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Coherent polarization stabilization in large-aperture rectangular post bottom-emitting vertical-cavity surface-emitting lasers

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ABSTRACT

The output characteristics of large-aperture rectangular post bottom-emitting vertical-cavity surface-emitting lasers (VCSELs) were investigated. It was shown that the output power of the rectangle VCSELs can be up to 660 mW at a current of 5 A. Both H-polarization (horizontal) and V-polarization (vertical) demonstrated a coherent stabilization over the entire range of operation current, and coherent spectrum blue-shift of H-polarization light occurred with respect to V-polarization light at three different injected currents. The polarization states of output light were stabilized in the two orthogonal directions and H-polarization was the most principal polarization which was parallel to the longer side of the rectangular aperture. From the relationship between polarization ratio and aspect ratio of the oxidation confinement aperture (OCA), it was found that the highest polarization ratio (about 2:1) took place when the appropriate aspect ratio was 5:3, which meant better polarization stabilization in large-aperture VCSELs.

1. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) present significant advantages over their edge-emitting counterparts, including low threshold current, low cost, circular output beam, and easy fabrication of two-dimensional arrays [1]. On the other hand, conventional VCSELs with cylindrical symmetry exhibit polarization instabilities in the output characteristics [2–4], which restricts their application in polarization-sensitive areas, such as light sources, optical interconnects, and optical communication. Many efforts have been made to stabilize the polarization directions of VCSELs by using anisotropic cavity geometry [5,6], amorphous silicon sub-wavelength grating [7], trench etching [8], anisotropic oxide aperture [9], incoherent optical feedback [10], photonic crystal [11], misoriented substrates [12] and quantum dots [13]. Most of those methods are very useful for VCSELs with small-aperture. For example, polarization was completely controlled in small-aperture rectangular-post VCSELs with a longer side of 6 μm and shorter sides of 3.5–5 μm. On the contrary, when the length of the shorter side was increased to more than 5 μm, polarization direction became randomly switching [5]. However, polarization dynamics in large-aperture VCSELs are not that well investigated and understood yet, although some recent studies on polarized patterns have been carried out [14]. Here a kind of large-aperture VCSELs was presented experimentally with a few hundred micron dimension which demonstrates high power coherent polarization stabilization. Up to now, an effective method for polarization stabilization of large-aperture VCSELs (>100 μm) with high output power has not been reported yet.

2. Methods and fabrication

Although many researchers anticipated that stable polarization preference could be controlled by introducing anisotropy in VCSELs, this approach has not completely succeeded, especially in the fabrication of large-aperture VCSELs. The problem may be that VCSELs cannot have a rigid polarization because of some irreproducible reason such as a scratch or partial reflection. Also, multi-transversal mode emission complicates the polarization problem because the polarization appears orthogonal in the next-order mode [15]. There are numerous high-order transverse modes emitted in large-aperture VCSELs, thus we will not take every single mode into consideration. Instead, during the investigation of large-aperture VCSELs, we will study lasing properties and optical field profile in the principal directions. In this paper, we describe our method where polarization is stabilized through the introduction of gain anisotropy by using anisotropic mesa shapes such as a rectangular post.

The wafers of 980-nm bottom-emitting VCSELs were grown by metal organic chemical vapor deposition (MOCVD) with good uniformity on an N-type <001>-GaAs substrate misoriented 2° toward <110>. It had a three-quantum-well $In_{0.17}Ga_{0.83}As$ active layer, which was sandwiched by a 30 pairs P-type $Al_{0.9}Ga_{0.1}As/Al_{0.12}Ga_{0.88}As$ distributed Bragg reflector

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(DBR) mirror and a 28 pairs $Al_{0.9}Ga_{0.1}As/Al_{0.12}Ga_{0.88}As$ N-DBR. To form the rectangular post mesa structure, electron-beam (EB) lithography, photolithography and wet etching were used for patterning the posts. Posts were then formed from the top layer to the high Al layer, $Al_{0.98}Ga_{0.02}As$ layer, and rectangular pattern resist masks were made. Because it has been demonstrated experimentally that practical VCSELs emit linearly light with preference of the polarization direction along the <110> or <1$\bar{1}$0> crystallographic axes [16], the shorter sides of rectangular patterns were aligned to <110> crystal orientations, as Fig. 1 shows. The correct size of the rectangular posts was confirmed by optical microscopic observation after etching. The current confinement was obtained not only by the mesa structure but also by oxidation window, and the oxidation width was about 50 μm long each side. Finally, Ti/Pt/Au layers were deposited for forming ohmic contact P-electrode pads, and AuGeNi/Au layers were deposited on the GaAs substrate for making the N-electrode contact. The light output side was not antireflection (AR) coated, for the sake of heat dissipation, although AR can help to enhance the output power. The output light was emitted from the rectangular optical window at the surface of the N-electrode contact [5,15,17].

