ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2018, Vol. 82, No. 4, pp. 427–430. © Allerton Press, Inc., 2018.
Original Russian Text © S.N. Nikolaev, V.S. Bagaev, V.S. Krivobok, E.T. Davletov, A.S. Gulyashko, G.F. Kopytov, A.A. Vasil'chenko, 2018, published in Izvestiya Rossiiskoi Akademii Nauk, Seriya Fizicheskaya, 2018, Vol. 82, No. 4.

Multicomponent Structure of an Electron-Hole Liquid in Shallow SiGe/Si Quantum Wells

S. N. Nikolaev[a], V. S. Bagaev[a], V. S. Krivobok[a, *], E. T. Davletov[a], A. S. Gulyashko[a], G. F. Kopytov[b, c], and A. A. Vasil'chenko[b, c]
[a]Lebedev Physical Institute, Russian Academy of Sciences, Moscow, 119333 Russia
[b]Kuban State University, Krasnodar, 350040 Russia
[c]Kuban State Technological University, Krasnodar, 350042 Russia
**e-mail: kolob7040@gmail.com*

Abstract—The fine structure of the emission spectrum lines is studied for a quasi-two-dimensional electron-hole liquid (EHL) embedded in SiGe/Si quantum wells. It is shown that the patterns observed in the spectra of the two-particle (IR band) and four-particle (visible band) recombination can be explained by the presence of both heavy and light holes in the condensed phase. Comparison of the experimental data and calculated photoluminescence spectra of EHL allow determination of its main parameters, e.g., the equilibrium density, work function for pairs of particles, and light hole—heavy hole splitting at the G-point of the Brillouin zone for quantum wells that are 3.7–5.1% Ge.

DOI: 10.3103/S1062873818040135

INTRODUCTION

Components containing quantum-dimensional heterostructures are now widely used in electronics. For instance, quantum wells (QWs) are used as channels in high electron mobility transistors (HEMTs). The spatial separation of 2D electron gas (2DEG) and dopants allows us to obtain record operating frequencies in devices operating on the basis of this principle. Such components are widely used in high-frequency radio electronics, including wireless communication. Work is now under way to create and develop microelectronic components with 2D electron (or hole) channels based on graphene, monolayers of transition metal chalcogenides, gallium nitride, silicon-germanium (SiGe) heterostructures, and so on.

Apart from DEG consisting of carriers of one type, we can obtain dense 2D plasma of charge carriers in heterostructures with quantum wells. Such plasma is a degenerate two-component gas. At low temperatures in such plasma, a quantum transition can occur that produces exciton gas and spatially bound regions of degenerate plasma—i.e., an electron—hole liquid (EHL). Unlike 2DEG, EHL consists of charge carriers of both signs and coexists with exciton gas.

A curious feature of multiparticle states (including an EHL) in SiGe heterostructures is the possibility of registering their luminescence in both the IR and visible bands. Such radiation is observed in the simultaneous recombination of two holes and two electrons from opposite valleys [1]. Since the energy of the emitted quantum is in this case close to the double width of the forbidden band, it is referred to as $2E_g$-luminescence. Simultaneous registration of photoluminescence spectra in the IR and visible bands is very informative when analyzing the electron spectrum of multiparticle states in a SiGE/Si quantum well. This is because analysis of the emission spectrum of two-component Fermi liquid in particular enables us to investigate experimentally the density of states and the mechanisms of scattering of carriers in quantum wells, which is important for understanding the fundamental properties of DEG in such structures.

A fine structure in the EHL spectrum in a QW of $Si_{1-x}Ge_x$ with $x = 4.5\%$ was recently observed in both the visible and IR bands [2]. The shape of the condensed phase line was explained in terms of a multicomponent Fermi liquid containing both heavy and light holes. Joint analysis of $2E_g$ and IR luminescence spectra allowed us to determine the energy of the ground states for each type of holes, working function, and EHL density. The main reason for hole-state splitting is the embedded strain fields in pseudomorphous SiGe films. We can alter the strain and thus the valence-band splitting in two ways: the first approach is to apply compensating uniaxial pressure to the heterostructure; the second is to use samples with quantum wells of different composition. In this work, we analyze the effect the composition of SiGe solid solution has on the properties of quasi-two-dimensional EHL. The experimental technique and approach used to approximate the experimental data fully correspond to those described in [2].

