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Surface lasing in micropillar cavity lasers

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Lasing in vertical micropillar cavity lasers at a temperature of 244 K was demonstrated. The threshold absorbed optical power, lasing wavelength and quality factor of a $4\,\mu$m diameter micropillar laser were ~ 2.8 mW, 989 nm and 12000. The minimum threshold absorbed optical power ($250\,\mu$W) corresponds to a temperature of 168 K.

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

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Neuromorphic computing is one of the alternatives to the von Neumann architecture [1]. Simulation of biological neural systems holds promise for real-time training and ultra-fast image/pattern recognition tasks [2]. Reservoir computing (RC) is one of the high-performance types of neuromorphic computing [3–6], which is attributable to the capacity for effective system training through linear regression and classification [2]. Compared to electronic RC, optical RC is promising in terms of providing high speed (GHz bandwidth) and scalability [2,7]. An array of diffraction-coupled lasers is one possible system for implementation of optical RC [8]. Such an array may be formed from vertical-cavity surface-emitting lasers (VCSELs), but the maximum reservoir size is then limited to 24 elements by the low VCSEL density [9]. Vertical micropillar cavity lasers with optical pumping allow one to increase significantly the density of an array that provides diffraction coupling [2]. However, their lasing at room temperature has not been demonstrated. The maximum reported lasing temperature was 220 K [10].

The first experimental data on lasing of vertical micropillar cavity lasers at elevated temperatures (up to 244 K) are presented below.

The microcavity heterostructure was formed by molecular beam epitaxy. The top and bottom distributed Bragg reflectors (DBRs) included 35 and 27 pairs, respectively, of quarter-wave $Al_{0.2}Ga_{0.8}As/Al_{0.9}Ga_{0.1}As$ layers that do not absorb at the wavelength of pumping laser radiation. Three layers of quantum dots (QDs) were formed using the Stranski–Krastanov method from a $In_{0.5}Ga_{0.5}As$ layer. The QD layers were separated by GaAs barriers 20 nm in thickness to prevent coupling and were positioned at the center of a vertical microcavity with a length of $1\lambda/n$, where λ is the lasing wavelength and n is the effective refraction index. Contact lithography and dry etching methods were used to form microlasers. SiO_2/Ta_2O_5 layers served as an antireflective coating.

Temperature measurements of microphotoluminescence (microPL) spectra were performed with the samples held in a Montana Instruments Cryostation s50 optical cryostat. A semiconductor laser with a lasing wavelength of 808 nm provided optical pumping. A micro-objective with 100-fold magnification was used for pumping and radiation collection. The pumping spot size was $1-2\,\mu$m. An Andor Shamrock 500i grating monochromator with a focal length of 500 mm was used to record microPL spectra. Radiation was detected by a cooled Andor DU 401A BVF silicon CCD array. The use of a diffraction grating with 1200 lines per 1 mm ensured a spectral resolution of 0.05 nm.

The microPL spectra were measured within the temperature range of 77–260 K. At 77 K, a superlinear growth of luminescence intensity with increasing pumping level was observed for the 981 nm line (see the inset in Fig. 1). An *S*-shaped dependence of output optical power P_{out} on optical pumping power P_{pump} (power characteristic) was obtained. Combined with narrowing of the luminescence line (Fig. 1) at higher optical pumping levels, this is indicative of a transition to lasing [11–13]. The quality factor of the vertical microcavity near the threshold was 13 400, which exceeds the previously reported values of 12 200 for a microlaser with a diameter of $3.6\,\mu$m [11]. At a higher optical pumping intensity, the microcavity quality factor increased to $\sim 20\,000$ (note that this value is limited by the spectral resolution of the monochromator).

