07.3

Two–state lasing in injection microdisks with InAs/InGaAs quantum dots

© *I.S. Makhov*[1], *A.A. Beckman*[2], *M.M. Kulagina*[2], *Yu.A. Guseva*[2], *N.V. Kryzhanovskaya*[1], *A.M. Nadtochiy*[1], *M.V. Maximov*[3], *A.E. Zhukov*[1]

[1] National Research University „Higher School of Economics“, St. Petersburg, Russia
[2] Ioffe Institute, St. Petersburg, Russia
[3] Alferov Federal State Budgetary Institution of Higher Education and Science, Saint Petersburg National Research Academic University of the Russian Academy of Sciences, St. Petersburg, Russia
E-mail: makhoviv@gmail.com

Received April 29, 2022
Revised May 4, 2022
Accepted May 4, 2022

Spectral dependencies of the electroluminescence intensity of a microdisk laser with a diameter of 31 μm with active region based on InAs/InGaAs quantum dots, operating in the continuous–wave regime, are investigated in a wide range of injection currents. Simultaneous lasing through the ground and excited states of quantum dots under intense excitation is demonstrated in injection microdisk laser for the first time. At low pumping powers lasing occurs via ground states of quantum dots only.

Keywords: microlaser, quantum dots, two–state lasing, ground state, excited state.

DOI: 10.21883/TPL.2022.06.53795.19242

Recently a great attention has been paid to studying and developing microdisk and microring lasers with high–Q whispering–gallery modes (WGM) based on A^3B^5 semiconductor compounds [1]. Such microlasers may be used as, for instance, light–emitting components of photonic integrated circuits. These microlasers employ as the active region self–organized quantum dots (QDs) that, being used, allow achieving low threshold current densities [2], stable operation at elevated temperatures [3], and high limiting direct–modulation frequencies [4]. In addition, sensitivity of microlasers with QDs as an active region to various epitaxial defects and surface recombination is significantly leveled down [5], which enables creation of microlasers monolithically or hybridly integrated with silicon [6].

The QD–based lasers are typically characterized by the optical amplification saturation attainable at the ground–state optical transition. As shown earlier for QD–based stripe lasers, lasing starts at the ground–state transition wavelength if the resonator optical loss does not exceed the saturated amplification [7]. However, even in this case the QD excited state occupancy will increase with injection current increasing above the lasing threshold, and, at a certain moment, an additional line of excited–state lasing will occur. Further increase in the pumping intensity leads to complete quenching of lasing via the ground–state transition, and lasing continues only through the excited states [8]. The two–state lasing, i. e. simultaneous emission of laser lines of the ground and excited states at strongly different wavelengths, can find practical application in optical data transmission with spectral information coding. For the QD–based microlasers operating with optical pumping, it was earlier observed that the lasing wavelength hops to the excited–state optical transition when the resonator size decreases [9]. To our knowledge, so far there is no information on observing lasing through the excited–state transition or two–state lasing in the QD–based injection microlasers.

The laser heterostructure was grown by molecular beam epitaxy on an n^+-GaAs substrate above the n^+-GaAs buffer layer 500 nm thick. The QD structures were created by deposition of 2.5 InAs monolayers followed by depositing $In_{0.15}Ga_{0.85}As$ (5 nm). The structure as a whole contained ten rows of QDs separated by 35 nm spacer layers of undoped GaAs. The QD–containing layers were confined by wide–bandgap emitter layers of *n*— and *p*-doped $Al_{0.25}Ga_{0.75}As$ 2.5 and 1.5 μm thick, respectively. In addition, the structure contained a highly doped p^+-GaAs contact layer 200 nm in thickness. Microdisk resonators about 31 μm in diameter and 6 μm in height (Fig. 1, *a*) were made from the laser heterostructure by photolithography and plasma chemical etching. Circular metal contacts to the p^+-GaAs layer were formed on the microresonator apexes by the AgMn/Ni/Au metallization. The solid metal *n*-contact AuGe/Ni/Au was applied on the side of the preliminary thinned–out substrate.

For measurements, the cleaved wafer with several microresonators was soldered onto a copper heatsink. The electrical connection with the microlaser *p*-contacts was realized using a Be–Cu microprobe. Power was fed to the microlasers from a stabilized DC source/meter Keithley 2401. The microlaser emission was collected by microobjective Mitutoyo MPlan x50 and directed with a lens into the optical fiber. The microlaser luminescence spectra were measured at room temperature by using optical spectrum analyzer Yokogawa AQ6370C (spectral resolution of 0.2 nm).

