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Optical properties of laser mesastructures with HgCdTe quantum wells formed by ion etching

© A.A. Razova[1,2], V.V. Rumyantsev[1,2], D.V. Shengurov[1], N.S. Gusev[1], E.E. Morozova[1], V.V. Utochkin[1], M.A. Fadeev[1], V.A. Verbus[1], N.N. Mikhailov[3], S.A. Dvoretsky[3], V.I. Gavrilenko[1,2], S.V. Morozov[1,2]

[1] Institute of Physics of Microstructures, Russian Academy of Sciences, Nizhny Novgorod, Russia
[2] Lobachevsky State University, Nizhny Novgorod, Russia
[3] Rzhanov Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
E-mail: annara@ipmras.ru

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The possibility of forming HgCdTe mesastructures with microdisk cavities using metal masks as part of the explosive lithography process is investigated. The operation of microdisk lasers in various spectral ranges from 3 to 25 μm with optical pumping is demonstrated. Single-mode generation was obtained at a wavelength of 4.05 μm at 60 K in a microdisk cavity with a diameter of 50 μm.

Keywords: ion etching, laser lithography, HgCdTe, mesastructures.

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In recent decades, the technology of molecular beam epitaxy of the ternary alloy HgCdTe (mercury cadmium telluride, MCT) has undergone unique improvements due to the low growth temperature and ellipsometric control of the layer composition in the process of material deposition [1]. The latter factor has made high-quality heterostructures based on mercury cadmium tellurides (including Dirac materials and two-dimensional topological insulators) widely available and opened up new opportunities for application of Hg(Cd)Te quantum wells (QWs) in infrared optoelectronics. This refers primarily to the design of receivers and emitters of the mid-infrared range with pronounced suppression of impact (Auger) recombination [2], which allows them to operate at higher temperatures than those typical of devices based on bulk solid solutions. This effect was demonstrated experimentally for stimulated emission (SE) at interband transitions in a series of recent publications (specifically, a wavelength up to 31 μm was achieved in [3]). However, the formation of cavities by cleavage in such structures is complicated by the (013) vicinal orientation of the substrate. At the same time, etching of HgCdTe materials is also a challenging process task, since exposure to temperatures above 180 °C leads to catastrophic degradation of HgCdTe. Wet etching of structures with bromine-containing etchants is often regarded as an auxiliary process to dry etching that is performed to remove the damaged layer [4,5]. A characteristic feature of dry (ion and plasma-chemical) etching is the formation of an n^{++} layer on the structure surface that extends over tens of micrometers even at moderate etching times [6–9]. This effect is observed mostly for compositions enriched with mercury. In the present study, we investigate the influence of ion etching (IE) on the optical properties of HgCdTe waveguide structures with a cadmium fraction of ~ 0.7 grown on a GaAs (013) substrate. This issue has remained understudied (especially in structures with QWs).

The examined structures contain an array of $Hg_{1-x}Cd_xTe/Cd_yHg_{1-y}Te$ QWs inside wide-bandgap cladding layers grown to confine radiation near the QWs. Waveguide layers were grown on a CdTe buffer with a thickness of 5 or 10 μm (depending on the spectral range of lasing). In the case of structures designed for long-wavelength lasing, the gallium arsenide substrate was doped additionally to a concentration on the order of 10^{18} cm^{-3}. Microdisk cavities were formed by argon ions with an energy of ~ 1.4 keV and an ion current of 12.7 mA/cm^2. The lift-off process with photoresist (PR) and metal masks was used. Masks based on aluminum, nickel, and other metals were applied by magnetron sputtering after the pattern was formed by laser lithography.

The obtained mesastructures were examined using an optical microscope (OM) and a scanning electron microscope (SEM). After that, SE or laser emission (LE) spectra were measured via Fourier spectroscopy. The measurement technique was detailed in [3]. High-speed photoelectric receivers based on MCT served as detectors; in certain cases of longest-wavelength lasing, a silicon bolometer cooled by liquid helium was used instead. An optical parametric oscillator (wavelength, 2 μm; pulse duration, 10 ns; pulse repetition rate, 10 Hz; maximum power density, 1 MW/cm^2) and a pulsed CO_2 laser (wavelength, 10.6 μm; pulse duration, ~ 100 ns; repetition rate, up to 50 Hz; maximum power density, 100 kW/cm^2) were used for pumping.

