Polarization Behavior and Mode Structure of Elliptical Surface Relief VCSELs

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We report on experimental studies of the polarization behavior and mode structure of the linearly polarized light emitted by transverse surface relief Vertical-Cavity Surface-Emitting Lasers. The latter were constructed such as to enhance the single mode operation by introducing spatially distributed losses and to enhance polarization stability by making these losses anisotropic. Investigating the influence of the orientation of the surface relief with respect to the [100] crystallographic axis shows that the polarization direction is governed by the orientation of the index ellipsoid, whereas the selection of the lasing mode is mainly determined by the anisotropy in the losses introduced by the surface relief.

I. Introduction

Vertical Cavity Surface Emitting Lasers (VCSELs) have a lot of advantages with respect to edge emitting laser diodes, like their circular beam shape and single longitudinal mode emission [1]. However, they suffer from multi-transverse mode behavior and polarization instabilities [2-4]. A lot of research has been devoted to controlling the mode behavior, especially for reliable high-speed data communications over large distances. Even for short distance links, problems due to changes of the mode properties with device age can arise when high speed multimode VCSELs are used [2]. Another intriguing aspect of VCSELs lies in their polarization behavior which differs from that of edge emitting lasers due to the lack of a dominating polarization selection mechanism in the quasi cylindrically symmetric structure. This cylindrical symmetry is broken in the presence of external stress to the device and introduces a small birefringence between the two orthogonal polarization modes due to the elasto-optic effect [5]. In this paper we study how these changes in the birefringence of the material influence the polarization stabilization in specially designed elliptical surface relief VCSELs. Such peculiar VCSELs provide both enhanced single mode emission and polarization stabilization [3].

II. Shallow etched VCSELs

One of the techniques used to fabricate single mode VCSELs is to spatially modify the effective refractive index and cavity loss by etching a surface relief in the top mirror, thereby introducing mode selective losses in a monolithic configuration [3, 6, 7]. Etching even a small part of the top mirror alters the mirror losses and consequently modifies the modal threshold gain as different modes overlap in a different way with the etched region. For lowering the threshold current it is crucial to achieve proper alignment of the oxide aperture and the surface relief [3]. The best way to proceed is to introduce the surface relief during device fabrication, in which case automatic self-alignment can be achieved [2].

Fig. 1 shows a schematic cross-section of an oxide-confined 850 nm VCSEL with an elliptical shallow surface relief etched in the top mirror, designed and fabricated in the Optoelectronics Department of University of Ulm. The VCSEL structure has been grown by MOVPE with three GaAs quantum wells in the active region. The top mirror is grown to resonance (maximum reflectivity) and etched in an elliptical ring shape to antiresonance depth (one quarter wavelength layer fully removed). Leaving out the etch process on some devices allows for a reliable comparison with standard VCSELs.

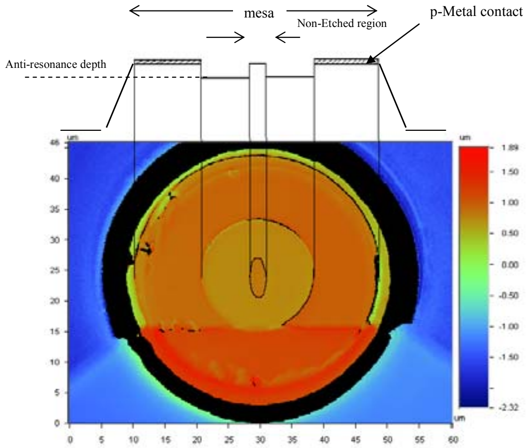

Figure 1. Top-view photograph and schematic cross section of the top-emitting elliptical shallow etched VCSEL. The elliptical shaped central region is surrounded by circular shallow etched region.

We study the polarization stabilization introduced by the elliptical surface relief for two orientations of the ellipse: the long axis parallel to the [1-10] and [100] crystallographic directions of the GaAs. We will show that polarization stabilization depends on how the etch is oriented with respect to the crystallographic axes of the wafer.

III. Experimental Results

In this section we present our experimental results on the polarization behavior and mode structure of the elliptical surface relief VCSELs.

