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Oxide-Confined VCSEL with Enhanced Single-Mode Output Power Via two Oxide Layers with multiple apertures

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Abstract— A novel vertical-cavity surface emitting laser (VCSEL) based on two oxide layers with multiple apertures for the purpose of enlarging window aperture and maintaining single transverse mode operation is suggested and numerically investigated. The oxide layers with multiple aperture sizes structure has a number of advantages including easier fabrication in compare with multi-oxide layer structures, better mechanical stability, and very strong and high single-mode optical output power. The simulation results also show that this structure has a low threshold current. A comprehensive optical-electrical thermal-gain self-consistent VCSEL model is used to simulate and investigate the proposed structure. It has been shown that by using two oxide layers with multiple apertures in VCSEL, high single mode optical output power and a possibility of single-mode VCSEL with a large active area could be achieved.

Keywords— VCSEL, Oxide layer, multiple apertures, Transversally single mode laser, Comprehensive VCSEL model.

1. Introduction

VERTICAL Cavity surface Emitting Lasers (VCSELs) are among the most successful novel semiconductor hetero-structure devices that have been introduced over the last decade [1]. Particularly, GaAs VCSELs have shown high performances based on AlAs oxidation techniques [2]. For many applications, the VCSEL's operation in the fundamental transverse mode is crucial for high system performance [3]. Since a VCSEL usually has a transverse dimension that is larger than its longitudinal length, several transverse modes can be supported. So, the VCSEL has the tendency to lase at multiple wavelengths. Single mode operation in the oxide-confined VCSELs can be achieved by reducing the radius of oxide aperture size, but this reduces the optical output power due to thermal rollover limitation, and increases threshold current as a result of increased scattering loss [4]. In fact, the single mode operation in oxide-confined VCSELs is achieved for aperture sizes smaller than 3 µm [4- 6]. So, the high power single mode operation in oxide-confined VCSELs is difficult to achieve.

Considerable effort has been invested to achieve single-mode operation with a high output power in VCSELs, including surface relief etching [7, 8], the use of an anti-guide cavity [9], and photonic crystal defects [10]. Although these techniques have shown effectiveness in controlling the emission mode, they typically require additional structural complexity and stringent fabrication control.

Using multiple oxide layers is another way to get high optical output power in single mode operation [4-7]. A 9 mW single transverse mode output power has been achieved by using multiple oxide layers [5, 6]. However, the oxide-confined VCSELs are very sensitive to slight changes in its structure [4-6]. Indeed, the VCSEL performance such as output power, threshold current, number of modes, modulation speed, etc., are impressed by the position, thickness, and diameter of oxide layers [4-6]. So, some careful designs of positions, aperture sizes, and thickness of oxide layers are required for increasing single-mode output power [4-6]. On the other hand, the fabrication tolerance of single-mode devices is quite critical due to the difficulty in oxidation control.

In this paper, a novel structure has been proposed for the purpose of enlarging window aperture maintaining single transverse mode operation by using two oxide layers with multiple apertures. So, instead of using multiple oxide layers, in this method, only two oxide layers with multiple apertures are used that is located near active layer on top. By using this structure, Single-mode operation was achieved in spite of its relatively large oxide aperture size of 8 µm. using this method does not need stringent control of oxidation and the performance of the VCSEL does not sensitive to slight changes in structure parameters extremely.

Using two oxide layers with multiple apertures in VCSEL structure could pin the optical output polarization, which is of interest for several applications in optical communication and sensing [11]. All approaches have up to now relied on either metallic stripes grating [12], or a dielectric grating etched into the VCSEL surface [13]. The effect of a dielectric surface grating strongly depends on its parameters like period and etching depth [13]. In this paper, to best of our knowledge for the first time, we have proposed a novel structure to achieve high single mode optical output power and low threshold current VCSEL. In compare with multiple-oxide-confined VCSELs, this structure has also high optical output power, low threshold current, but the fabrication process is easier because the performance of structure is not affected by details of oxide layer significantly.