The tilt angle of walls in mesa structures formed using PR only does not exceed 78−80°, which translates into a low Q-factor of Fabry−Pérot cavities [10]. The present study was focused on microdisk cavities, since they exhibited a pronounced mode structure in emission spectra in the

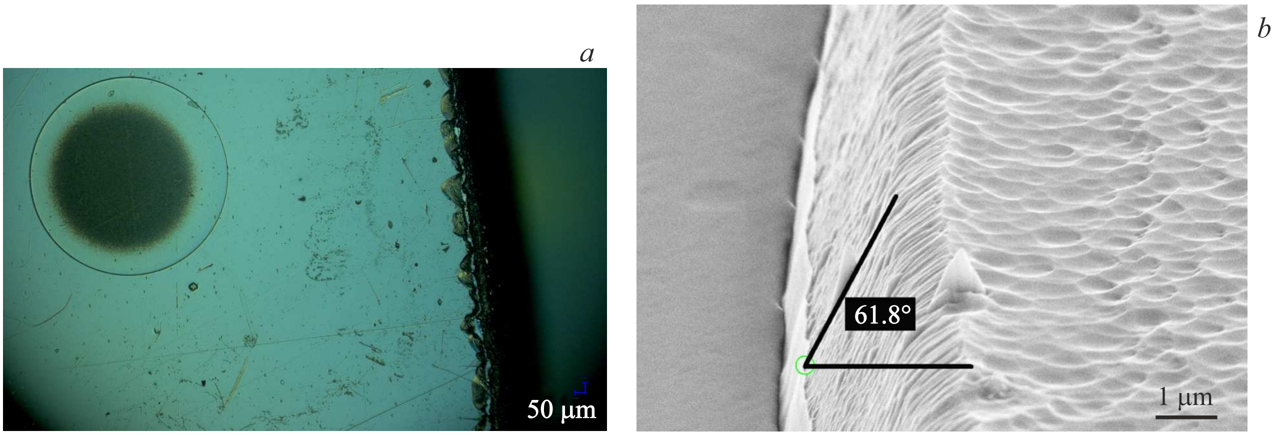

Figure 1. Images of the surface of HgCdTe heterostructures with QWs and microdisks based on them. *a* — OM image of the surface of the studied structure with a microdisk 1 mm in diameter; *b* — SEM image of the microdisk side surface with the tilt angle indicated.

Parameters of the studied structures

Structure number	λ, μm	Mask	h, μm	D, μm	T_{max}, K	I, kW/cm^2
0422	4	Ni/V	1.7	50	60	26 ± 2
0201	2.8	Al	1	40/20	230	120 ± 5 (170 K)
1201-2	25	Ni/V/Cr	4.5	300	50	25 ± 3
1201-3	25	Al	4.3	200	50	30 ± 3

Note. λ — lasing wavelength, h — etching depth, T_{max} — maximum lasing temperature, I — lasing threshold at 30 K, and D — microcavity diameter (external). The internal diameter is also indicated for the 0201 ring cavity (separated with a slash).

vicinity of both 4 μm [11] and 25 μm [12]. The analysis of OM and SEM images revealed that continuous IE over a period of more than 3 min leads to catastrophic degradation of the structure surface (Fig. 1). The OM image (Fig. 1, *a*) demonstrates that the disk surface differs markedly in color from the rest of the structure surface. The SEM image is indicative of a high defect density of the wall and the microdisk surface (Fig. 1, *b*), which suggests a high rate of non-radiative (surface) recombination in such mesastructures. Spectroscopic studies revealed no laser/stimulated emission in them. The tilt angle of the side wall in these mesas was $\sim 62^\circ$ (Fig. 1, *b*). Thus, continuous IE induces intense heating of the photoresist and the structure, which leads to surface degradation. Cyclic etching with intervals for structure cooling in an argon atmosphere provided an opportunity to suppress this effect or eliminate it completely.

An etching depth up to 10 μm is needed to fabricate mesastructures operating in the long-wavelength region of the spectrum, while the selectivity of etching with PR does not exceed 1.5. To improve selectivity, metal masks were used as part of the lift-off lithography process. In addition to enhancing the etching depth, metal masks allowed us to increase the angle of inclination of the mesastructure walls to the structure plane to 90°. The characteristics of the studied structures are listed in the table.

