Study of p-type contact topography influence on characteristics of microdisk and microring lasers

A S Novikov¹, E I Moiseev¹, N V Kryzhanovskaya¹,², B I Afinogenov³, Y A Guseva¹,², K Kotlyar¹, A L Lipovskii¹,², A G Nasibulin³, M V Maximov¹,⁴, V G Tikhomirov⁵, A E Zhukov¹,²

¹ St Petersburg Academic University, St Petersburg, Russia
² Peter the Great St Petersburg Polytechnic University, St Petersburg, Russia
³ Skolkovo Institute of Science and Technology, Nobel str. 3, 143026 Moscow, Russia
⁴ Ioffe Institute, St Petersburg, Russia
⁵ Saint-Petersburg State Electrotechnical University “LETI”, St. Petersburg, Russia

Abstract. The results are presented for injection microlasers with InAs/InGaAs self-organized quantum dot active region grown on a GaAs substrate. Lasing wavelength is around 1.26…1.28 µm. It is demonstrated that the use of ring-shaped p-contact for microdisk quantum dot lasers provides lowering the threshold current as compared to that of conventional microdisk lasers with round-shaped contact topology. Both spectral characteristics and thermal resistance are preserved, whereas the series electrical resistance slightly increases.

1. Introduction

Microdisk/microring lasers are considered as a part of future on-chip optical interconnect systems and planar optoelectronic circuits [1]. Owing to the total internal reflection of light traveling at a periphery of a circular resonator, this type of lasers sustains the so-called Whispering Gallery Modes (WGMs). WGMs provide low threshold current and inter-mode distance (free spectral range) sufficient for realization of singlemode or, at least, quasi-singlemode lasing [2, 3]. However, nonradiative surface recombination at microresonator sidewalls can be an issue as the resonator size is reduced down to tens of microns. Self-organized quantum dots (QDs) provide a lateral carrier transport suppression as compared to two-dimensional quantum well structures. This property allows one reducing a size of resonator or use ring-type of resonator without significant threshold increasing. Another advantage of InAs/InGaAs/GaAs QDs is their ability of emitting at wavelengths around 1.3 µm [4] that corresponds to a transparency window of silicon- or silicon-germanium-based planar waveguides as well as standard optical fibers.

Since the WGM field intensity is localized near the resonator edges, the central part of the active region interacts with the optical mode inefficiently and, hence, its pumping is useless. It has been demonstrated in optically pumped QD microring lasers [5] that an increase of the inner diameter (i.e. the diameter of the etched hole in the center) initially results in reduction of the threshold pump power. On the other hand, low thermal resistance seems to be important for CW operation of injection microlasers at room and elevated temperatures. In this respect, microdisk lasers may have certain advantage over microring counterparts owing to larger area of thermal contact between the substrate and the microcavity itself. A reasonable tradeoff can probably be achieved by combining a disk-shaped microresonator, which provides good thermal contact, with ring-shaped top electrical contact. In this work we study quantum dot microdisk lasers emitting at 1.26…1.28 µm in CW regime at room temperature. We use ring-type top contact for reducing the threshold current and compare characteristics with those of microdisk lasers with traditional (round-shaped) top contact.
2. Experiment
A laser structure was grown by molecular beam epitaxy on an $n^+$ GaAs(100) substrate with $n^+$ doped GaAs:Si epitaxial buffer. The laser active region comprises ten layers of InAs/In$_{0.15}$Ga$_{0.85}$As QDs separated from each other with 35-nm thick GaAs spacers. The active region was deposited in the middle of a 0.44-$\mu$m thick GaAs waveguiding layer confined with $n$-doped (bottom) and $p$-doped (top) Al$_{0.25}$Ga$_{0.75}$As claddings. The structure was terminated with a 0.2-$\mu$m thick $p^{++}$ GaAs cap layer. In general, the layered structure corresponds to a conventional separate confinement heterostructure (SCH). Depending on post-growth processing, it can be used for fabrication of either edge-emitting stripe laser diodes, or (as it was done in the present work) for disk/ring microlasers.