2. Proposed preamplifier topology

The 1600nm long VCSEL structure that we have investigated is shown in Fig.1. As is clear this structure has two oxide layers with multiple apertures. In this structure, the oxide apertures are repeated periodically. A detail of two oxide layers is depicted in Fig.2.The VCSEL has six 5.5 nm $In_{0.24}Ga_{0.76}As_{0.82}P_{0.18}$ QWs separated by 8 nm GaAs barriers. The 700 nm optical cavity is surrounded by DBRs consisting of 60 pairs GaAs/$Al_{0.67}Ga_{0.33}As$ on top and 56 pairs GaAs/AlAs on the bottom of the active layer. There are two oxide layers on top of the active layer. The depth and duration of oxide layers is 0.7 µm and 0.5 µm respectively. The oxide layer thickness is 80 nm. N-electrode behaves also as an ideal heat sink and its temperature is considered to be equal to 300° K for all simulations. The structure of the VCSEL under consideration is considered similar to that of previous works in [4-6] to compare the proposed structure with conventional oxide-confined and multiple-oxide-confined structures. As is clear from the figure, the VCSEL has two oxide layers that is similar to two-oxide layer VCSEL structures. However, the oxide layers have multiple aperture sizes and are located on top of active layer instead of both sides of active layer.

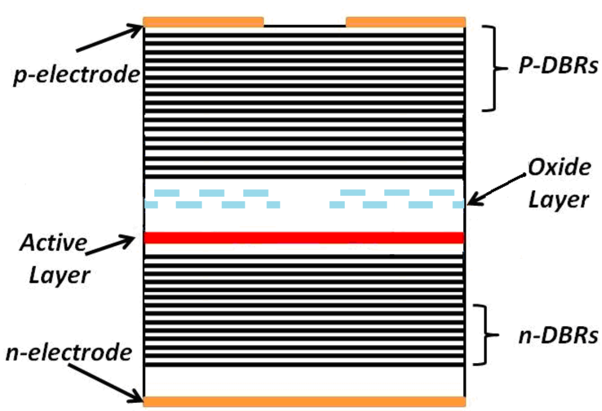

Fig. 1. Structure of the VCSEL under consideration

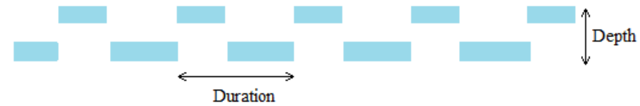

Fig. 2. Details of two oxide layers with multiple apertures

3. The NUMERICAL MODEL

Due to intense interaction of optical, electrical, and thermal phenomena occurring in the VCSELs operation, it is necessary to take their effects into account in the VCSEL model. Recently, various methods have been introduced to improve the accuracy of optical solution [14]. As for the numerical analysis we have used, a VCSEL simulator which applies a vectorial three-dimensional self-consistent electro-thermo-optical model.

Although the vectorial models are accurate, the complexity of these methods makes the self-consistent electro-thermo-optical simulation impractical, regarding the calculation time. For VCSEL simulation, the vectorial models are reduced to the scalar forms to get a reasonable calculation time.

The computer model used to simulate room-temperature operation of the VCSEL consists of four principal parts:

A. Optical Model: Successive optical modes and electromagnetic field within the laser resonator are described by the optical model. Maxwell vectorial equations are reduced to the scalar Helmholtz equation in cylindrical coordinates as following:

$$\nabla^2 E(r,z,\phi) + \frac{\omega^2}{c^2}\varepsilon(r,z,\phi,\omega)E(r,z,\phi) = 0$$

(1)

Where c, ω, ε(r, z, ϕ, ω) and E(r, z, ϕ) are speed of light, frequency, dielectric permittivity and electrical field in the cylindrical coordinates respectively.

A well-developed effective index model is used to solve the Helmholtz equation. This method is often referred to as Effective Frequency Method (EFM). EFM is a fast and flexible method in analysis of VCSELs.

B. Electrical Model: The electrical model characterizes both the current spreading (including carrier diffusion) between the top and bottom contacts and the injection of carriers of both kinds into the active region. The Poisson equation is solved by using the finite element method (FEM). Poisson's equation is as follows:

$$div(\varepsilon\nabla\psi) = -\rho. \quad (2)$$

Where ψ is the electrostatic potential, ε is the local permittivity, and ρ is the local charge density.

