Influence of dielectric overlayers on self-heating of a microdisk laser

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Abstract. We studied experimentally and numerically self-heating of a microdisk laser developed in the AlGaNAs material system and covered with dielectric layers. By experiments, we found that planarization of the microlaser with SU-8 photoresist significantly (almost, 2-fold) decreases the microlaser thermal resistance. Calculations demonstrate that a downward heat flux through the substrate to the heat sink is a dominant way of heat dissipation, and upward convection is much less relevant. Also, the calculations showed that covering microlaser with a TiO₂ layer barely affects microdisk temperature but decreases heat localization in the structure.

1. Introduction

Increase of internal temperature (self-heating) of a microlaser negatively affects its performance [1]. In optical microdisk (MD) lasers, the self-heating effect with increasing pump power is pronounced due to their small size (a few microns) and low thermal conductivity of materials, including Al₂O₃, which is often used for optical confinement on the substrate side. Self-heating leads to a decrease in the differential efficiency of the lasers due to a decrease in the inverted population and an increase in the threshold pumping power due to additional optical losses through scattering by the free carriers. Also, internal heat of the laser causes saturation not only of the output optical power, but also of the modulation bandwidth [2]. These impede using such microlasers as light sources in all-optical interchip communications. Thus, ways to improve microlasers thermal properties and studies of these properties are of interest. One of the most effective solutions of the problem of overheating of a microlaser is using an additional heat sink with high thermal conductivity.

Recently, a novel strip-loaded horizontal slot waveguide (SLSW) based on dielectric TiO₂/SiO₂/TiO₂ layers have been proposed for routing microdisk lasers emission [3]. The substrate with a microdisk semiconductor laser is planarized with the use of SU-8 photoresist, and on the top of this structure a planar (horizontal) slot optical waveguide composed of TiO₂/SiO₂/TiO₂ layers is deposited. Both SU-8 and waveguide layers influence thermal behavior of the structure. In this paper we analyze the influence of covering dielectric layers on self-heating of a microdisk laser.
2. Experiment and methods
A semiconductor heterostructure was grown using molecular beam epitaxy on a semi-insulating GaAs (100) substrate. An active region comprises five layers of InAs/In_{0.15}Ga_{0.85}As/GaAs quantum dots (QDs) with a 30-nm-thick GaAs spacer between the layers. The spectral position of the QD ground-state transition is located around $\lambda = 1.3 \, \mu m$ at room temperature. The active region is placed in the middle of the GaAs layer confined from both sides with 10 nm thick Al_{0.3}Ga_{0.7}As barriers. The total thickness of the vertical waveguide is 360 nm. This waveguide layer was grown on the top of a 400-nm-thick Al_{0.98}Ga_{0.02}As layer. The Al_{0.98}Ga_{0.02}As layer was then transformed into an (AlGa)$_3$O$_y$ layer by selective oxidation to ensure the optical confinement on the substrate side. MDs of different diameters from 4 to 11.5 $\mu m$ were fabricated using photolithography and argon-ion beam etching. The scanning electron microscopy (SEM) image of a typical MD laser fabricated is shown in figure 1. The microdisk lasers were studied at room temperature under optical pumping with a cw-operating YLF: Nd laser ($\lambda = 527$ nm). When the microdisk laser operates in continuous wave regime, its temperature increases due to self-heating, and the released Joule heat is dissipated through the ambient of limited thermal conductivity. The microlaser heating with increase in the optical pump power results in a redshift of the lasing resonance lines. Lasing spectra were measured with a following optical setup: the signal was collected by a microobjective x100 and detected by ANDOR iDus multi-channel detector and a confocal optical spectroscopy setup (Integra Spectra, NT MDT). The redshift of the lines is mainly determined by the temperature-induced change of the refractive index and is about 0.08 nm/K for GaAs-based microlasers in the temperature range of 20–80 °C [4]. Using the dependence of the resonance wavelength on the optical pump power one can estimate the active region temperature.

