

UDC 538.915
EDN: JVZIUO

PACS: 85.60.-q

Radiation resistance of light-emitting structures with Ge/Si nanoislands on SOI substrate

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Received 22.07.2025; revised 18.08.2025; accepted 20.10.2025

Theoretical and experimental research results are presented to demonstrate the impact of γ -neutron radiation on the parameters of light-emitting structures with an array of Ge(Si) nanoislands grown by methods of molecular beam epitaxy on SOI substrates. These structures showed a high level of resistance to the impact of γ -neutron radiation comparable with resistance level of structures with Ge(Si) nanoislands on Si(001) substrates. Reduction of luminescence intensity of these structures coincides with theoretical estimate of radiation defects influence level. Simulation results and experimental data show that the Ge(Si) nanoislands array structures affect the radiation resistance of LEDs to the greatest extent.

Keywords: light-emitting structures; Ge(Si) nanoislands arrays; SOI structures; radiation resistance; γ -neutron radiation.

DOI: 10.51368/2949-561X-2025-5-27-35

Introduction

Silicon-on-insulator (SOI) structures, along with Silicon-on-sapphire (SOS) structures, are widely used as base materials for creating radiation-hardened microelectronic hardware components. A buried dielectric layer acts as a barrier that reduced the impact of radiation-induced defects of a substrate on the active regions of semiconductor devices and integrated circuits. SOI structures also have special properties that are of interest for developing optoelectronic devices [1, 2]. The difference in refractive indices between Si and SiO₂ (3.5 and 1.45, respectively) simplifies the task of creating waveguide couplings between planar geometry elements made on SOI structures. The light wave field concentrated between the buried dielectric and the heterostructure surface develops maximum intensity within the silicon layer. Heterostructures exhibit intensity-enhancing effects due to vertical Fabry-Perot type resonances caused by interference of waves

reflected from the surface-Si and Si-SiO₂ interfaces [3]. In the future, SOI structures can be considered as a basis for nanostructured integrated optics with devices for generation, amplification, and detection of optical signals, with waveguides and couplers as passive elements, while still being compatible with standard silicon technology.

The use of heteroepitaxial structures with Ge(Si) nanoislands (quantum dots) allows expanding spectral characteristics of silicon-based optical elements into the near- and mid-infrared ranges and overlapping the communication wavelength band of 1.3–1.55 μm , which corresponds to the optical fiber transparency window. Spatial confinement of charge carriers in all three dimensions reduces the sensitivity of radiative properties of nanoisland structures to radiation-induced defects as compared to structures with lower degrees of confinement, such as bulk silicon and structures incorporating quantum wells [4]. Although Ge(Si) nanoisland structures feature

photoluminescence (PL) and electroluminescence (EL) signals up to the room temperature, the low radiative recombination efficiency of charge carriers hinders their commercialization. According to the research results [5], one of the most promising methods to enhance the radiation intensity of Ge(Si) nanoisland structures is to integrate an active radiating medium into various types of optical resonators. The possibility of integrating Ge(Si) nanoisland structures into resonator structures is enabled by the use of SOI substrates. A positive effect of increased emission intensity is observed when using resonators such as microdisks, photonic crystals, plasmonic, and dielectric microresonators [3, 5, 6]. Radiative recombination efficiency can also be increased by using waveguide structures made on SOI substrates and having optimized parameters and design. In this case, the process of forming Ge(Si) nanoislands according to the Stranski-Krastanow mechanism is integrated into the waveguide structure fabrication route. The application of these methods for enhancing the photoresponse enables a realistic way to develop effective photon sources based on Ge(Si) nanoisland structures.

