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PHYSICS OF SEMICONDUCTOR DEVICES

Electroluminescence of InAs/InAs(Sb)/InAsSbP LED Heterostructures in the Temperature Range 4.2–300 K

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Abstract—The electroluminescence of InAs/InAsSbP and InAsSb/InAsSbP LED heterostructures grown on InAs substrates is studied in the temperature range $T = 4.2$–300 K. At low temperatures ($T = 4.2$–100 K), stimulated emission is observed for the InAs/InAsSbP and InAsSb/InAsSbP heterostructures with an optical cavity formed normal to the growth plane at wavelengths of, respectively, 3.03 and 3.55 μm. The emission becomes spontaneous at $T > 70$ K due to the resonant "switch-on" of the CHHS Auger recombination process in which the energy of a recombining electron–hole pair is transferred to a hole, with hole transition to the spin–orbit-split band. It remains spontaneous up to room temperature because of the influence exerted by other Auger processes. The results obtained show that InAs/InAs(Sb)/InAsSbP structures are promising for the fabrication of vertically emitting mid-IR lasers.

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1. INTRODUCTION

It is known that the characteristic absorption bands of numerous chemical compounds (CH_4, CO_2, NO_2, H_2S, CO, etc.) lie in the mid-IR spectral range (wavelengths 2–6 μm). Sensors for these compounds are in demand both for monitoring the state of the atmosphere and for use in industrial production. The most promising are optical IR sensors based on light-emitting diodes (LEDs). Compared with thermal sources of light, LEDs have a higher operation speed, smaller size, lower power consumption, longer service life, and lower cost when mass produced. LEDs for the mid-IR spectral range are commonly fabricated on the basis of narrow-gap semiconductor compounds and III–V solid solutions [1].

To raise the operating efficiency of optoelectronic devices, it is necessary to have a full understanding and control of processes occurring upon the generation or absorption of light in these devices. For this purpose, it is useful to examine the operation of device structures not only at their working temperature (which is commonly room temperature), but also at lower temperatures. In this case, it becomes possible to observe effects that can serve to more precisely determine the mechanisms of processes occurring in the structures. For example, the appearance of a stimulated emission peaked at $\lambda = 3.0$ μm was earlier observed upon cooling to $T = 77$ K in flip-chip LEDs based on InAsGaP/InAs/InAsGaP double heterostructures that were grown on InAs substrates and emitted light at a wavelength of $\lambda = 3.4$ μm at a working temperature of $T = 300$ K [2]. We have recently observed the same effect at $T = 77$ K for narrower gap structures with an InAsSb active region, also grown on an InAs substrate. In our structures, the active region was bounded by an InAsSbP barrier layer only on one side (i.e., the structure had the form InAs/InAsSb/InAsSbP) [3]. No effect of stimulated emission at $T = 77$ K has been observed in similar structures with an InAs active region, for which a higher quantum efficiency would be expected. A study of this phenomenon seems to be topical as regards both improving the efficiency of LED structures and developing semiconductor lasers for the mid-IR spectral range. Therefore, we examine the electroluminescence (EL) from structures of this kind in a wide range of temperatures, from that of liquid helium ($T = 4.2$ K) to room temperature, and report the results in the present work.