A similar *S*-shaped power characteristic was observed at temperatures of 168, 205, 226, and 244 K (Fig. 1). When the temperature was raised further to 260 K, a linear dependence of luminescence intensity on the optical pumping level was obtained. At 168, 205, 226, and 244 K, the quality factor of the microcavity determined near the

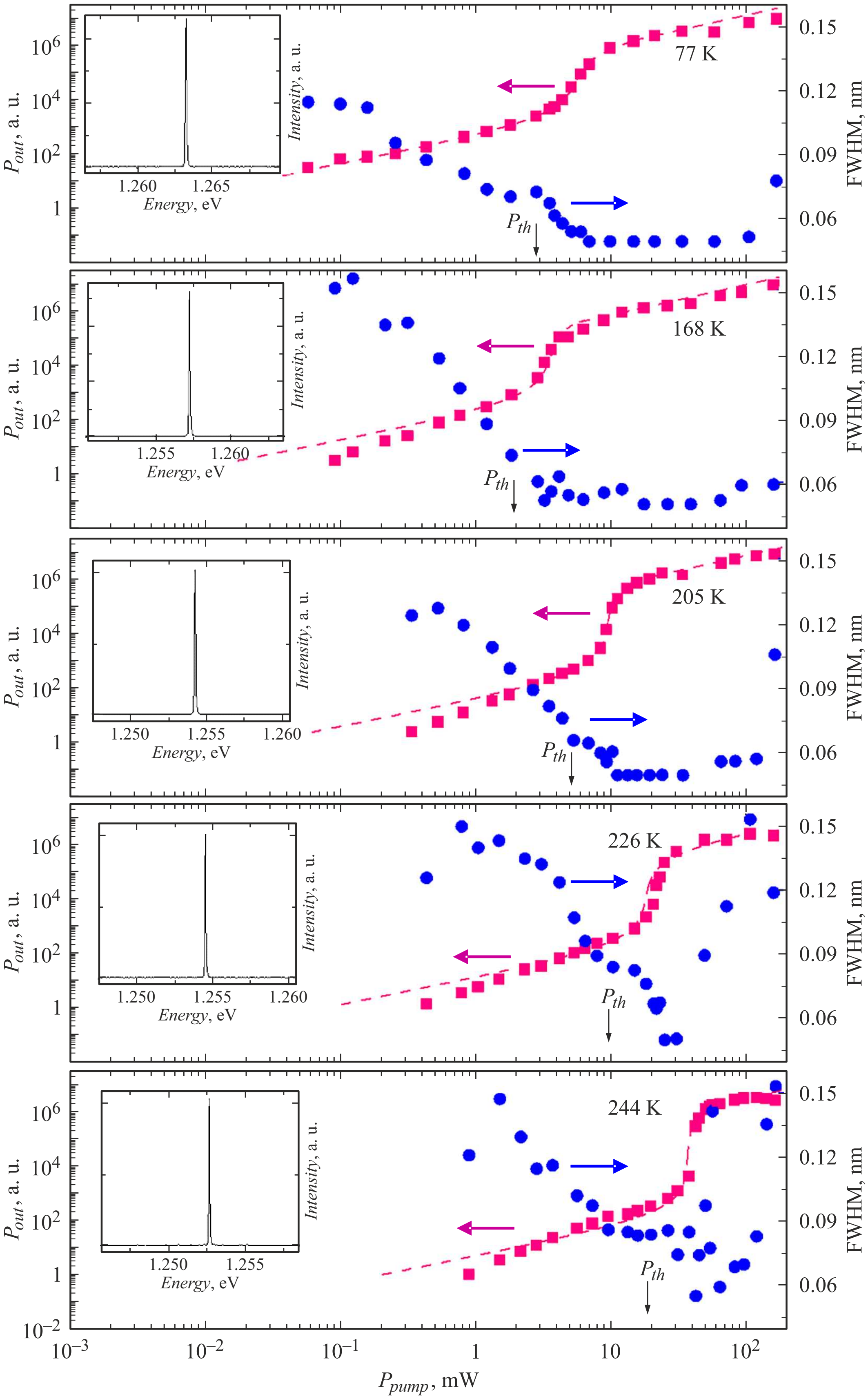

Figure 1. Dependences of the output power (left axis Y) and the full width at half maximum of the lasing line (right axis Y) on the pumping power at different temperatures.

