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Low threshold lasing in InP/GaInP quantum dot microdisks

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Abstract. We report a realization of room temperature lasing threshold of 1 μW in GaInP microdisk containing a few self-aggregated InP/GaInP quantum dots (QDs) grown by metal-organic vapor phase epitaxy. InP/GaInP QD microdisk cavities emitting in the spectral range of 700 - 800 nm and having the size of $\sim 2 \mu\text{m}$, free spectral range of $\sim 35 \text{ nm}$ and quality factors $Q \sim 4000$ were formed by wet chemical etching. Low dot density ($\sim 2 \mu\text{m}^{-2}$) and large dot size ($\sim 150 \text{ nm}$), suggesting a single dot lasing and maximum overlap of QD and cavity mode, were achieved using deposition of 3 ML of InP layer at 700°C .

1. INTRODUCTION

Microdisk cavities (MD) are considered to be very attractive for being used in lasers owing to their small size, high quality factor and low threshold [1, 2]. This is because MDs have specific eigen modes, which are known as whispering gallery modes (WGM). MD lasers with an active area based on different nanostructures performed laser generation in a wide spectral range: InGaAs quantum dots in AlGaAs MDs demonstrated laser emission at 1300 nm [3], green laser emission (520 nm) was produced by ZnSe MD with CdSe QDs [4], blue laser emission was produced by MD with InGaN quantum wells [5]. Moreover low threshold behaviour was demonstrated by microdisk lasers with an active area based on QDs [6-8]

Here we studied the emission properties of MD lasers with an active area based on InP/GaInP QDs having an increased size of ~ 150 nm and a reduced density $\sim 2\mu\text{m}^{-2}$, which expected to perform with a low laser generation threshold, due to its large oscillator strength. We present preliminary study of these MDs with help of microphotoluminescence (μPL) spectroscopy.

2. EXPERIMENTAL

The initial heterostructure was grown on semi-insulating GaAs (100) substrate misoriented 0.2 degrees toward [111] by metalorganic vapour phase epitaxy (MOVPE). Initially a 100 nm buffer layer of GaAs was deposited followed by 700 nm AlGaAs layer, then GaInP waveguide was deposited (thickness 120 nm), which contained one layer of InP QDs. From this structure MDs having diameters 2 - 3 μm were fabricated by optical photolithography and wet chemical etching, using HCl, H_3PO_4 and CH_3COOH . μPL spectra excited by solid state laser ($\lambda=532$ nm) were measured by MS520i spectrograph with CCD as detector. The laser power on the sample was controlled by a set of neutral filters with different optical density. To investigate the single dot emission a cantilever-based NSOM setup consisted of an AFM head with a built-in 6-mm

working distance 100x objective (0.7NA, Mitutoyo) was used. Light input-output module connected to AFM base unit (NTEGRA Spectra, NT-MDT) and confocal spectrometer (OMU34, NT-MDT).

3. RESULTS AND DISCUSSION

Low temperature PL of the initial structure demonstrates two peaks at 725 nm and 793 nm with wide FWHM 30 nm (figure 1). This indicates the formation of two QD types with different thickness: 10-20 nm and 30-50 nm, also known as type B and type C QDs [9]. We expected low density for these QDs because of the deposition of only 3 InP monolayers at 700 °C. The influence of growth condition on the formation and density of InP/GaInP QDs is described in our previous papers [10, 11].

An NSOM image of QDs emitting at 715 nm at room temperature is presented in figure 2a. It is seen that QDs are distributed homogeneously with the density of 1-5 μm^{-2} . From these results we also may estimate the lateral size, which is about 100-200 nm. This allowed to make MDs which contains only few QDs. For illustration purposes the disk “image” is put on the NSOM photo. The external circle corresponds to the disk, while the inner circle corresponds to the WGM propagation area border. One can see, that it may be accordingly expected 1 QD location and WGM field in the structure, which should result in a QD emission directly into the cavity mode. The SEM photo of the produced microdisk is shown in the figure 2b.

The mode structure of the investigated microdisks was analyzed with the help of COMSOL multiphysics program. The radial and azimuthal numbers of the modes were determined by an analysis based on the Oxborrow model [12]. It was concluded that for MDs with such geometry the free spectral range (FSR) is about 35 nm.

The microphotoluminescence (μ PL) spectrum is presented in the figure 3. One can see two sharp intensive lines, corresponding to WGMs. Its FWHM is 0.2 nm, which allows to estimate mode quality factor $\lambda/\Delta\lambda \sim 4000$. The power input-output dependences are presented in the insert. It is clearly seen that at power exceeding 1 μ W the PL intensity increased rapidly. This indicates the onset of laser generation. For such cavities low thresholds at room temperature was observed for microdisks with InP/GaInP QDs as active area (6 μ W) [6], for AlGaAs microdisks with InAs QDs [7] (1 μ W) and for microrings with InAs/GaAs QDs (1.8 μ W) [8].