It turned out to be problematic to use traditional materials for metal masks, such as titanium and nickel. Owing to the high adhesion of Ti and Ni, the potential for their removal by chemical means is limited, and the mesastructure gets destroyed in approximately 75 % of all cases. An auxiliary vanadium layer on the surface of Ni masks was used to facilitate removal of the mask with an H_2O_2 solution. However, even with this layer, the maximum lasing temperature decreased to 60 K (the typical SE quenching temperatures in unprocessed samples are 240–270 K; Fig. 2).

Aluminum masks have an advantage in that, despite the high level of adhesion of Al to the MCT surface, the material may be removed with an alkali solution. When an aluminum mask is used, the maximum lasing temperature is just 30–40 K lower than that of the unprocessed sample, although defects in the form of dimples and grains are seen clearly on the surface of microdisks in the SEM images (Fig. 3, *a*). Note that LE was observed in both microdisk and microring cavities, where the surface area of side walls is significantly larger. This implies that surface recombination on the side walls of the mesastructure plays only a minor role (Fig. 3, *b*).

Aluminum masks and a three-layer Ni/V/Cr mask (for the most efficient removal of all metals from the structure surface) were also tested for long-wavelength structures. In this case, etching was performed over one half of the waveguide thickness, which is sufficient to obtain a pronounced mode structure in the emission spectra (Fig. 4, *a*). The key characteristics of LE corresponding to these two types of masks were similar: the operating temperature

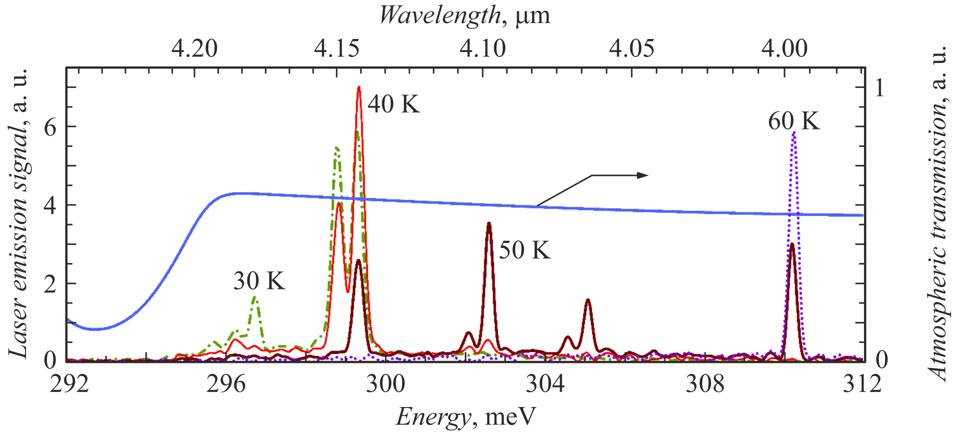

Figure 2. LE spectra of microdisk 0422 at different temperatures and atmospheric absorption spectrum.

