ISSN 1068-3356, Bulletin of the Lebedev Physics Institute, 2017, Vol. 44, No. 12, pp. 371–373. © Allerton Press, Inc., 2017.
Original Russian Text © S.N. Nikolaev, V.S. Krivobok, V.S. Bagaev, E.E. Onishchenko, 2017, published in Kratkie Soobshcheniya po Fizike, 2017, Vol. 44, No. 12, pp. 41–46.

Visible Luminescence Enhancement Methods in SiGe/Si Heterostructures

S. N. Nikolaev, V. S. Krivobok, V. S. Bagaev, and E. E. Onishchenko

Lebedev Physical Institute, Russian Academy of Sciences,
Leninskii pr. 53, Moscow, 119991 Russia; e-mail: nikolaev-s@yandex.ru

Received December 5, 2017

Abstract—The possibility of increasing the photoluminescence signal of $Si_{1-x}Ge_x$/Si quantum wells in the visible spectral range due to a change in the conduction band structure and the interaction of many-body states with plasma oscillations of metal nanoparticles is studied. The sample band structure was controlled using a uniaxial strain of $\sim 10^{-4}$. It is found that such an approach allows an increase in the emission intensity of biexcitons in the quantum well ($x = 9\%$) by a factor of 2.4 at a temperature of 5 K. Metal nanoparticles deposited on the sample surface with a protective layer thickness of 20 nm allowed us to increase the luminescence intensity of quantum wells approximately by a factor of 2.7.

DOI: 10.3103/S1068335617120077

Keywords: Si, Ge, quantum wells, $2E_g$-luminescence, deformation, metal nanoparticles.

In heterostructures based on indirect-gap semiconductors (such as Si and Ge), the emission associated with simultaneous recombination of two electrons from opposite valleys and two holes is observed. Such emission is referred to as $2E_g$-luminescence [1, 2]. In $Si_{1-x}Ge_x$/Si quantum wells, such emission is observed in the visible spectral range and allows the study of many-body states in a dense quasi-equilibrium lower-dimensional electron—hole system [2—5]. However, the low intensity of $2E_g$-luminescence limits its use in both basic research and practical applications. At the same time, a significant increase in the efficiency of $2E_g$-luminescence could be of particular interest from the viewpoint of the development of alternative methods of silicon photonics. In this study, we tested two approaches to an increase in the signal of visible luminescence of SiGe/Si quantum wells: the plasmon and deformation ones.

The study was performed on samples with $Si_{1-x}Ge_x$/Si quantum wells 5 nm thick with Ge contents in quantum wells $x = 5\%$ and $x = 9 - 15\%$. The structures were grown by molecular-beam epitaxy on high-resistivity Si (001) substrates. To measure photoluminescence spectra of structures, radiation was analyzed using an Acton SP2500 grating monochromator and was measured by a PyLoN 100F CCD camera. The electron—hole system was excited by a Toptica semiconductor tunable laser with a wavelength of 800 nm. To increase the spatial uniformity and reduce the role of carrier diffusion, laser radiation was not focused, the spot size was $\sim$3 mm. The sample was placed into an Utrex helium cryostat allowing operation in both vapor at a temperature of 5—300 K and in liquid helium at a temperature of 2 K. A special press was developed and fabricated, which was placed in the cryostat and allowed bending of planar samples at liquid-helium temperatures.

Local field enhancement by surface and local plasma oscillations of metal structures and particles became widely used in both basic research and the development of various devices (detectors, non-aperture microscopes, and others). In this work, we studied the effect of gold nanoparticles on the spectra of low-temperature photoluminescence of $Si_{1-x}Ge_x$/Si quantum wells with a thin silicon cap layer. Metal nanoparticles were selected so that their plasma resonance corresponded to the region of $2E_g$- luminescence of the structures under study and significantly exceeded the photon energy of laser excitation and IR luminescence of quantum wells. Gold nanoparticles 11 nm in diameter were deposited on the sample surface with $Si_{0.95}Ge_{0.05}$/Si quantum well.