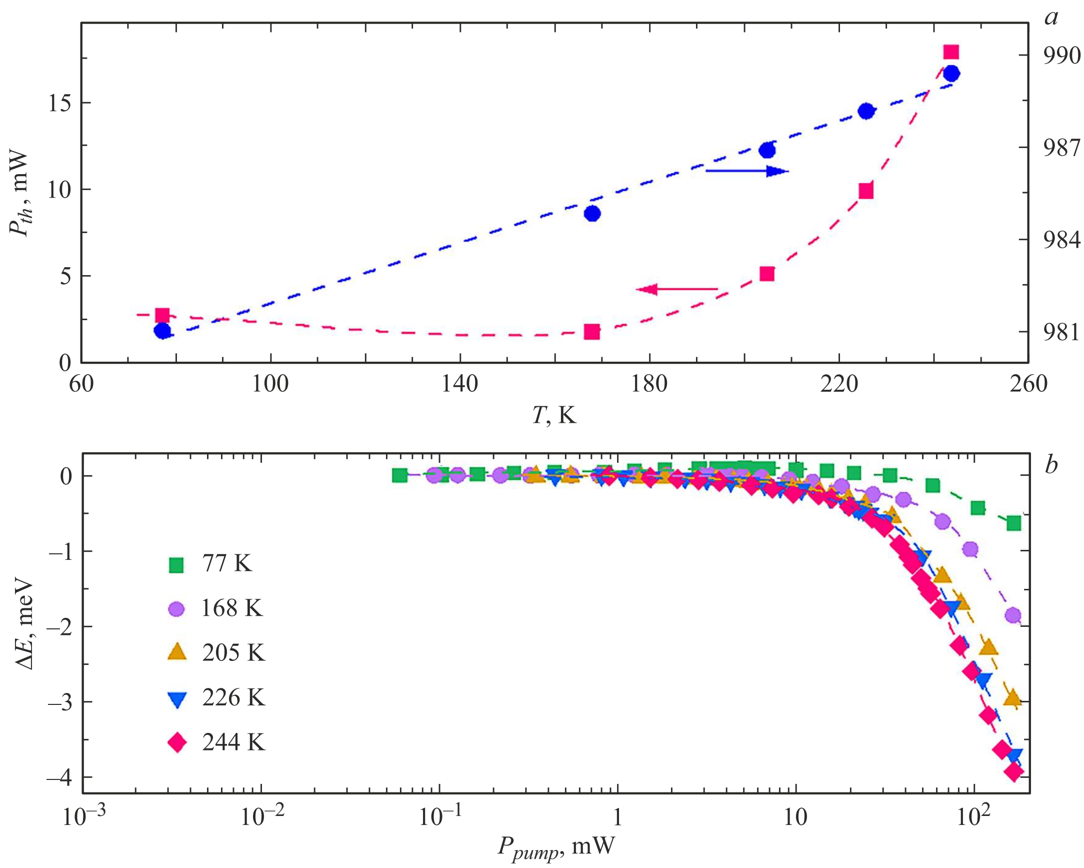

Figure 2. *a* — Threshold optical pumping power (left axis Y) and lasing wavelengths (right axis Y) of the microlaser at different temperatures. *b* — Shift of the lasing line position as a function of the optical pumping level at temperatures of 77, 168, 205, 226, and 244 K.

threshold value was 13 500, 15 000, 11 700, and 11 800, respectively. The maximum quality factor of the microcavity was $Q_{\max} \geq 20\,000$; the results of measurements at a temperature of 244 K were the sole exception: $Q_{\max} = 18\,000$.

The S-shaped power characteristic may be approximated by solving the rate equations [11,12]:

$$P_{pump} = \Gamma/\beta[1 + \xi + 2\beta(P_{out} - \xi/2)]P_{out}/(1 + P_{out}),$$

where P_{pump} and P_{out} are the optical pumping power and the output optical power, Γ is the rate of photon ejection from a „cold“ cavity, β is the factor specifying the fraction of spontaneous emission in the lasing mode, and ξ is the parameter characterizing the number of photons in the lasing mode at the point when the transparency threshold is reached. To determine the value of ξ, the dependence of the full width at half maximum (FWHM) of the lasing line on the level of optical pumping in the subthreshold regime was approximated as $\text{FWHM} = \hbar\Gamma(1 + \xi)/(1 + 2P_{out})$, where $\hbar$ is the reduced Planck constant. Quantity $1/\Gamma$ is defined as the sum of reciprocal values of the quality factor of the microcavity in the subthreshold regime and at the maximum level of optical pumping. The result of approximation is shown in Fig. 1. Threshold pumping power P_{th} is determined as [11,12]

$$P_{th} = \Gamma/\beta[1 + \xi + 2\beta(1 - \xi/2)]/2.$$

The threshold absorbed power is obtained by multiplying the threshold pumping power by effective pumping absorption coefficient κ. The latter quantity is defined as a product of transmittance of the top DBR and the absorption coefficient of DBR layers at the pumping wavelength.