Microresonators under study were formed by means of deep chemical plasma etching. The etch depth was about 7 $\mu$m, i.e. the etch process was done though both cladding layers with the active region and the waveguide in between, and was terminated somewhere in the buffer layer. AgMn/NiAu (AuGe/Ni/Au) metallization was used to form ohmic contacts to $p^{++}$ cap layer ($n^+$ substrate, respectively). The outer diameter $D$ of microdisk resonators ranges from 9 to 28 $\mu$m. Micrograph is shown in Figure 1(a). In the majority of microdisk lasers, the top $p$-contact has a round shape with the contact diameter $D_c$ being approximately 3 $\mu$m smaller than $D$ (Figure 1(b)). The top contact of some microdisk lasers was ring-shaped (Figure 1(c)) with the inner contact diameter $d_c$ varied from 0 to 0.6$D$. In still other devices, a ring-shaped top contact was accompanied by a micro-ring resonator shape as it was achieved by means of etching of the inner hole in the resonator center. Microlasers were mounted on a copper heatsink and tested at room temperature under CW excitation without external cooling. Electroluminescence signal was collected with a piezoelectrically adjustable $\times10$ Olympus LMPlan IR objective. A Horiba FHR 1000 monochromator in combination with a Horiba Symphony InGaAs array was used for spectral detection. The spectral resolution was about 30 pm.

![Figure 1](image1.png)

Figure 1. Scanning electron microscope images of an array of microdisk and microring lasers with different type of contact and different diameters (a); microdisk with disk-shaped contact ($D = 9$ $\mu$m and $D_c = 6$ $\mu$m) (Inset: Schematic band diagram of the laser heterostructure) (b); microdisk with ring-shaped contact ($D = 24$ $\mu$m, $D_c = 21$ $\mu$m, $d_c = 7$ $\mu$m) (c); microring laser ($D = 28$ $\mu$m, $d = 6$ $\mu$m, $D_c = 25$ $\mu$m, $d_c = 12$ $\mu$m)).

3. Results and discussion
First we studied electrical characteristics. We found that the diode voltage $U$ as a function of injection current $I$ for all microlasers studied can be fitted well using equation: $U = IR_s + U_0$, where $R_s$ is the
series resistance, $U_0$ the diode turn-on voltage. Figure 2(a) summarizes $R_S$ and $U_0$ for microlasers with disk contract. The turn-on voltage slightly increases from 1.09 to 1.228 Volts as the disk diameter gets smaller ($D$ changes from 28 down to 9 μm). Because $U_0$ is directly associated with the quasi-Fermi levels separation at lasing threshold, such a behavior reflects the fact that optical loss becomes higher in smaller microresonators. The series resistance as a function of microlaser size can be satisfactorily described by two terms: $R_S \approx \rho_S / (\pi D^2/4) + r_S / (2D)$, of which the former corresponds to current flow through the etched mesa with specific resistance $\rho_S = 5.5 \times 10^{-5} \text{ Ωcm}^2$, whereas the latter describes current spread in substrate [6] with the coefficient $r_S = 4 \times 10^{-2} \text{ Ωcm}$. For simplicity we suggested that the mesa series resistance scales inversely with the disk (not electrical contact) area. However, the situation can be more complicated because of incomplete current spread over the mesa. The fact that the current spread in the mesa is suppressed can be illustrated by comparison of I-V curves of several microdisk lasers with ring-shaped top contact with various inner contact diameter $d_C$ (Figure 2(b)). It is seen that while the turn-on voltage remains unchanged, the series resistance increases with decreasing area of the ring-shaped electrical contact. It is explicitly demonstrated in Figure 2(c) where the resistance is shown as a function of the inner contact diameter $d_C$.

![Figure 2](image1)

**Figure 2.** Turn-on voltage (open symbols) and series resistance (solid symbols) in microlasers with round-shaped top contact against disk diameters. Dotted line is the fit curve (see the text), dashed line is guide for eyes (a); I-V curves and their linear fits for disk microlasers with ring-shaped contact (b); series resistance of microlasers of Figure (b) as a function of inner contact diameter: solid symbols – total series resistance, open symbols – mesa-related term only.

Meanwhile we found that the contact topology does not affect the mode structure of the microresonator. In other words, WGM intermode distance is preserved (it is illustrated in Figure 3(a)), however their relative intensities can vary. We also did not found any noticeable impact of ring-shaped contact or even ring-shaped resonator on thermal resistance of microlasers under study. To confirm this statement, Figure 3(b) shows spectral positions of the dominant (lasing) WGMs as a function of injection current for microdisk and microring laser resonators of the same outer diameter. The red-shift of the microlaser mode is caused by the active region self-heating under CW operation. It is seen that the slope $d\lambda / dI$ is practically same (about 0.106-0.108 nm/mA for the presented size of the microresonator). This finding indicates that the main path of heat dissipation in microlasers of this sort is heat removal from the active region through the bottom cladding layer. This path is obviously independent of the top contact geometry and/or inner hole etched via the top cladding only (see Figure 1(d)).