In the framework of the study, electroluminescence spectra of the InAs/InGaAs quantum dots were measured

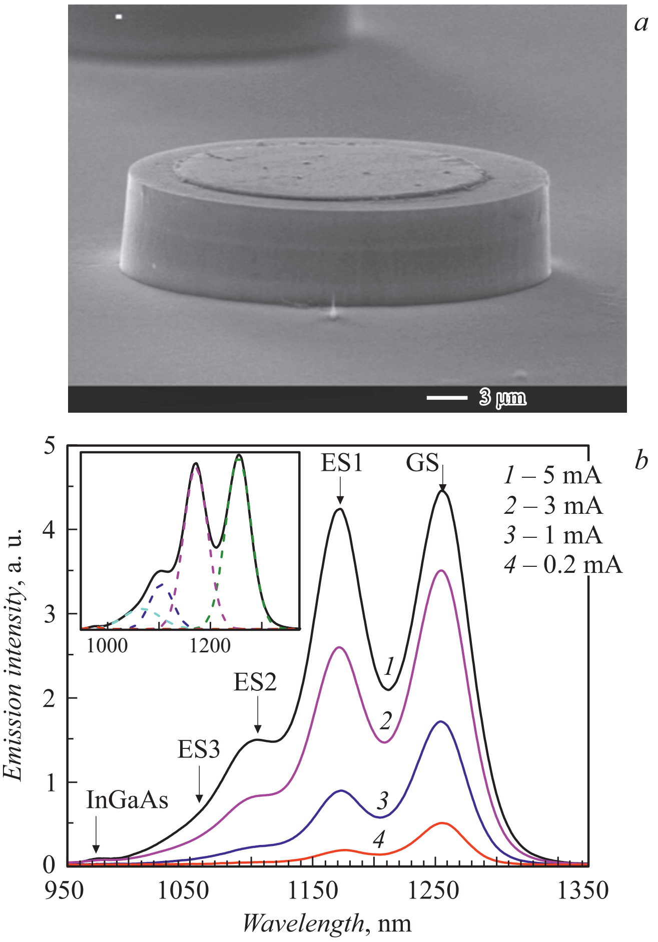

Figure 1. *a* — the scanning electron microscopy image of the microresonator; *b* — spontaneous luminescence spectra of the InAs/InGaAs quantum dots measured at different injection currents (indicated in the figure). The inset presents the Gaussian decomposition (dashed lines) of the luminescence spectrum measured at the 5 mA current.

in a wide range of injection currents. The spontaneous luminescence spectra (Fig. 1, *b*) exhibit several intense peaks typical of the InAs/InGaAs quantum dots [10]. The Gaussian decomposition of the luminescence band measured at the 5 mA current (see the inset to Fig. 1, *b*) allows more explicit monitoring of the existence of several emission bands associated with optical transitions involving one ground and three excited QD states, as well as bands associated with luminescence of the InGaAs quantum well covering the QD-containing layers (indicated in Fig. 1, *b* with arrows GS, ES1, ES2, ES3 and InGaAs, respectively).

The microlaser lasing onset is characterized by the appearance of narrow high-intensity stimulated-emission lines near the 1250 nm wavelength (which corresponds to the QD ground-state transition) at the injection current threshold of about 11 mA. The laser emission spectra measured near the lasing threshold (Fig. 2, *a*) exhibit several WGMs with the characteristic intermode interval of about 4.3 nm. An increase in the injection current results also in an insignificant (0.081 nm/mA) mode shift towards longer wavelengths (Fig. 3, *a*), which is connected with the microlaser self-heating. Using the experimentally obtained coefficient (0.075 nm/K) for the spectral mode shifting with temperature, it is possible to determine the coefficient indicative of the level of the microlaser heating with current, which equals approximately 1.1 K/mA. Further increase in the current results in sequential lasing intermode switching towards longer wavelengths, while the wavelength remains within the ground-state transition.

When injection currents are large, then, in addition to the ground-state transition lasing, a laser line near the 1191 nm wavelength arises, which relates to the first QD excited-state transition. Spectra of the microdisk laser emission measured near the lasing threshold for the QD excited-state transition are presented in Fig. 2, *b*. Threshold current of the two-state lasing is about 46 mA. Lasing