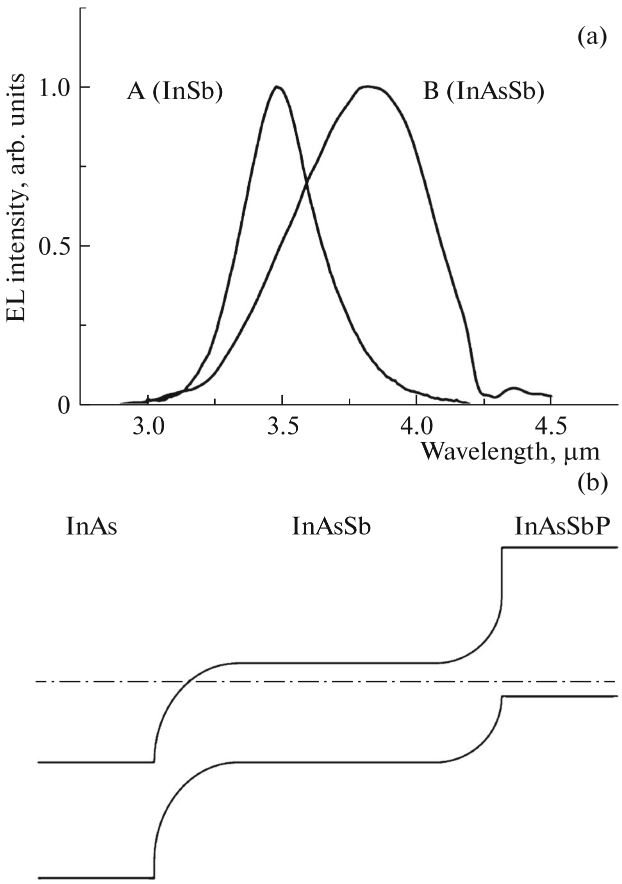

Fig. 1. (a) EL spectra of type-A and -B heterostructures at $T = 300$ K and (b) band diagram of a type-B heterostructure at $T = 300$ K. The dot-dash line shows the Fermi level in equilibrium (in the absence of bias).

2. EXPERIMENTAL

The heterostructures were grown by metal-organic vapor-phase epitaxy at Microsensor Technology (Russia) by a procedure similar to that described in [4]. To fabricate heterostructures on an *n*-InAs substrate (S-doped, electron concentration $n \approx 2 \times 10^{18}$ cm^{-3}), an InAs (type-A structures) or $InAs_{0.93}Sb_{0.07}$ (type-B structures) active layer with a thickness of 6–8 µm was grown. This layer was *n*-type with an electron concentration of 2×10^{16} cm^{-3}. Growth of the heterostructures was completed with the deposition of a barrier layer: $InAs_{0.15}Sb_{0.31}P_{0.54}$ for type-A structures and $InAs_{0.70}Sb_{0.10}P_{0.20}$ for type-B structures. The barrier layer was doped with an acceptor impurity (Zn) to a hole concentration of 2×10^{18} cm^{-3}.

Light-emitting chips (0.38 × 0.38 mm) were fabricated by standard photolithography and wet chemical etching. A contact system based on the multilayer composite Cr–Au–Ni–Au was used. A solid contact was formed on the epitaxial side of the structure, and a ring contact with a width of 35 µm and an inner diameter of 200 µm, on the InAs substrate. Thus, emission was extracted from the heterostructure through the heavily doped (and, therefore, transparent to this light) InAs substrate. The samples were mounted in TO-18 cases.

We examined the EL spectra of the structures under pulsed excitation with a pump current of up to 4 A, a pulse-repetition rate of 1 kHz, and a pulse width of 1 µs. The signal was recorded with a BCI280 lock-in detector and a cooled InSb photodiode. During measurements, the samples were situated in a helium cryostat. The temperature in the cryostat was monitored with a germanium thermally sensitive resistor and a copper–constantan thermocouple. The spectra were recorded with an MDR-23 monochromator.

3. EXPERIMENTAL RESULTS

Figure 1a shows the normalized EL spectra of structures of both types at the LED working temperature $T = 300$ K. The spectra were recorded at a pump current of 1 A and had a form characteristic of LEDs with an InAs(Sb) active region. The typical full widths at half-maximum (FWHM) of the emission lines at $T = 300$ K were 280 nm for type-A structures and 430 nm for type-B structures. Figure 1b shows the band diagram of a type-B structure at $T = 300$ K, constructed in accordance with the principles presented in the monograph [5] and with parameters (band-gap width E_g of materials, electron affinity energy, etc.) taken from [6]. It can be seen in the diagram that the substrate material is distinctly degenerate, the *n*-type active region has a comparatively low electron concentration, and the *p*-type barrier layer has a high hole concentration. It would be expected that optical transitions in a structure of this kind at $T = 300$ K will occur with an energy corresponding to the $InAs_{0.93}Sb_{0.07}$ band-gap width of 0.303 eV, which corresponds to $\lambda = 4.09$ µm. In the experiment (Fig. 1a), the EL peak of a type-B structure corresponds to $\lambda = 3.83$ µm because the electron quasi-Fermi level goes upwards due to filling of the conduction band as a result of injection. In type-A structures, this effect was substantially less pronounced because of the wider band gap and heavier effective electron mass, and the emitted photon energy (355 meV) was close to the calculated value of E_g for the active region (354 meV).