Since the use of SOI structures for integrated optics devices has great potential, ensuring the radiation hardness of light-emitting structures grown on SOI substrates is a relevant research issue. The studies performed to research the impact of ionizing radiation on the photoluminescence and electroluminescence of heteroepitaxial structures with Ge(Si) nanoislands grown by molecular beam epitaxy on bulk silicon substrates – Si(001) [4, 7] have proved their potentially high radiation hardness. Self-generation processes of Ge(Si) nanoislands are stimulated by accumulation of elastic stress in the epitaxial layers due to the significant mismatch of lattice parameters between the substrate and the film. When the growing layer thickness exceeds critical values, the elastic stress relaxes due to nanoislands growing according to the Stranski-Krastanow mechanism. The elastic stress field of the buried dielectric layer in SOI structures, along with the standard thickness of the submicron silicon epitaxial film for integrated circuits, can have a potential influence on self-generation processes of Ge(Si) nanoislands, thus increasing the concentration of structural defects and reducing the radiation hardness of devices. This

paper presents the findings of studying the impact of pulsed γ -neutron radiation on parameters of light-emitting structures with Ge(Si) nanoisland arrays grown on SOI substrates. These findings are given in comparison with the findings for radiation of similar structures on bulk silicon substrates.

Experiment procedure

LED samples were grown by molecular beam epitaxy (MBE) using Balzers UMS-500 system. Silicon-on-insulator (SOI) structures with (001) orientation fabricated by the bonding method were used as substrates. The thickness of the surface silicon layer was 200 nm, and the buried dielectric layer was 1 μm . On the substrate surface, at the temperature of 600 $^{\circ}\text{C}$ a lower contact layer Si of p^{+} -conductivity type of 30 nm thickness, boron-doped, with concentration of $\sim 5 \times 10^{18} \text{ cm}^{-3}$ was deposited. The thickness of the lower silicon contact layer was increased compared to the bulk silicon structures to maintain low resistance of contacts. After that a 50 nm thick layer of undoped Si was grown. Ge(Si) nanoisland arrays were formed on the substrate surface at the temperature of 600 $^{\circ}\text{C}$. The LED active region contained up to 20 layers of nanoislands separated by silicon barriers with thicknesses ranging from 15 to 20 nm, which ensured their vertical ordering. Islands formed during deposition of the Ge layer with a thickness of 6.5–8.5 monolayers (ML) (1 ML $\sim 0.136 \text{ nm}$). Si and Ge layers were deposited from two electron-beam evaporators at growth rates of 0.1 nm/s and 0.02 nm/s, respectively. During growth the elastic stress fields of underlying layers influenced the sizes of nanoislands in the next layers. For better size uniformity of the islands, the Ge amount deposited was decreased by approximately ~ 0.1 ML for each next layer. Formation of LED structures was completed by depositing a 50 nm thick layer of undoped Si and a 200 nm thick n^{+} -type Si contact layer doped with antimony at the concentration of $\sim 10^{19} \text{ cm}^{-3}$.

One of the significant challenges in the epitaxial growth of multilayer nanoisland structures on SOI substrates is monitoring the wafer surface temperature. The substrate temperature is a critical parameter that determines

the structure and properties of the nanoisland array. According to the MBE method, wafers are heated by a radiation source from the substrate side. Temperature is monitored from the substrate side too. A difference in the surface temperature between SOI structures and standard Si(001) substrates was observed at the same power supplied to the heater and identical thermocouple readings. The reason for this is a relatively thick ($\sim 1 \mu\text{m}$) buried dielectric layer found in the SOI structures being studied. During formation of the structures the epitaxial growth conditions were calibrated to estimate the actual surface temperature of the SOI substrates as a function of the power supplied to the heater. This calibration was based on experimental data of the temperature dependence of Ge(Si) nanoisland parameters on bulk silicon substrates – Si(001) – and on SOI structures.

The morphology of the grown structures was studied using the atomic force microscopy (AFM) method under the atmospheric conditions with NT-MDT "Silver Pro" microscope (Russia). The crystal structure of epitaxial layers was studied by high-resolution transmission electron microscopy (TEM) using JEOL JEM 2100F microscope. The film thickness during transition from the two-dimensional to the three-dimensional formation of nanoislands was determined by the reflected high-energy electron diffraction (RHEED). Photoluminescence (PL) spectra were measured using DA3-36 Fourier transform spectrometer. PL signal was excited by Nd:YAG laser with the wavelength of $\lambda = 532 \text{ nm}$. Electroluminescence (EL) and PL spectra were recorded using cooled Ge and InSb photodetectors. The samples under study were exposed to the pulsed γ -neutron irradiation. A pulsed reactor with a characteristic neutron energy of $\sim 1 \text{ MeV}$ and a fluence of up to 10^{15} n/cm^2 was used as a neutron source. The exposure dose of γ -radiation was $\sim 400 \text{ kR}$.