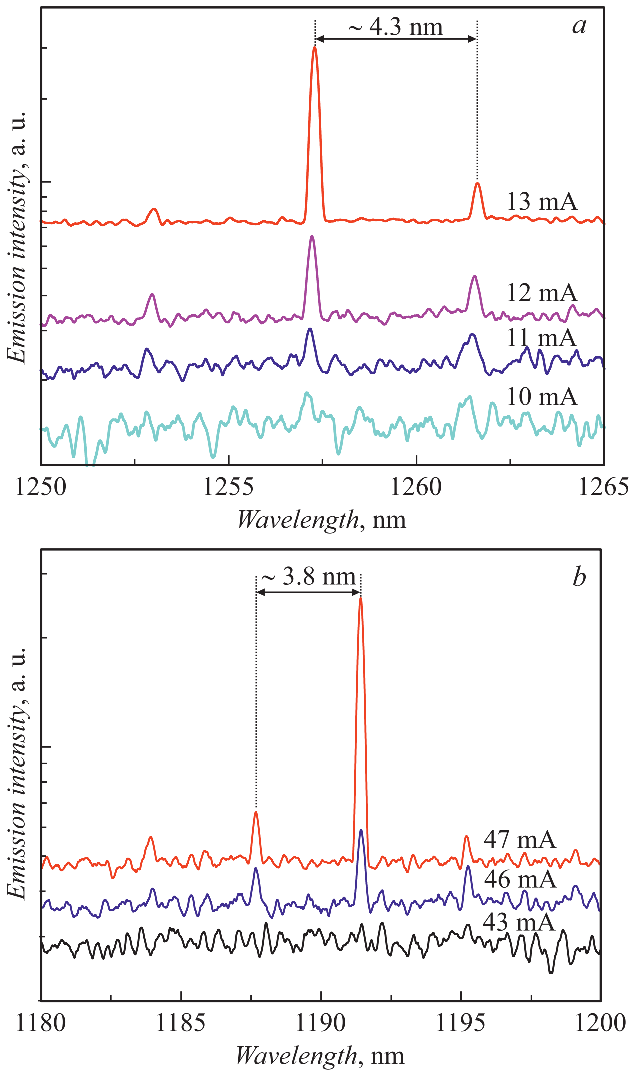

Figure 2. The microdisk laser luminescence spectra measured near the threshold of lasing with participation of the quantum dot ground (*a*) and first excited (*b*) states. For clarity, the curves in both panels are shifted vertically; the axis scales are different.

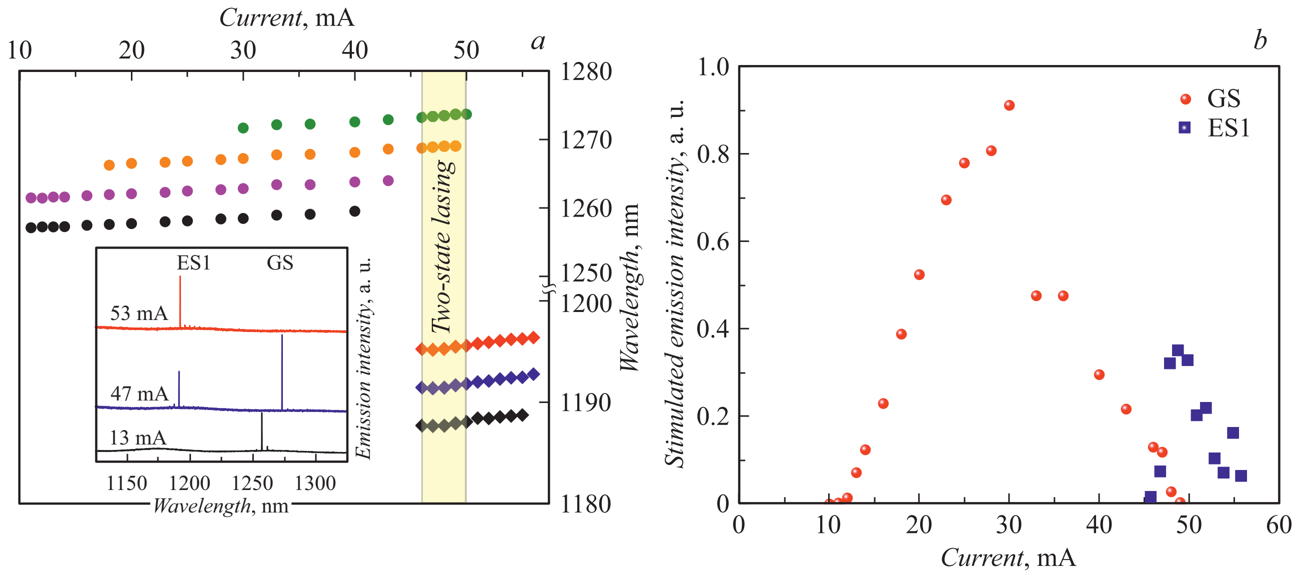

Figure 3. *a* — dependence of the spectral positions of the most intense laser modes on the injection current. The inset presents the microdisk laser emission spectra at different injection currents. For clarity, the curves are vertically shifted. *b* — injection current dependences of the stimulated emission intensity defined as the „under−curve"area for the laser modes during transitions involving the quantum dot ground (circles) and excited (squares) states.

involving QD excited states is characterized also by the presence in the emission spectrum of several WGMs with the characteristic intermode interval of about 3.8 nm.