Figure 2a shows the EL spectra of a type-A structure at $T = 4.2$ K and various pump currents. It can be seen here that a second, narrow line I_2 with an FWHM of 12 nm (~2 meV) appears on the short-wavelength edge of the broad emission band I_1 with an FWHM ~200 nm (~20 meV). This narrow line can be regarded as a stimulated emission band. A study of how the intensity of the lines depends on current at $T = 4.2$ K

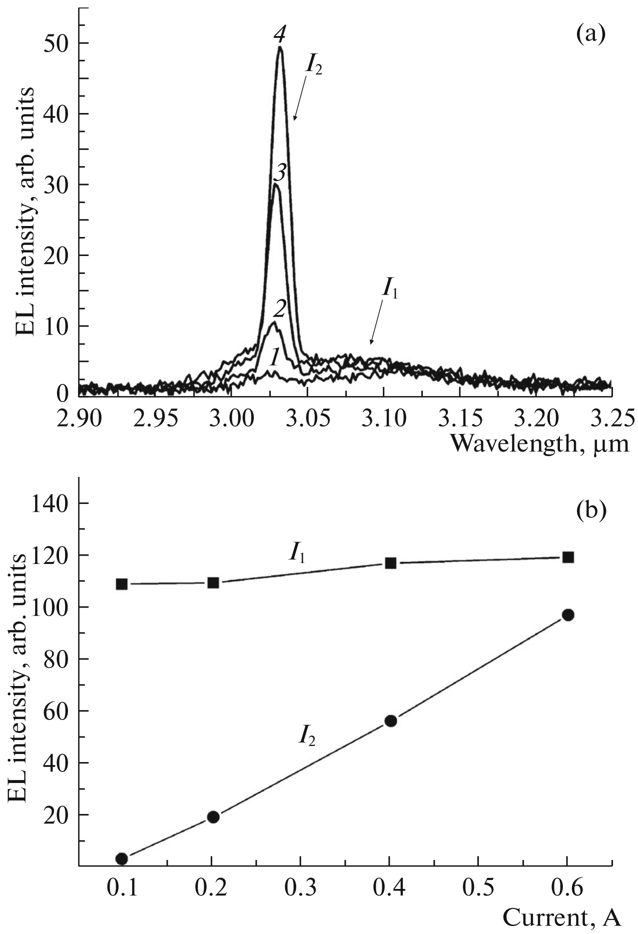

Fig. 2. (a) EL spectra of type-A heterostructure at T = 4.2 K at drive currents of (*1*) 0.1, (*2*) 0.2, (*3*) 0.4, and (*4*) 0.6 A and (b) dependences of the intensity of I_1 and I_2 lines on current.

demonstrated that, with the current raised from 0.1 to 0.6 A, the intensity of line I_1 increased only slightly, and that of line I_2 did so to a considerable extent (see Fig. 2b). As the temperature was raised from 4.2 to 70 K at a constant pump current of 0.6 A, the intensity of line I_2 became approximately three times lower, and that of lines I_1 increased by a factor of 1.5. Only one I_1 band peaked at $\lambda = 3.05$ μm remained in the spectrum at a temperature of ~70 K, with its intensity exceeding the integrated EL intensity at a temperature of 55 K. The EL intensity somewhat increased in the temperature range 70–85 K, and decreased above 85 K and up to 300 K, with the spectrum retaining its shape.

