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Influence of coating layers on characteristics of microdisk lasers with InAs/InGaAs quantum dots active region

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Abstract. Quantum-dot microdisk lasers coated with different dielectric layers transparent in spectral diapason of laser radiation were studied. We observe that the coating influences the mode spectra of the microlasers, reduces the resonator Q factor and improves their thermal resistance.

1. Introduction

In recent years, semiconductor microlasers based on whispering gallery mode (WMG) resonators have attracted increased attention. Due to a low optical loss WMG resonators demonstrate high quality factors (Q). Moreover, WMG modes are very sensitive to the refractive index discontinuity at the resonator surfaces and in regions outside the resonator where the mode evanescent tails penetrate into [1, 2]. Microlasers are of great interest as ultra-sensitive sensors due to their narrow linewidth capable of reporting slight changes in resonance that would not be resolved by passive resonators [3]. For the onset of lasing, besides a significant increase of the signal-to-noise ratio, also a reduction in bandwidth of the lasing modes is expected, thus improving the detection limit of the sensors [4]. WGMs are based on effect of total internal reflection. From the point of view of classical optics for total internal reflection the critical angle θ_c can be defined from a ratio $\theta_c=\arcsin(n_2/n_1)$, where n_1 and n_2 are refraction indices of the resonator and surrounding material. Thus, the surrounding material influences total internal reflection, and thereby resonant spectrum and quality factor of the resonator. Various microdisk sensors are based on detecting of these changes. Presently lasing in different types of semiconductor microdisks [7-9] as well as influence of surrounding material on WGM mode frequencies in various passive microspherical resonators (sensors) [5,6] has been reported. However the impact of surrounding material on lasing characteristics of GaAs–based microdisk resonators hasn't been studied yet. These studies are very important for efficient light outcoupling from the lasers, realization of highly sensitive microdisk detectors and for proper choose of coating layers for planarization, passivation, etc. In this work we study spectral and lasing characteristics of microdisk lasers with InAs/InGaAs quantum dots active region coated with different dielectric layers transparent in spectral diapason of laser radiation (SU-8 photoresist and TiO_2) and compare the results with characteristics of the micordisks without coating (air environment).

2. Experiment details

An epitaxial structure used for fabrication of the microdisk lasers was grown by molecular beam epitaxy on a GaAs substrate. The epitaxial structure for optically pumped microlasers contains an active region which represents 5 layers of InAs/InGaAs quantum dots (QDs) inserted into a 0.35-µm-thick GaAs waveguiding layer. The waveguide is cladded with 400-nm-thick $Al_{0.98}Ga_{0.02}As$ layer from the substrate side. Optically pumped microdisk resonators were fabricated using photolithography and Ar+ ion beam etching. The diameter of the microdisks was varied from 5.4 to 10.4 µm. The $Al_{0.98}Ga_{0.02}As$ bottom cladding layer was selectively oxidized to be transformed into an AlGaO oxide. Spectral position of quantum dot ground-state transition was located around 1.28 µm at room temperature.
An epitaxial structure for electrically pumped microlasers consists ten layers of $InAs/In_{0.15}Ga_{0.85}As$ QDs deposited in the middle of a 0.44 µm thick GaAs waveguiding layer confined with $Al_{0.25}Ga_{0.75}As$ claddings. Microdisk resonators were formed by means of chemical plasma etching to have a diameter of 30 µm. Etch depth was about 7 µm. AgMn/NiAu (AuGe/Ni/Au) metallization was used to form ohmic contacts to *p*+ GaAs cap layer (*n*+ substrate, respectively).
Spin coating was used to cover the microdisks with epoxy-based photoresist SU8 (n_{SU-8} =1.56 @ 1.3 µm). Atomic layer deposition was utilized to cover the disks with TiO_2 layer with different thickness 100, 150, 200 and 250 nm (n_{TiO2}=2.46 @ 1.3 µm).
The microdisk lasers were studied by confocal optical spectroscopy (Integra Spectra, NT MDT) at room temperature under optical pumping with YAG: Nd laser (λ=532nm) using Olympus x100 microobjective. Needle probes were exploited for electrical connections. A piezoelectrically adjustable Olympus LMPlan IR objective x10 was used to collect in-plane emitted light from a microlaser. The emission was detected with a Horiba FHR 1000 monochromator and a Horiba Symphony InGaAs CCD array.

