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THERMAL PROBLEMS IN ARSENIDE VECSELs

Different aspects of thermal management of GaAs-based vertical-external-cavity surface-emitting lasers (VECSELs) are described and analyzed by example of typical configurations of GaInNAs/GaAs multiple-quantum-well (MQW) VECSEL. Simulations of two-dimensional heat-flux spreading within investigated structures have been carried out with the aid of the self-consistent thermal finite-element method. Influence of pumping-beam and heat spreader properties on maximal temperature increase have been studied and different heat management techniques have been compared.

Keywords: VECSEL, semiconductor disk laser, heat management,
thermal management, GaInNAs.

1. INTRODUCTION

Nowadays there are two distinctly different groups of semiconductor lasers: edge-emitting lasers (EELs) and vertical-cavity surface-emitting lasers (VCSELs). EELs may emit very intense high-power radiation of the order of many watts, but their output beams are very divergent, with astigmatism effects, and contain many longitudinal modes. On the other hand, VCSELs emit low-divergent circularly symmetric output beams without astigmatism, but their single-mode emission is limited to relatively low output power of the order of few milliwatts. New optically pumped vertical-external-cavity surface-emitting lasers (VECSELs), also known as semiconductor disk lasers, seem to combine simultaneously virtues of both these laser types, i.e. they may emit high-power radiation with high-quality output beams. Unfortunately their possible applications can be currently a bit limited, especially by their poor thermal behavior. It follows mostly from both a very intense heat generation within their volumes, especially in active regions, and ineffective heat-flux extraction from these volumes. Since it is impossible to determine an exact temperature distribution within such devices by direct measurement, computer simulation is often applied to thermal management investigations. A numerical model enables to simulate thermal processes within VECSEL volumes to understand deeper their physics of an operation which should help with thermal optimization of their structures. Until now different thermal management approaches [1, 2, 3] and factors which may influence on temperature distribution within VECSELs volumes such as: power [1, 3], a diameter [1, 4], a wavelength [1, 2, 4] and a spatial profile [1] of a pumping beam, as well as thermal conductivity and a thickness of different laser layers (a heat spreader [1, 2, 3, 5], a window [1] and a DBR mirror [3]) have been investigated with the aid of computer modeling.

This paper is devoted mainly to a comparative analysis of typical arsenide VECSEL thermal management techniques. Moreover, an influence of a heat spreader properties on maximal temperature increase within laser volume has been studied. As the subject of our modeling we've chosen GaInNAs/GaAs MQW VECSEL operating at 1.3 μm, which can be a source of high-power visible radiation with the help of frequency doubling. Such visible-emitting laser could be potentially used in color projection displays from full cinema projection to laser television and mobile micro projectors.

2. LASER STRUCTURES

Structure of a typical VECSEL is schematically shown in Fig. 1. It is made as a semiconductor chip and consists of: a quantum-well (QW) or quantum-dot (QD) active region, a Bragg reflector (DBR) mirror, a carrier-confinement window and a cap layer. The window layer prevents carriers from diffusing to the semiconductor-air interface, where they could recombine nonradiatively and hence deplete laser gain. In turn, the cap layer protects underneath layers from oxidation. The characteristic virtue of VECSEL is that the laser cavity, extended between the DBR mirror and an external spherical mirror, enables to place additional external optical elements for transverse mode control, pulse repetition rate control or for harmonic generation. The whole structure is attached to a copper or brass heat sink. Optically pumped VECSEL works as a beam converter i.e. it converts a high-power and low-quality pumping beam into high-quality and relatively still high-power output beam (see Fig. 1).

In view of comparative analysis of different heat management approaches, four VECSEL structures have been investigated. Their configurations are schematically shown in Fig. 2. All of them have been projected on the grounds of the structure Fig. 2c described in [6], but some parameters, such as: substrate and spacers thicknesses or submount dimensions, have been determined by us.