![Figure 1. SEM image of a MD laser.](image1)

![Figure 2. Scheme of numerical simulations (half cross-section of the structure).](image2)

To analyze microdisk self-heating we used numerical simulation in COMSOL Multiphysics environment via the finite element method. The scheme of the problem is shown in figure 2. We considered axially symmetric problem. We used a boundary condition of convective heat flux at upper and side air boundaries and a constant (room) temperature condition at a lower boundary. The latter corresponds to an ideal heat sink beneath the structure. Also, we assumed that the resonators heating power is equal to the power of optical pump, since free space emission of the MD laser is negligible in this case. The material properties used in the simulation are presented in table 1.

| Material   | Thermal conductivity (W m$^{-1}$K$^{-1}$) | Heat capacity (J kg$^{-1}$K$^{-1}$) | Density (kg m$^{-3}$) |
|------------|------------------------------------------|-----------------------------------|----------------------|
| Air        | 0.0026                                   | 1005                              | 1.2                  |
| GaAs [5]   | 51                                       | 327                               | 5300                 |
| Al$_2$O$_3$ [6] | 34                                     | 780                               | 4000                 |
| SU-8 [7]   | 0.2                                      | 1200                              | 1200                 |
| TiO$_2$ [8] | 8                                       | 500                               | 4200                 |
3. Results and discussion

3.1 Self heating vs. pump power

We evaluated temperature increase of the 6-µm MD surrounded by air in accordance with a measured shift of a lasing wavelength for different pumping power. The threshold pump power for this laser is about 0.4 mW. Also, we carried out corresponding numerical simulation of temperature distribution. The results of experimental and calculated heating of the microlaser vs pump power are presented in figure 3.

![Figure 3](image1.png)

**Figure 3.** Measured (dots) and calculated (dashed line) heating of the MD laser of 6 µm in diameter and surrounded by air; \( P_{th} \) – threshold power.

![Figure 4](image2.png)

**Figure 4.** Distribution of heat flux magnitude in the MD vicinity; MD diameter is 6 µm, pump power – 1.2 µW. Arrows qualitatively indicate the heat flux direction.

The dependences in figure 3 are almost linear as expected and their slope is called thermal resistance. One can find that self-heating of the MD laser under consideration is moderate – about 7 °C at pump power 3-times exceeding the threshold. Moreover, experimentally evaluated heating noticeably exceeds the calculated one. Probably, this is because of imperfection of the real heat sink and the imperfect thermal contact between it and the structure. In figure 4 we demonstrate calculated heat flux distribution in the structure, arrows there qualitatively indicate the heat flux direction. A bright spot in the corner in figure 4 is an artifact of numerical modeling, since the flux suffers discontinuity at cutting edges. Important to note that heat flux through the substrate and further to the heat sink significantly dominates the heat flux to the upper surrounding. Particularly, the overall downward heat flux exceeds the overall upward heat flux by about 4 orders. This supports abovementioned reasonings: since the downward heat flux to the heat sink is dominant, imperfection of the thermal contact can significantly increase the experimental heating compared to the ideal simulated one.

3.2 Thermal resistance vs. disk diameter and SU-8 influence

Thermal resistance shows a change of the structure temperature relatively to a change of the input power. In accordance with the described above method, we determined thermal resistance of MD lasers with different diameters under air surrounding and planarized with SU-8 photoresist. Experimental results are demonstrated in figure 5a. Also, we carried out corresponding calculations, results of which are presented in figure 5b.

In figure 5a we observe that thermal resistance is expectedly lower for larger MDs, i.e. thermal resistance is inversely proportional to a MD diameter. Basic difference between measured and
calculated results in figure 5a and b is the same as in figure 3: heating and, therefore, thermal resistance of the real structure are higher than ones of the ideal modeled structure. Also, the measurements showed that planarization of a microlaser with the use of SU-8 leads to a noticeable decrease in thermal resistance, whereas, according to the calculations, the influence of SU-8 is almost negligible (two curves in figure 5b coincide). The result of the calculations is explained by dominance of the downward heat flux, for it makes influence of cover layers insignificant. The experimental result, in turn, offers that the downward heat flux is somehow restricted, probably, by imperfect thermal contact between the structure and the heat sink, and the upward heat flux becomes relevant. The SU-8 cover increase the upward heat flux, since its thermal conductivity, albeit low, is still higher than the one of air (see table 1). Thus, planarization with SU-8 noticeably improves thermal resistivity.