Figure 3 shows the temperature dependences of the energy position of the EL peaks for a type-A structure. The spectra were recorded at the same pump current I = 0.6 A. It can be seen that at T > 70 K the emission energy corresponds to E_g of the active region, calculated on the basis of data from [6]. At lower temperatures, when there are two peaks in the spectrum, their energies lie below the value of E_g.

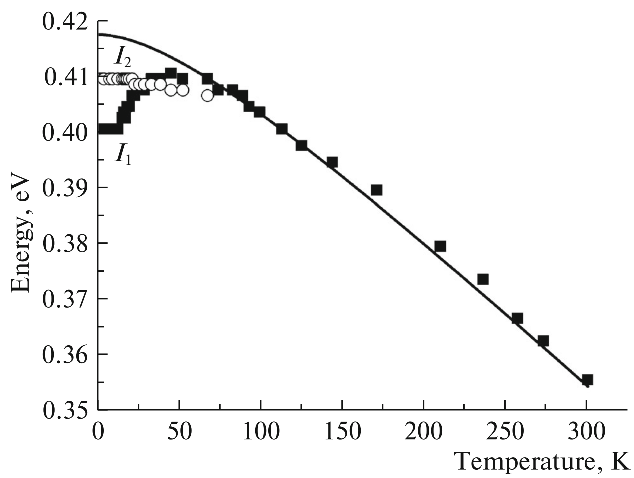

Fig. 3. Temperature dependences of the energy positions of the EL peaks for a type-A structure at a current of 0.6 A (points) and the calculated dependence $E_g(T)$ for the InAs active region (solid line).

Only narrow stimulated-emission peaks with FWHMs of about several nanometers were observed at nearly liquid-helium temperatures for the type-B (InAs/InAsSb/InAsSbP) structures (Fig. 4a). As the current was raised, the integrated intensity of the EL signal increased linearly and the peak maximum shifted to shorter wavelengths ("blue shift"), thereby apparently reflecting the ascent of the electron quasi-Fermi level. The stimulated-emission spectrum demonstrated a clearly pronounced mode structure, shown in Fig. 4b for the spectrum recorded at T = 77 K. Figure 5 shows the energy positions of the EL peaks as a function of temperature for one of the type-B structures under study. The spectra were recorded at the same pump current I = 0.2 A. At T > 100 K, the emitted photon energy for this structure was ~20 meV higher than the calculated value of E_g in the active region. As already mentioned, this can be attributed to the shift of the electron quasi-Fermi level into the conduction band and to the Moss–Burstein effect [3]. At T < 100 K, the energies of the emission peaks were close to E_g or were somewhat lower than this value.

4. DISCUSSION OF RESULTS

Analysis of the results obtained show that the conditions for the appearance of a stimulated emission were created in the heterostructures under study at low temperatures (4.2–100 K). If structures with an InAs active region are considered, a similar effect was reported, as mentioned above, in [2]. So far, the stimulated emission from narrower gap, compared with InAs, InAsSb solid solutions has been observed only in