The electric field is calculated using equation:

$$\vec{E} = -\nabla\psi \quad (3)$$

Using Laplace equation (Eq.(4)) and a finite element method, current densities in VCSEL are calculated [5].

$$\Delta \cdot \left[\sigma(r,z,\phi)\nabla\left(V(r,z,\phi)\right)\right]=0 \qquad (4)$$

Where σ and V are three-dimensional electrical conductivity and potential profile, respectively. By solving these equations and Poisson equation in the active region, current spreading and carrier densities within the active region are calculated [5].

B. C. Thermal Model: The below heat equation is solved by using the FEM [12].

$$\nabla.\left(k_T(r,z)\nabla T(r,z)\right)=-\rho_T(r,z) \qquad (5)$$

Where T is the spatial variation of the temperature distribution, κT is the material thermal conductivity, and ρT is the distribution of internal heat source density.

D. Gain Model: We have applied the standard gain model to calculate optical gain [5].
In addition, the VCSEL model has a self-consistent part which describes all interactions between the above physical effects. In other words, electrical equations, Helmholtz equation, thermal equation and the gain equation are solved self-consistently. The non-linear solution, iteration method and their parameters, such as convergence criteria and iteration number, are specified in the model to converge the solution. The system nonlinear equations that result from FEM on a mesh are solved iteratively starting from an initial value [5]. Results obtained from solving the linearized problems provide corrections that are used to update the ongoing estimation of the solution. Iteration continues until convergence criteria are met and in this case, the solution will be accepted. If the iteration number passes a maximum allowable number, a different technique is tried. In this case, a different grid, a different initial value, or a different non-linear iteration technique is tried.

4. Results and discussion

The single-mode behavior of the two-oxide layers structure as shown in Fig. 1 is investigated by using the model proposed in section III. The carrier distribution profile in the active layer is shown in Fig.3. The carrier distribution profile has a shape which has a good overlap with fundamental optical mode intensity. As a result, the single mode optical power could be increased. In compare with multi oxide layer VCSEL considered in [5, 6], this structure has flatter carrier distribution profile.

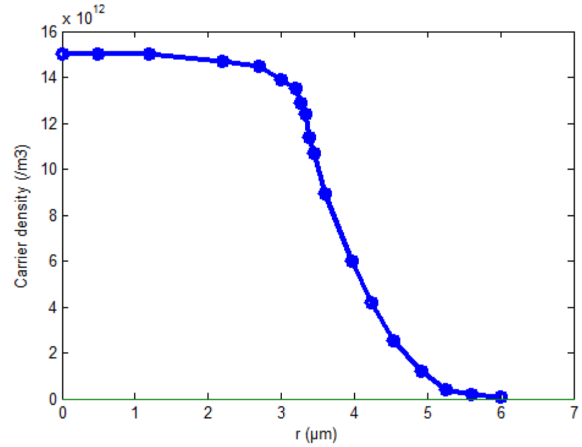

Fig.3. Carrier distribution Profile of the two oxide layers with multiple apertures VCSEL.

Fig. 4 shows the calculated optical output power as a function of oxide aperture size. As is clear from the figure, by using two oxide layers with multiple apertures, the single mode operation is ensured even for aperture sizes as large as 8 μm. for comparison, the results for a conventional one-oxide layer VCSEL is plotted as well. The multi-mode operation is specified by dotted line in the figure. As is shown, for one-oxide layer structure, the single mode operation is possible only for aperture sizes less than 3 μm. So, using proposed structure increases not only the single mode optical output power but also extends the range of single mode operation.