Experimental results and their discussion

Conditions to ensure the radiation hardness, namely the localization of charge carriers, are determined by the system of Ge(Si) nanoislands formed in the light-emitting structures. Island characteristics (size, shape, composition, elastic

stress) depend on the growth conditions [8]. Self-generation processes are influenced by such parameters as substrate temperature, deposition rate, surface morphology, rates of surface and bulk diffusion of components, etc. During epitaxial growth, the shape of the Ge(Si) nanoislands is observed to be transforming. After the layer-by-layer growth changes over to the three-dimensional growth, a system of Ge(Si) nanoislands with a rectangular base (hut islands) and pyramidal islands forms, which then transforms into a system of uniform dome-shaped islands (dome islands) ordered in the substrate plane [9]. This changeover is favorable in terms of energy because the elastic strain energy for dome-shaped islands is lower than for islands of other shapes. Dome-shaped Ge(Si) islands faceted by (105) and (113) planes do not have a highly developed surface. Reflecting boundaries of the nanoislands along with the low surface recombination contribute to the charge carrier localization. Dome islands exhibit the deepest potential well for holes. Spatially ordered arrays of Ge(Si) dome islands form with high density, occupy the maximum substrate area, and provide the highest efficiency for parameters of light-emitting structures due to high localization of charges in the potential wells.

Ge(Si) nanoisland arrays were grown under optimal conditions to achieve efficient parameters of light-emitting structures. The substrate temperature was one of the most critical parameters during formation of the Ge(Si) nanoisland system. It was established that when heated in the temperature range from 550°C to 650°C , the surface temperature of SOI structures was 40°C higher than that of bulk silicon wafers. The optimal wafer surface temperature for the characteristic array of dome islands to form is 600°C . Figure 1a shows an AFM image of an SOI structure with the formed array of Ge(Si) nanoislands. The morphology of Ge(Si) nanoislands grown on SOI structures at the optimal substrate surface temperature of $\sim 600^\circ\text{C}$ is similar to the morphology of nanoislands grown on bulk Si(001). The obtained typical morphological parameter values exhibit a small spread in sizes of dome islands. The surface density $N \sim 5,0 \times 10^9 \text{ cm}^{-2}$, average island height $h \sim 15 \text{ nm}$, average lateral dimensions D less than 100 nm with the spread of $\sim 15\%$ (determined at

the $0.1h$ level from the Ge wetting layer surface), and the average germanium fraction in $\text{Ge}_x\text{Si}_{1-x}$ ($x = 0.54$) are close to the parameter values of nanoislands grown on Si(001). The similarity in

morphologies of nanoislands grown on SOI and Si(001) structures facilitates the comparative analysis of radiation effects under exposure to γ -neutron radiation.

