Single-Mode Emission in VCSELs with Antiresonant Oxide Islands

Marta Więckowska, Maciej Dems
Institute of Physics, Lodz University of Technology, ul. Wólczańska 219, 90-924 Łódź, Poland

***Abstract*—We study optical properties of an ARROW-VCSEL, in which the antiresonant effect is provided by an oxide island located inside the optical cavity and manufactured with a planar oxidation technique. We analyze the impact of a refractive antiresonant oxide island buried in a top VCSEL mirror on the lasing conditions of lateral modes of different orders. By using the Bessel Expansion Transfer Method—suited for axisymmetric structures—we show that this oxide island strongly influences all lateral modes. By merely altering its radius (which can be easily controlled through the time of the planar oxidation process), we can put different lateral modes into resonance or antiresonance states, strongly affecting their optical losses and profiles. This allows to tune the threshold currents for modes of different order and—with the use of the spatial hole burning effect—to find a single-mode operation conditions.**

While vertical-cavity surface-emitting Lasers (VCSELs) are nowadays an important class of semiconductor lasers, there are still some significant challenges in their design. One of such challenges is ensuring their operation on a single lateral mode with high power emission. The reason for this is that these goals are contradictory: large powers require large laser aperture, while the single lateral mode operation is most easily achieved by decreasing the aperture size. Hence, there is a need for finding alternative methods of eliminating higher order modes. On of good methods is use of antiresonant structures [1], [2]. Several such approaches have been successful, including a simplified version of the ARROW (AntiResonant Reflecting Optical Waveguide) structure containing a low-index core surrounded by a single high-index ring. With this structure, substantial mode discrimination has been observed for 980 nm VCSELs with a core diameter of 8–12 µm [3], [4], [5], [6], [7], [8], [9].

In the presented work we study optical properties of an ARROW-VCSEL, in which the antiresonant effect is provided by an oxide island buried in a top VCSEL mirror (Fig. 1) and manufactured with a planar oxidation technique [10], [11]. Such island affects both optical mode distribution and the current flow. The latter is shown in Fig. 2, which illustrates how the current crowding effect depends on the position of the oxide island. The direct conclusion of this analysis is that the island must be located sufficiently far away from the cavity. Hence, the following results are shown for the island in the 7th DBR pair and further.

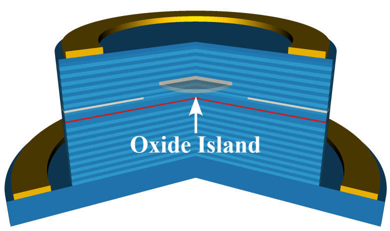
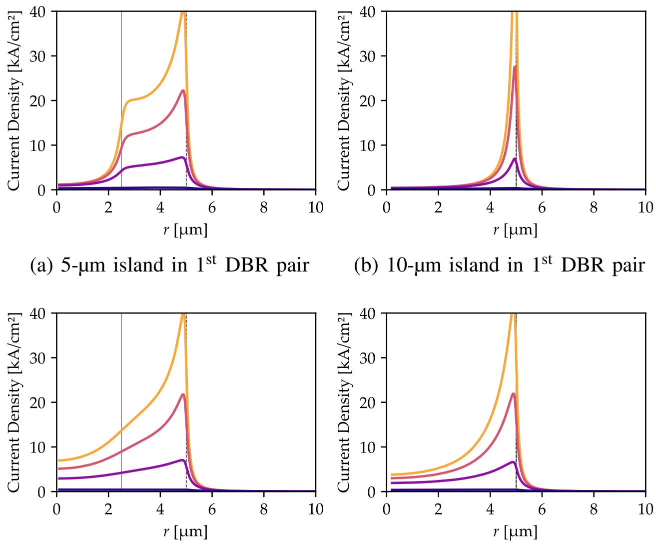


Figure 1: The analyzed laser with the oxide island located in the top DBRs.



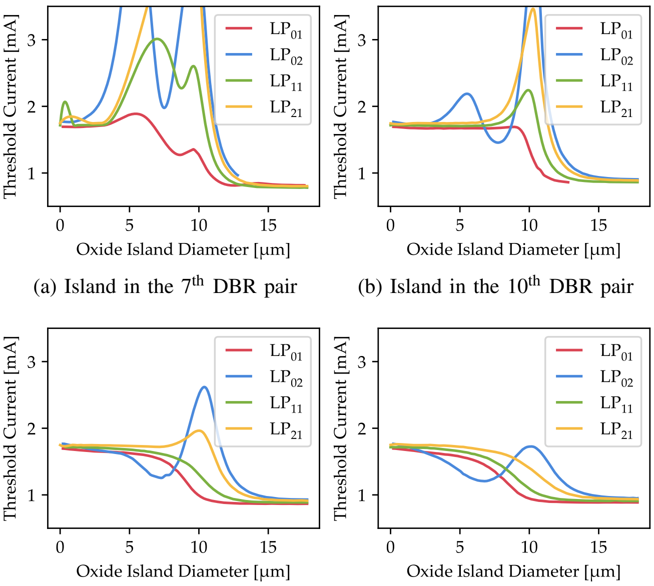
(a) 5-µm island in 1st DBR pair (b) 10-µm island in 1st DBR pair

(c) 5-µm island in 6th DBR pair (d) 10-µm island in 6th DBR pair

Figure 2: Current density distribution in the active region for several contact-to-contact voltages and with oxide islands of different sizes to the external aperture in different positions. If the island is too close to the cavity, it almost completely block the current flow.