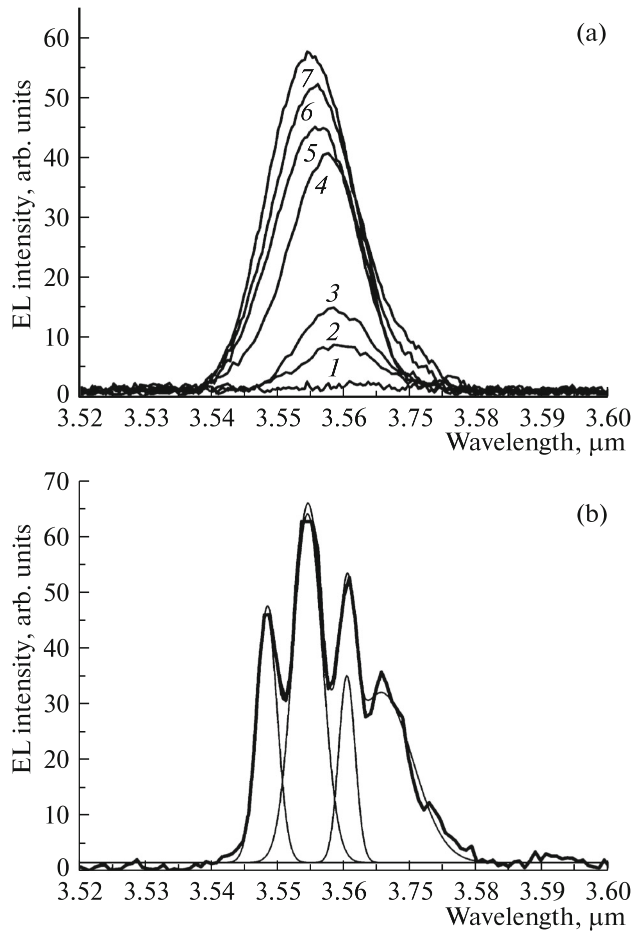

Fig. 4. (a) EL spectra of a type-B heterostructure at T = 4.2 K and pump currents of (*1*) 0.02, (*2*) 0.08, (*3*) 0.10, (*4*) 0.28, (*5*) 0.30, (*6*) 0.35, and (*7*) 0.40 A. (b) The spectrum at T = 77 K and a current of 0.2 A, in which the mode structure is seen. The thin lines in (b) show fitting to the spectrum and its decomposition into separate lines for the three left modes. The spacing between the modes is 6 nm. The FWHM of the lines is ~2 nm.

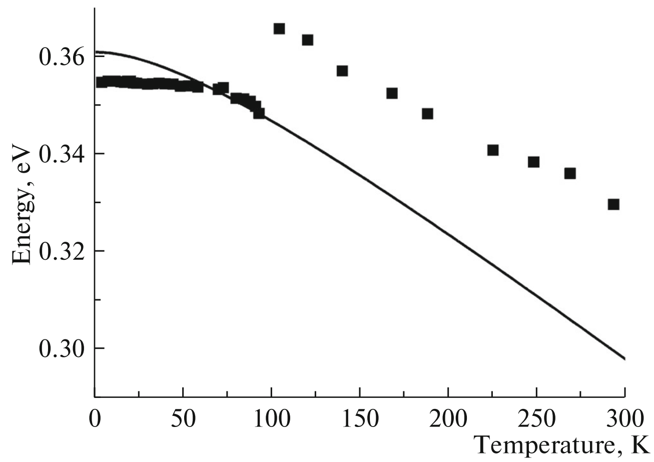

Fig. 5. Temperature dependence of the position of the EL peak for a type-B structure (points) and the calculated temperature dependence of E_g for the $InAs_{0.93}Sb_{0.07}$ active region (solid line).

specially fabricated laser structures and, in particular, in those with a strip-type cavity and electron confinement due to the fabrication of a double heterostructure with symmetric high barriers (see, e.g., [7–9]). In our case, however, no cavities were specially formed and the cleaved surfaces of the chips were not mirror-like. The data in Fig. 4b were used to determine the spacing between separate modes in the EL spectrum. It was 6 nm, which made it possible to estimate, by the procedure described in [9], the cavity length to be 280 μm. This value is far closer to the chip thickness (~300 μm) than to the distance between its cleaved surfaces (380 μm). In addition, it was found that, for type-B structures for which stimulated emission was observed at T = 77 K, the EL signal collected from the chip surface (InAs substrate) exceeded by several orders of magnitude that recorded in measurements from cleaved surfaces. Hence, an unambiguous conclusion could be made that the optical cavity was formed perpendicularly to the heterostructure layers, in all probability between the well-ground lower face of the crystal with the solid gold contact and the upper face that was chemically polished and formed the semiconductor/air interface similarly to the case described in [2]. In this case, the threshold current density for type-A structures at T = 4.2 K could be estimated to be j_{th} ~ 140 A/cm^2.