A comparison of IR luminescence spectra of the quantum wells with deposited nanoparticles and without nanoparticles showed insensitivity of the spectra to the presence of metal particles on the

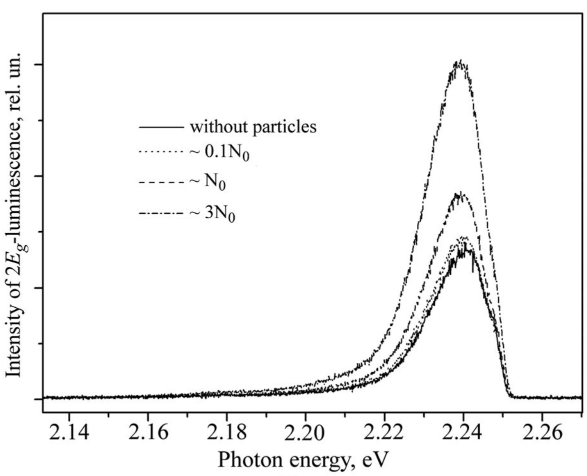

Fig. 1

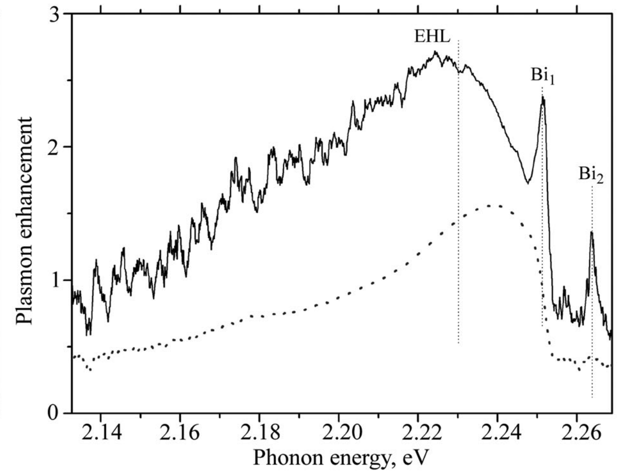

Fig. 2

Fig. 1. Spectra of $2E_g$-luminescence of $Si_{1-x}Ge_x/Si$ quantum wells with various densities of gold nanoparticles (the luminescence intensity sequentially increases with the nanoparticle density). The excitation power density is $\sim$0.25 W/cm^2, the temperature is 5 K. $N_0 \sim 3 \cdot 10^{10}$ cm^{-2}.

Fig. 2. Spectral dependence of plasmon enhancement (solid curve) and logarithmic intensities of $2E_g$-luminescence (dots).

sample surface. In the $2E_g$-luminescence spectrum, exclusively radiation of many-body states appears; in SiGe/Si quantum wells with low Ge content, radiation of electron–hole liquid (EHL) dominates; at the short-wavelength edge of the EHL emission band, weak radiation of multiexciton complexes, presumably biexcitons, is observed.

As seen in Fig. 1, the $2E_g$-luminescence intensity increases in the whole spectral range. In this case, the $2E_g$-luminescence enhancement factor increases with the surface density of gold nanoparticles, reaching $\sim$2.7 (see Fig. 2). Thus, the data obtained conclusively indicate plasmon enhancement of the $2E_g$-luminescence intensity by gold nanoparticles in the absence of noticeable changes in IR spectra.

As seen in Fig. 2, the plasmon enhancement factor depends strongly on not only the many-body state type, but also notably changes for various regions of the EHL line. In addition to the basic biexciton line Bi_1 in the $2E_g$-luminescence spectrum of SiGe/Si quantum wells, the additional luminescence line Bi$_2$ is also observed, which is shifted by 12 meV to high energies with respect to line Bi$_1$. This peak can be associated with biexciton states involving light holes.

As the Ge content in the solid solution layer is increased to 9%, the EHL formation is suppressed, and the biexciton with a binding energy of 2–2.5 meV appears to be the ground state of the electron–hole system [3, 4]. Its degeneracy factor is controlled by the conduction band and valence band structures. The presence of the built-in strain in quantum wells leads to splitting of light and heavy hole states at the Brillouin zone center; therefore, biexcitons in quantum wells contain two heavy holes with opposite spins. In this case, the conduction band remains fourfold degenerate ($\pm x$ and $\pm y$ valleys are the ground state, and $\pm z$ is the excited state). At such a valley configuration, the biexciton degeneracy factor is $8 \cdot 7/2 = 28$; however, only biexcitons involving two electrons from opposite valleys are emitting in the $2E_g$-spectrum; the number of such states is $8 \cdot 2/2 = 8$, i.e., 2/7 of the total number of biexciton states are "bright".