![Figure 5](image_url)

**Figure 5.** Experimental (a) and calculated (b) dependences of thermal resistance on MD diameter for microlasers under air surrounding and with SU-8 planarization.

### 3.3 Influence of TiO$_2$ cover

We calculated and compared temperature distribution in the MD laser under air surrounding and with upper TiO$_2$ cover. An actual SLSW consists of layers TiO$_2$/SiO$_2$/TiO$_2$, however, the inner SiO$_2$ layer is much thinner than the clad TiO$_2$ layers. Therefore, in the calculations we considered the covering layer as uniform TiO$_2$. We analyzed the MD of 6 μm in diameter under pump power of 1.2 mW (~3 $P_{th}$). We calculated temperature distribution in the structure with and without the TiO$_2$ cover, particularly, temperature dependence along a vertical axis. The result of the calculations is presented in figure 6.

![Figure 6](image_url)

**Figure 6.** Temperature distribution along a vertical axis in the microlaser structure with and without (under air) the TiO$_2$ cover. The MD diameter is 6 μm, pump power – 1.2 mW. Inset – spatial temperature distribution in case of the TiO$_2$ cover, vertical axis $z$ is designated.
The average MD self-heating in both cases is similar: ~2.9 °C with the TiO\textsubscript{2} cover and ~3.1 °C without cover. The reason is the one discussed above – dominance of the downward heat flux makes upper covers almost irrelevant. However, temperature distribution in the structure with TiO\textsubscript{2} cover becomes less localized compared to the air surrounding. This, possibly, can make the structure with the SLSW cover more sensitive to any kind of additional active air cooling – less localized heat is easier to dissipate.

**Conclusion**

We studied experimentally and numerically thermal resistance of microdisk lasing structures. We determined self-heating of MDs of different diameters against pump power via measurements of the lasing wavelength shifting. Thermal resistance, which is a slope of the dependences obtained, was lesser for larger diameter of the MD, i.e. inversely proportional to diameter. Qualitatively, this was supported by numerical calculations of temperature distribution in the structures. Though, modeled ideal structures had lesser thermal resistance than real ones. This is probably because of the imperfect thermal contact between the substrate and the heat sink. Modeling showed that the downward heat flux through the substrate to the heat sink was much greater than the upward convective heat flux, therefore, good quality of the heat sink and thermal contact there is crucial. We also experimentally demonstrated that planarization of the structure with SU-8 noticeably decreases thermal resistance of the structure. By numerical modeling, we showed that the TiO\textsubscript{2} cover of the MD slightly decreases its temperature and reduces heat localization. The latter makes the structure with a dielectric cover more sensitive to convective heat dissipation, e.g. by active air cooling.

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**References**

[1] Zhukov A E et al 2020 *IEEE J. Quantum Electron.* **56** 1–8
[2] Zhukov A E, Moiseev E I, Nadtochii A M, Kryzhanovskaya N V, Kulagina M M, Mintairov S A, Kalyuzhnyi N A, Zubov F I and Maximov M V 2020 *Tech. Phys. Lett.* **46** 515–9
[3] Fetisova M et al 2020 *J. Opt. Soc. Am. B* **37** 1878
[4] Zhukov A E, Kryzhanovskaya N V, Maximov M V, Lipovskii A A, Savelyev A V, Shostak I I, Moiseev E I, Kudashova Y V, Kulagina M M and Troshkov S I 2015 *Semiconductors* **49** 674–8
[5] Blakemore J S 1982 *J. Appl. Phys.* **53** 123–81
[6] https://www.makeitfrom.com/material-properties/Alumina-Aluminum-Oxide-Al2O3
[7] Oh S H, Lee K-C, Chun J, Kim M and Lee S S 2001 *J. Micromechanics Microengineering* **11** 221–5
[8] Thurber W R and Mante A J H 1965 *Phys. Rev.* **139** 1655–65