To investigate input-output behavior in the threshold area we fitted experimental data with the expression introduced by Bjork and Yamamoto for the microcavities, which relates photon number p to the excitation intensity I [13]:

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

Here, A is the scale factor $A = \hbar\omega\gamma/\delta\beta$, 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 area and τ_{sp} is the spontaneous emission lifetime. This parameter ξ may be consider as a number of photons in the cavity at transparency condition.

Fitting the data under variation of A and ξ yields $\beta = 0.1$. It is known that the quality factor of the microcavity eigen modes together with the position of the emitters relative mode area determine the modification of the spontaneous emission by the cavity (Purcell effect). This allowed to observe laser generation at quite low threshold for different types of microcavities [14, 15]. We assume that in our case such low threshold value is consequence of the fact that a specific whispering gallery mode overlaps with an enlarged QD. This resulted in

the increasing of the spontaneous emission factor β and the decreasing of the laser generation threshold.

4. CONCLUSION

In this paper MD cavities with enlarged low-density InP/GaInP QDs were studied with help of a μ PL technique. WGMs with quality factor ~ 4000 were detected. It was observed that laser generation threshold for these MDs is as low as $1 \mu\text{W}$. The possible reason of such low threshold value is the overlapping of a single QD emission area with a eigen the WGM of MD.

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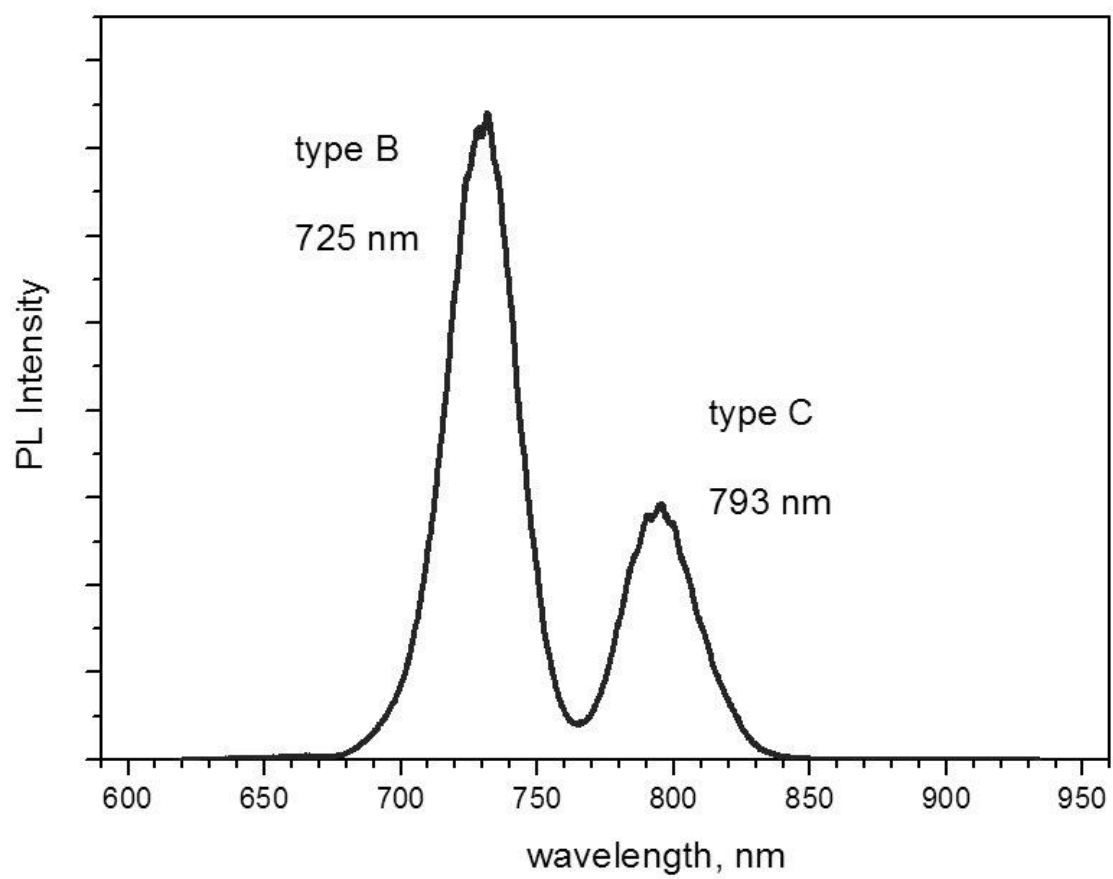


Fig. 1.

