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Multi-state lasing in microdisk lasers with InAs/GaAs quantum dots

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Abstract. The paper reports on the implementation of two-level lasing in injection microlasers with self-organized InAs/GaAs quantum dots. Emission bands related to the radiative electron-hole recombination involving ground and several excited states of quantum dots are observed in the spontaneous electroluminescence spectra. We investigated two-level lasing via the ground and first excited states of quantum dots in microdisks with different cavity diameters. A decrease in the threshold currents is observed for both ground and first excited transitions in quantum dots with a decrease in the microdisk diameter. The temperature dependences of the threshold current density for microdisks of various diameters suggest that two-level lasing is observed up to 90—100 °C.

Keywords: Two-state lasing, quantum dots, microdisks, electroluminescence

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Многоуровневая лазерная генерация в микродисковых лазерах с InAs/GaAs квантовыми точками

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Аннотация. В данной работе исследованы особенности реализации двухуровневой лазерной генерации в инжекционных микролазерах с активной областью на основе самоорганизованных InAs/GaAs квантовых точек. В спектрах спонтанной электролюминесценции обнаружены полосы излучения, связанные с оптическими электрон-дырочными переходами через основное и возбужденные состояния квантовых точек. Обнаружен спад пороговых токов для лазерной генерации через основное и первое возбужденное состояния квантовых точек при уменьшении диаметра микродискового лазера.

Исследованные температурные зависимости пороговых токов двухуровневой генерации в микролазерах демонстрируют возможность реализации двухуровневой генерации в InAs/GaAs квантовых точках вплоть до 90–100 °C.

Ключевые слова: Двухуровневая лазерная генерация, квантовые точки, микродиски, электролюминесценция

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Introduction

In the past decades, substantial progress has been achieved in the field of injection lasers with a quantum-dot (QD) active region. Self-organized InAs/GaAs quantum dots emitting in the spectral range of 1–1.3 μm allow to achieve low threshold current densities and sufficiently high temperature stability of laser characteristics [1], showing promise for applications in various fields including data transmission. Depending on the type of cavity, structures with the same active region may have different purposes and advantages. In particular, microdisk cavities supporting the propagation of whispering gallery modes also allow to reduce threshold currents, achieve small lateral sizes and reach high Q compared to Fabry-Perot cavities [2, 3]. Vertical-cavity surface-emitting lasers have the same advantages as microdisks, however, the ease of manufacture and the possibility of radiation output in the lateral direction make microdisk lasers promising radiation sources for use in photonic integrated circuits [4].

The effect of two-level lasing has been previously observed in lasers with an active region with quantum dots [5]. Lasing at relatively low pumping currents occurs upon the ground state (GS) transition of quantum dots, while lasing at high pumping levels occurs at a different wavelength, corresponding to the first excited-state (ES) transition of quantum dots. This effect can be used to increase the data transmission rate by introducing spectral coding. However, the implementation of two-level generation in injection microdisk lasers has not been studied to date. For this reason, this work considers the effect of two-level lasing in microdisk lasers with quantum dots.

Materials and Methods

The heterostructure for microlasers was grown by molecular beam epitaxy on an n-GaAs substrate with a 500 nm thick GaAs buffer layer doped with donors with a concentration of $3 \cdot 10^{18}$ cm^{-3}. Then an n-emitter of n-Al$_x$Ga$_{1-x}$As was grown with a thickness of about 2500 nm. An active region of the heterostructure was represented with 10 layers of self-assembled InAs quantum dots separated from each other with 35 nm thick GaAs layers. Finally, a p-emitter of a 2200 nm thick p-Al$_x$Ga$_{1-x}$As layer and a p-GaAs of 200 nm thick contact layer were grown over the active region.

Microdisk cavities with diameters of 12, 16, 20, 24, 28 and 32 μm were formed from the grown heterostructure using a photolithography and plasma chemical etching processes. Multilayered metallic contacts were also deposited on both sides of the heterostructure.