3. Results

Microdisks were first studied in the air environment (n_{air}=1). All the lasers demonstrate lasing at room temperature. Spectra of the microlasers obtained above the threshold contain broad spontaneous emission of InAs/InGaAs quantum dots and sharp lines corresponding to the WGM resonances.
To inverstigate the influence of surrounding material the 6 µm in diameter microdisk lasers were covered with SU8 dielectric layers and studied under optical pumping (Figure 1). Use of external dielectric layers leads to change of mode spectrum, at the same time spectral position of the lasing line remains in the spectral range of the ground transition of the InAs/InGaAs QDs. A threshold values were determined from the dependence of integrated intensity of the dominant line on the pump power as 350 µW for initial microdisks and 400 µW for microdisks in SU8 layer. The quality factor of both resonators was about 30000. Thus, one can conclude that surrounding microlasers with SU-8 dielectric layers doesn't lead to deterioration in laser performance.

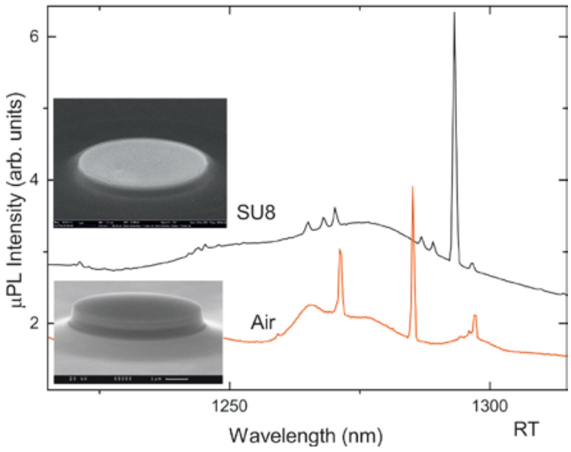

Figure 1. µPL spectra of the 6µm in diameter optically pumped microdisk lasers without coating (Air) and covered with SU8 layer obtained above threshold at room temperature. The spectra are vertically shifted for clarity.

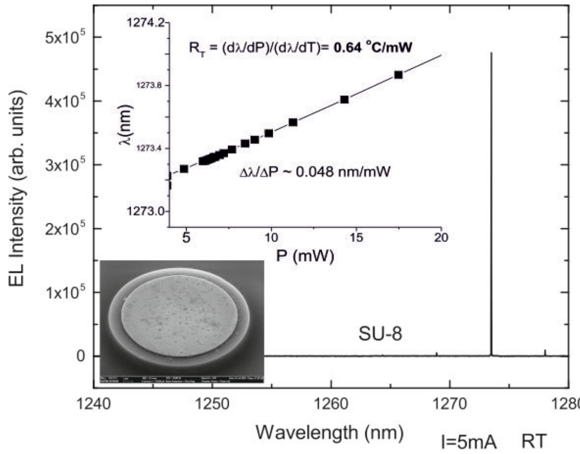

Figure 2. EL spectra of the 30µm electrically pumped microdisk lasers covered with SU8 layer obtained above threshold at room temperature. The inset: spectral position of the lasing line vs pump power.

