Lasing in microdisk resonators with InAs/InGaAs quantum dots transferred on a silicon substrate

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Abstract. Semiconductor microdisk lasers with an active region based on InAs/InGaAs quantum dots before and after transferring on silicon substrate were investigated. High-temperature lasing up to 105°C in a 6-µm GaAs-based microdisk laser is demonstrated. The simple technology of transferring of microdisk laser on a silicon substrate is developed. Immersing of the transferred microdisk into glue does not lead to deterioration of surface quality and to significant increase in radiation losses. Multi-mode room temperature lasing in 6-µm microdisk laser transferred on a silicon substrate is obtained. Quasi single mode lasing is observed at 78 K.

1. Introduction
Currently there is a need to develop radiation sources for optoelectronic integrated circuits with small size, low power consumption, planar design and high temperature stability [1, 2]. The non-direct gap energy structure of Si, which is dominant in electronics, is significantly hampering the development of Si-based microlasers. Thus, the problem of integration of high performance III-V radiation sources with silicon platform remains topical. Currently developed integration methods are based on bonding procedure of InP-based microdisk on silicon substrate [3, 4]. The smallest diameter of microresonator demonstrating room temperature lasing published is 15µm. Further scaling down is limited by thermal deterioration of the laser characteristics due to weak carrier confinement in active region. At the same time ring and disk microcavities with active region based on InAs/InGaAs/GaAs quantum dots (QDs) demonstrate high thermal stability of characteristics [5, 6].

In this work we develop the simple technology of transferring of microdisk lasers with InAs/InGaAs/GaAs QDs on a silicon substrate and make it characterization in 78-380K temperature range.

2. Experiment
The structure was grown by molecular beam epitaxy with Riber 49 setup with a solid-state As source on a semiinsulating GaAs (100) substrate. For selective etching, a buffer GaAs layer was deposited and then Al0.9Ga0.02As stop-layer was grown. The InAs/InGaAs QDs layers were inserted into a
0.2-µm thick GaAs waveguiding layer. Microdisk resonators with different diameters (3 µm, 4 µm, 6 µm and 8 µm) were formed using photolithography and etching by an Ar+ ion beam (figure 1, a). The Al_{0.98}Ga_{0.02}As layer was transformed into a (AlGa)_xO_y layer by selective oxidation to create optical confinement on the substrate side (for investigation of microdisks not transferred on the Si substrate). The epitaxial side of the structure was then fixed on the Si substrate by glue (figure 1, b). The GaAs substrate and buffer layers and Al_{0.98}Ga_{0.02}As stop-layer were subsequently removed using an etching agents (figure 1, c). Microphotography of microdisk (D=6µm) is shown at figure 1, d.

Figure 1. Schematic sequence of microdisk transfer technology: (a) photolithography and etching by an Ar+ ion beam, (b) gluing of microdisk to a Si substrate, (c) removal of a sacrificial layers; (d) microphoto of disk microresonator on silicon.

Figure 2. PL Spectra of unprocessed sample with InAs/InGaAs QDs obtained at 300 K.

The structures were investigated under optical pumping with Nd:YAG laser (λ = 532nm). The laser beam was focused using an Olympus LMPlan IR 100 NA 0.8 objective onto the microlaser top surface. The same objective was used to collect the PL signal, which was passed through FHR 1000 monochromator and detected by cooled InGaAs CCD array Horiba Symphony.

