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Lasing of InP/AlInAs quantum dots in AlInAs microdisk cavity

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Abstract. AlInAs microdisk cavities having quality factor $Q \sim 15\,000$ were fabricated from lattice-matched InP/AlInAs (interface/aggregation) quantum dot (QD) structures using wet chemical etching. The QD emission coupled to whispering gallery modes was observed at spectral range 920 - 1000 nm at temperatures of 10 - 160 K. The laser generation with threshold power density of 50 W/cm^2 at $T = 10$ K was observed under optical pumping. It was found that the spontaneous emission coupling factor β equals 0.23 for these microdisks. The low temperature lasing operation and the small coupling factors observed suggest the existence of small QDs formed at the InP/InAlAs interface as the main active elements.

1. Introduction

Whispering gallery mode (WGM) semiconductor microdisk (MD) cavities with embedded quantum dots (QDs) represent modern nano-photonic platform for the realization of low-threshold lasers [1], single photon sources [2] and experiments on cavity quantum electrodynamics [3] and quantum optics [4]. For these cavities which have sizes of few micrometers and quality factors Q from 10^3 - 10^5, lasing under optical pumping from cryogenic to room temperatures was demonstrated in the spectral range 0.32 - 1.3 μm using InGaAs/GaAs [5], InP/GaInP [1], CdSe/ZnSe [6] and GaN/AlN [7] QD systems having a type-I band alignment. Recently MD lasers with GaAs/GaSb [8] QDs having a band alignment type-II were also reported. The lowest, subnanowatt, threshold was achieved at $T = 10$ K for InP/GaInP QDs having a large lateral size (~ 100 nm) providing strong coupling of the WGM with the QD emission, and low density (~ 10^9 cm^{-2}) suggesting single dot lasing. Accounting for the low Q values used (~ 5000) one can suggest that further increase in QD size and quality factor will lead to lower thresholds which is very important for understanding the fundamental limitations on efficiency for the generation of coherent light in the solid state and for the creation of the nanophotonic devices having low energy consumption.

Here we investigated the novel type-II InP/AlInAs QDs which can show a large size (~ 250 nm) and a reduced density (~ 10^8 cm^{-2} showing nevertheless a broad phenomenology with growth conditions as discussed in Ref. [9]), as an active layer of MD lasers having a diameter in the 2.5 - 4 μm range. The QD emission coupled to whispering gallery modes was indeed observed at the spectral range

920 - 1000 nm at temperatures of 10 - 160 K. The laser generation with threshold power density of ~50 W/cm^2 at T = 10 K was observed under optical pumping. For these microdisks it was found that the spontaneous emission coupling factor β equals 0.23. Indeed, the low temperature lasing operation and the small coupling factors observed suggest the existence of small QDs formed at InP/InAlAs interface as the main active elements instead of their larger size relatives reported in [9].

2. Experimental

The structures were grown on InP substrate using metal-organic vapour phase epitaxy. The structures consist of a 100 nm thick InP buffer layer, 250 nm thick AlInAs waveguide with InP QD embedded at the waveguide centre. The aggregation dots were formed following a deposition of 0.75 nm InP [9]. We expect a type-II band alignment of these QDs with conduction/valence band off sets 300/220 meV [10]. Thus, an electron is confined in a QD with activation energy of ~ 100 meV. Accounting for the type-II band structure we used modulation doping of QDs which was achieved by the insertion of a 20 nm n-type AlInAs ($n = 5\cdot 10^{17}$ cm^{-3}) layer at a distance of 20 nm from the QDs. From this structure MDs having diameters of 2.5 - 4 μm were fabricated by optical photolithography and wet chemical etching using HCl, H_3PO_4 and CH_3COOH.

Photoluminescence (PL) experiments were conducted under CW (532 nm) and pulsed (635 nm, frequency 10 – 80 MHz) excitation in a standard microphotoluminescence set-up with photon correlation capability, as described elsewhere [11]. The system enabled exciting and probing regions as small as a few μm^2 using an objective with 50 times magnification and numerical aperture of 0.5. Spectra were registered by Horyba Jobin Yvon THR1000 monochromator coupled with a Symphony 2 CCD camera. Experiments were conducted at T = 10 – 300 K. The optical power on the sample was regulated by a set of neutral filters with different transmissions.