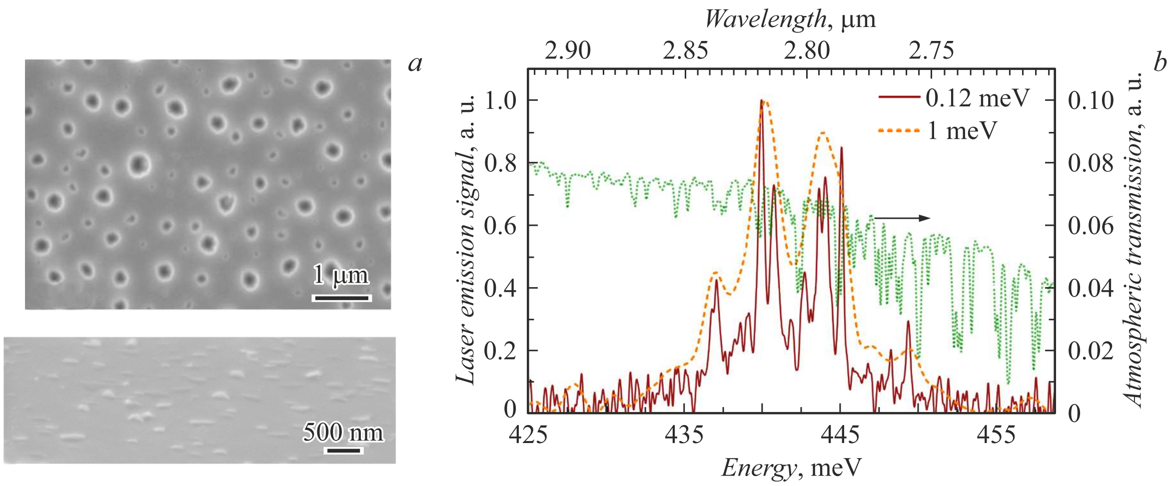

Figure 3. *a* — SEM images of the surface of the studied mesastructures formed using an aluminum mask. *b* — LE spectra of the 0201 sample microring with different resolutions at 130 K and atmospheric absorption spectrum.

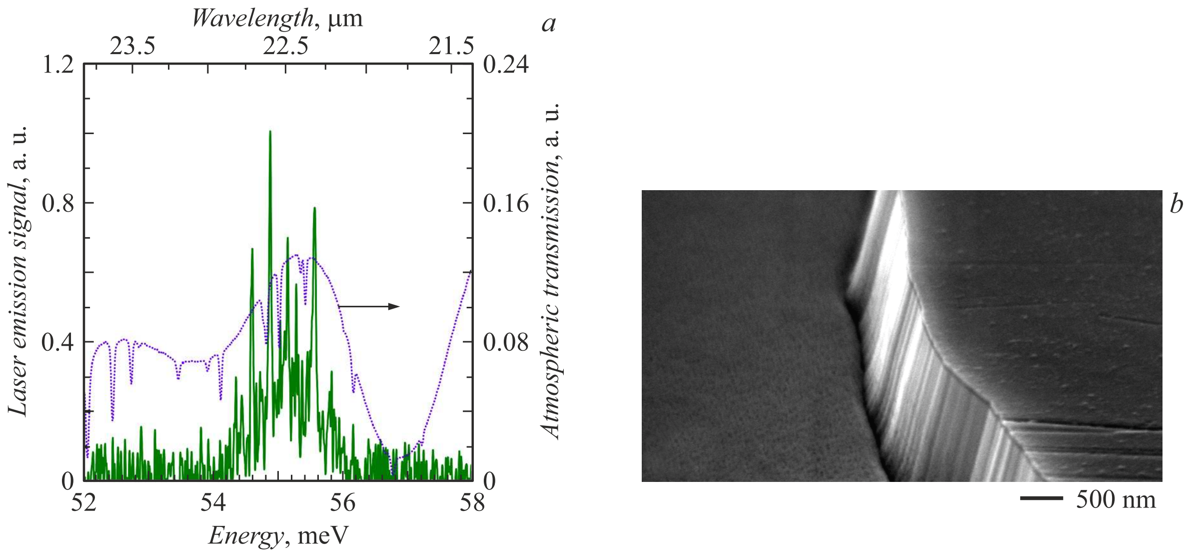

Figure 4. *a* — LE spectrum for microdisk 1201-3 at 30 K and atmospheric absorption spectrum. *b* — SEM image of the side wall of microdisk 1201-2, which was formed using a Ni/V/Cr mask.

dropped by 45 K relative to that for unprocessed samples, and the threshold pump power density at 30 K was within the range of $(25-30) \pm 3\,\text{kW/cm}^2$. Although the etching depth increased, the angle of inclination of the walls to the structure surface remained at the level of 83° (Fig. 4, *b*).

Note that the smoothness of the microdisk walls formed using metal masks is generally worse than the one obtained with PR only, which may contribute additionally to degradation of the lasing parameters. Corrugation of the side surface of the mesastructures (Fig. 4, *b*) is associated with the discrete nature of motion of the illumination source in the laser lithography technology used. This effect is expected to be minimized when a photomask is used to form mesastructures.

Thus, the use of metal masks in lift-off lithography provides an opportunity to form microdisk cavities based on HgCdTe structures with QWs, where lasing is possible both in the atmospheric transparency window $(3-5\,\mu\text{m})$ and in the „ultra-long-wavelength" range $(20-25\,\mu\text{m})$. The tested process allowed us to reduce the angle of deviation of the side walls of the mesastructure from the normal to 7°, revealing potential for improvement in the Q factor of Fabry–Pérot cavities in comb lasers fabricated in a similar IE process.

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Conflict of interest

The authors declare that they have no conflict of interest.

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