Impact of bottom DBR radius and electric aperture radius on GaN VCSEL operation

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***Abstract*— We present the results of a numerical analysis of a nitride-based vertical-cavity surface-emitting laser (VCSEL) with an upper mirror composed of a monolithic high-contrast grating (MHCG) and with a bottom dielectric mirror. Using numerical simulations, we investigated the impact of the size of the lower dielectric mirrors on laser performance. Additionally, we examined the effect of changing the electrical aperture radius (active area dimensions) of the laser. Based on the obtained results, we demonstrated that the appropriate selection of these two parameters allows, among other benefits, the reduction of the temperature inside the laser, the lowering of the laser's threshold current, and a significant increase in its optical power.**

Keywords—GaN, VCSEL, DBR, electric aperture

I. Introduction

Due to the specific physical properties of nitride materials, the technology for manufacturing such devices is challenging and subject to many limitations. Currently, there are still issues with the commercial production of nitride-based VCSELs. While there are laboratory constructions of nitride-based VCSELs that achieve power levels of several to even tens of milliwatts, many GaN-based VCSEL prototypes remain in the research phase, primarily due to the difficulty in fabricating their monolithic GaN-based structures. The main difficulties are associated with the production of nitride distributed Bragg reflectors (DBRs), which are fundamental components ensuring the proper operation of the laser. These difficulties stem, among other reasons, from the specific physical properties of these materials, particularly the lattice mismatch between GaN, AlN, and InN. One consequence of this mismatch is the challenge in creating native nitride DBR mirrors, which significantly limits the efficiency of these devices [1–6].

Over the past few years, various concepts have emerged to address this problem. Different types of DBR mirrors have been developed: epitaxial, dielectric, air-gap DBRs, nanoporous GaN, and monolithic curved mirrors [3]. Recently, it has been demonstrated that upper DBR mirrors can be successfully replaced with high-index contrast gratings (HCGs) and monolithic high-refractive-index contrast gratings (MHCGs). There is considerable hope that these types of mirrors will be used in nitride-based VCSELs.

Designing highly efficient single emitters of VCSELs based on gallium nitride and optimizing their operational parameters would enable their effective use in applications such as color displays, projectors, transparent displays, lighting devices, high-density data storage and retrieval devices, high-resolution printing, visible light wireless communication, underwater communication, LiDAR systems [1–7]. This development would also open up the possibility of constructing two-dimensional arrays of these devices.

In this study, we present a numerical analysis of a nitride-based hybrid VCSEL, which an MHCG GaN on one side and dielectric DBRs on the other (see Fig. 1). The base structure chosen for this analysis was proposed by Hong et al. and operated only under pulsed conditions [7]. The emitter was designed for light emission at a wavelength of 403 nm. The main objective of the research was to explore design solutions that improve the performance of the mentioned laser, particularly aiming for continuous-wave (CW) operation. We sought to enhance the device's efficiency by improving its thermal properties and more effectively utilizing the injected current in its active region. Accordingly, we conducted an analysis of the impact of the radius of the lower dielectric mirrors and changes in the laser's electrical aperture radius on the conditions and parameters of the studied design.

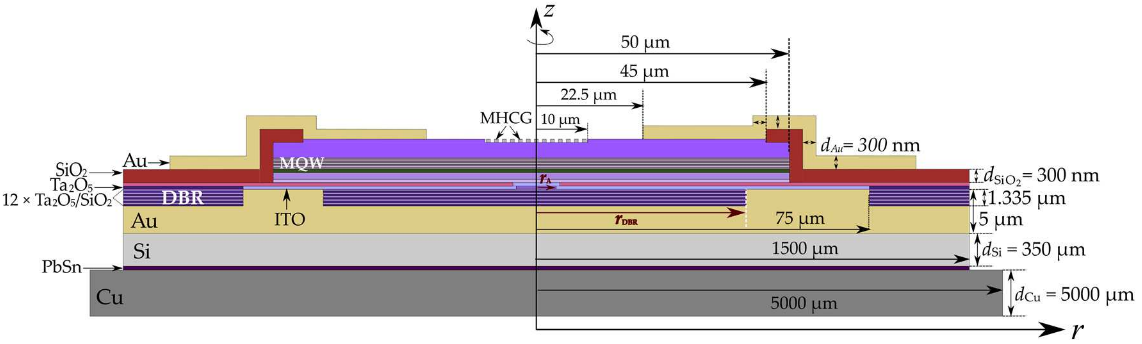

Fig. 1. Schematic of the structure of the GaN VCSEL with MHCG (not to scale). The structure's foundation consists of a silicon carrier substrate with a thickness of 350 µm. Directly on it, there is a gold layer connecting the carrier substrate to the laser structure. Next, there are the bottom DBR mirrors consisting of 12 pairs of Ta_2O_5 and SiO_2 layers with thick-nesses of 41.4 nm and 67.1 nm, respectively, and a radius denoted as r_{DBR}. Above the bottom DBRs is a Ta_2O_5 phase-shifting layer surrounded by an ITO layer. The size of the phase-shifting layer, along with the correlated inner radius of the SiO_2 layer, serves as the electrical aperture of the laser with a radius of r_A and simultaneously determines the boundary of the active region of the device in the radial direction. The active region consists of ten 3 nm InGaN quantum wells separated by nine 8 nm GaN barriers. The laser resonator was designed to be 21.5 wavelengths long. At the top of the laser, on its surface, an MHCG with a combined radius of 10 µm was placed.