Electroluminescence spectra of the microlasers were obtained in pulsed-current mode (300 ns, 4 kHz). Individual electric contact to each microlaser was achieved with a conductive microprobe. The radiation of microlasers was collected by a 50x objective supplemented with an optical fiber, the output of which was located in front of the entrance slit of the Andor Shamrock 500i grating monochromator. Detection of radiation was carried out by a TE-cooled InGaAs array.

Temperature measurements were carried out with a PID-controlled heater built-in into the measuring table.

Results and Discussion

For the initial analysis of the structures, the spectra of spontaneous electroluminescence in the structure without a cavity were measured. The emission spectrum measured at a high current density of about 23 kA/cm^2 is shown in Fig. 1. It is seen that the spectrum can be well approximated by 4 Gaussian functions, which correspond to the ground (GS in Fig. 1) and first, second and third excited (ES1, ES2, ES3 in Fig. 1, respectively) state optical transitions in quantum dots. In addition, radiation from the wetting layer (WL in Fig. 1) of the structure is observed in the short-wavelength region of the luminescence spectrum. The obtained spectral positions of emission bands are in good agreement with studies of similar QD structures made by other scientific groups, however the designation of these excited optical transitions in different articles varies slightly (1st, 2nd ..., or GS, ES1 ...., or *s*-, *p*-, *d*- etc.) [6–8]. This characterization of the active region makes it possible to determine the spectral range where two-level lasing can be observed in the studied QDs.

Typical electroluminescence spectra measured at different injection currents for a microdisk laser with a diameter of 28 μm are shown in Fig. 2, *a*. Spontaneous electroluminescence is only observed at the lowest injection current. An increase in the current above 3 mA leads to the appearance of lasing lines (at 1160 and 1183 nm), that corresponds to the GS transition. These lasing lines correspond to different whispering gallery modes propagating in the microcavity. It is worth mentioning that the intensity of the spontaneous emission remains practically unchanged beyond the lasing threshold, which reflects the Fermi level pinning. With the further increase of the injection current up to 13 mA, lasing also occurs via the first ES transition of quantum dots at the wavelength of about 1099 nm. This corresponds to the beginning of two-state lasing. For microdisk lasers of other diameters, a similar behavior is observed, but with different threshold currents for the onset of GS and ES1 lasing. The lasing wavelength corresponded to the ES1 transitions in microdisks of other diameters lies in the range of 1090–1110 nm.

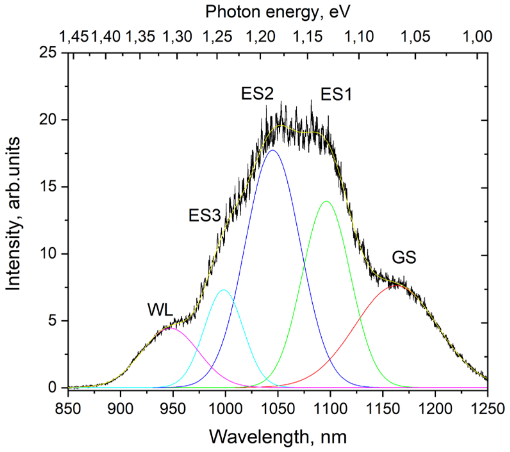

Fig. 1. Spontaneous electroluminescence spectrum from the active region of the structure, measured at the injection current density of about 23 kA/cm^2 and the room temperature