3. Results and discussion

Figure 1 shows the μPL spectrum of the MD having the diameter of 3.2 μm at T = 77 K under CW excitation. This spectrum contains a broad band corresponding to the emission of QDs located near the centre of the MD which are weakly coupled to WGM, and sharp emission lines corresponding to WGMs generated by QDs located near the circumference. The intensities of the WGMs show strong temperature quenching (figure 2) which may be approximated by an exponential decay: $I(T)$~$I_0/(1+A\exp(-E_a/kT))$, where k is the Boltzman constant and E_a = 40 meV. The quenching is normally caused by thermal escape of holes.

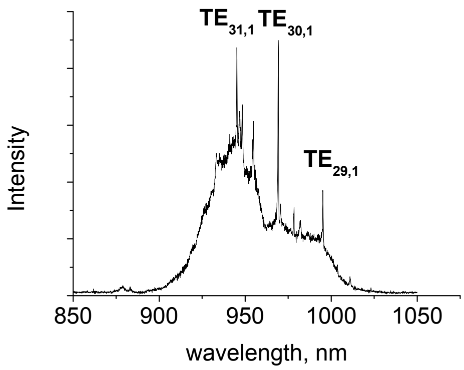

Figure 1. μ-PL spectra of 3.2 μm diameter InP/AlInAs MD at T=77 K at CW 532 nm excitation.

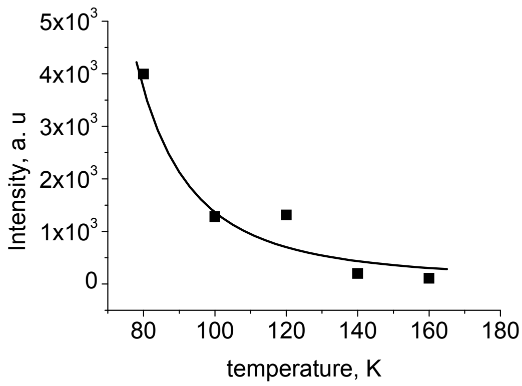

Figure 2. Intensity of WGM versus temperature.

We observed a lasing behaviour of these MDs at temperatures from 10 - 90 K. The lasing spectra at $T = 10$ K for three MDs denoted 1, 2 and 3 having diameter of 2.5 μm are shown in figure 3. Single mode lasing at $\lambda = 952$ and $\lambda = 947$ nm was observed for MD 1 and 2, respectively, and two mode lasing was observed for MD 3 at $\lambda = 926$ nm and 936 nm. A width of the lasing mode $\Delta\lambda$ of 0.06 nm was observed which corresponds to a quality factor $Q = \Delta\lambda/\lambda$ of ~15000. From Input-Output (I/O) power dependences shown in figure 4 the lasing threshold was estimated to be 50 W/cm^2.

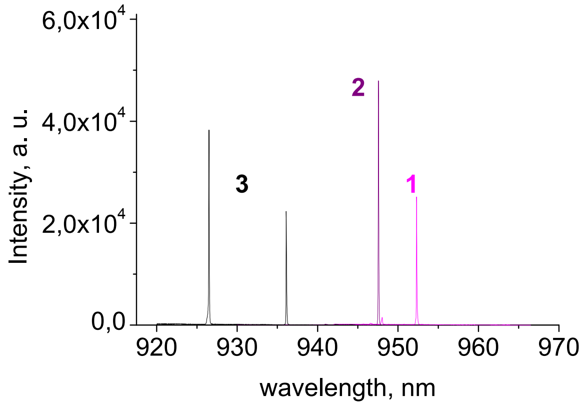

Figure 3. Lasing spectra of three InP/AlInAs QD MDs having diameter of 2.5 μm at 10 K and pump power of 100 μW (300 W/cm^2).

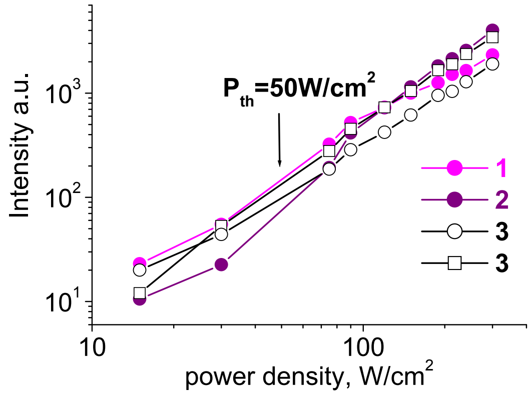

Figure 4. Input-Output power dependence of InP/AlInAs QD MDs having diameter of 2.5 μm at 10 K.

