Output power of multilayered InGaAs/GaAs quantum well-dot microdisk lasers

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Abstract. We studied the output optical power of microdisk lasers with InGaAs/GaAs quantum dots active region. An increase in the number of layers in the active region in the waveguide from 2 to 6 leads to increase in the peak output optical power due probably to increase of the gain. We also observe a corresponding increase of the threshold current due to the increase on the transparence current. The maximal optical power is achieved for structure with 6 layers at approximately 60 mA injection current. Further increase of the number of the QD layers to 10 results in increase of the threshold current and sudden drop of the output power.

1. Introduction
In recent years, much attention has been paid to the development of microlasers based on III-V materials that could be integrated with elements of silicon microelectronics. Injection III-V microdisk (MD) and microring lasers with quantum dots (QDs) show noticeable success: lasing was demonstrated in a continuous wave mode at a temperature of 60 °C in MD lasers synthesized directly on silicon substrates [1], the possibility of direct modulation with a frequency of up to 6.5 GHz [2] was shown, a threshold current density of 0.36 kA/cm\textsuperscript{2} was achieved [3], the estimated mean time to failure is more than 80,000 hours [4].

The use of QDs makes it possible to achieve low values of the threshold current density at room and elevated temperatures, significantly reduce the effect of nonradiative recombination on the side walls of the resonator due to the short lengths of lateral diffusion of charge carriers. The disadvantages of the QD material are associated with the low optical gain of QD arrays and the relatively slow relaxation of carriers, as well as their accumulation at excited levels and in the matrix at high pump levels. It was found that the output power of the microlasers can be increased by using dense arrays of QDs in active region deposited by special technological methods (InGaAs/GaAs quantum-well dots (QWD) [5]), or arrays consisting of several layers of such QWDs. When using several active layers in a waveguide, a situation can be realized that only a certain part of the QD layers quantum dots will be in the immediate vicinity of the lightwave maximum. As can be seen from Figure 1, the side layers of

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QDs are located outside the maximum of the mode, so that the electric field strength of the optical mode in position of the i-th layer is less than the electric field strength of the optical mode at the center of the waveguide ($\varepsilon(z_i)<\varepsilon(z_0)$) and, therefore modal gain increases sublinearly with the number of QD layers.

In this work we study optical output power of MD lasers containing different number of QD active region layers, while the waveguide thickness is the same and is optimized to maintain only the fundamental mode of the laser vertical waveguide.

2. Experiment
The laser structures were grown by metal-organic vapor phase epitaxy (MOVPE) on an n+ GaAs substrate misoriented by 6° toward [111] direction. The laser active region consists of several QWDs layers. Each QWDs layer was formed by the deposition of 8 monolayers of In$_{0.4}$Ga$_{0.6}$As. The QWDs represent a dense array of indium-rich regions formed inside In-depleted residual quantum well and can be also considered as shallow QDs of high density. The QWD layers were separated from each other with 40 nm thick GaAs spacer layers and placed in the center of the undoped 0.78 µm thick GaAs waveguide. The waveguide was sandwiched between p- and n-type doped 1.5 µm thick Al$_{0.4}$Ga$_{0.6}$As claddings. Five structures (A2, A4, A5, A6 and A10), having 2, 4, 5, 6 or 10 layers of the active region were studied. MD lasers were fabricated by dry etching of 30 µm in diameter circular mesas through both cladding layers and the active region/waveguide layer to the depth of about 5 µm.

For structural characterization scanning electron microscope JSM 7001F (JEOL, Japan) was used (Figure 2). Round-shaped AgMn/Ni/Au contacts were formed individually to each MD on top of p+ GaAs cap layers. After that the GaAs substrate was thinned down to approximately 100 µm, and a n-type contact was deposited onto the back surface of the GaAs substrate. Then, the wafer was cleaved into chips containing single microdisk.