Finally, we compared threshold characteristics of microlasers with different geometry. Figure 4(a) reveals how the threshold current $I_{th}$ reduces with decreasing the outer diameter $D$ of microlasers with conventional (round-shaped) top contact. For the larger microlasers ($D = 24$ and 28 μm) the threshold current density (i.e. $I_{th} / (\pi D^2/4)$) is approximately 1 kA/cm$^2$. It does not remain constant for smaller microdisks being 3 times higher for the smallest microdisk lasers ($D = 9$ μm). This finding correlates with previously mentioned increase of the optical loss in smaller resonator. This conclusion is further confirmed by behavior of the lasing wavelength. It is seen in Figure 4(a) that the wavelength of lasing WGM is gradually blue-shifted but still remains within the ground-state optical transition of QDs.
However, for the smallest microdisk resonator lasing proceeds via the first excited-state QD optical transition (~1.2 μm).

Figure 3. Emission spectra (a) and wavelength of the dominant mode against injection current (b) of disk and ring \((d = 6 \, \mu m)\) microlasers of the same outer diameter \(D = 28 \, \mu m\). In Figure (a), the ring spectrum is shifted by 4 nm for clarity. In Figure (b), dotted lines are linear fits.

Figure 4. Threshold current (solid symbols) and lasing wavelength (open symbols) against outer diameter of microdisks with round-shaped top contact; dotted line – approximation with constant current density of 1 kA/cm² (a); threshold current against inner contact diameter for microdisk (solid symbols) and microrings (open symbols) of different size: \(d_c = 0\) corresponds to round-shaped contact (b); lasing mode intensity (triangles) and wavelength (squares) against current for microlasers with ring-shaped \((D = 20 \, \mu m, d_c = 4 \, \mu m)\) and round-shaped \((D = 9 \, \mu m)\) microdisk lasers (c).

Important finding is that the threshold current can be reduced by applying ring-shaped top contact rather than by bare scaling the outer diameter. It is shown in Figure 4(b) that \(I_{th}\) drops (up to 1.5 times) as the inner contact diameter increases initially. Owing to this effect, it is possible to achieve the threshold current as low as 2.3 mA \((D = 20 \, \mu m, d_c = 4 \, \mu m)\). It is comparable with that of the smallest microlaser with round-shape top contact \((D = 9 \, \mu m)\) where \(I_{th}\) of 2 mA was measured. At the same time, the former microlaser has two advantages over the latter one (Figure 4(c)). First, lasing still proceeds on the ground-state transition of QDs with sufficiently long emission wavelength (~1.28 μm) and, second, the intensity of the lasing mode does not saturates up to at 10 mA (whereas it start to drop already at 6 mA in the \(D = 9 \, \mu m\) round-shaped contact microlaser).

4. Conclusions
Quantum dot based injection microdisk and microring lasers operating at room temperature in CW regime were demonstrated. Although it is expected that the resonators of these types are characterized by very low optical loss, we found evidences (such as growth of the threshold current density and of turn-on diode voltage) that the loss does increase with reducing the microresonator outer diameter. As a result of this, lasing wavelength switches from the ground-state to the first excited-state optical
transition of QDs as soon as the microdisk diameter reaches 9 μm. It was found that the top contact topology does not affect the WGM structure as well as the thermal resistance of the microresonator provided that the outer diameter is kept unchanged. At the same time, the electrical series resistance increases as the top contact surface area is reduced. The most important finding is that the microdisk lasers with ring-shaped top contact or microring lasers are capable of lowering the threshold current as compared to the microdisk lasers with round-shaped contact of the same outer diameter. The most noticeable effect was found in the microdisk laser having the following geometrical parameters: \( D = 20 \mu m, D_C = 17 \mu m, d_C = 4 \mu m \). In this device, the threshold current of about 2 mA was achieved without a transition to the excited-state lasing. These properties make microlasers with ring-shaped top contact very promising for applications in future optical interconnections on a chip.

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