These dependences do not show a strong "knee" at the laser threshold region which is typical for micro-lasers. An absence of strong knee indicates a large spontaneous emission coupling factor β. To investigate Input-Output behavior in the threshold region we fitted the experimental data with the expression introduced by Bjork and Yamamoto for microcavities which relates the photon number p to the excitation intensity I [12]:

$$I(p) = A\left[\frac{p}{1+p}(1+\xi)(1+\beta p) - \xi\beta p\right]$$

Here, A is the scale factor $A = h\omega\gamma/\delta\beta$, where ω is the frequency of the mode, γ is the cavity decay rate, and δ is the photon conversion efficiency. For an optical excitation I corresponds to the pumping power and p is proportional to the output intensity. The dimensionless parameter $\xi = N_0\beta V/\gamma\tau_{sp}$, where N_0 is the transparency carrier concentration of the gain material, V is the volume of the active material and τ_{sp} is the spontaneous emission lifetime, may be considered as a number of photons in the cavity at transparency condition.

Fitting the data under variation of A and ξ yields $\beta = 0.23$ for MD 1 (see figure 5). For comparison, the theoretical curves with $\beta = 1$ and $\beta = 0.1$ are also introduced. It was discussed that the power threshold is defined when the mean number of photons in the laser mode is equal to unity. From the rate equation analysis [13] it follows that the threshold power corresponds to the "knee" position.

We carried out time resolved experiments which showed that the emission decays of WGMs τ_{res} are 1.4 times shorter than that for the background τ_0 (figure 6). Decay times were extracted from monoexponential fit of the PL decay. It is known that spontaneous emission coupling ratio may be estimated from [14]:

$$\beta \approx 1 - \frac{\tau_{cav}}{\tau_{free}}$$

where τ_{free} is the lifetime for the emission in free space, τ_{cav} is the lifetime for the emission in cavity mode. Assuming that τ_{cav}/τ_{free} is close to τ_0/τ_{res}, the spontaneous emission coupling factor may be estimated. It was estimated that $\beta \approx 0.29$ which is in good agreement with the β value obtained from the fitted I-O curves.

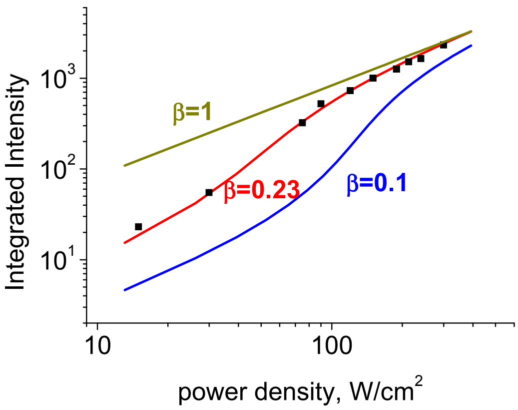

Figure 5. Input-Output power dependence for MD 1 obtained at 15K. Theoretical curves with different β values are included.

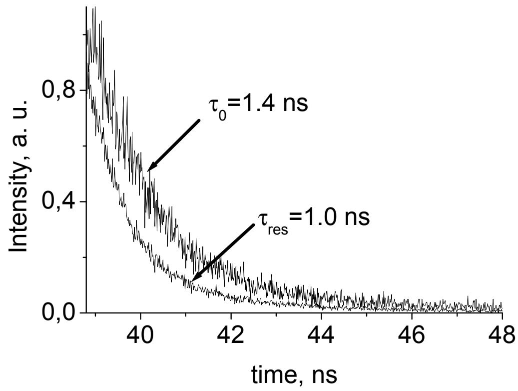

Figure 6. Emission decays of WGM (τ_{res}) and background (τ_0).

The β factor obtained in this work (0.23) is similar to that (0.195) obtained for InP/GaInP QD MDs prepared by wet etching [15] but much lower than that (0.8) for InP/GaInP QD MDs prepared by ICP-RIE etching [16]. Since wet etch InP/GaInP QD have lateral size ~20 nm we suggest that in our structures the emission occurs through "small" QDs formed at InP/InAlAs interface [17]. This could explain the low-temperature operation of the lasers and the relatively low thresholds.

4. Conclusion

Here we used the novel type-II InP/AlInAs nanostructure [9] as an active layer of MD lasers having the diameter of 2.5 - 4 μm. The QD emission coupled to whispering gallery modes was observed at spectral range 920 - 1000 nm at temperatures of 10 - 160 K. The laser generation with threshold power density of 50 W/cm^2 at $T = 10$ K was observed under optical pumping. For these microdisks it was found that the spontaneous emission coupling factor β equals 0.23. The low temperature lasing operation and the small coupling factors observed suggest the existence of small QDs formed at InP/InAlAs interface.

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