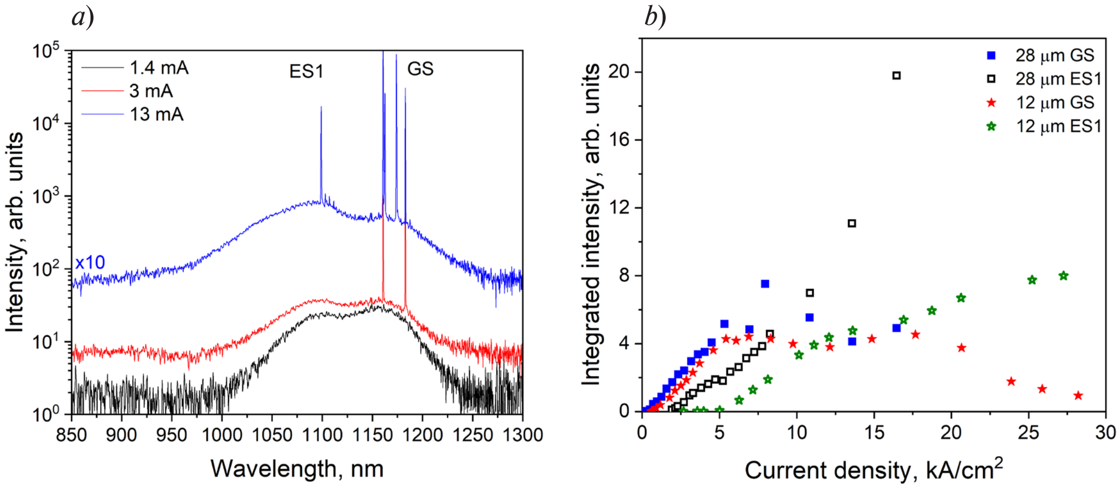

Fig. 2. Electroluminescence spectra of the microlaser with cavity diameter of 28 μm, measured at different pumping currents at the room temperature (*a*) and dependences of the integrated intensity of lasing modes for the GS and ES1 transitions on the current density for microlasers with cavity diameters of about 28 and 12 μm (*b*)

Fig. 2, *b* shows the dependences of the integrated emission intensity for the laser modes involving the ground and first excited states of quantum dots on the current density in microlasers with cavity diameter of 28 and 12 μm, obtained from the analysis of electroluminescence spectra, measured at the different injection currents. According to the Fig. 2, *b* and the abovementioned discussion, laser generation occurs at first for the ground-state optical transitions leading to the increase in its integrated intensity with the current density. At relatively high injection currents, lasing occurs for the optical transitions via the first excited state of quantum dots corresponding to the two-state lasing regime. At the same time, as certain current densities above the ES1 lasing threshold are reached, this results in saturation and subsequent decrease in the integrated stimulated emission intensity for the GS-induced optical transition for both 12 and 28 μm microdisk lasers. The observed decline of the GS lasing intensity is related to the effective depopulation of hole states in quantum dots due to the ES1 induced optical transitions. The energy distance between the lower hole states in the studied QDs is much lower than thermal energy at room temperature. In this case, the competition between electrons from the ground and first excited states of QDs for common holes is observed. However, due to the greater degeneration factor for the first excited state than for the ground state ones, ES1 induced optical transitions starts to dominate resulting in the decrease of the GS lasing intensity [9].

The dependences of threshold currents for the GS and ES1 lasing on the diameter of the microdisk cavities were investigated at room temperature. For each diameter, several microdisks were investigated. The obtained dependences of threshold currents for the ES1 and GS lasing on the diameter of microdisk lasers are shown in Fig. 3, *a*. As can be seen from the experimental data, a decrease in the diameter of the microdisk laser leads to a decrease in the threshold current for lasing at both ground and first excited optical transitions of quantum dots. Such a decrease in the threshold current for the GS lasing was already observed in Ref. [10]. In our case, the dependences of the threshold currents for GS and ES1 lasing on the microcavity diameter are almost quadratic leading to slight dependence of the threshold current densities on the microdisk diameter.