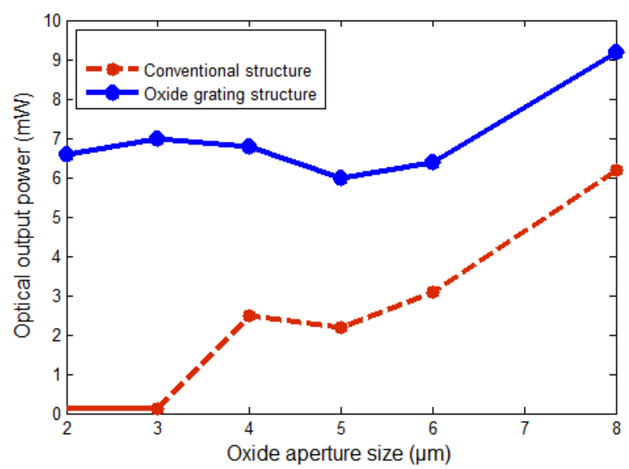

Fig. 4. Optical output power as a function of oxide aperture size for one-oxide layer VCSEL and two oxide layers with multiple apertures structure. Solid line shows single-mode operation region and dotted line shows multi-mode operation region.

So, the single mode optical output power as high as 9 mW could be achieved by using proposed structure. The similar result for optical output power has been achieved using multiple oxide layer structure [5].

To find the threshold current, the output power for another lower current is calculated and by considering a linear p-i curve, the threshold current is determined. The p-i curve for fundamental and six higher order modes for the oxide aperture size of 8 µm is plotted in Fig.5. As is clear from the figure, the optical output power of higher order modes is extremely lower than the fundamental mode. In fact, the maximum optical power of higher order modes is almost 1 µW.

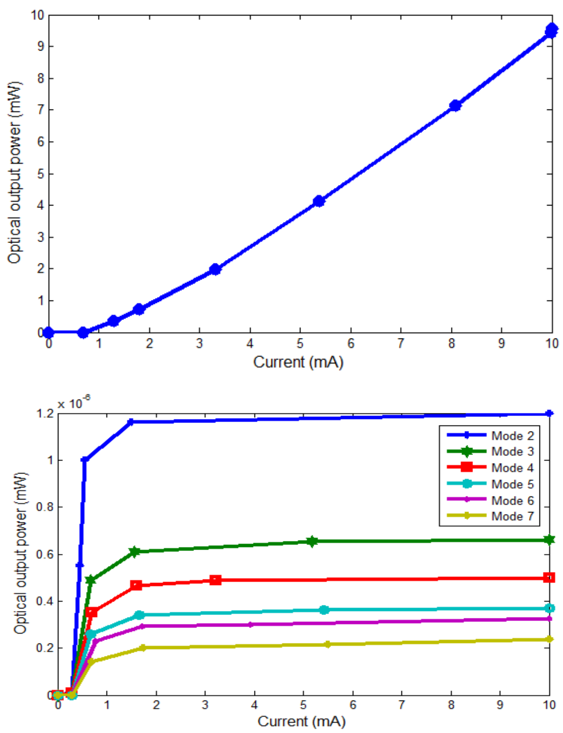

Fig.5. p-i curve of the VCSEL structure with two oxide layers with multiple apertures, for fundamental mode (left) and six higher order modes (right).

From the diagram, threshold current of this structure is 0.7 mA.

Threshold current as a function of oxide aperture size is plotted in Fig. 6 for proposed structure and conventional structure. As is clear from the diagram, threshold current is extremely lower for proposed structure than that for conventional structure. Threshold current for proposed structure is about 0.7 mA for all oxide aperture sizes. However, for conventional structure, threshold current may be as high as 5 mA for 3 µm aperture size. The low threshold current of proposed structure is similar to the results of multi oxide layer structure [5].

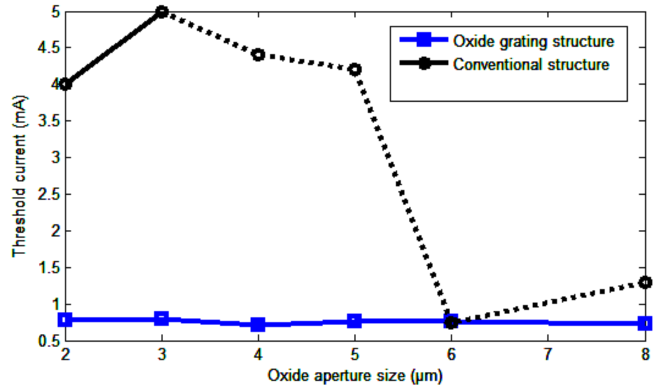

Fig. 6. Threshold current as a function of oxide aperture size for one-oxide layer VCSEL and two oxide layers with multiple apertures structure. Solid line shows single-mode operation region and dotted line shows multi-mode operation region.