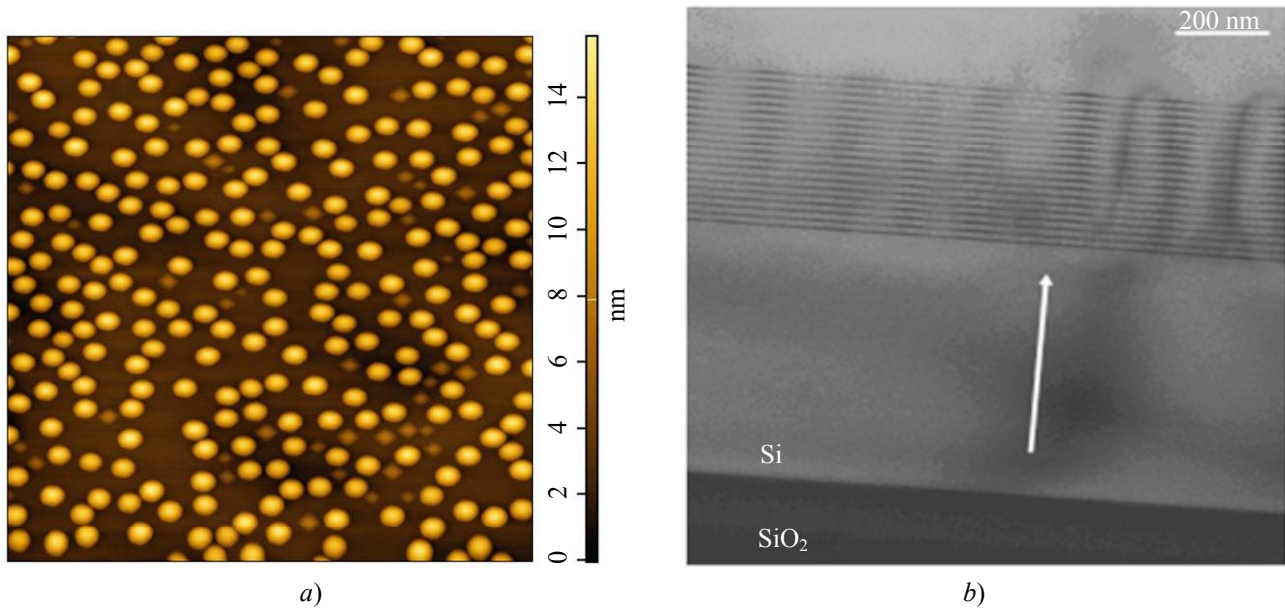


Fig. 1. AFM image of the SOI structure surface with the self-generated array of dome-shaped Ge(Si) nanoislands (a) and TEM image of the multilayer structure with Ge(Si) nanoislands grown on the SOI substrate (b)

The TEM image (Fig. 1b) shows the multilayer structure of Ge(Si) nanoislands in the active region of the light-emitting $p-i-n$ diode formed on the SOI substrate. The vertical arrangement of the layer structure is caused by the influence of the elastic strain field from the underlying Ge(Si) nanoislands. The layer-by-layer correlation of the island array depends on the parameters of the Si spacer layers. The optimal thickness of these spacer layers ranges from 15 to 20 nm. Studies of multilayer structures with silicon spacer layer thicknesses between 15 and 20 nm have also shown a significantly lower concentration of defective regions compared to structures with Si layer thicknesses greater than 25 nm. When the spacer layer thickness is comparable to the size of the Ge(Si) nanoislands in the growth direction, the silicon deformation takes the form of tension between adjacent islands, which results in formation of a deep (up to 100 meV) potential well for electrons at the Ge/Si interface. The formation of this potential well causes

charge carriers to concentrate near the nanoislands and contributes to the increased electroluminescence intensity of the structures. Since a visible interface between the initial silicon layer of the SOI structure and the MBE-grown Si buffer layer cannot be seen in the image, it proves the wafer surface preparation methods used prior to epitaxy to be effective.

To measure parameters of light-emitting $p-i-n$ diodes with a Ge(Si) nanoisland array in the active region, mesastructures sized 1×1 mm and 1×0.5 mm were formed using plasma chemical etching. The upper contact to the n^+ -Si layer was made as a metallization grid to increase the free surface area to enable light emission. The lower contact to the p^+ -silicon region surrounded the mesastructure along its perimeter. Gold with a Ti sublayer was used for metallization. Figure 2a compares the photoluminescence spectra of multilayer structures grown on Si(001) and SOI substrates and similar Ge(Si) nanoisland arrays.