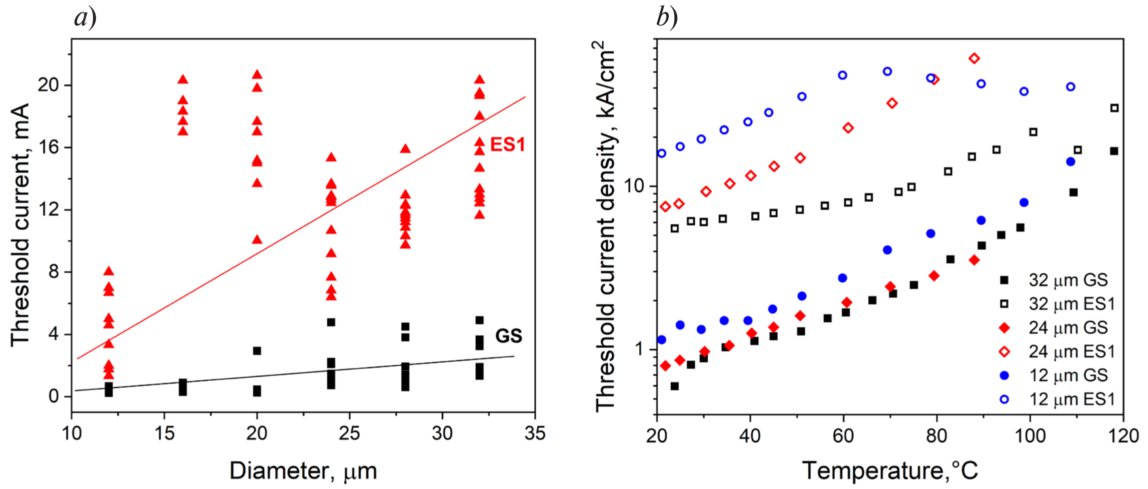

Fig. 3. Dependences of threshold currents for the ground and first excited induced optical transitions on the diameter of the microdisk lasers (*a*) and on the temperature for microdisks of different diameters (*b*). Solid lines in the left panel are guides for the eye

It is worth noting that a deviation of the threshold currents from the approximation curve based on the data for microdisks of other diameters is observed for microdisks with diameters of 16 and 20 μm. This spike is probably related to the deviation of the parameters of microlasers with cavity diameters of 16 and 20 μm from the technological parameters of microlasers of other sizes, arising at the stages of cavity formation by photolithography and plasma chemical etching.

It was also important to obtain the temperature dependences of the threshold current, which makes it possible to determine the optimal operating temperatures for different diameters of microdisks. The resulting dependences are shown in Fig. 3, *b* for the microdisks of different cavity diameters. The temperature increase leads to the increase in the threshold current density for both ground and first excited state transitions in all investigated microdisks. Such increase in the threshold current is associated with several factors. First, the increase in temperature results in the thermal broadening of the charge carrier distribution function and the corresponding redistribution of charge carriers between the states of quantum dots. Second, an increase in temperature leads to the increase in the equilibrium concentration of charge carriers in the waveguide layers of the structure, which leads to an increase in free carrier absorption and a corresponding increase in internal loss in microlasers.

It is worth noting that two-level lasing up to 90–100 °C is observed for all studied microlasers of different diameters. With a decrease in the size of microdisks the characteristic temperature remains constant for the GS lasing and is about 44 K. The decline of the characteristic temperature was observed for the excited state lasing with the cavity diameter decrease. We associate it with a greater influence microlaser self-heating in microdisks of smaller diameters at high injection currents corresponded to the ES1 lasing conditions. In addition to the above-mentioned effects, as the temperature increases, the probability of charge carriers escape from quantum dots is essential for the excited states of quantum dots, which also affects the growth of the threshold current with temperature.

Conclusion

We considered two-level lasing in injection microdisks with InAs quantum dots grown in the GaAs matrix. The two-level lasing emission involving ground and first excited states of quantum dots was detected in microlasers with cavity diameters of 12–32 µm. The dependences of integrated intensity of laser lines on the injection current for ground and first excited induced optical transition in quantum dots were studied. The emergence of the first excited state lasing leads to the decrease of the ground state lasing with the injection current increase. We have observed a decrease in the GS and ES1 threshold currents with a decrease in the microlaser cavity diameter. The temperature dependences of the current thresholds suggest that two-state lasing does not disappear with an increase in temperature up to 100 °C, however, there is an increase in the current density values.

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