

Single-mode lasing of lasers based on a vertical microcavity at room temperature

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Single-mode lasing at 300 K was achieved in vertical microcavity microlasers. For lasers with a semiconductor output mirror, the threshold pump power density was 6.5 kW/cm^2 . The quality-factor and emission wavelength, determined at the lasing threshold, were 8800 and $\sim 959.8 \text{ nm}$, respectively. Using a microcavity design with a hybrid output mirror allowed us to increase the quality-factor (to 12360) and decrease the threshold pump power density (to 6.0 kW/cm^2). For the microlaser with a hybrid output mirror, the mode-energy shift at a twofold excess of the lasing threshold was $220 \mu\text{eV}$.

Keywords: microlasers, vertical microcavity, quantum dots, Stranski–Krastanov mechanism, optical reservoir computing.

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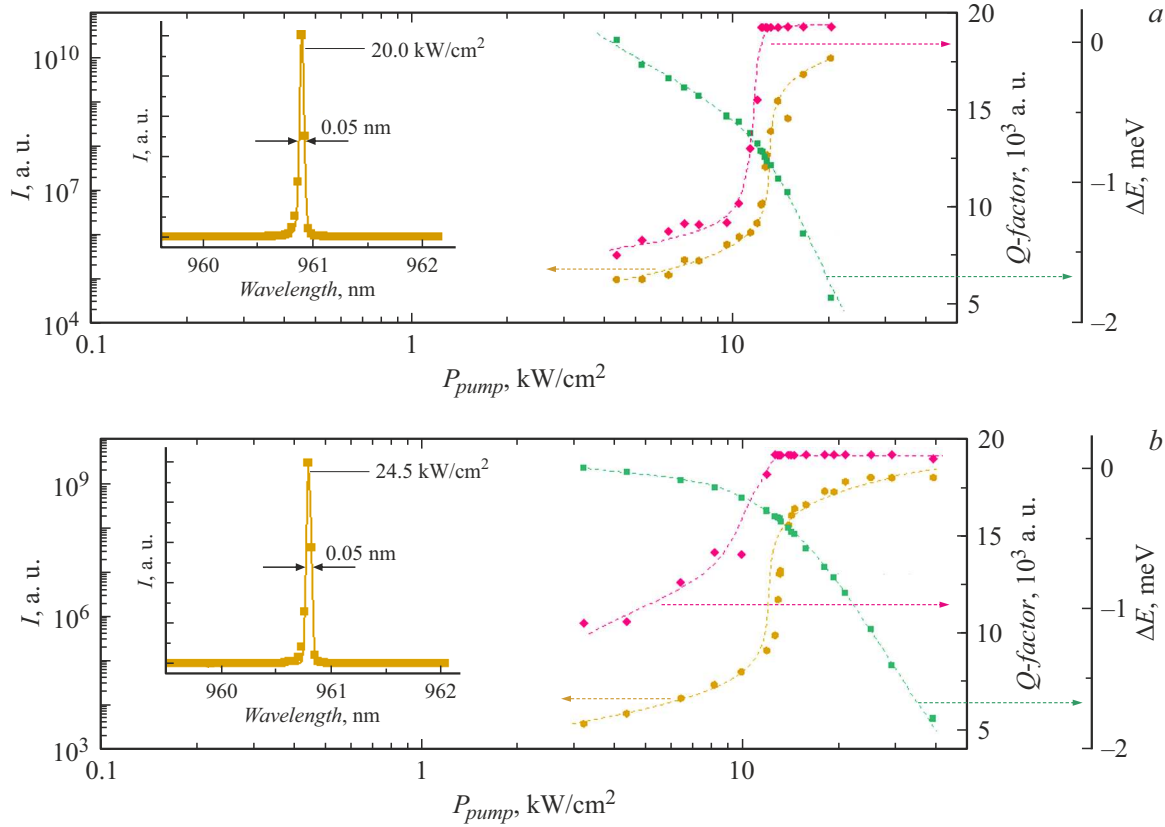
Vertical-microcavity surface-emitting lasers are promising as laser sources for implementing a photonic reservoir computing scheme [1–4], including diffraction-coupled lasers. Current-pumped and optically-pumped vertically-emitting lasers (VEL) may serve as radiation sources [4]. Diffraction coupling in a current-pumped VEL array is implemented both for monolithic VELs with a lasing wavelength of 980 nm [5–9] and for VELs with a lasing wavelength of 1300 nm [10,11] formed via a plate sintering technique [12–14]. Difficulty in compensating the lasing wavelength variation in the current-pumped VEL array [4] and a significant laser spacing on the plate [4] limit the maximum number of components in the array (24 lasers per array [8]).