3. Results and discussion

The earlier discussion mentioned that the shorter sides of the rectangular patterns were aligned to <110> crystal orientations. A polarization beam splitter (PBS) was used for measuring the polarization properties of VCSELs. The light transmitted through PBS can be divided into transmission light and reflection light. Now we define the emitting light parallel to the longer sides as H-polarization (horizontal) light. Correspondingly, the longer sides were aligned to <1$\bar{1}$0> crystal orientations and we denote the emitting light parallel to the shorter sides as V-polarization (vertical) light. There were mainly three kinds of sizes which affected the output characteristics in VCSELs. These were mesa size, output aperture, and oxidation confinement aperture (OCA). The most effective size for laser resonance and emission was OCA which provides current confinement of active layer and reduces lateral current diffusion. The OCA was calculated by subtracting the oxidation width from the mesa size.

In the experiment, D.C. currents were injected from the electrodes into the active layer. The measurements of VCSELs were performed under a continuous wave (cw) operation at room temperature (RT). As can be presented in Fig. 2, the typical light output power–current–voltage (L–I–V) characteristics of rectangular post VCSELs with OCA 450 × 150 μm² were demonstrated. The solid line is the L–I curve and the dashed line is the I–V curve. From Fig. 2, we can find that the rectangular output aperture VCSELs can emit a high power laser up to 660 mW in all when the saturation current is 5 A and the current density is 7407.4 A/cm². The threshold current of this device is 90 mA and the threshold current density is 133.3 A/cm². It shows that a bottom-emitting device has a good performance of heat dissipation for the inner resistance is 0.09 Ω, and the reason could be injection symmetry which was induced by broad area mesa size for current injection.

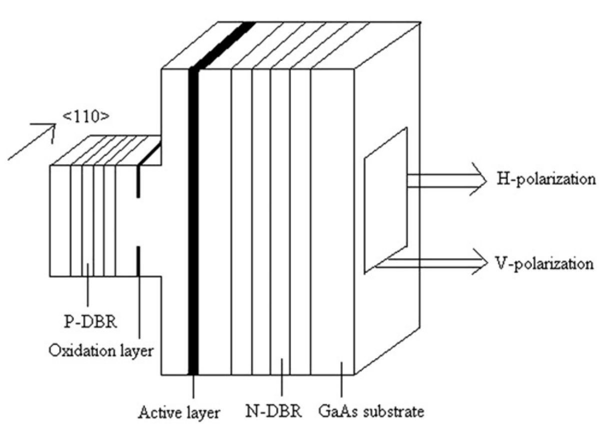

Fig. 1. Schematic structure of the large-aperture VCSELs and three-dimensional view of rectangular post by etching P-DBR layer with the shorter side parallel to <110>.

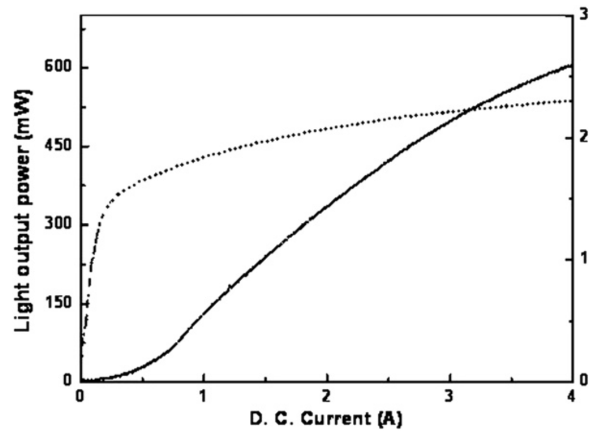

Fig. 2. Typical light output power–current–voltage (L–I–V) characteristics of oxidation confinement aperture (OCA) 450 × 150 μm² 980-nm bottom-emitting VCSELs.