3. Results
The PL spectra at different excitation power of unprocessed sample with InAs/InGaAs QDs obtained at room temperature are shown at figure 2. The wavelength of PL spectra maximum is 1.27 µm and corresponds to QD ground state emission. Increase of excitation density results in linear increase of the PL intensity with slope k ~ 1 evidencing high optical quality of the QD active region. First, we investigated properties of µdisk lasers before transferring. The µPL spectra obtained at 300K from µdisk lasers with different diameters (3 µm, 4 µm, 6 µm and 8 µm) are shown at figure 3. The spectra are shifted along axis "Intensity" for clarity. Sharp lines observed at the spectra correspond to high quality whispering-gallery (WG) modes. Decrease of the resonator diameter from 8 µm to 3 µm results in increase of the resonator free spectral range (FSR) from 23 nm to 48 nm and in reducing of the WG modes quantity. One can see that in case of 3 µm microdisk resonator the number of the WG modes within the range of the InAs/InGaAs QDs gain spectra is quite low. Thus, the microcavities with diameter of less than 3 µm are candidates for single-mode radiation sources. Along with the high quality WG modes, low-quality modes exist in the disk microcavities. These modes modulate QDs spontaneous emission spectra. Ring microcavity provides suppression of these modes (figure 4). The lack of material in the center of the resonator does not deteriorate emission characteristics as compared with the disk microcavities since the high-Q WG modes are located near the resonator external rim.
Increase of the optical pump power results in the transition to the lasing regime with rapid increase of the intensity of a WG modes of the resonators. Inset in fig. 5 shows the dependence of 1294 nm line intensity of 6 µm disk on the pump power (light-light curve). The threshold pump power is 0.34 mW. The FWHM of the 1294 nm line near the threshold is 34 pm and it is limited by resolution of the measurement system. We can estimate the quality factor $Q$ factor to be more than $3.4 \times 10^4$. Room-temperature threshold characteristics of the microresonators with different outer diameters were compared. The lowest threshold of 0.34-0.4 mW was found in microdisks having an outer diameter of 6–7 µm. Both larger and smaller microdisks demonstrate higher threshold power as shown at figure 6. Lasing in the 6 µm µdisk was observed up to 105°C. Due to the temperature shift of the InAs/InGaAs QD ground state emission the lasing wavelength was observed at $\lambda = 1336$ nm at 105°C.

The dependence of the threshold power on the temperature in range 20-105°C is shown at figure 7. Increase of the temperature results in increase of the threshold power ($P_{th}(105°C) \approx 4 P_{th}(25°C)$) due to the various factors. First, temperature driven carrier escape from quantum dots increases non-

Figure 3. µPL spectra of a microdisk lasers (D = 3 µm, 4 µm, 6 µm and 8 µm) at 300 K. Figure 4. Emission spectrum of a ring and disk microcavity (D = 6 µm, d = 2 µm) at 78 K.

Figure 5. µPL spectrum of microdisk lasers (D = 6 µm) at 300 K. Insert: Spectrally integrated emission intensity of a WG mode as a function of incident optical pump power.

Figure 6. Dependence of the threshold power on the outer diameter of a WG mode at a function of incident optical pump power.
radiative recombination. Second, the misalignment of the mode wavelength and the maximum of QD gain curve wavelength at certain temperature also increases threshold power.

Then we investigated 6 μm in diameter microdisks transferred on Si substrate. μPL spectrum obtained at 300 K above threshold (P=1.2 Pth) is shown at figure 8. The light-light curve of dominant line (λ=1296 nm) has a pronounced threshold (see inset in figure 8). The quality factor of the line Q=λ/Δλ exceeds 3.4 × 10^4 at 300 K. This value is the same for initial microdisk measured before transferring. The measured threshold pump power at 300K (Pth300K) is 0.63 mW that is higher approximately by 2 than in initial microdisks. This is allows us to conclude that developed technology of transferring and immersing of the microdisk into the glue do not lead to deterioration of microdisk surface quality or to a significant increase in radiation losses due to decrease in the contrast of the refractive index.

μPL spectra before threshold (P=0.8 Pth) and above threshold (P=1.3 Pth) obtained at 78K are shown at figure 9. The wavelength of dominant line is shifted to λ = 1237 nm due to the temperature driven active region band-gap shrinkage. Decrease of temperature to 78 K results in slight decrease of lasing threshold by 2 (Pth78K=0.5 Pth300K) due to suppression of nonradiative recombination processes. The side mode suppression ratio at 78K is 14 dB. Thus, the microdisk demonstrates quasi single mode lasing. Increase of the excitation density leads to long-wavelength shift of the dominant line wavelength due to heating of the microdisk under optical pumping. We estimate the value of this heating to be 0.03 K/(W/cm²) that is five times higher than in the initial microdisks on (AlGa)xOy layer. We explain this heating by weak thermal conductivity of the glue and poor thermal contact with Si substrate. This problem can be solved by glue with better thermal conductivity.
4. Conclusion

III-V microdisk lasers with InAs/InGaAs QDs active region before and after transferring on Si substrate are characterized in 78-380K temperature range. High-temperature lasing up to 105°C in a 6-µm GaAs-based microdisk laser is demonstrated. The method of transfer of the microdisk resonators on the silicon substrate is developed. Room temperature lasing in 6 µm microdisk laser on Si substrate is demonstrated. The quality factor $Q$ in transferred microdisk exceeds $3.4 \times 10^4$. This value is the same for initial microdisk. This allows us to conclude that developed technology of transferring and immersing of the microdisk into the glue do not lead to deterioration of microdisk surface quality or to a significant increase in radiation losses due to decrease in the contrast of the refractive index.

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