In the electrically pumped microlasers with planar electric contacts formed on SU8 dielectric layer room temperature lasing has been also achieved (Figure 2). The threshold current did not change compare to the initial microlaser. Lasing wavelength shifts to longer wave as bias current increases because of the laser self-heating effect. Inset in Figure 2 displays the lasing wavelength as a function of electric power dissipated inside the device. Slope of this dependence, which is 0.048 nm/mW can be used to calculate a thermal resistance of the device. Taking into account a temperature induced shift of a WGM line (0.075 nm/^{o}C) one can calculate a thermal resistance to be 0.64 ^{o}C/mW. The obtained value is much smaller than in initial microlaser 0.9 ^{o}C/mW and becames comparable to thermal resistance of the best vertical cavity surface emitting lasers on GaAs substrates [10-11]. Thus, covering the microdisk with a transparent dielectric layer of SU8 reduces microlaser thermal resistance due to more efficient heat dissipation through the microlaser's sidewalls.

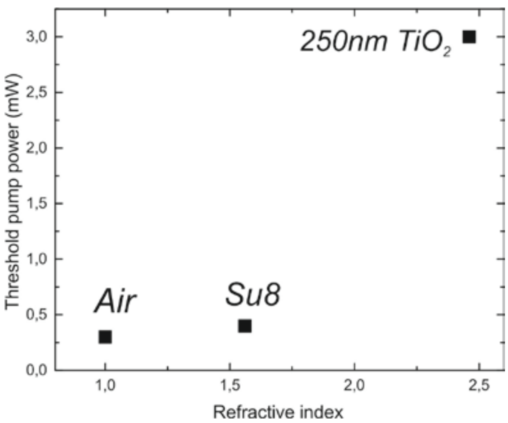

Figure 3. Threshold pump power of 6.4 µm microlaser vs refractive index of the ambient environment.

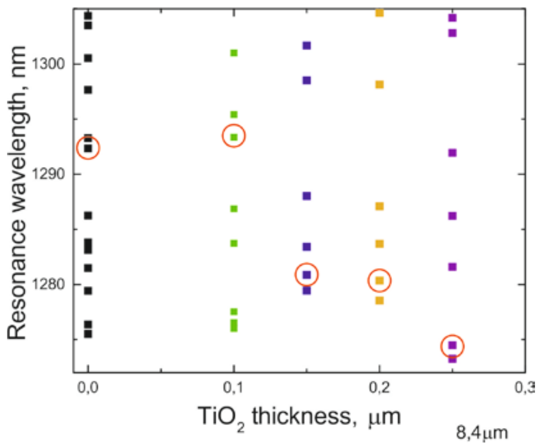

Figure 4. Spectral position of the resonances observed at PL spectra of 8.4 µm in diameter microlaser in air and covered with TiO2 layers of different thickness. The spectral position of the lasing wavelength is denoted by circles.

Next we studied spectral and threshold characteristics of the optically pumped microlasers covered with TiO_2 layer with different thickness (92 nm, 152 nm, 199 nm and 254 nm). Diameter of the studied microlasers was varied in the range from 5.4 to 10.5 µm. Figure 3 compares the threshold pump power obtained for 6.4 µm microlaser surrounded by air (the highest optical confinement), by 1 µm-thick SU8 and by 250 nm TiO_2 coating layer. We observe that the deposition of theTiO_2 dielectric layer leads to ten-times increase of the threshold power up to 3 mW. Increase of the refractive index of the environment (i.e. decrease of the refractive index discontinuity at the surface of the resonator) results also in worsening the Q-factor ($\lambda/\Delta\lambda$). Q-factor for the air-coated microdisk exceeds 30 000, and it drops down to 22000 in case of TiO_2 coating layer.

Deposition of TiO_2 layer also results in thinning of the resonances observed at photoluminescence (PL) spectra of microlasers (Figure 4). One can observe dramatic change in spectral positions of different WGM and their quantity caused by increase of refractive index of the surrounding material (layer thickness). We observe an increase in side mode suppression ratio that results and quasi-singlemode lasing at TiO_2 layer thickness more than 100 nm (Figure 5). Increase of the TiO_2 layer thickness also results in blue- shift of the lasing wavelength that can be explained by increase of radiation loss (circles on Figure 4). However room temperature lasing is still achieved even with 250 nm TiO_2 coating layer with the lasing wavelength within the quantum dots ground state optical transition.