Optically-pumped vertical microcavities can increase the packing density (microlaser spacing in the array is $\sim 8 \mu\text{m}$ [4]) by an order of magnitude compared with current-pumping VEL. Disadvantage of the approach for reservoir computing is in low operating temperatures (130 K for $\text{GaAs}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ mirror microcavities [15]). For structures grown via the molecular-beam epitaxy (MBE) technique, the use of low-loss mirrors (at a laser wavelength used for pumping) made it possible to implement microlasing at room temperature for the first time [16]. Moreover, a significant lasing line shift should be noted as the pumping level grows due to thermal heating of microlasers. In turn, the maximum temperature, at which lasing was demonstrated in microlasers formed via the vapor-phase epitaxy technique, is not higher than 200 K [17].

This paper describes experimental data on formation of vertical-microcavity lasers with lasing at room temperature, which provide a small lasing line shift with increasing optical pumping level.

MBE technique was used for high-quality vertical microcavity heterostructure epitaxy. GaAs microcavity with the optical length λ/n was formed on the basis of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ mirrors with 37.5 and 32.0 pairs in the upper and lower mirrors. An active region on the basis of three InGaAs quantum dot layers arranged using the Stranski–Krastanov mode of growth from a $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$ layer was used [16]. Lasers with a diameter of $15 \mu\text{m}$ were examined experimentally. For additional increase in the microcavity Q factor, a hybrid output mirror was formed, which allowed the microcavity Q factor (without considering the active region absorptin) to be doubled compared with the semiconductor microcavity Q factor [16]. Hybrid output mirror was formed via magnetron sputtering of two $\text{SiO}_2/\text{Ta}_2\text{O}_5$ pairs onto a semiconductor microcavity surface.

The Montana Instruments Cryostation s50 was used for optical measurements of samples. A semiconductor laser with a 808 nm radiation wavelength (continuous pumping mode) was used as an optical pumping laser. The Mitutoyo MPlan Apo NIR microlens was used for radiation focusing. The Andor Shamrock 500i grating monochromator was used for recording luminescence spectra. Diffraction grating (1200 lines/mm) provided a spectral resolution of the system of $\sim 0.05 \text{ nm}$. The Andor DU 401A BVF cooled silicon CCD matrix was used for signal acquisition.



Power dependence of the integral luminescence line intensity of the vertical microcavity with a semiconductor (a) and hybrid (b) output mirror (left axis) and dependences of the luminescence line FWHM and relative quantum energy shift ΔE with various optical pumping levels (right axes). Insets show single-frequency lasing spectra with a pumping power density of 20.0 kW/cm^2 (a) and 24.5 kW/cm^2 (b).

At 300 K, in luminescence spectra of microlasers with semiconductor and hybrid output mirrors, superlinear intensity growth was demonstrated in a long-wavelength line corresponding to the vertical microcavity resonance wavelength as the optical pumping level increased. The figure shows dependences of integral intensity and luminescence line FWHM at various pumping power densities for the vertical microcavity with a semiconductor (a) and hybrid (b) output mirrors (approximation using the Voigt function [16]). Insets show typical single-frequency lasing spectra.

The superlinear growth of luminescence peak radiation intensity at 958 nm with optical pumping level growth is demonstrated in Figure, a. S-shaped type of power curve (log-log) along with luminescence line narrowing indicates transition to lasing [16] in the microcavity with the semiconductor output mirror.