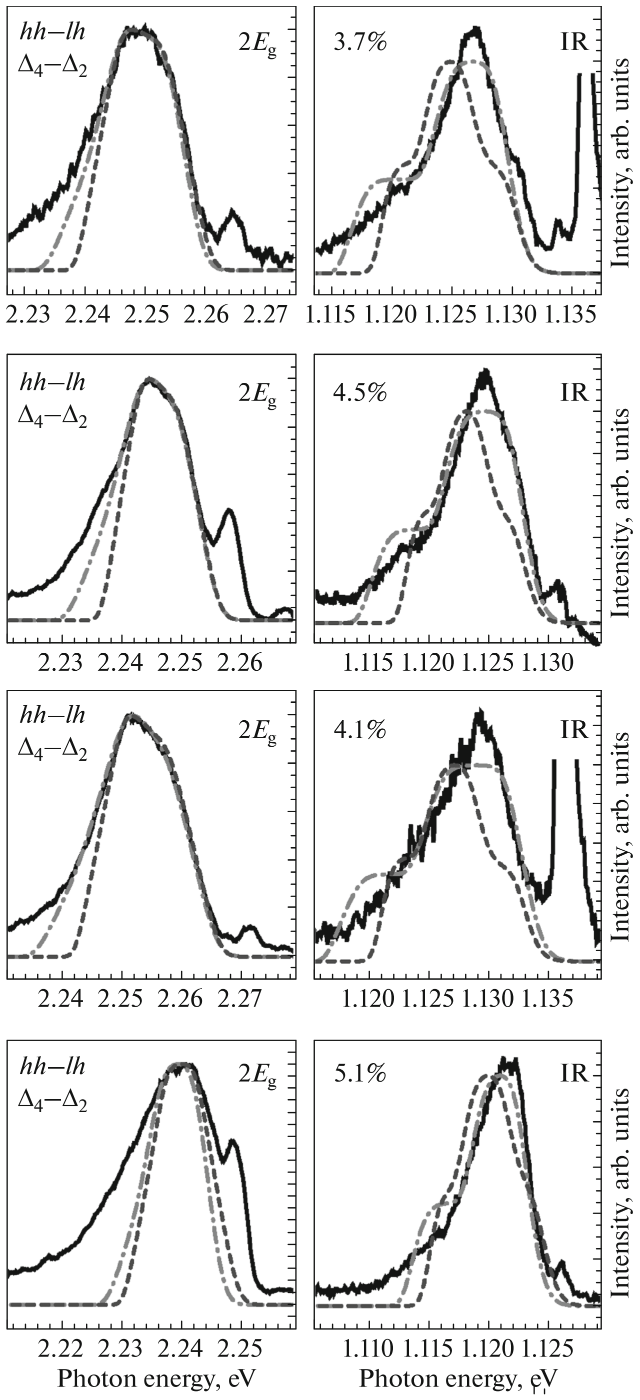

Fig. 1. Emission spectra in the visible ($2E_g$) and IR bands for the structures with SiGe/Si quantum wells with Ge concentrations of 3.7–5.1% at an excitation density of 0.1 W cm^{-2} and a temperature of 5 K (solid lines). The curves are an approximation of the experimental data by the model of a liquid with light and heavy holes *lh–hh* (Δ_4 and Δ_2 electrons).

EXPERIMENTAL

The investigated samples were SiGe/Si-heterostructures with single QWs of SiGe, grown by means of molecular-beam epitaxy. The QW width was 5 nm in all the structures. The solid solution composition varied from 3.7 to 5.1%. To analyze the EHL electron spectrum in a SiGe QW, we used a setup that allowed us to measure simultaneously the spectra of photoluminescence structures in the visible and near-IR bands [2]. Photoluminescence structures were analyzed on an ActionSpec SP2500 grating spectrometer with subsequent detection by a cooled PyLoN CCD matrix. The samples were placed in a flow helium cryostat, allowing optical measurements in the temperature range of 4.2–300 K.