In order to check out if the large-aperture VCSELs is emitting linear polarization in many high-order transverse modes, we measure a lot of different kinds of OCA VCSEL, the light vs current (L–I) curves for H-polarization and V-polarization (Fig. 3). A great number of VCSELs were monitored to remove the problem of fabrication. As can be seen from this figure, there is a distinct region above the lasing threshold where the rectangular output window VCSEL emission is linearly polarized. The curves of H-polarization and V-polarization are the lasing light parallel to the longer side direction and the shorter side direction, respectively. In the large-aperture VCSELs, the light emitted parallel to one side of rectangular must have much a more complicated high-order multi-transverse modes

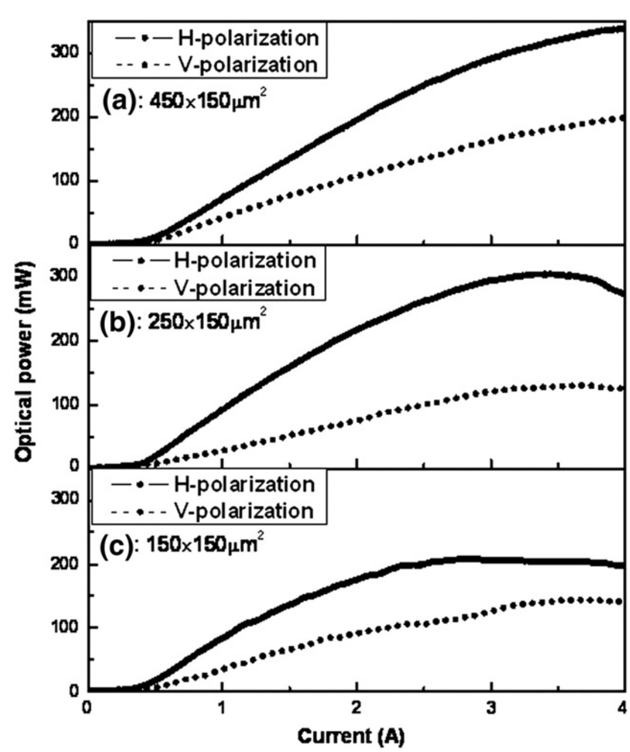

Fig. 3. Polarization-resolved L–I curves for three oxidation confinement aperture (OCA) VCSELs: (a) 450 × 150 μm²; (b) 250 × 150 μm²; and (c) 150 × 150 μm².

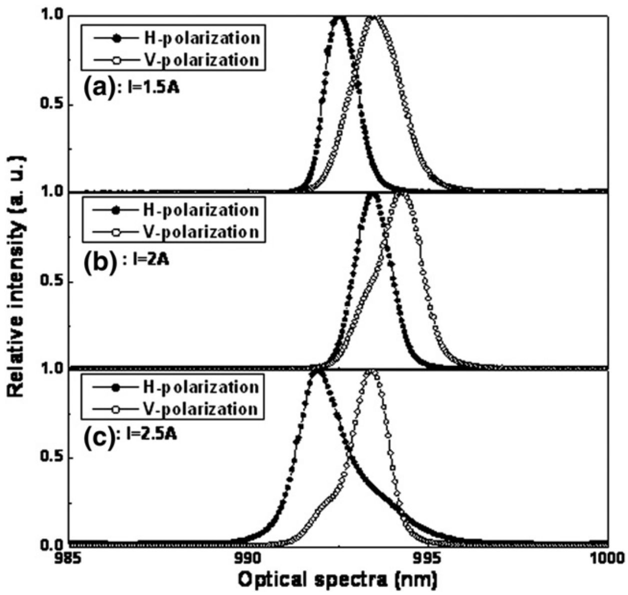

Fig. 4. Optical spectra of H-polarization and V-polarization in OCA $250 \times 150\ \mu m^2$ VCSELs at three different kinds of current: (a) 1.5 A; (b) 2 A; and (c) 2.5 A.

coupling. We can easily find that the principal polarization of VCSELs is H-polarization which parallel to the longer side of the output aperture. Both H-polarization and V-polarization can demonstrate coherent stabilization over the whole range of operation current. Correspondingly, the mechanism of gain anisotropy can play an important role in the selection of the polarization of the device [18]. In a rectangular pattern, the longer transversal size allows more carriers to be injected into the active region for radiation combination. Then more gain is acquired in the longer side relative to its orthogonal direction. Therefore, the gain anisotropy between the two directions is introduced to select the lasing polarization of large-aperture VCSELs. As a result of the spatial symmetry of current injection structure, coherent polarization stabilization is achieved by cross gain saturation between the two polarization directions of the rectangular output window. The transverse sizes of VCSELs are so large (at least >100 μm) that gain saturations can be obtained above lasing threshold in the two orthogonal directions. Lots of multi-transverse modes are coupled with each other for linear fitting in the cross orientation. Hence, cross gain saturation arises induced with different gain overlaps in the two orthogonal directions. In this case, for both sides of rectangular pattern, the centralization of current profile leads to the coherent stabilization