It is noteworthy that energy of the emitted photon, at which a transition from stimulated to spontaneous emission occurs with increasing temperature, coincides with the spin-orbit splitting Δ_{SO} in the heterostructures under study. For example, the energy $h\nu$ of the emitted photon for a type-A structure, which corresponds to the transition to spontaneous emission, was ~0.41 eV at Δ_{SO} = 0.39 eV (according to [6], where the range 0.37–0.41 eV was actually reported). The equality $h\nu \approx \Delta_{SO}$ corresponded to a temperature of ~75 K, which accounts for the fact that we observed no stimulated emission from type-A structures at T = 77 K [3]. In turn, the transition to spontaneous emission occurred for type-B structures at $h\nu \approx 0.36$ eV at calculated values of Δ_{SO} in the range from 0.33 to 0.37 eV. Thus, as the temperature increased and E_g of the active region became lower, there occurred the resonant “switching-on” of the CHHS Auger process in which the energy of a recombining electron–hole pair is transferred to a hole, with the transition of this hole to the spin-orbit-split band. This effect is well known for III–V narrow-gap semiconductors (see, e.g., [10–12]). As E_g decreased further with increasing temperature, the $E_g = \Delta_{SO}$ resonance disappeared and we observed some increase in the EL intensity. How-

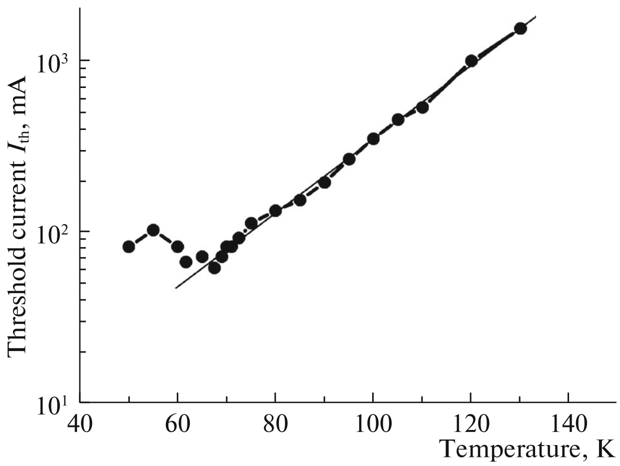

Fig. 6. Temperature dependence of the threshold current I_{th} at which stimulated emission appears for a type-B structure. The solid line is the result of fitting to the exponential portion of the dependence, used to determine the characteristic temperature.

ever, this EL was by this time a spontaneous emission due to the influence exerted by other Auger processes that suppress the gain. Further, as the rate of these processes became higher with increasing temperature, the EL signal again gradually decreased. In this case, the effect of the Auger processes was also manifested at lower temperatures. For example, we measured the light–current characteristics for type-B structures at temperatures at which stimulated emission is still observed. If a pronounced "break" is observed in the curve, j_{th} can be determined from the intercept formed by a characteristic of this kind on the abscissa axis [13]. Figure 6 shows an example of the dependence obtained in this way. For the sample under study, it was possible to obtain a pronounced $j_{th}(T)$ dependence in the temperature range 50–130 K. It can be seen that it was exponential in the portion ranging from 70 to 130 K (linear in the coordinates chosen for the figure). According to known concepts about the temperature dependence of the threshold current of a semiconductor laser, this is indicative of the predominance of nonradiative (Auger) recombination [14] (we emphasize once more that, in the case in question, we do not mean the CHHS process, but other forms of Auger processes and, in particular, that involving two electrons and a heavy hole, with an electron excited to a higher energy state, CHCC, and that involving two heavy holes and an electron, with a heavy-to-light hole transition, CHHL). The characteristic temperature of the threshold current was found to be 30 K for the 50–130 K range. No pronounced $j_{th}(T)$ dependence was observed for the 50–70 K portion, which could be indicative of the predominance of Shockley–Read recombination.