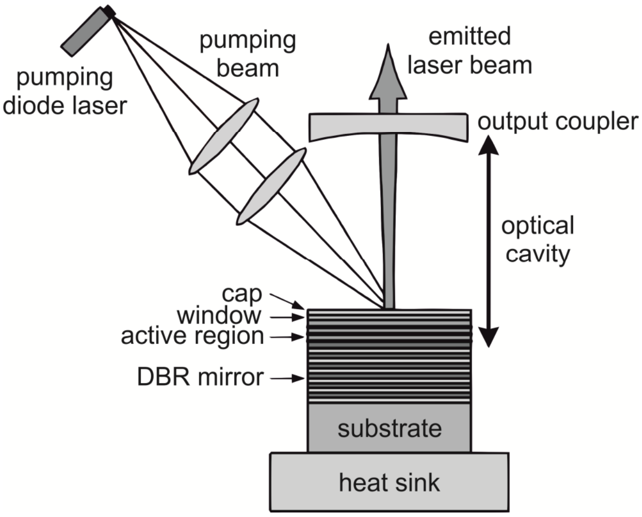

Fig. 1. Structure of a typical VECSEL

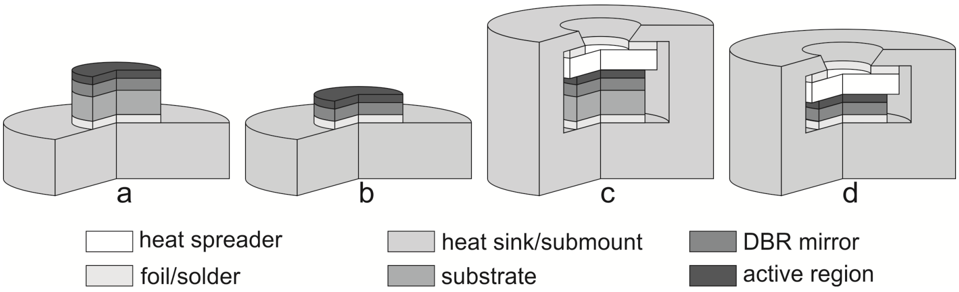

Fig. 2. Configurations of all investigated VECSELs: a – as-grown, b – thin device, c – as-grown with the heat spreader, d – thin device with the heat spreader. Not to scale

The structure was grown on the 300-μm GaAs substrate. The active region consists of five pairs of 7-nm $Ga_{0.63}In_{0.37}N_{0.012}As_{0.988}$ quantum wells separated in each pair by 13-nm and between pairs by 158-nm GaAs barriers to form the resonant-periodic-gain (RPG) configuration. The internal resonator length is 3λ (emitted wavelength – 1315 nm). Over the active region, there are the upper 282-nm window $Al_{0.3}Ga_{0.7}As$ layer and the 1-nm cap GaAs layer. The DBR mirror is composed of 25.5 periods of the quarter-wave GaAs/AlAs layers. The 270-μm natural diamond heat spreader of high thermal conductivity coefficient – k = 2200 W/(Km) is bonded directly on the laser chip with the aid of liquid capillarity. The laser chip is attached to the 15-mm copper heat sink and closed in the copper submount. The clamping has been realized by using the 125-µm indium foil. The bottom heat sink surface is held at 278 K. The laser is optically pumped with the aid of an external diode laser emitting the 808-nm high-power radiation.

Three other VECSEL configurations, based on the already described structure, have been also investigated. The first one is schematically shown in Fig. 2a. This is a simply as-grown structure directly attached to the heat sink without any heat spreader or submount. It is characterized by high thermal resistance which is the result of a heat flux flow through its DBR mirror and the thick substrate. The second VECSEL configuration (Fig. 2b), known as thin device, is almost identical to the as-grown one, but the GaAs substrate is completely removed in order to reduce laser thermal resistance. Since in both above configurations there are no additional submounts, semiconductors chips are attached to their heat sinks with the aid of the 4-µm indium solders instead of the indium foil. The last investigated structure (Fig. 2d) is in fact the thin device structure with the diamond heat spreader. It is supposed to combine advantages of both configurations presented in Fig. 2b and Fig. 2c.