The mode structure depends on the size of the elliptical central region. For example, for an ellipse of 2.4 μm by 2.1 μm the first high order mode appears at 2.7 times the threshold current. We have also observed a strong dependence of the frequency of the fundamental mode on both injection current and temperature. By measuring the redshift of the fundamental mode with current and with temperature, we trace back a value of the thermal resistance between 4 and 11 ˚K/mA depending on the size of the device.

The first VCSEL under study shows a PI curve and an etch orientation as shown in Fig. 2.

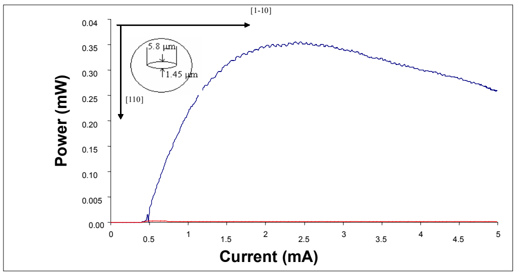

Figure 2. PI curve of the device.
Inset: schematic drawing of the VCSEL and crystallographic axes.

During the experiments on polarization behavior we investigated the impact of an anisotropic in-plane strain on the polarization characteristics of the VCSELs. All the measurements are performed at a fixed temperature of 25 ˚C and a fixed injection current (for which the device is monomode). The uniaxial tensile strain is applied either along the [110] or along the [1-10] direction.

To quantify the effect of this externally applied anisotropic strain, we observe the polarization resolved optical spectrum of the emitted light. Without any external stress, the mode with the highest frequency is lasing. The frequency splitting between the two orthogonal modes is 9 GHz. By applying external stress to the VCSEL we observed that the frequency splitting between the two modes decreases, reaches zero and afterwards increases again. In such a way, at the end the low frequency mode is the lasing one.

This behavior can clearly be seen in Fig. 3 where we present the orientation of the low frequency mode with respect to the crystallographic orientation as a function of the frequency splitting between the two orthogonal polarization modes. The squares in Fig.3 represent the experimental results while the solid line is theoretically calculated taking the elasto-optic effect into account [4,5]. The Mode Suppression Ratio (MSR: the ratio of the power of the lasing mode to the power of its orthogonally polarized counterpart) is shown in Fig. 4 as a function of the frequency splitting. Apparently the MSR exhibits a minimum around the minimal frequency splitting between these two modes.

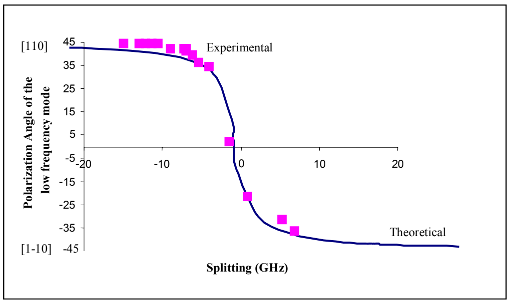

Figure 3. Experimental (squares) and theoretical (solid line) plots of the polarization angle of the low frequency mode versus the splitting between the two modes.

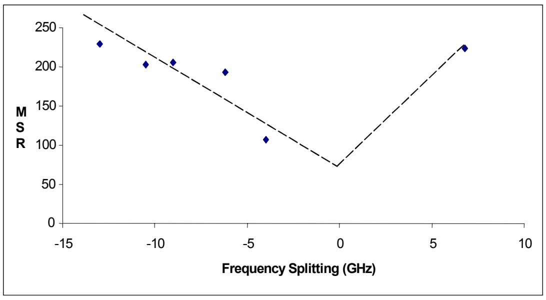

Figure 4. Mode Suppression Ratio as a function of the frequency splitting, for a fixed current and for a strain along [1-10] direction. (The dashed line represents the expected evolution of MSR [4,5]).

Analogous measurements are performed for the laser wafer oriented with its [110] direction parallel to the direction of the uniaxial tensile strain. When the frequency splitting exceeds 5 GHz the lasing mode keeps its orientation parallel to the [1-10] direction due to the orientation of the elliptical etched surface. Therefore stabilization of the polarization is achieved for this device.