II. NUMERICAL MODEL

The presented results were obtained using numerical simulations employing a proprietary model and computer program developed by the Photonics Team of the Institute of Physics at the Lodz University of Technology. This program allows for simulating physical phenomena occurring, particularly during the operation of semiconductor lasers. Self-consistent calculations were performed by integrating thermal, electrical, optical, and active region gain models. A detailed description of the models used for the calculations, as well as the method for integrating these models for VCSEL calculations, can be found in the literature [8].

III. RESULTS

The flow of current through the laser structure generates heat inside the device, leading to an increase in temperature throughout. This temperature rise adversely affects the operating parameters and performance of the laser, potentially preventing CW operation. This issue occurs when the electrical aperture is 9 µm. However, after reducing the radius of the bottom mirrors, an improvement in the laser performance was observed, enabling CW operation. Table 1 lists the combinations of the mentioned parameters that guarantee CW operation, along with the corresponding threshold currents. It was demonstrated that optimizing the size of the electrical aperture by adjusting its radius reduces the threshold currents, which in turn lowers the maximum temperature in the active region at the laser action threshold.

TABLE I. THRESHOLD CURRENTS VALUES FOR DIFFERENT LASERS. FOR STRUCTURES THAT DO NOT OPERATE IN CONTINUOUS WAVE MODE, THE TABLE INDICATES: ~~CW~~.

CW	**I_{th} [mA]**						
	r_{DBR} [µm]						
r_A [µm]	**10**	**15**	**20**	**25**	**30**	**35**	**40**
3.0	5.64	5.77	5.89	5.98	6.04	6.09	6.14
3.5	8.09	8.48	8.79	9.06	9.28	9.48	9.67
4.0	11.13	12.14	13.51	12.85	12.66	13.32	14.40
4.5	15.09	16.37	~~CW~~	~~CW~~	~~CW~~	~~CW~~	~~CW~~

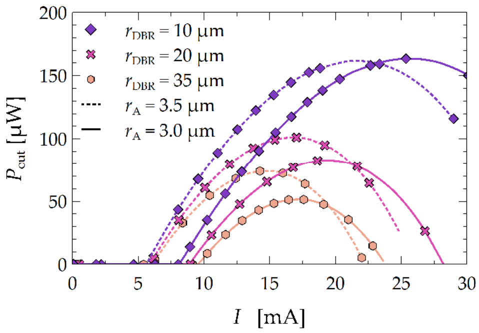

Fig. 2. Power-current characteristics of the analyzed VCSEL, with different values of the active region aperture radius (r_A) and the bottom DBR mirror radius (r_{DBR}).

By selecting an appropriate combination of the radius of the lower DBR mirrors and the radius of the laser's active region, we also significantly increase the maximum optical power emitted by the device. From the power-current characteristics shown in Fig. 2, we see that changes in the maximum output power of the laser are closely related to the radius of its lower DBR mirrors. For example, in a laser with an electrical aperture radius of 3.0 µm, changing the DBR mirror radius from 35 µm to 10 µm reduces the threshold current by 0.45 mA and doubles the maximum optical power. In the case of larger apertures, even greater changes in threshold current and maximum power are observed. For instance, with an aperture radius of 3.5 µm, the threshold current decreases by 1.39 mA, and the maximum power increases threefold.

The increase in optical power emitted by the laser is not solely due to improved thermal conditions, but also results from better overlap between the laser mode and the current distribution in the active region, as shown in Fig. 3. Simulation indicates that structures with larger apertures tend to operate in higher-order modes, which is associated with increased current flow at the edge of the aperture. In contrast, in narrower active regions, we observed that the current distribution flowing through the active region is narrower and more uniform.

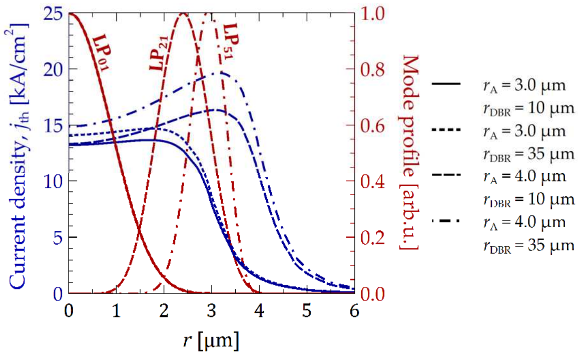

Fig. 3. The radial distribution of the electromagnetic field intensity and the current density distribution in the active region for lasers with different aperture radii (r_A) and different lower DBR radii (r_{DBR}).

IV. CONCLUSIONS

In summary, based on the numerical analysis of the presented nitride-based VCSEL structure, it can be concluded that the proper design of the laser's active region size and the size of the lower DBR mirrors allows for continuous-wave operation, reduction of the threshold current, and a significant increase in the emitted optical power.

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