![Figure 1. Schematics of the laser structure in the AlGaInAs material system.](image1)

![Figure 2. SEM image of 30 µm in diameter QD microdisk laser.](image2)
Electroluminescence was excited by a stabilized DC current with a Keithley 2400 Series SourceMeter® power supply. During measurements of MDLs in CW regime the devices were pumped using BeCu probe with Ø20 µm tip. During spectral measurements light emitted by an individual microlaser was collected with a Mitutoyo M Plan Apo NIR objective with 50× magnification. Emission spectra were acquired with a Yokogawa AQ6370C optical spectrum analyzer. The spectral resolution was 20 pm. To measure the optical power emitted into free space, the radiation was collected with Thorlabs S132C photodiode placed closely to the MDL under test.

3. Results and discussion
All the microlasers operate in continuous wave (CW) regime at room temperature. The typical lasing spectra (Figure 3) contains narrow lasing line, corresponding to whispering gallery mode of the resonator, the intensity of which increases sharply at a current above the threshold. The lasing wavelength was about 1100 nm for the lasers under consideration. When the MD laser operates in CW regime, its temperature increases because of the self-heating. The MD laser overheating with increase in the injection current results in a redshift of the WGM lines Δλ. One can estimate the temperature of the active region versus injection current of the microlasers (Figure 3, right axis) taking into account the temperature coefficient Δλ/ΔT of about 0.08 nm/K, where ΔT is temperature increase of the MD laser active region. The data presented in the inset to Figure 3 allows determining the thermal resistance RT of the device as:

$$R_T = \frac{\Delta T}{\Delta Q} = \frac{\Delta \lambda / \Delta Q}{\Delta \lambda / \Delta T}$$  

(1)

where ΔQ is the Joule heat. Since in MD lasers emitting into free space the wall-plug efficiency is low, the Joule heat ΔQ can be estimated as the total consumed electric power, i.e. the product of the bias voltage and the injection current. The thermal resistance RT of the lasers structure was calculated to be ~ 0.55 K/mW.

The dependencies of the optical power of the structures A1-A10 are presented at Figure 4. Each light-current dependence has three characteristic parts. In the first part at low (sub-threshold) currents the optical power linearly increase with pumping. Above the threshold (second part) we observe rapid increase of the output power. It should be noted, that near the threshold the emission is predominantly of single-mode kind. Increase of the current and subsequent heating of the structure results in the involvement to the lasing resonances with longer wavelengths. We observe this transition to multimode lasing as smoothed steps appeared at the light-power dependence. And next at certain current value the optical power saturates and starts to drop down (third part of the dependence) due to
the thermal rollover. Increase of the number of QD layers from 2 to 6 leads to an increase in the peak output optical power due probably to increase of the gain. We also observe a corresponding increase of the threshold current due to the increase on the transparency current. The maximal optical power is achieved for A6 structure at approximately 60 mA injection current. Further increase of the number of the QD layers to 10 (structure A10) results in increase of the threshold current and sudden drop of the output power. Possible reason is that the threshold current in this case becomes too high leading to strong microlaser overheating already below the threshold. What is essential is that for lasers based on self-organizing QDs one can found such a design that allows you to achieve optimal threshold current density and sufficient output power.

![Optical power vs. Current](image)

**Figure 4.** Room temperature light-current dependencies of the 30µm in diameter microdisk lasers with different number of QWDs layers.

4. Conclusions
Microlasers with multilayered InGaAs/GaAs quantum dots active region operating in CW regime are studied at room temperature. Increase in the injection current results in saturation of the output power due to the MD laser overheating (thermal roll-over) and gain saturation. Increase of the number of QD layers from 2 to 6 leads to an increase in the peak output optical power due to increase of the gain. We also observe a corresponding increase of the threshold current due to the increase on the transparency current. The maximal optical power is achieved for structure with 6 layers. To achieve optimal threshold current density and sufficient output power in the microlasers one should manage heat conductance.

Acknowledgement
This study was supported by Russian Science Foundation grant 18-12-00287, https://rscf.ru/project/18-12-00287/. SEM characterization were performed using equipment owned by the Federal Joint Research Center "Material science and characterization in advanced technology".

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