These experimental results point out that the polarization direction is governed by the orientation of the index ellipsoid and that the selection of the (linearly polarized) lasing mode is determined by the anisotropy in the losses introduced by the elliptical surface relief. In Fig. 5 we explain qualitatively how this mechanism works. Strain is increased as we go down from situation a) to e); the left column represents the index ellipsoid and the right column schematically represents the distribution of the losses.

This sequence explains how the lasing mode is selected: as strain is applied, the two linearly polarized modes rotate (Fig.5a-e), being fixed to the two axes of the refractive index ellipse. Observing the loss that each of the modes experiences, we determine the mode that lases (the one with lower loss).

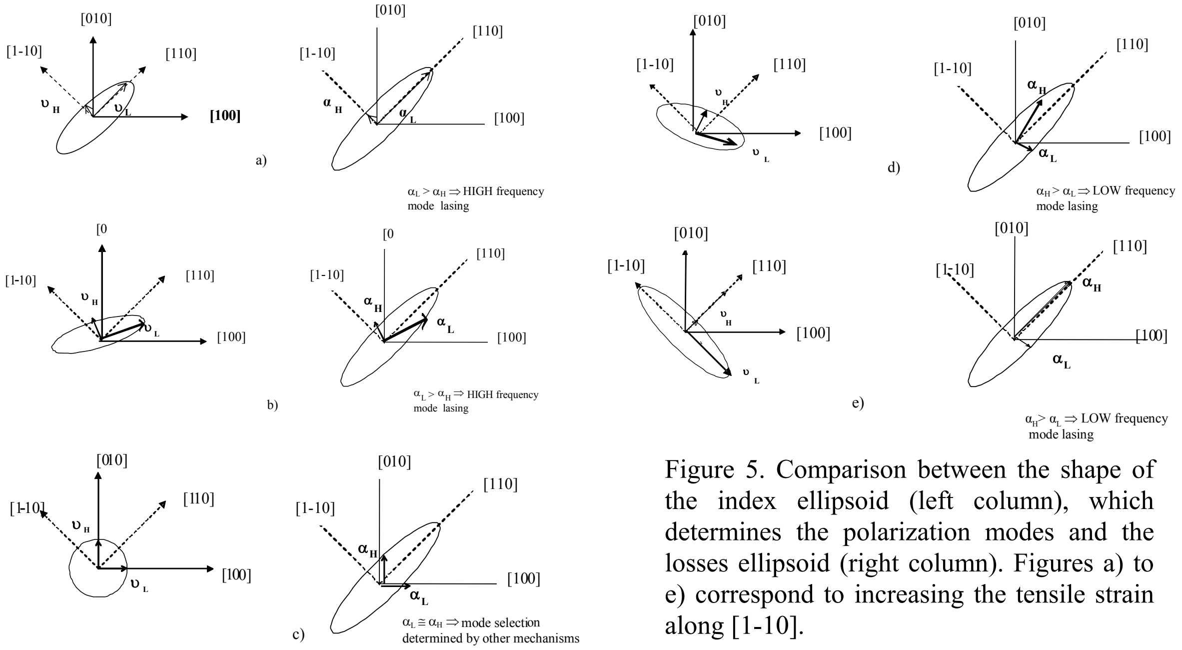

Figure 5. Comparison between the shape of the index ellipsoid (left column), which determines the polarization modes and the losses ellipsoid (right column). Figures a) to e) correspond to increasing the tensile strain along [1-10].

We clearly see a correspondence with Fig. 3, in which we observe how the low frequency mode lases parallel to the [110] crystallographic direction and after applying strain, it rotates until finally the electrical field oscillates parallel to [1-10] direction.

IV. Conclusions

We presented an experimental study on the influence of anisotropic strain applied to elliptical shallow etched 850 nm VCSELs and their polarization behavior. Stabilization of the polarization is achieved due to anisotropy in the mirror losses introduced by the surface relief. The strongest polarization stabilization is achieved when the etch is along the [110] or [1-10] crystallographic orientation. External strain can overcome this polarization stabilization. We explain our results in a qualitative way taking the elasto-optic effect and anisotropic losses into account.

Acknowledgments

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