3. RESULTS

Simulations have been carried out with the aid of the self-consistent thermal finite-element method. Side and top walls of a laser chip have been assumed to be thermally isolated, since the acceptance of thermal energy by air particles by free convection and thermal radiation from laser these walls have been found to be negligible as compared with an intense heat-flux removing by the laser copper heat sink. In our calculations, the constant temperature $T_{\mathrm{hs}} = 278$ K of the heat sink bottom surface has been assumed (any temperature increase occurring in the paper refers to this temperature). Steadily reduced intensity of the pumping beam in successive laser layers has been determined on the basis of optical absorption coefficients found in [7, 8] and the assumption that the radial intensity profile is described by the Gaussian distribution. Reflection from both sides of the heat spreader has been taken into account. Normal incidence of pumping beam have been assumed following authors of [9] where the structure similar to that from Fig. 2c has been described. Radiation conversion efficiency and power of heat sources have been determined on the basis of power transfer characteristic from [6].

Self-consistence of thermal model consists in taking into account thermal dependence of thermal conductivity coefficients of different laser layers. For $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ the following equation [10] can be written:

$$k_{\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}}(T) = k_{\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}}(300\,\mathrm{K})\left(\frac{300\,\mathrm{K}}{T}\right)^{\frac{5}{4}} \frac{\mathrm{W}}{\mathrm{Km}} \tag{1}$$

The thermal conductivity coefficient of $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ at 300 K can be determined from [11]:

$$k_{\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}}(x) = \frac{100}{2.27 + 28.83x - 30.00x^2} \frac{\mathrm{W}}{\mathrm{Km}} \tag{2}$$

The thermal conductivity coefficient of $\mathrm{Ga}_{0.63}\mathrm{In}_{0.37}\mathrm{N}_{0.012}\mathrm{As}_{0.988}$ at 300 K has been estimated using Vegard's law. Thermal dependence of this coefficient has been assumed to be the same as for $\mathrm{In}_{0.445}\mathrm{Ga}_{0.555}\mathrm{As}$ [12-14].

Some of our results are presented in form of 'thermal maps' which show a relation between maximal temperature increase within VECSEL volumes (referred to $T_{\mathrm{hs}} = 278$ K) and pumping beam parameters. They are shown in Fig. 3, where φ is the Gaussian-pumping-beam $1/e^2$ diameter, P_{p} is power of incident pumping radiation and P_{Q} is power of heat sources i.e. P_{p} reduced by power of reflected pumping radiation and emitted laser radiation. Power of emitted radiation and threshold incident pumping power (1.8 W for a and b structures, 1.5 W for c and d ones) has been determined by using power transfer characteristic from [6]. One can see that in the case of the simple as-grown structure enormous temperature increase even over melting temperatures of used materials should be expected. Although this configuration is characterized by very poor thermal properties, map from Fig. 3a may be used in comparative analysis with other 'thermal maps', so calculations have been carried out for such wide pumping-power range. Enormous temperature increase follows from an ineffective heat-flux extraction by the heat sink. Main barriers for the heat flow are the DBR mirror and the thick GaAs substrate. For narrow pumping beams a heat-flux density has high values in the central part of the structure what is an additional difficulty for heat removal and leads to huge temperature increase.

Results for the 'thin device' structure are shown in Fig. 3b. One can see that substrate removal contributes to significant reduction of maximal temperature increase, however in the case of using high-power and low-diameter pumping beams the temperature is still quite high.

Applying the high-conductive heat spreader on the upper surface of the laser chip (Fig. 3c) leads to dramatic temperature reduction, even if the structure is placed on the thick GaAs substrate. The principle of the heat spreader operation consists in accepting heat generated in the active region and radial heat-flux spreading, so the cross-section of the heat flow towards the laser heat sink is considerably increased leading to lower temperature increase within laser volume.