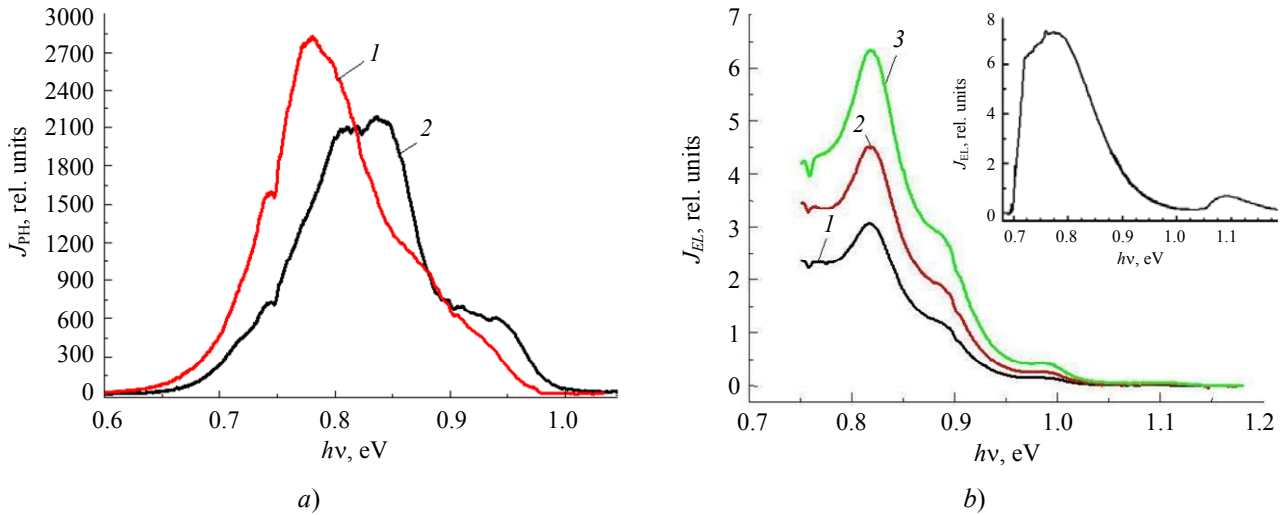


Fig. 2. PL spectra of structures formed on Si(001) (1) and SOI (2) substrates with Ge(Si) nanoisland arrays (a), and EL spectra of structures with Ge(Si) nanoisland arrays on SOI substrates at different pump currents (1 – 150 mA, 2 – 200 mA, 3 – 250 mA) (b); the inset shows the EL spectrum of structures with Ge(Si) arrays on Si(001) substrates. Spectra were measured at temperatures of 77 K (a) and 300 K (b)

The PL intensity J_{PL} is given in terms of relative units. Both the Si(001) and SOI structures exhibit broad PL peaks (Fig. 2a) associated with the radiative recombination of charge carriers localized in the Ge(Si) nanoisland regions. A slight shift of intensity maxima is observed within the quantum energy range of $h\nu \sim 0.7\text{--}1.0$ eV ($\lambda \sim 1.3\text{--}1.7$ μm). The intensity of luminescent responses in both spectra is comparable, suggesting similar morphology of the Ge(Si) nanoislands. The buried dielectric seems not to have significant effect on the nanoisland morphology and, consequently, the radiative properties of the diodes, while the crystalline quality of the active regions in SOI wafers made by the bonding method is not inferior to that of bulk silicon. However, the spectral characteristics differ in nature. The spectra of light-emitting structures formed on SOI substrates contain at least two maxima. Specific features of structures on SOI substrates result in Fabry-Perot vertical resonances caused by interference of waves reflected from the Si-surface and Si-buried SiO_2 interfaces.

Figure 2b shows the electroluminescence spectra of multilayer LED structures grown on SOI substrates at different pump currents. The spectra were measured at the room temperature. The EL intensity J_{EL} is given in relative units. The EL signal was detected from the surface of the LED structures. The sample surface was fixed perpendicular to the optical axis of the measurement system during measurements.

As can be seen in the figure, the luminescence intensity changes depending on the pump current value, but the spectral shape remains unchanged. The intensity maxima can still be observed on the curve. The main emission peak corresponds to the wavelength of ~ 1.50 μm ($h\nu \sim 0.83$ eV). The figure shows that the ratio of magnitudes and positions of the intensity maxima do not depend on the pump current. Therefore, these intensity maxima are not associated with various radiation processes within the structure being studied but are determined by wave interference phenomena.

The studies of the EL intensity of diodes on SOI substrates vs. the observation angle showed that the nature of radiation spectra does not change with the angle varying. As the angle relative to the normal of the structure surface was changed (range from 0 to 90°), the peak radiation wavelength changed within the range of $\lambda \sim 1.45\text{--}1.60$ μm , while the EL intensity magnitude remained practically unchanged. The studies of the angular dependence of the EL signal allow attributing the observed spectral maxima to wave interference within the active region of the structure. The EL signal maxima usually appear at the wavelengths, the optical paths of which contain an integer number of half-waves. Another distinctive feature of spectra of diodes on SOI structures is the absence of a signal associated with interband recombination of charge carrier in Si in the quantum energy region of 1.12 eV (inset, Fig. 2b). The signal from silicon for structures grown on Si(001) is largely

the result of radiative recombination of holes and non-equilibrium electrons within the substrate volume. In LED structures grown on SOI, the buried oxide prevents non-equilibrium carriers from diffusing into the substrate, which results in a reduced luminescent response from silicon.