5. CONCLUSIONS

Thus, we observed the appearance of stimulated emission in studying the electroluminescence from InAs/InAs(Sb)/InAsSbP LED structures at low temperatures ($T = 4.2$–100 K). However, this effect disappeared with increasing temperature due to the resonant "switch-on" of the CHHS Auger-process, and the emission was spontaneous at $T > 70$ K for InAs/InAs/InAsSbP structures and at $T > 100$ K for InAs/InAsSb/InAsSbP structures because of the influence exerted by other Auger processes (CHHC, CHHL). The effect of the latter on recombination was also observed at low temperatures. The results obtained in the study demonstrate the following. First, the heterostructures under study are promising for the development of vertically emitting mid-IR lasers required for gas sensors operating in this spectral range [15]. Second, the problem of suppressing Auger recombination in light-emitting heterostructures based on III–V narrow-gap semiconductors is topical. An important conclusion consists in that, even if the recombination rate is limited by nonradiative processes in InAs/InAs(Sb)/InAsSbP heterostructures of simple design, it is possible to observe stimulated emission at the minimum requirements to the cavity.

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REFERENCES

1. *Mid-Infrared Semiconductor Optoelectronics,* Ed. by A. Krier, Springer Ser. in Optical Sciences, Vol. 118 (Berlin, Springer, 2006).
2. B. Matveev, N. Zotova, N. Il'inskaya, S. Karandashev, M. Remennyi, and N. Stus', Phys. Status Solidi C **2**, 927 (2005).
3. N. K. Zhumashev, K. D. Mynbaev, N. L. Bazhenov, N. D. Stoyanov, S. S. Kizhaev, T. I. Gurina, A. P. Astakhova, A. V. Chernyaev, S. S. Molchanov, Kh. Lipsanen, Kh. M. Salikhov, and V. E. Bugrov, Vestn. ITMO **16** (1), 57 (2016).
4. M. Sopanen, T. Koljonen, H. Lipsanen, and T. Tuomi, J. Cryst. Growth **145**, 492 (1994).
5. A. Milnes and D. Feught, *Heterojunctions and Metal–Semiconductor Junctions* (Academic Press, New York, 1972; Mir, Moscow, 1975).
6. I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, J. Appl. Phys. **89**, 5815 (2001).

7. B. Lane and M. Razeghi, J. Cryst. Growth **221**, 679 (2000).

8. A. P. Astakhova, T. V. Bez'yazychnaya, L. I. Burov, A. S. Gorbatsevich, A. G. Ryabtsev, G. I. Ryabtsev, M. I. Shchemelev, and Yu. P. Yakovlev, Semiconductors **42**, 228 (2008).

9. E. A. Grebenshchikova, N. V. Zotova, S. S. Kizhaev, S. S. Molchanov, and Yu. P. Yakovlev, Tech. Phys. **46**, 1125 (2001).

10. J. R. Lindle, J. R. Meyer, C. A. Hoffman, F. J. Bartoli, G. W. Turner, and H. K. Choi, Appl. Phys. Lett. **67**, 3153 (1995).

11. P. Adamiec, R. Bohdan, A. Bercha, F. Dybala, W. Trzeciakowski, Y. Rouillard, and A. Joullié, Phys. Status Solidi B **244**, 187 (2007).

12. K. J. Cheetham, A. Krier, I. P. Marko, A. Aldukhayel, and S. J. Sweeney, Appl. Phys. Lett. **99**, 141110 (2011).

13. N. L. Bazhenov, K. D. Mynbaev, V. I. Ivanov-Omskii, V. A. Smirnov, V. P. Evtikhiev, N. A. Pikhtin, M. G. Rastegaeva, A. L. Stankevich, I. S. Tarasov, A. S. Shkol'nik, and G. G. Zegrya, Semiconductors **39**, 1210 (2005).

14. V. N. Abakumov, V. I. Perel', and I. N. Yassievich, *Nonradiative Recombination in Semiconductors* (PIYad. Fiz. RAN, St.-Petersburg, 1997; North-Holland, Amsterdam, 1991).

15. A. B. Ikyo, I. P. Marko, K. Hild, A. R. Adams, S. Arafin, M. C. Amann, and S. J. Sweeney, Sci. Rep. **6**, 19595 (2016).

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