The temperature dependence of the threshold power is shown in Fig. 2, *a*. At 77 K, P_{th} was 2.7 mW. The minimum threshold optical pumping power (1.7 mW) corresponds to a temperature of 168 K. A further increase in temperature leads to an increase in P_{th}. The threshold pumping power at a temperature of 244 K was $\sim$ 18 mW. Having estimated the threshold absorbed optical power using the approach discussed earlier in [11,14], we obtained the values of $\sim 250\,\mu$W ($83\,\mu$W per a QD layer) and 2.8 mW ($930\,\mu$W per a QD layer) at temperatures of 168 and 244 K, respectively.

The temperature dependence of the lasing wavelength determined near the lasing threshold is shown in Fig. 2, *a*. An increase in temperature leads to a shift of the lasing wavelength toward longer waves at an average rate of 0.05 nm/K. The position of the dip in the reflection spectrum of the vertical microcavity heterostructure was also determined at different temperatures. It was demonstrated that the rate of temperature shift of the dip position in the reflection spectrum is 0.041 nm/K. These differences in the temperature shift of two quantities may be attributed to heating of the sample. This conclusion is also supported by broadening of the lasing line at high levels of optical pumping, which has already been noted in [11] and was demonstrated experimentally at a pumping power of > 60 mW at 205 K and > 20 mW at ≥ 226 K.

To evaluate the magnitude of sample heating, we analyzed the dependence of shift of the lasing line (ΔE) on the level of optical pumping at different temperatures (Fig. 2, *b*). At 77 K, the emission wavelength was shifted by 96 μeV toward shorter waves when the optical pumping level was raised to 5 mW, which is attributable to an increase in carrier density. A larger shift of the lasing wavelength ($-150\,\mu$eV at 2 mW) has been reported earlier in [11] for microlasers with a diameter of 3.6 μm. In experiments with the studied microlaser, a similar shift of the lasing wavelength ($-150\,\mu$eV) was observed at an optical pumping level of 60 mW. When the pumping power was raised to 160 mW, a long-wavelength shift of the lasing wavelength with a magnitude of $-640\,\mu$eV was recorded. At a higher temperature of 168 K, the optical pumping range within which a short-wavelength shift of the lasing line is observed was narrowed to 1 mW. With a further increase in temperature to 205 K, thermal effects become prevalent and the region of short-wavelength shift of the lasing line vanishes completely. The rate of shift of the luminescence line with temperature was estimated at 0.048 nm/K based on the position of this line in the subthreshold pumping regime.

The temperature change at the maximum pumping level of 160 mW was assessed. At 77 K, the lasing line shift corresponds to an estimated laser heating of ~ 10 K. With the temperature increased to 244 K, the lasing line shift (at 160 mW) corresponds to a heating magnitude of ~ 65 K.

Thus, the first results of studies into lasing of vertical micropillar cavity lasers at a temperature of 244 K were reported. Three layers of InGaAs quantum dots formed by the Stranski–Krastanov method were used as an active region in order to suppress surface recombination on the side wall of the microcavity. The use of a top DBR with an antireflective coating allowed us to reach a high microcavity quality factor, which was $\sim 12\,000$ near the threshold within the entire studied temperature range. Further research will be aimed at increasing the operating temperatures for implementing a room-temperature RC setup based on an array of spectrally uniform optically pumped microlasers. This research is expected to involve the investigation of a possibility to raise further the quality factor of the microcavity (with the aim of lowering the lasing threshold) and to exclude the vertical alignment of QDs located in different layers (with the aim of increasing the material gain).

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Conflict of interest

The authors declare that they have no conflict of interest.

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