The impact of a neutron flux on the semiconductor structure is accompanied by generation of primary radiation defects, such as Frenkel pairs. Array atoms are believed to be always displaced when they acquire energy greater than a certain threshold displacement energy. Although a large amount of energy is unlikely to be transferred to the displaced substrate atom, this event is probable practically in every collision cascade during radiation of silicon by neutrons. Consequently, radiation defects in the collision cascades of the radiated region are distributed non-uniformly, thus forming local disordered regions (DR) [10]. These DRs of radiation defects act as centers for non-radiative recombination and cause a reduction in luminescence intensity.

When considering the effects of γ -neutron radiation, the complex multilayer structure of LEDs with heterogeneous interfaces between different materials shall be taken into account. Using the "TRIM" program, the structure of radiation defects in SOI and SOS substrates was calculated under conditions of radiation with a

fast neutron flux featuring the fluence of $5 \times 10^{14} \text{ n/cm}^2$ and average energy of $\sim 1 \text{ MeV}$. The calculation was performed for the condition of isotropic radiation. The calculations analyzed the silicon interfaces with the buried dielectric layer for SOI and SOS structures, as well as the metallization-silicon interfaces. Figure 3a shows the calculated the defect concentration (N) in the silicon layer for "SiO₂-Si", "Al₂O₃-Si", "Al-Si", "Au-Si", and "air-Si" structures as expressed in relative units versus the distance from the interface X . The calculations accounted for the fact that DRs in silicon can be formed by Al, Au, and O atoms, which are injected from the material adjacent to silicon upon interaction with neutrons. Since the interaction cross-section of fast neutrons with Au atoms is larger than with Si or Al atoms, their interaction with neutrons is much more efficient. The defect concentration at the Au-Si heterointerface in the near-surface silicon layer ($\sim 50 \text{ nm}$ thick) is significantly higher than that in bulk silicon. The interface with sapphire is also effectively modified: the DR concentration is $\sim 10^{15} \text{ cm}^{-3}$ in the silicon layer adjacent to the interface, which is up to 150 nm thick. In SOI structures the interaction with oxygen does not lead to the increased concentration of radiation defects at the buried SiO₂-Si heterointerface as compared to bulk silicon.