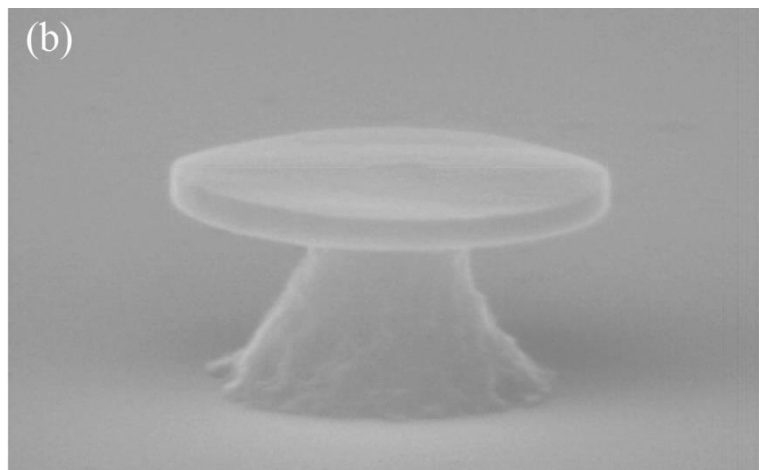
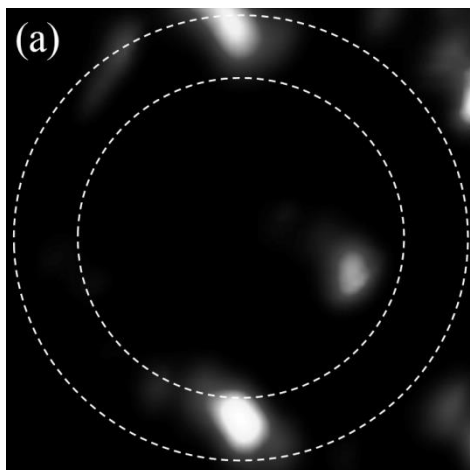


Fig. 2.

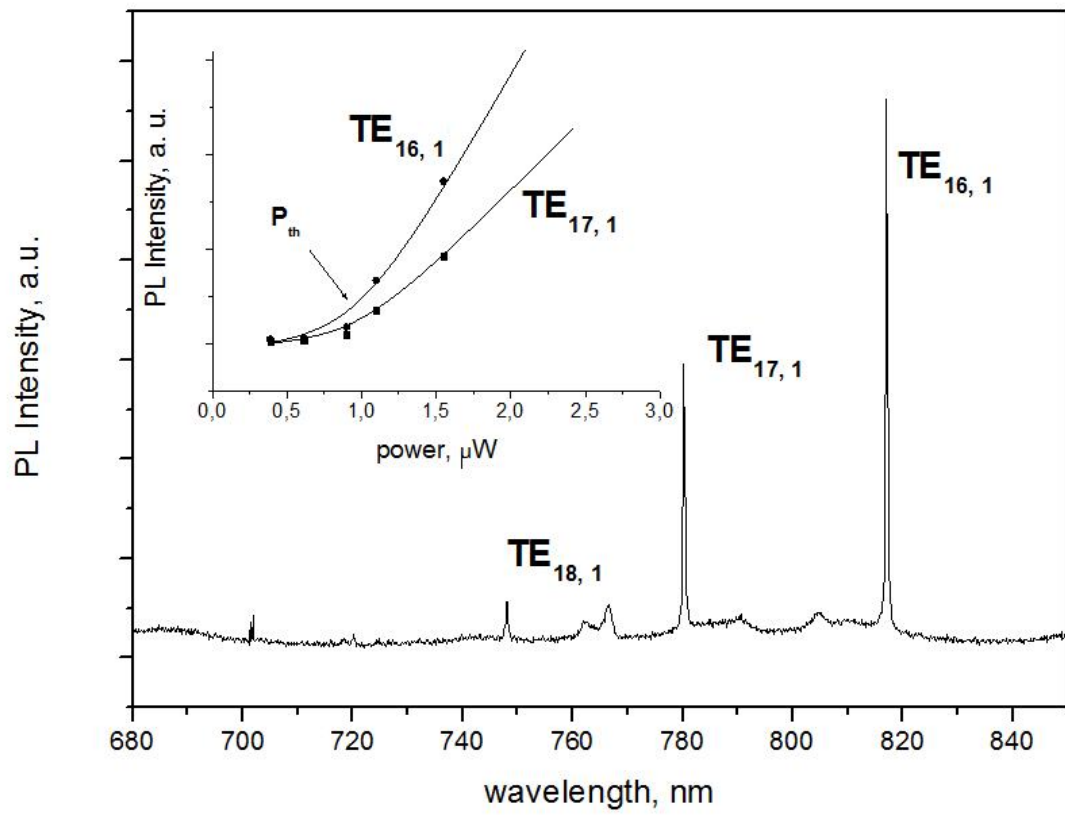


Fig. 3.

Figure captions

Fig. 1. PL spectrum of initial heterostructure with InP QDs.

Fig. 2. (a) NSOM image of the initial structure recorded at 715 nm. (b) SEM photograph of the microdisk formed by wet chemical etching.

Fig. 3. μ PL spectrum of the MD. Input-output dependences fitted with the expression (1) are presented in the insert.