Analysis of the lasing characteristics of InGaAs/GaAs WGM microlasers

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Abstract. We present an analysis of spectral and threshold characteristics of InGaAs/GaAs quantum well-dot microlaser operated under cw current injection at room temperature without external cooling. The experimental values of the threshold current for the disk and ring microlasers are compared. We observe that the threshold current can be significantly decreased in devices with large diameters (more than 30 μm) by using the ring geometry.

1. Introduction

Semiconductor resonators supporting whispering gallery modes (WGM) are very attractive for the development of small-footprint lasers with low thresholds. Semiconductor lasers in the form of thin microdisks were first successfully demonstrated in the early 1990s as extremely compact sources of light ([1]). In order to achieve lasing, the total loss coefficient (side-wall scattering loss, radiation loss, etc) must be balanced by the gain. Fortunately, the threshold current of the microdisk is mostly limited by the transparency current (the current needed to make the medium transparent), since a high Q-cavity microdisk cavity does not require a high optical gain. Thus quantum dots (QDs) are very promising for application as the microdisk laser active region owing to low transparency currents. Indeed, for the ridge waveguide QD lasers, several research groups have reported ultralow-threshold current densities [2-7], surpassing the best QW results ~50A/cm2 [8-10] by almost an order of magnitude. Other advantages of QDs are reduced lateral migration of charge carriers over the active region, suppressed non-radiative recombination via growth-related defects and/or surface recombination on etched sidewalls. Since the optical field in high-Q WGMs is localized near the outer boundary of the cavity, the central part of the active region practically does not interact with the field, but it consumes a certain portion of the current density. The ring geometry of the WGM resonator was found to be more effective [11, 12] providing lower thresholds in InAs/InGaAs QDs microlasers. Recently we developed microdisk lasers with novel InGaAs/GaAs quantum-well dot (QWD) active region [13]. The microlasers demonstrated superior characteristics: high output power, high operation temperatures and data transmission at 10 Gbit/s [14, 15]. Though InGaAs QWDs provide three-dimensional localization of the carriers, the shallow energy levels are thermalized at room temperature and nonradiative recombination starts play more significant role compared to Stranski-Krastanow
QDs. For these reasons the realization of the effective InGaAs QWDs microring lasers with etched surfaces may be challenging especially when the typical dimension become about or less than 10 µm \[16\]. In this paper we compare characteristics of the In(Ga)As/GaAs QWD microlasers with disk and ring geometry having different diameters (10-50 µm).

2. Experiment
A laser heterostructure was grown by low pressure MOVPE on an n+-GaAs substrate with a surface off-axis oriented by 6° from the (100) plane. An active region represents 5 planes of quantum well dots formed by the deposition of 8 monolayers of In\(_{0.4}\)Ga\(_{0.6}\)As and separated with 40 nm-thick GaAs spacers. The active region was placed in the middle of a 0.8 µm-thick GaAs waveguide. GaAs waveguide was inserted between n- and p- doped Al\(_{0.39}\)Ga\(_{0.61}\)As cladding layers. Microdisk and microring lasers with outer diameters \(D_{\text{out}}\) varied from 10 to 50 µm were formed by photolithography and dry etching. The width of the ring resonators was \(w=9\) µm, so the inner diameter of the ring resonator can be found as \(d_{\text{in}}=D_{\text{out}}-2w\). Mesa height was chosen about 5µm to ensure sufficient optical confinement of the whispering gallery modes. Sidewall verticality was controlled with the precision of 5 degrees. AgMn/NiAu and AuGe/Ni/Au metallization was used for formation of ohmic contacts to the p+ GaAs cap layer and the n-doped GaAs substrate, respectively. Micrographs of representative microdisk and microring lasers are shown in Figure 1(a) and (b).

![Figure 1. Scanning electron microscope images of a InGaAs/GaAs QWDs microdisk laser \((D = 20 \, \mu m)\) (a) and microring laser \((D_{\text{out}} = 30 \, \mu m, \, d_{\text{in}} = 12 \, \mu m)\) (b).](image)

Microlasers were planarized using SU-8 epoxy resist and top metal contact pads were formed over the resist. A chip comprising MDs of different diameters was soldered on a holder suitable for sample transportation and mounting in experimental setup. The top contact pad of the individual microlaser was connected using a 50 µm-thick gold wire. All measurements were done at room temperature without external temperature stabilization and cooling.

For the electrical pumping and measurements of I-V characteristics the Kethley 2401 sourcemeter was used. The emission was collected in lateral direction using x20 Mitutoyo NIR long working distance objective with 0.4 numerical aperture. The objective was coupled with optic fiber and the emission spectra were recorded using AQ6370C Yokogawa spectrum analyzer with 0.2 nm spectral resolution.