Additional substrate removal (Fig. 3d) contribute to even better results, as the thick substrate is the main barrier for the heat flow towards the heat sink. Maximal temperature increase within the structure d is reduced by 10-25% as compared with the structure c. However, complete substrate removal is a difficult and expensive technological process, but in the case of applying the high-conductive heat spreader it is often unnecessary for a proper VECSEL operation.

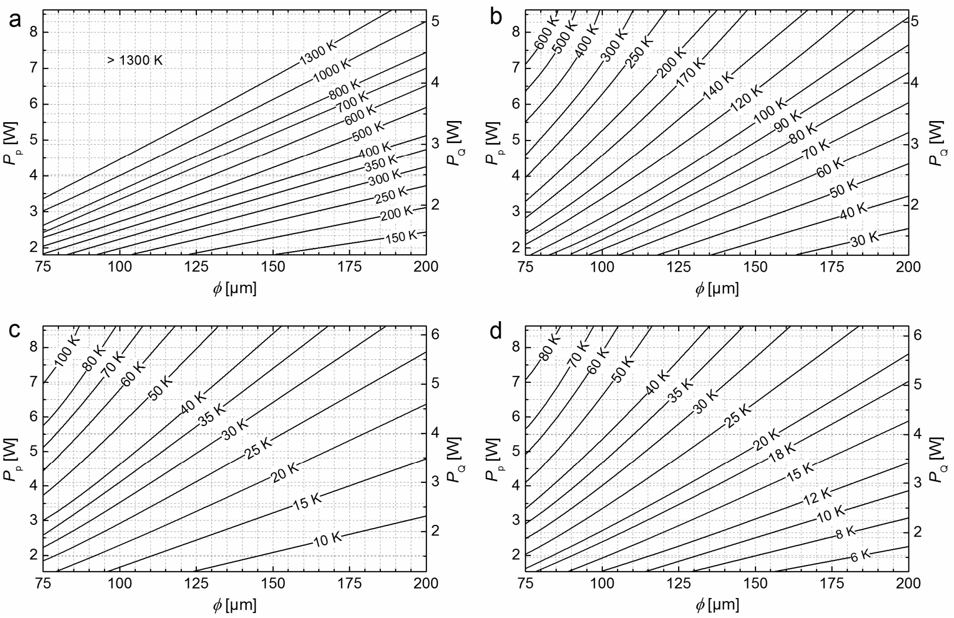

Fig. 3. Maximal temperature increase ΔT_{max} versus the pumping-beam diameter φ, incident power P_p and power of heat sources P_Q for the investigated GaInNAs/GaAs MQW VECSEL structures: a, b, c and d

Fig. 4 shows the dependence between thermal resistance R_{th} of investigated VECSEL configurations and the diameter φ of the pumping beam of incident power $P_p = 8$ W. Thermal resistance is defined as the ratio of the maximal temperature increase within the laser volume to the power of heat sources ($R_{th} = \Delta T_{max}/P_Q$). It is an important parameter which may be used to compare thermal properties of different VECSEL configurations. One can see that additional substrate removal in the structure with the diamond heat spreader is not crucial, since this relatively expensive and difficult technological process improves heat-flux extraction in much smaller degree than in the structure without the heat spreader.

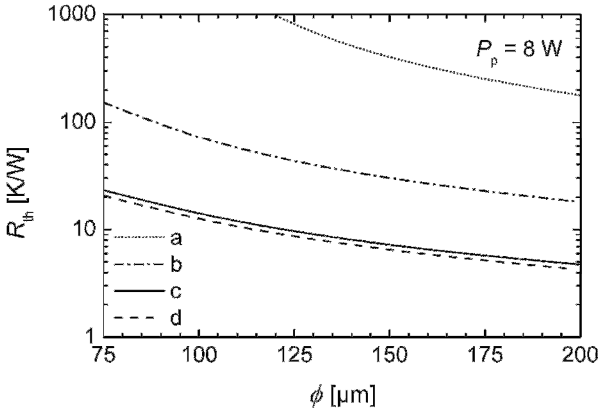

Fig. 4. Thermal resistance R_{th} of structures a, b, c and d versus the pumping-beam diameter φ for pumping power P_p = 8 W