To evaluate the lasing threshold, input-output characteristic was approximated using the following expression [18–20]:

$$I(p) = A[Bp(1+\xi)(1+\beta Bp)/(1+Bp) - \xi\beta Bp],$$

where $I(p)$ are dependences of pumping intensity on the number of excitons in the microcavity p , $\xi = n_0\beta/\gamma\tau_{sp}$, $\gamma = 2\pi c/Q$, A and B is the input and output scaling factors,

β is the proportion of spontaneous radiation in induced radiation. n_0 characterizes the number of carriers at the pumping level corresponding to transparency, τ_{sp} is the spontaneous radiation lifetime, c is the speed of light, Q is the microcavity Q factor. Approximation of experimental curves is shown as dashed lines in the figure. Lasing threshold was evaluated assuming that the mean number of photons in the microcavity determined at the lasing threshold was equal to 1 [17]:

$$I = A[(1+\xi)(1+\beta)/2 - \xi\beta].$$

Threshold pumping power density (P_{th}) for the microlaser with the semiconductor output mirror was equal to 6.5 kW/cm^2 . Radiation wavelength and Q factor at the lasing threshold were 959.76 nm and 8800. Increase in the pumping level to $1.9P_{th}$ caused luminescence line narrowing at least to 0.05 nm . This FWHM of the lasing line meets the microcavity Q factor ≥ 19200 . Further increase in the optical pumping level up to $3.1P_{th}$ doesn't result in luminescence line narrowing, which is typical when using mirrors absorbing at the mirror pumping wavelength (GaAs/Al_{0.9}Ga_{0.1}As) due to significant sample heating.

To evaluate laser heating, lasing (quantum energy) line shift was analyzed as the optical pumping level increased (see Figure a). Two-fold exceedance of the lasing threshold

resulted in the quantum energy shift (ΔE) with respect to the lasing threshold ($-620 \mu\text{eV}$). This long-wavelength shift is 3.5 times as small as that for microlasers with a diameter of $5 \mu\text{m}$ [16], which is due to an increase in the laser diameter to $15 \mu\text{m}$ and, consequently, to lower heating for larger lasers similar to the case of current-pumped VEL [12]. Three-fold exceedance of the lasing threshold caused an increase in ΔE (with respect to the lasing threshold) to 1.46 meV . Taking into account the lasing line shift defined at the lasing threshold ($-71 \mu\text{eV/K}$), laser heating was evaluated. Three-fold increase in the pumping power density causes heating of $\sim 20^\circ\text{C}$.

For a microlaser with the hybrid output mirror, P_{th} was 6.0 kW/cm^2 (see Figure *b*). Radiation wavelength and Q factor at the lasing threshold were 960.0 nm and 12360 . Compared with the Q factor of the microlaser on the basis of the semiconductor output mirror, the microcavity Q factor was 1.4 times greater. Increase in the optical pumping level to $2.0P_{th}$ resulted in luminescence line narrowing at least to 0.05 nm . There was no lasing line broadening with a growth of the pumping level (to $6.0P_{th}$). It was shown that two-fold increase in the lasing threshold caused the quantum energy shift with respect to the lasing threshold equal to $220 \mu\text{eV}$ (compared with a shift of $620 \mu\text{eV}$ discussed for the microlaser with the semiconductor output mirror). This effect can be caused by an increase in the vertical microcavity Q factor and, consequently, by lower heating. As the pumping level grew to $6.0P_{th}$, the quantum energy shift with respect to the lasing threshold was 1.64 meV , which corresponded to estimated heating of $\sim 23^\circ\text{C}$. Further increase in the pumping power density (to 50 kW/cm^2) leads to heating ($\Delta E = 2.2 \text{ meV}$ with respect to the lasing threshold), which is 1.6–2.0 times lower than for microlasers with a diameter of $5 \mu\text{m}$ ($\Delta E = 3.5\text{--}4.5 \text{ meV}$) [16], which is due to lower heating for larger lasers as discussed above.

Thus, the paper describes the first results of lasing at room temperature in microlasers with a diameter of $15 \mu\text{m}$ on the basis of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ mirrors. For vertical microcavity designs on the basis of the semiconductor and hybrid output mirrors, lasing at 300 K was implemented. Increase in the vertical microcavity made it possible to reduce laser heating (caused by absorption in heterostructure layers during optical pumping) by a factor of 5 (with two-fold increase in the threshold [16]) compared with heating of $5 \mu\text{m}$ microlasers [16].

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Conflict of interest

The authors declare that they have no conflict of interest.

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