3. Results and discussion
3.1. Electrical characteristics
First we compared the I-V characteristics of the lasers. Microdisk and microring lasers demonstrated the diode behaviour with I-V characteristics fitted by equation \(U=IR_s+U_0\), where \(R_s\) is series resistance and \(U_0\) is the turn-on voltage. The obtained values of \(R_s\) and \(U_0\) are nearly the same for microdisk and microring lasers as presented in Figure 2 for the studied outer diameters. The series resistance \(R_s\) scales inversely with the ring area and can be fitted with two terms: \(R_s \approx \rho_s / (S_{\text{out}} - S_{\text{in}}) + r_s / (2(D_{\text{out}} - d_{\text{in}}))\). We observe that specific resistance in the first term \(\rho_s = 7 \times 10^{-5} \Omega \cdot \text{cm}^2\) and describe
the current flow through the mesa. The coefficient $r_S = 5 \times 10^{-2}$ $\Omega \times \text{cm}$ in the second term describes the current spread in the substrate. The fact that the microdisk behaviour is very similar to the ring one is due to incomplete current spread over the mesa [12]. A turn-on voltage values approximately correspond to the emission wavelength of the lasers near the threshold (~1.09$\mu$m) and $U_0$ demonstrates increase from 1.06 to 1.24 Volts as the outer diameter decreases from 50 to 15 $\mu$m. Such a behaviour is usually associated with increased loss in smaller microresonators.

![Figure 2](image-url)

**Figure 2.** Turn-on voltage (open symbols) and series resistance (solid symbols) in disk (circles) and ring (squares) microlasers against the outer diameters.

### 3.2. Lasing and output emission

The lasing spectra of the disk and ring microlasers are presented in Figure 3(a) and Figure (b). In the spectra we observe narrow lines in the spectral range corresponding to the ground-state optical transition of In$_{0.4}$Ga$_{0.6}$As/GaAs QWDs near 1095 nm for all the lasers. At the spectra we observe lines corresponding to high-Q WGMs with various azimuthal numbers and separated by free spectral range (FSR). The FSR value can be calculated using expression $\text{FSR} \approx \frac{\lambda^2}{\pi D N_{\text{eff}}}$, where $N_{\text{eff}}$ - group index. The obtained experimental values of FSR are well fitted with $N_{\text{eff}} = 3.4$ (Figure 4), which is close to refractive index of GaAs [17, 18].

![Figure 3](image-url)

**Figure 3.** Emission spectra of the disk microlasers of different outer diameters shifted vertically for clarity (a) and of the ring lasers (b) obtained at current $I \sim 2I_{\text{th}}$. 
Figure 4. Experimental values of microlasers FSR (symbols) and calculated (solid line) for $N_{\text{eff}} = 3.4$ versus the outer diameter.

The dependence of the output power of the dominant WGM line on the current has a characteristic kink corresponding to the lasing threshold (Figure 5). We observe the saturation of the output power of the microlasers smaller that 20 $\mu$m in diameter of both kinds at the injection currents exceeding approximately $2I_{\text{th}}$ due probably to device overheating. The laser self-heating also causes jump of the lasing wavelength from shorter-wavelength WGM to the next longer-wavelength WGM with increasing pumping [19].

Figure 5. Light-current characteristics of the dominant WGM lines of the disk (a) and of the ring lasers (b).

The lasing threshold is shifted towards higher currents for larger devices due to an increase in the active region volume and, accordingly, the transparency current (Figure 6). We do not observe the difference in threshold current for the disk and ring microlasers with diameters less than 30 $\mu$m. The
obtained values are overlapped in the range of experimental error. It means that recombination of carriers at the etched sidewalls of the ring resonator in the chosen geometry (9 µm width) do not increase loss compare to the disk resonator but may hide the awaited profit of the lower current consumption in the central part. For the diameters larger than 30 µm, we see that the threshold current rises faster in the microdisks compared to the microrings so that the ring geometry becomes more profitable.

Figure 6. Experimental values of threshold current of In$_{0.4}$Ga$_{0.6}$As/GaAs quantum well-dots microdisk (circles) and microring (triangles) lasers.

4. Conclusion
Injection microdisk and microring lasers with InGaAs/GaAs quantum well-dots operating at room temperature in CW regime were demonstrated. It was found that the chosen topology does not affect the WGM structure as well as FSR. The electrical series resistance increases as the top contact surface area is reduced also for both kind of lasers. Although it is expected that the ring geometry provides lower transparency currents, we found that the threshold currents are approximately the same for the disk and ring microlasers if the diameter is less than 30 µm. However, the ring geometry does provide lower threshold currents for the devices with 40 and 50 µm. In these devices we do not observe the saturation of the output power.

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