RESULTS AND DISCUSSION

Figure 1 shows the EHL emission spectra in the visible ($2E_g$) and infrared (IR) bands at an excitation density of 0.1 W cm^{-2} and a temperature of 5 K. Under such conditions, the EHL line predominates, allowing us to analyze it in detail and estimate the main EHL parameters. The weak short-wave peak observed in the $2E_g$ spectra in each of the investigated samples corresponds to the biexciton luminescence.

The IR spectrum of EHL in a first-order approximation is a convolution of the electron and hole distribution functions in the condensed phase. The long-wave step in the EHL emission line in the IR spectra is thus clear evidence of patterns in the density of states. This step is most distinct for the sample with a germanium content of 4.5%. The rough profile of the step is due to the homogeneous broadening that emerges due to the short lifetime of excited states generated during the recombination of holes with energies much lower than the Fermi energy [3].

The $2E_g$ spectrum can be qualitatively described by a double convolution of the electron and hole distribution functions [2, 4]. The steps in the density of states for the EHL emission in the visible band are thus apparent as kinks in the spectral line contour. As with IR spectra, homogeneous broadening results in some smearing of these kinks. However, signs of patterns in the density of states are observed for the $2E_g$ spectra of each investigated sample.

The patterns in the combined density of states that determines the shape of the EHL line could be due to both the electron and hole subsystems [2]. In the first case, an additional step appears as a result of electron valley splitting (Δ_2–Δ_4) in the SiGe layer; in the second case, it results from the coexistence of heavy and light holes (*hh–lh*) in EHL. The choice between the two models of EHL can be made on the basis of a simultaneous approximation of the shape of the EHL line in the IR and $2E_g$ spectra.

The lines in Fig. 1 are an approximation of the shape of the EHL line in the IR and visible bands by one set of parameters in terms of the *lh–hh* (Δ_2–Δ_4) model for the combined density of states. These parameters are the concentration of carriers in EHL,

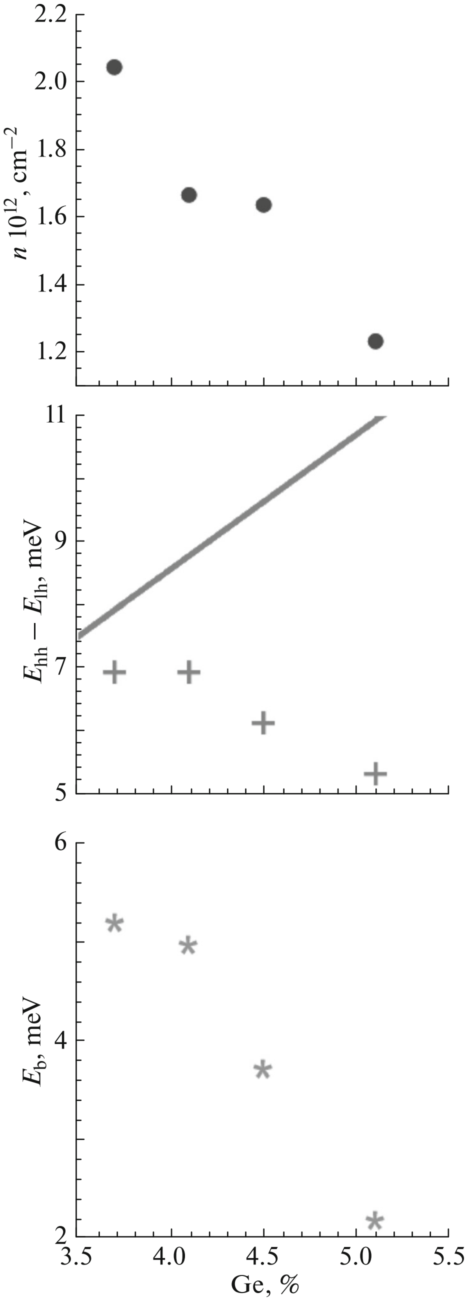

Fig. 2. Dependence of EHL density, light hole–heavy hole splitting in the center of the Brillouin zone, and the bonding energy of the condensed phase of a pair of particles, depending on a SiGe layer's composition. The solid line is the theoretical dependence of the splitting in a strained layer of solid solution with the same composition.

electron- or hole-state splitting (depending on the model), and the binding energy of carriers in EHL. The only independent parameter for the IR and $2E_g$ spectra is the scale factor that determines the ratio of the emission intensities in the corresponding bands. The details of this approach and the necessary mathematical manipulations were described in [2].