The relative threshold power (P_{th}/P_{th}^0, where P_{th}^0 is threshold power of the initial microlaser) dependences on the TiO_2 layer thickness for 5.4, 6.4 and 10.4 μm in diameter microlasers are demonstrated in Figure 5. In case of the smallest microlaser (5.4 μm) covering with only 100 nm of TiO_2 results in 3-fold increase of threshold power. For thicker TiO_2 layers the room temperature lasing does not occur. In case of the microlaser with 6.4 μm diameter lasing is observed up to 200 nm of TiO_2. In the largest microlaser (10.4 μm) the obtained pump power does not exceed 1.5 P_{th}^0 even for 200 nm of TiO_2.

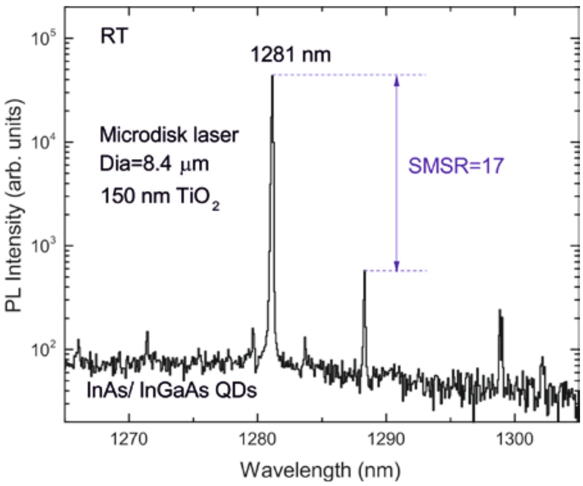

Figure 5. μPL spectra of the 8.4μm in diameter optically pumped microdisk lasers covered with 150 nm TiO_2 layer obtained above threshold (P=1.5 P_{th}) at room temperature.

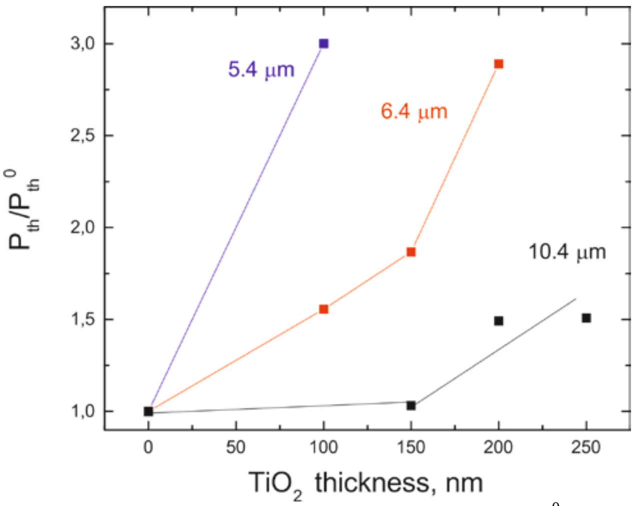

Figure 6. The relative threshold power (P_{th}/P_{th}^0, where P_{th}^0 is threshold power of the initial microlaser) dependences on the TiO_2 layer thickness for microlasers with 5.4, 6.4 and 10.4 μm obtained at room temperature.

To conclude, we observe that the SU8 coating helps to reduce microlaser thermal resistance. SU8 coating can be successfully used for top contact pads formation without deterioration of the threshold properties. Increase of coating refractive index to 2.56 (TiO_2) results in drastic spectral and threshold changes of microlasers even for 100 nm thick layer. The covering of the largest microlaser (10.4 μm in diameter) with the TiO_2 layer helps to achieve quasi-singlemode lasing while the threshold level is preserved. In other words, the coating layers with high-index can be used to improve lasing characteristics of the device. However, the covering of the smallest microlaser (5.4 μm in diameter) with the TiO_2 layer demonstrates its high sensitivity to surrounding. This means that lasers of such diameters can be successfully used for sensing purposes.

Acknowledgments
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