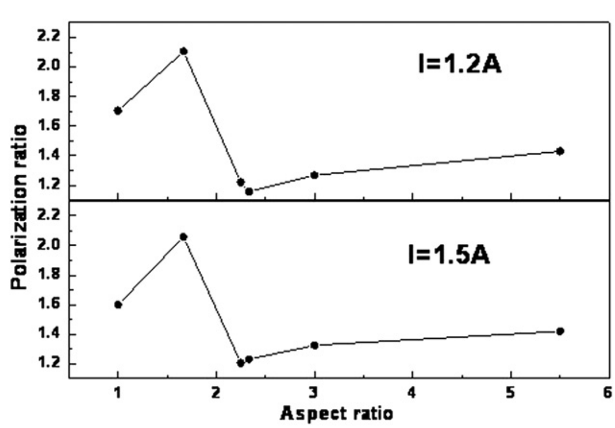

Fig. 5. Polarization ratio versus aspect ratio of the longer side and the shorter side of rectangular OCA.

polarizations without polarization switching, which is different from the emitting properties in cylindrical symmetric structure VCSELs.

Furthermore, as depicted in Fig. 4, the optical spectra of both H-polarization and V-polarization directions are considered at three different kinds of current. It is found that coherent spectrum blue-shift of H-polarization light occurs with respect to V-polarization light at three different injected currents. When the injected current is 1.5 A, 2 A and 2.5 A, the centre wavelengths of H-polarization light and V-polarization light are 992.5 nm and 993.5 nm; 993.4 nm and 994.3 nm; and 991.9 nm and 993.4 nm, respectively. It is also revealed that it is not smooth in the right side of H-polarization's spectra. The reasons for this phenomenon maybe heat effect or the strain caused during chip packaging. The spectra difference for horizontal and vertical polarizations can be mainly manifested as centre wavelength shift. On one hand, much more high-order transverse modes are emitted from the longer sides of the rectangular pattern comparing with the shorter sides. As a consequence, higher transition energy between the conduction and the valence band is achieved in the longer sides. But the transition energy is inversely proportional to the centre wavelength, and then the centre wavelength of H-polarization is smaller than V-polarization. On the other hand, this can be deduced from the gain spectra in phenomenology. As is known to all, more gain will be achieved in the longer side of the rectangular pattern. The higher gain is acquired, the smaller wavelength will be correspondingly attained at gain peak. Therefore, optical spectra blue-shift of H-polarization takes place regardless of the current variation.

Because more loss is brought when the injected current exceeds 2 A, the investigation of polarization characteristics below 2 A is more meaningful. Then we study how the aspect ratio of the longer side and the shorter side of OCA affects the light output polarization ratio, it may be helpful to understand the polarization mechanism in large-aperture VCSELs. Then the relationship between output polarization ratio and aspect ratio of the longer side and the shorter side is shown in Fig. 5. In this figure, the operation current is 1.2 A and 1.5 A which is about $3I_{th}$ and $4I_{th}$ respectively, and the highest polarization ratio is 2.105. So the best aspect ratio (5:3), at which the highest polarization ratio is obtained over the operation current, is the optimum OCA ratio for polarization stabilization in large-aperture VCSELs. Excluding the influence of fabrication, the worst polarization ratio happens when the aspect ratio is about 2.3. When the aspect ratio is bigger than 2.3, the polarization ratio is positively correlated with the aspect ratio value.

4. Conclusions

In summary, the large-aperture rectangular post 980-nm bottom-emitting VCSELs were investigated. It was shown that the rectangular aperture VCSELs can emit up to 660 mW high power laser while the current is 5 A. The most principal polarization of VCSELs was H-polarization which was parallel to the longer side of the rectangular aperture. The polarization states of output light were stabilized in the two orthogonal directions. Both H-polarization and V-polarization demonstrated coherent stabilization over the whole range of operation current. It was found that coherent spectrum blue-shift of H-polarization light occurred with respect to V-polarization light at three different injected currents. The optimum OCA aspect ratio was 5:3, at which the highest polarization ratio was obtained for polarization stabilization in large-aperture devices. These results would make it possible to use VCSELs arrays with polarization-sensitive optical element, and will thereby improve VCSELs applications.

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