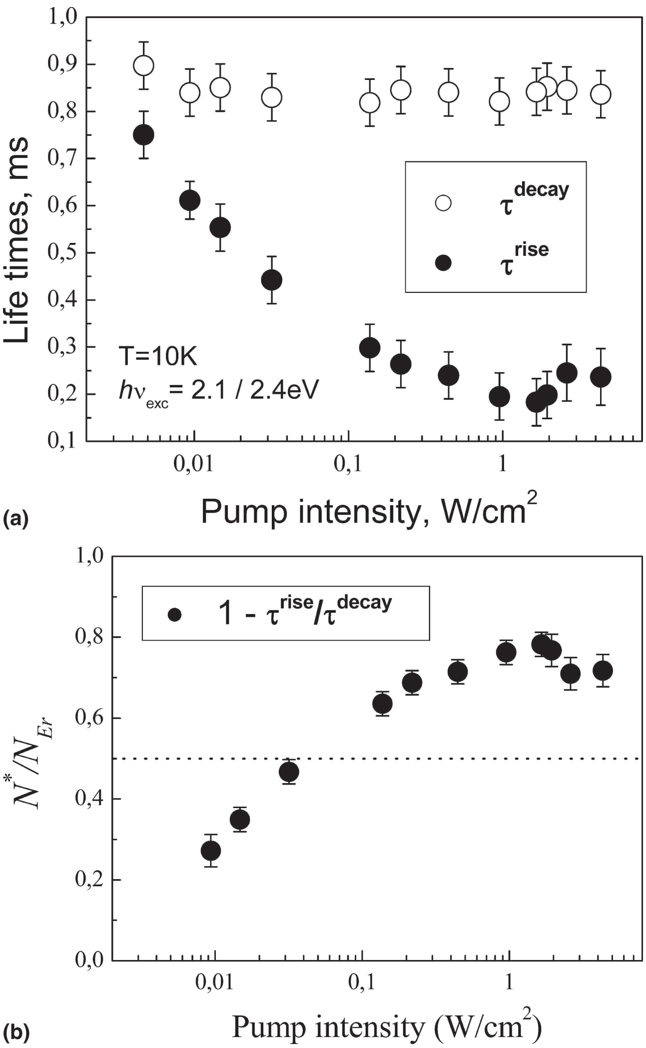


FIG. 10. (a) Life times measured for the Er-related PL peak in Si/ $Si_{0.72}Ge_{0.28}$:Er/Si heterostructure, and (b) the ratio of Er ions in the excited state to the total concentration of optically active Er ions determined as a function of the excitation intensity.

progress in this field with new approaches to the design of the Si:Er-based light-emitting devices. Among them, we consider LEDs on the basis of selectively doped multilayer structures radiating under forward bias and LEDs with expanded space charge region, including multidiode structures, emitting at the breakdown regime. We believe that an all-silicon laser operating at a 1.54 μm can be realized on the basis of SMBE grown Si:Er structures with the dominating Er-1 center characterized by extremely narrow PL line (less than 10 μeV at 4.2 K). At last, we suppose that a practically applicable device can be developed on the basis of the observed electro-optical storage effect.

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