Room temperature continuous wave operation of injection quantum dot microdisk lasers

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Abstract. We present results of characterization of injection microdisk lasers with InAs/InGaAs self-organized quantum dot active region grown on a GaAs substrate. The minimal microdisk diameter is 15 µm. The microlasers operate in continuous wave regime at room temperature without external cooling. Lasing wavelength is around 1.26…1.27 µm, minimal threshold current is 1.6 mA (threshold current density 900 A/cm\textsuperscript{2}). Specific thermal impedance is estimated to be 5\texttimes{}10\textsuperscript{-3} °C\textsuperscript{°}C•cm\textsuperscript{2}/W.

1. Introduction
Microdisk lasers are considered as candidates for development of planar optoelectronic circuits for on-chip optical interconnect systems (see, e.g. [1]). Owing to total internal reflection of light traveling at periphery of a microdisk resonator, very high quality factor can be achieved even in resonators several order of magnitude smaller as compared to conventional edge-emitting (macro)lasers [2]. Microdisk lasers operating at room under injection pumping in continuous wave (CW) regime are highly desired for practical usage. However, nonradiative surface recombination at microresonator sidewalls becomes an issue as the resonator size is reduced down to tens of microns. Since the first demonstration [3], most of microdisk diode lasers rely upon InP-based material system, which is characterized by low surface loss, and a quantum well active region.

Meanwhile, self-organized quantum dots (QDs) deposited on a GaAs substrate may provide characteristics very promising for their application in microlasers. In particular, edge-emitting QD lasers have reached the record-low threshold current density less than 10 A/cm\textsuperscript{2} [4]. One property that makes QDs especially attractive for microlaser applications is lateral carrier transport suppression in QD arrays as compared to a two-dimensional quantum well structures [5]. Another advantage of InAs/InGaAs/GaAs QDs is their ability of emitting in the 1.3 µm spectral band [6] that corresponds to a transparency window of silicon- or silicon-germanium-based planar waveguides as well as standard silica optical fibers. Lasing operation of a QD microcavity as small as 2 µm has been recently reported under optical pumping at 100°C with a lasing wavelength of 1.3 µm [7]. At the same time, characteristics of injection QD microdisks reported so far are less optimistic. Room temperature
operation has been reported for a 6.5 µm microdisk emitting at 1.06 µm [8], whereas the laser emitting at longer wave of 1.23 µm has much larger diameter of 80 µm [9].

In this work we report on successful realization of QD microdisk lasers emitting at 1.26…1.27 µm in CW regime at room temperature.

2. Experimental
Epitaxial structure was grown by molecular beam epitaxy on an $n^+$ GaAs(100) substrate. Ten layers of InAs/In$_{0.15}$Ga$_{0.85}$As QDs were 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 15…31 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). A micrograph of an array of microdisk lasers of different diameter is shown in Fig. 1. Lasers were mounted on a copper heatsink and tested at room temperature without external cooling. Light was collected with a microlens-tipped fiber and analysed with an optical spectrum analyser (spectral resolution 0.1 nm).

3. Results and discussion
All the microdisk lasers demonstrate well pronounced turn-on behaviour of current-voltage dependence (example is shown in Fig. 2). Series resistance is scaled as $D^{-2}$; specific series resistance is estimated to be about $10^{-4}$ Ohm•cm$^2$ (see insert of Fig. 2).
Integrated light intensity against bias current reveals a knee on the curve which is a characteristic of a lasing threshold (Fig. 3). The smallest threshold current measured at room temperature is 1.6 mA in a microlasers with diameter of 15 µm. Threshold current vs diameter dependence can be fitted well using a constant threshold current density of 900 A/cm².

**Figure 3.** Light-current curve taken for a $D = 15$ µm microdisk. Insert: Threshold current as a function of diameter. Fit: $J_{th} = 900$ A/cm².

Emission spectra contains a dominant lasing line, which corresponds to a resonant whispering gallery mode (WGM), and one or few less intensive side lines of WGMs having other azimuthal orders (Fig. 4). In lasing regime the dominant line is typically two orders of magnitude more intensive as compared to other WGMs. In different microdisks studied the dominant line wavelength is varied in the 1.26…1.27 µm spectral interval. To the best of our knowledge, this is the longest lasing wavelength ever reported for injection QD microdisk lasers on GaAs substrates.

Mode spacing $\Delta \lambda$ between nearest WGMs is plotted against the microdisk diameter in insert of Fig. 4. The best fit of the dependence reveals an effective group mode index of 3.64.

**Figure 4.** Series of emission spectra taken at various currents for a $D = 15$ µm microdisk. Insert: Mode spacing as a function of diameter. Fit: $N_{eff} = 3.64$.

Lasing wavelengths shifts to longer wave as bias current increases because of the laser self-heating effect. Fig. 5 displays the lasing wavelength as a function of electric power dissipated inside the device. Slope of this dependence, which is 0.207 nm/mW for the example shown, can be used to calculate a thermal impedance of the device. The results are shown in the insert of Fig. 5 for the microlasers of different diameters. We took into account a temperature induced shift of a WGM line, which is as small as 0.075 nm/°C. The thermal impedance is scaled with the diameter as $D^2$; a coefficient of this dependence provides an estimation of a specific thermal resistance, which is $5 \times 10^{-3}$ °C·cm²/W.
Data on current induced shift of the WGM spectral position (Fig. 6) were used to evaluate an increment of the active region temperature with respect to the ambient temperature. It is seen that the microlasers under study still lase even if the temperature increment is as high as 75°C. On the grounds of this finding one can suggest that the maximal operation temperature of the QD microlasers of this sort can be as high as 100°C.

4. Conclusions
Quantum dot based uncooled injection microdisk lasers were tested at room temperature in CW regime. A combination of device characteristics achieved (low threshold, long wavelength, operation at elevated temperatures) makes them suitable for application in future optoelectronic circuits for optical interconnect systems.

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