The fraction of "bright" biexcitons in the $2E_g$-spectrum can be increased by lifting the degeneracy of valleys lying in the quantum well plane. In this study, anisotropic deformation of samples was used to decrease the degeneracy factor of the ground state in SiGe/Si quantum wells. To this end, samples were subjected to bending with respect to various crystallographic directions ([110] and [100]). During deformation of structures with respect to the [110] direction, monotonic quenching of biexciton IR and $2E_g$-luminescence with increasing deformation and a blue shift of the biexciton band (by $\sim$4 meV in the IR spectrum and by $\sim$8 meV in the $2E_g$-spectrum for the strain of $1 \cdot 10^{-4}$) were detected. The detected effect is explained by an increase in the energy of $\pm x$, $\pm y$ valleys and a decrease in the energy

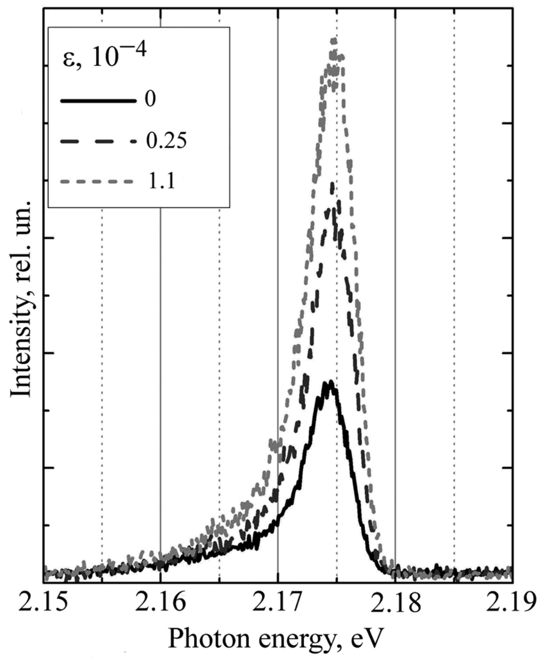

Fig. 3. Dependence of the $2E_g$-luminescence spectra on the applied deformation ε at the excitation power density of ~ 50 mW/cm^2 and a temperature of 5 K.

of $\pm z$ valleys. The experiments also detected that $2E_g$-luminescence is quenched notably more rapidly than IR emission, which indicates a decrease in biexciton stability, presumably, due to an increase in the dipole moment of excitons.

The significantly different behavior of luminescence spectra is observed under bending of $Si_{1-x}Ge_x/Si$ structures with $x = 12 - 15\%$ with respect to the [100] direction (Fig. 3). The $2E_g$-luminescence band of biexcitons almost does not change its spectral position with increasing deformation; in this case, the emission intensity increases to saturation (the intensity increases approximately by a factor of 2.4). The saturation is recorded at strains of $\sim 0.6 \cdot 10^{-4}$. The measured increase in the intensity approximately corresponds to the ratio of fractions of "bright" states in the total number of biexciton states after and before structure deformation (4/6 against 8/28). Hence, the detected effect points to removal of the degeneracy of biexciton states (from 28 to 6) at which the system ground state is formed by "bright" biexcitons.

Thus, two approaches to an increase in the intensity of visible luminescence of SiGe/Si quantum wells were successfully demonstrated: the plasmon enhancement of luminescence by metal nanoparticles and an increase in the fraction of "bright" states of biexcitons by changing the band structure under anisotropic deformation.

ACKNOWLEDGMENTS

This study was supported by the Russian Science Foundation, project no. 14-22-00273.

REFERENCES

1. T. Steiner, L. Lenchyshyn, M. Thewalt, et al., Solid State Commun. **89**, 429 (1994).
2. V. S. Bagaev, V. S. Krivobok, S. N. Nikolaev, et al., Phys. Rev. B **82**, 1153131 (2010).
3. V. S. Bagaev, V. S. Krivobok, S. N. Nikolaev, et al., Pisma Zh. Eksp. Teor. Fiz. **94**, 63 (2011) [JETP Lett. **94**, 63 (2011)].
4. V. S. Bagaev, E. T. Davletov, V. S. Krivobok, et al., Zh. Eksp. Teor. Fiz. **148**, 1198 (2015) [J. Exp. Theor. Phys. **121**, 1052 (2015)].
5. S. N. Nikolaev, V. S. Krivobok, V. S. Bagaev, et al., Pisma Zh. Eksp. Teor. Fiz. **104**, 161 (2016) [JETP Lett. **104**, 163 (2016)].