Fig. 5 presents an illustration of the heat-flux flow within the structure d for the pumping beam of power 8 W and the diameter 75 μm. As you can see heat generated in the active region is accepted by the heat spreader and spread in its volume. Then it is extracted from the heat spreader in two different ways. Most of heat flows directly towards the heat sink through the whole semiconductor chip, but cross-section of this flow is considerably increased in comparison with that within structures a and b. This leads to reduction of maximal temperature increase. Moreover, a certain amount of heat is also removed by the ring contact on the top of the heat spreader and the upper part of the laser copper submount, but this is only the subsidiary channel for the heat flow towards the heat sink.

In order to efficient excess heat spreading, the heat spreader should be characterized by high thermal conductivity, appropriate geometrical dimensions and high-quality thermal contact with the semiconductor chip. Fig. 6 shows an influence of heat spreader thermal conductivity on maximal temperature increase within the structure c. One can see that this influence is stronger for narrower pumping beams. In general, it is better to use as high-conductive materials as possible, but in some cases – for low-power and low-diameter pumping beams – an application of lower-conductive heat spreader (e.g. made of SiC) may be sufficient to provide effective heat extraction.

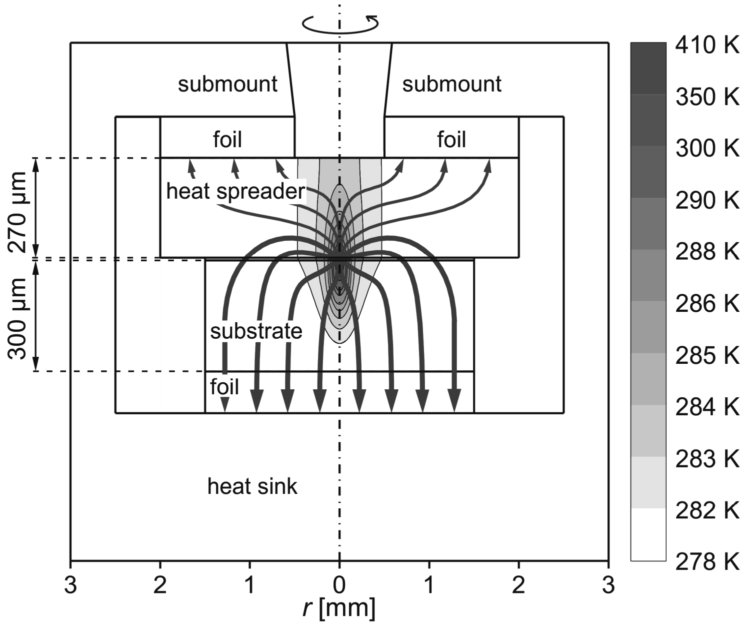

Fig. 5. The illustration of the heat-flux flow in the structure c for the pumping beam of power P_p = 8 W and the diameter φ = 75 µm

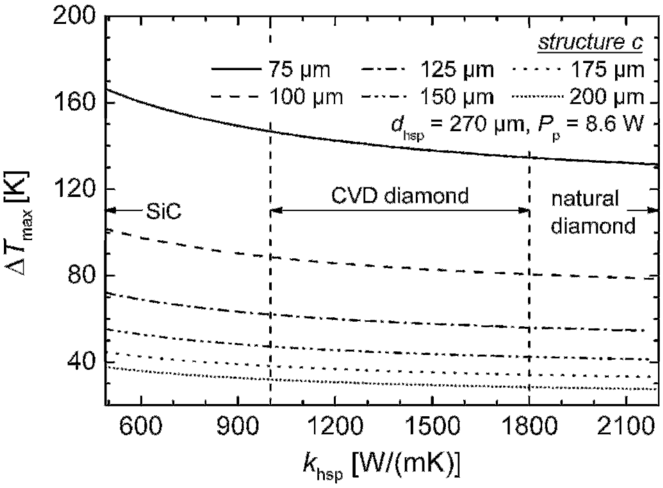

Fig. 6. Maximal temperature increase within the structure c versus thermal conductivity coefficient k_{hsp} of the heat spreader for different pumping-beam diameters