The optical output power as a function of oxide aperture size is plotted in Fig. 7. The depth and duration of oxide layer is 0.5 µm. One can see that, in compare with the results of multi-oxide layer structures presented in [5, 6], the variation of optical output power is extremely less.

Threshold current as a function of oxide aperture size is plotted in Fig.8. The changing of this parameter is also negligible. So, the characteristics of proposed structure are not changed by details of oxide layers significantly.

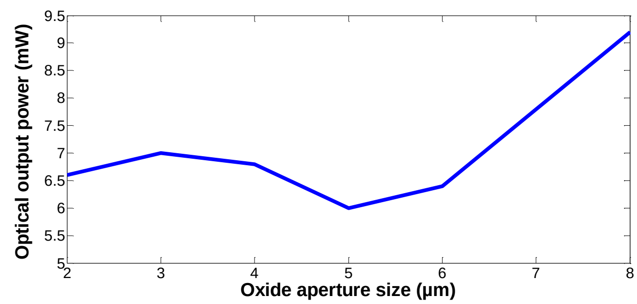

Fig. 7. Optical output power as a function of oxide aperture size.

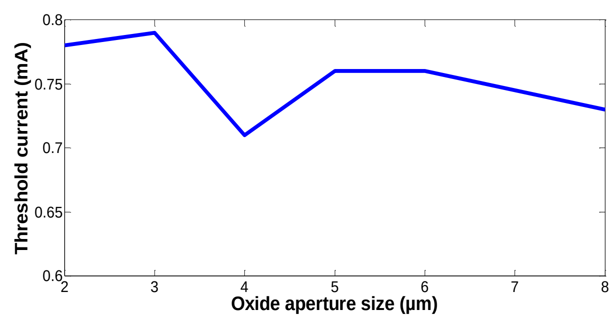

Fig. 8. Threshold current as a function of oxide aperture size

The comparison of different structures is summarized in TABLE I.

TABLE I Comparison of different VCSEL structures

.Appendix A	**.Appendix B**	**.Appendix C**
One- .Appendix D oxide layer	1 **.Appendix E**	4 **.Appendix F**
[4] .Appendix G	6.2 **.Appendix H**	0.7 **.Appendix I**
[5] .Appendix J	9.6 **.Appendix K**	0.3 **.Appendix L**
[6] .Appendix M	12 **.Appendix N**	0.7 **.Appendix O**
This .Appendix P work	9.2 **.Appendix Q**	0.7 **.Appendix R**

To compare the transient response of the structure of proposed VCSEL with conventional oxide-confined VCSEL and multi-oxide-confined VCSEL, a pseudo random binary sequence (PRBS) current is applied to these structures. The result is plotted in Fig.9. As is clear from the figure, the response for the structure with oxide layer grating is improved significantly, and the relaxation oscillation is almost removed for this structure.

So, the oxide layer grating technique provides very strong mode control, has high single mode optical output power, has low threshold current, has excellent transient response, and holds great promise for commercial VCSELs applications.

5. Conclusion

A novel structure for VCSEL is proposed using two oxide layers with multiple apertures. By using this technique, the high single mode optical output power could be achieved. In contrast to multi oxide layer structures that suffers from difficulty in control of oxide layer parameters (i.e. oxide aperture sizes, oxide thicknesses, and oxide layer positions), this structure is not sensitive to oxide parameters significantly. By using one two oxide layers with multiple apertures located on top and near the active layer the single mode operation could be ensured even for oxide aperture sizes as large as 8 µm. The single mode output power and threshold current for this structure could be 9.2 mW and 0.7 mA that are similar to the results of multi oxide layer structure. The transient response of this structure is much better than conventional and multi-oxide layer structures. Relaxation oscillation for this structure is almost removed causing better transient performance.

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