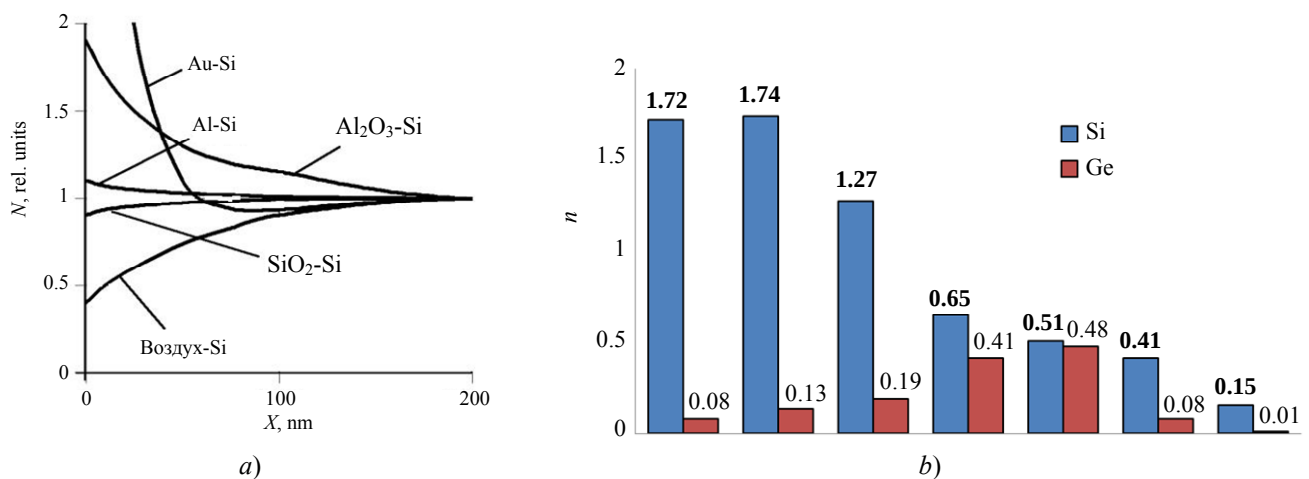


Fig. 3. Defect concentration in the silicon layer N vs. the distance to the interface X in the heterostructures "Al₂O₃-Si", "Al-Si", "Au-Si", "SiO₂-Si", and "air-Si" under exposure to the fast neutron flux (defect concentration in bulk silicon corresponds to 1) (a). Average number of subclusters in atomic displacement cascades n for Si and Ge atoms vs. subcluster size L (b)

Atomic displacement cascades initiated by primarily knocked-on Si and Ge atoms during radiation of the LED structure with the fast neutron flux (fluence $5 \times 10^{14} \text{ n/cm}^2$, average energy $\sim 1 \text{ MeV}$) were simulated using the Monte Carlo method based on the TRIM algorithm. The formation of DRs for the light-emitting structures with the Ge(Si) nanoisland array was calculated without accounting for disturbances at the buried $\text{SiO}_2\text{-Si}$ interface, which are of local nature according to calculations (Fig. 3a). The displacement energy from crystal lattice sites for Si and Ge atoms was set to 20 eV. For the nanoisland array, the quantities of Si and Ge in the $\text{Ge}_x\text{Si}_{1-x}$ solid solution ($x = 0.54$) were taken into account. The density of silicon was 2.33 g/cm^3 , and the density of the $\text{Ge}_x\text{Si}_{1-x} \sim 3.80 \text{ g/cm}^3$ solid solution was $\sim 3.80 \text{ g/cm}^3$. Primarily knocked-on Si and Ge atoms form atomic displacement cascades in the form of local defect clusters - subclusters. Figure 3b shows the results of simulating atomic displacement cascades for Si and Ge atoms. The average number of subclusters in atomic displacement cascades, n , as a function of subcluster size L is shown. DRs for primarily knocked-on Si and Ge atoms have different geometric sizes. Si atoms typically exhibit the formation of a large number of small subclusters (less than 10 nm) in the active region of the LEDs is characteristic, whereas Ge atoms - the formation of a small number of large subclusters ($\sim 40 \text{ nm}$). In the depletion region of $p\text{-i-n}$ diodes, provided that Si spacer and buffer layers are present, the fraction of Ge atoms is much smaller than the fraction of silicon atoms. According to the calculation results, Ge atoms have a significantly smaller impact on the degradation of optoelectronic properties of heterostructures with Ge(Si) nanoislands as compared to Si atoms.

A theoretical assessment of DR influence on properties of light-emitting structures with Ge(Si) nanoislands grown on Si(001) substrates under γ -neutron radiation was conducted in reference [11]. The electric field of the DR space charge area reduces the concentration of carriers localized in the Ge(Si) nanoislands and, combined with non-radiative recombination processes at radiation defects, causes the luminescence intensity to decrease. The calculated fraction of nanoislands falling within

the influence zone of the DR electric field for LED structures on Si(001) substrates was 40%. This calculation of the DR field was performed without accounting for primarily knocked-on Ge atoms. Considering the local nature of disturbances at the buried dielectric-silicon heterointerface ($\text{SiO}_2\text{-Si}$) (Fig. 3a) and the predominant influence of Si on the formation of atomic displacement cascades (Fig. 3b), the fraction of nanoislands within the influence zone of the DR field for heterostructures grown on Si(001) substrates shall be comparable to the fraction for structures on SOI substrates. This conclusion is supported by the experimental data. Figure 4 shows the PL spectra of structures with Ge(Si) nanoisland arrays grown on SOI substrates before and after γ -neutron radiation. The PL intensity J_{PL} is shown in terms of relative units.