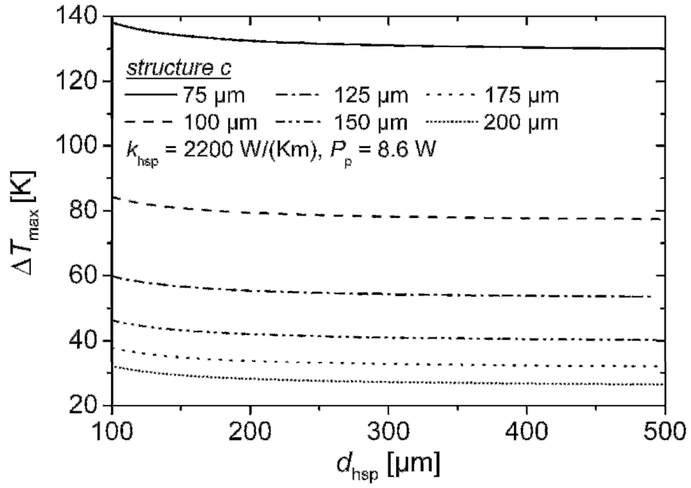

Fig. 7. Maximal temperature increase within the structure c versus thickness d_{hsp} of the heat spreader for different pumping-beam diameters

Fig. 7 presents an influence of heat spreader thickness on maximal temperature increase within the structure c. One can see significant temperature increase for thickness values below about 200 μm. It means, that there is no possibility to use very thin epitaxial layers as heat spreaders in the case of VECSELs pumped by high-power beams and designed for high output power.

4. CONCLUSIONS

From among all described VECSEL structures the thin device configuration with the diamond heat spreader (see Fig. 2d) turns out to be the most efficient heat management technique. However, substrate removal is a quite difficult and expensive technological process and in many cases an application of a high conductive heat spreader solely is sufficient enough to provide proper laser thermal behavior. Our ‘thermal maps’ enable determination of the maximal temperature increase within presented lasers for different pumping-beam parameters in quick and simple way. They can be useful especially at laser designing. It should be noted that these maps can be used is some cases to estimate thermal properties of some other arsenide VECSELs, on condition that their geometrical dimensions are similar, since in majority of cases they are made of the same materials such as: GaAs, AlAs, AlGaAs.

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ZAGADNIENIA CIEPLNE W ARSENKOWYCH LASERACH TYPU VECSEL

Streszczenie

W pracy zostały opisane i przeanalizowane wybrane aspekty dotyczące własności cieplnych optycznie pompowanych laserów półprzewodnikowych o emisji powierzchniowej z zewnętrzną pionową wnęką rezonansową (VECSELs, ang. *vertical-external-cavity surface-emitting lasers*) na podłożu z GaAs. Obliczenia wykonano dla typowych konfiguracji montażowych lasera typu VECSEL z obszarem czynnym w postaci wielokrotnej studni kwantowej wykonanej w systemie materiałowym GaInNAs/GaAs. Do symulacji dwuwymiarowego rozpływu ciepła wykorzystano samouzgodniony model cieplny oparty na metodzie elementów skończonych (MES), przy pomocy którego porównano własności cieplne poszczególnych struktur oraz określono wpływ parametrów wiązki pompującej (moc, średnica) i *heat spreadera* (przewodność cieplna, grubość) na maksymalny przyrost temperatury w ich wnętrzach.