As we can see from Fig. 1, the Δ_2–Δ_4 model, which assumes discontinuity in the density of states for the electron subsystem, describes the $2E_g$ spectra satisfactorily; however, it does not reproduce even qualitatively the shape of the IR-emission line. At the same time, the *hh*–*lh* model, which assumes discontinuity in the hole density of states, allows us to describe qualitatively the shape of the emission line in both the IR and $2E_g$ spectra. We may therefore state that the EHL spectrum in the first-order approximation is determined by the hole subsystem, while electron valley splitting plays no significant role.

It should be noted that the *lh*–*hh* model, while providing a qualitative description of the shape of the EHL emission line, does not allow us to quantitatively describe the line in the IR spectra. This can be explained by the electron–hole correlations in the vicinity of the Fermi surface, the broadening of one-electron states far from the Fermi surface, and the superposition of exciton radiation and the short-wave wing of the FHL line (in the IR spectra).

Figure 2 shows the working functions for EHL, its density and hole-state splitting, depending on the structure composition. These values were determined by approximating the shape of the emission line in terms of the *lh*–*hh* model. For hole-state splitting, we can also see the theoretical dependence obtained for a strained layer of a solid solution; it displays an inverse dependence on the Ge content. These results show the approach of the hard shift of hole subzones cannot be used to describe the electron spectrum of a quasi-two-dimensional EHL in a SiGe/Si quantum well.

As can be seen from Fig. 2, the equilibrium concentration of EHL and the bonding energy of a pair of particles diminish as the Ge concentration grows. The latter is expected, since EHL becomes unstable with growing Ge concentration [5]. One unexpected result is the observed reduction in splitting between light and heavy holes as the Ge concentration in a QW grows. This could be a consequence of the complicated dependence of the exchange-correlation energy for two hole subzones in an EHL.

CONCLUSIONS

The emission spectra of an EHL localized in shallow SiGe/Si quantum wells were obtained experimentally. Based on an approximation of the shape of the EHL emission line in the IR and visible bands by a set of parameters, it was shown that patterns observed in the spectra of two-particle (IR band) and four-particle (visible band) recombination are explained by the presence of both heavy and light holes in the condensed phase. Comparison of the calculated and experimental photoluminescence spectra of EHL allowed us to determine its main parameters (density and working function for a pair of particles) and the light hole–heavy hole splitting at the G-point of the Brillouin zone for quantum wells that were 3.7–5.1% Ge.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research and the government of Krasnodar krai, project no. 16-42-230280; and by the President of the Russian Federation for the State Support of Young Russian Scientists and Candidates of Science, grant no. MK-2332.2017.2.

REFERENCES

1. Steiner, T., Lenchyshyn, L., Thewalt, M., et al., *Solid State Commun.*, 1994, vol. 89, p. 429.
2. Nikolaev, S.N., Krivobok, V.S., Bagaev, V.S., Onishchenko, E.E., Novikov, A.V., and Shaleev, M.V., *JETP Lett.*, 2016, vol. 104, p. 163.
3. Bagaev, V.S., Zaitsev, V.V., Krivobok, V.S., Lobanov, D.N., Nikolaev, S.N., Novikov, A.V., and Onishchenko, E.E., *J. Exp. Theor. Phys.*, 2008, vol. 107, no. 5, p. 846.
4. Burbaev, T.M., Kozyrev, D.S., Sibeldin, N.N., and Skorikov, M.L., *JETP Lett.*, 2013, vol. 98, no. 12, p. 823.
5. Bagaev, V.S., Krivobok, V.S., Nikolaev, S.N., Onishchenko, E.E., Skorikov, M.L., Novikov, A.V., and Lobanov, D.N., *JETP Lett.*, 2011, vol. 94, no. 1, p. 63.

Translated by E. Smirnova