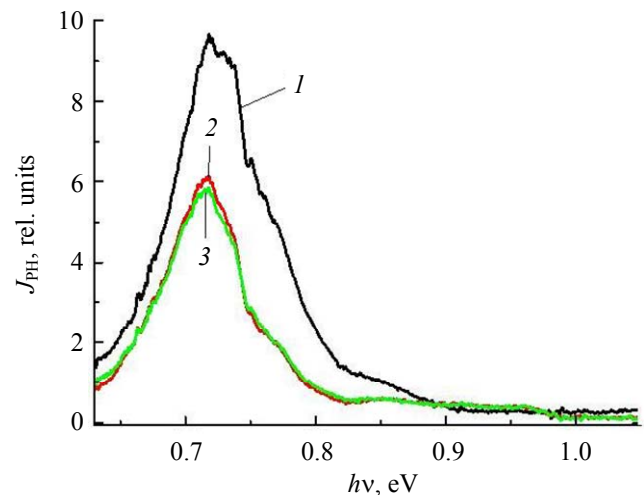


Fig. 4. PL spectra of structures with Ge(Si) nanoislands grown on SOI substrates before (1), after single (2), and after double (3) γ -neutron radiation with fluences of $2 \times 10^{14} \text{ n/cm}^2$. Spectra were measured at the temperature of 77 K

The PL peaks of both radiated and non-radiated structures lie within the wavelength range of $\lambda \sim 1.4\text{--}1.8 \mu\text{m}$ (quantum energy $h\nu \sim 0.65\text{--}0.85 \text{ eV}$). The wavelength of the maximum intensity of PL spectrum does not change after radiation. No decrease in luminescence intensity is observed after double radiation as compared to single irradiation, which is apparently due to the formation of stable clusters that act as sinks for radiation defects. The spectra shown in Fig. 4 indicate the 35 % reduction in PL signal intensity after exposure to fast neutrons, which is consistent with the

theoretical assessment of the DR influence on properties of structures incorporating Ge(Si) nanoislands and with the experimental data proving the reduction of luminescence intensity for structures grown on Si(001) substrates [11]. [11]. The simulation results and experimental data on the impact of γ -neutron irradiation demonstrate that the level of LED radiation hardness is primarily determined by the structure of the Ge(Si) nanoisland array. The use of SOI substrates does not degrade the radiation hardness of the structures.

Conclusion

The characteristics of light-emitting structures incorporating Ge(Si) nanoisland arrays and grown by MBE on SOI substrates were studied. Morphological parameters of Ge(Si) nanoislands on SOI structures (surface density, average height, lateral dimensions) were shown to approach the parameter values of nanoislands grown under similar conditions on Si(001) substrates. The PL spectra of light-emitting structures on SOI and Si(001) substrates are comparable in terms of luminescence response intensity but differ in their nature. The derived dependence of the EL intensity of light-emitting structures on SOI substrates on the pump current magnitude does not affect the spectra nature. Since the intensity maxima positions in the spectra do not depend on the pump current, their occurrence is not associated with various radiation processes within the structure being studied. The intensity maxima in the spectra of structures on SOI substrates are determined by Fabry-Perot type vertical resonances caused by the interference of waves reflected from the

silicon interfaces with the surface and the buried dielectric layer.

The findings of the study of the impact of γ -neutron radiation on parameters of light-emitting structures are presented. When the impact of radiation on depletion regions of LEDs incorporating Ge(Si) nanoisland arrays grown on SOI substrates was studied, their complex multilayer structure with heterogeneous interfaces between different materials was considered. The structure of radiation defects in SOI substrates was calculated using the "TRIM" program. The interaction of neutrons with the oxygen in the buried dielectric layer was shown not to cause the defect level at the Si-SiO₂ heterointerface to exceed the defect level of the Si layer. Atomic displacement cascades initiated by primarily knocked-on Si and Ge atoms were simulated in the LED structures by the Monte Carlo method using the "TRIM" program. Si atoms were shown to have a significantly greater impact on the degradation of optoelectronic properties of heterostructures with Ge(Si) nanoislands as compared to Ge atoms. Considering the local nature of disturbances at the buried SiO₂-Si heterointerface, the fraction of nanoislands within the influence zone of radiation defects for structures grown on SOI substrates corresponds to the fraction of nanoislands on Si(001) substrates. The PL signal intensity for structures on SOI substrates is 35% lower after exposure to neutrons, which corresponds to the intensity reduction for structures on Si(001) substrates and aligns with the theoretical assessment of the influence of induced defects. The simulation results and experimental data demonstrate that the structure of the Ge(Si) nanoisland array has the greatest influence on the level of LED radiation hardness.

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