The oxide island strongly influences all lateral modes parameters. By merely altering its radius (which can be easily controlled through the time of the planar oxidation process), we can put different lateral modes into resonance or antiresonance states, strongly affecting their optical losses. This results in a strong oscillatory behavior of the threshold currents, especially for the higher-order modes (Fig. 3). This allows to select a configuration providing high modal discrimination i. e. the difference in the threshold currents between the lowest threshold (*lasing*) mode and the second lowest threshold (*competing*) one (Fig. 4a, solid line). By performing comprehensive thermal, electrical, and optical numerical analysis of the VCSEL device, we show the impact of the size and location of the oxide island on the current crowding and spatial hole burning (SHB) effects. This allows us to compute threshold currents for various lateral modes and the maximum single-mode output power. The SHB effect decreases the effective gain available to the competing mode (Fig. 4b) and, hence, the single mode operation is observed for the currents higher than the ones estimated for a single-mode threshold analysis.

In order to test this, we check how the threshold of the competing mode is affected by the SHB effect. The results are shown in Tab. I. As expected, taking SHB

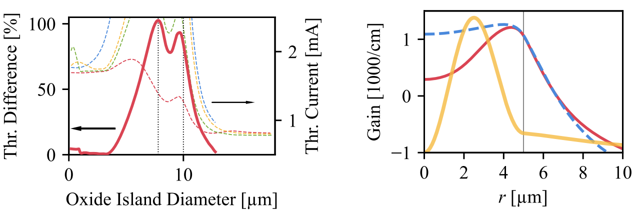


(a) Island in the 7th DBR pair (b) Island in the 10th DBR pair

(c) Island in the 11th DBR pair (d) Island in the 12th DBR pair

Figure 3: Dependence of the threshold currents on the oxide island diameter for its various positions. The oscillations are more pronounced for the island closer to the cavity, which results in stronger modal discrimination.

into account increases the threshold of competing mode in each case. However, the proportional raise strongly depends on the considered island parameters and the lasing mode. In particular, in the cases where the lasing mode is LP_{02}, the threshold of the LP_{01} mode increases only slightly due to the SHB effect. In consequence, the maximum single-mode power is very small. On the other hand, for the island parameters, for which the lasing mode is LP_{01} (in all considered cased, the competing mode is then LP_{11}), this raise is strong: the lasing mode effectively burns the carriers available to the other modes. In the extreme—if the island is in the 7th DBR pair—the competing mode cannot reach the threshold at all. The reason of this is the mismatch of the mode profile and gain in the active area. Along with hole burning effect caused by the LP_{01} mode, the gain profile changes in a way that is unfavorable for the LP_{11} mode, making it impossible to reach the threshold. This not, however, the case, for which the highest single-mode



(a) (b)

Figure 4: (a) Threshold currents and their difference between for the two lowest-threshold modes as the function of the island size for the island placed in the 7th DBR layer, which provides the highest modal discrimination. (b) Gain with consideration of SHB effect (solid red) and without it (dashed blue) compared with the second mode profile (yellow, show schematically with 0 at the bottom frame of the plot) for the island with the 5 µm radius (marked with vertical gray line).

Table I: Threshold voltage calculated for three sets of island parameters in two cases: with and without the spatial hole burning effect. Maximum power is determined by appearance of the competing mode or—in case of the island in 7th DBR pair—by thermal rollover.

Oxide Island DBR	Oxide Island ϕ [µm]	Mode lasing / competing	Th. Current [mA] No SHB	Th. Current [mA] SHB	Max. Power [mW]
7th	10.0	LP_{01}	1.271		1.89
		LP_{11}	2.354	×	
9th	9.0	LP_{02}	1.819		0.25
		LP_{01}	2.531	2.630	
10th	10.2	LP_{01}	1.247		2.87
		LP_{11}	1.771	3.75	
11th	10.0	LP_{01}	0.991		0.87
		LP_{11}	1.308	2.124	

power is achieved. The maximum is reached for the 10.2 µm island located in the 10th DBR, where 2.87 mW single-mode output power is emitted.

In consequence, we have shown that implementation of an S-ARROW structure inside the DBR can facilitate the high power single mode VCSEL operation. As the presented structure is a proof of concept and has not been thoughtfully optimized, we expect that it will be possible to find a configuration competing or exceeding current record single-mode VCSELs.

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