The 46−50 mA range of currents contains simultaneously two stimulated emission lines caused by transitions involving the ground and excited quantum dot states (Fig. 3, *a* and *b*). When currents slightly exceed the two−state lasing threshold, laser lines of the ground−state and excited−state transitions have comparable intensities. When the injection currents are higher than 50 mA, there is only one stimulated emission line induced by the QD excited−state transitions (the Fig. 3, *a* inset and Fig. 3, *b*).

We associate the relative narrowness of the current range in which the two−state lasing is observed with the microlaser self−heating up to 60 degrees with respect to room temperature at high injection levels. It seems reasonable that reduction of the laser heating because of improvement of heat removal from the active region by, for instance, *p*-contact down mounting of the microlaser or by transferring the microlaser onto a silicon substrate [11] will result in a later kink in the microlaser watt−ampere characteristic and also in broadening of the current range where lasing involving simultaneously the QD ground and excited states is observed.

Thus, the paper presents the results of studies that have for the first time experimentally demonstrated the possibility of achieving two−state lasing involving the ground and excited quantum dot states in the microdisk injection lasers.

Financial support

Characteristics of the structures were studied in the framework of the NRU HSE Program of Fundamental Research. Fabrication of the structures was supported by the RF Ministry of Science and Higher Education (Project 0791-2020-0002).

Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] A.E. Zhukov, N.V. Kryzhanovskaya, E.I. Moiseev, M.V. Maximov, Light Sci. Appl., **10**, 80 (2021).
DOI: 10.1038/s41377-021-00525-6

[2] E.I. Moiseev, N.V. Kryzhanovskaya, F.I. Zubov, M.S. Mikhailovskii, A.N. Abramov, M.V. Maximov, M.M. Kulagina, Yu.A. Guseva, D.A. Lifshits, A.E. Zhukov, Semiconductors, **53** (14), 1888 (2019).
DOI: 10.1134/S106378261914015X

[3] N.V. Kryzhanovskaya, E.I. Moiseev, Yu.V. Kudashova, F.I. Zubov, A.A. Lipovskii, M.M. Kulagina, S.I. Troshkov, Yu.M. Zadiranov, D.A. Lifshits, M.V. Maximov, A.E. Zhukov, Electron. Lett., **51** (17), 1354 (2015).
DOI: 10.1049/el.2015.2325

[4] Y. Wan, D. Inoue, D. Jung, J.C. Norman, C. Shang, A.C. Gossard, J.E. Bowers, Photon. Res., **6** (8), 776 (2018).
DOI: 10.1364/PRJ.6.000776

[5] A. Fiore, M. Rossetti, B. Alloing, C. Paranthoën, J.X. Chen, L. Geelhaar, H. Riechert, Phys. Rev. B, **70** (20), 205311 (2004). DOI: 10.1103/PhysRevB.70.205311

[6] A.E. Zhukov, N.V. Kryzhanovskaya, E.I. Moiseev, A.S. Dragunova, M. Tang, S. Chen, H. Liu, M.M. Kulagina, S.A. Kadinskaya, F.I. Zubov, A.M. Mozharov, M.V. Maximov, Materials, **13** (10), 2315 (2020). DOI: 10.3390/ma13102315

[7] A. Marcus, J.X. Chen, C. Paranthoën, A. Fiore, Appl. Phys. Lett., **82** (12), 1818 (2003). DOI: 10.1063/1.1563742

[8] M.V. Maximov, Yu.M. Shernyakov, F.I. Zubov, A.E. Zhukov, N.Yu. Gordeev, V.V. Korenev, A.V. Savelyev, D.A. Lifshits, Semicond. Sci. Technol., **28** (10), 105016 (2013). DOI: 10.1088/0268-1242/28/10/105016

[9] M.V. Maximov, N.V. Kryzhanovskaya, A.M. Nadtochiy, E.I. Moiseev, I.I. Shostak, A.A. Bogdanov, Z.F. Sadrieva, A.E. Zhukov, A.A. Lipovskii, D.V. Karpov, J. Laukkanen, J. Tommila, Nanoscale Res. Lett., **9** (1), 3266 (2014). DOI: 10.1186/1556-276X-9-657

[10] M.V. Maximov, A.M. Nadtochiy, S.A. Mintairov, N.A. Kalyuzhnyy, N.V. Kryzhanovskaya, E.I. Moiseev, N.Yu. Gordeev, Yu.M. Shernyakov, A.S. Payusov, F.I. Zubov, V.N. Nevedomskiy, S.S. Rouvimov, A.E. Zhukov, Appl. Sci., **10** (3), 1038 (2020). DOI: 10.3390/app10031038

[11] F. Zubov, M. Maximov, E. Moiseev, A. Vorobyev, A. Mozharov, Yu. Berdnikov, N. Kalyuzhnyy, S. Mitairov, M. Kulagina, N. Kryzhanovskaya, A. Zhukov, Opt. Lett., **46** (16), 3853 (2021). DOI: 10.1364/OL.432920