Polarization switching in Vertical-Cavity Surface-Emitting Lasers tuned by quantum well in-plane anisotropic strain

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Using a special VCSEL holder, allowing us to introduce a controllable in-plane anisotropic strain, we experimentally demonstrate that the injection current at which switching between two fundamental VCSEL modes with orthogonal linear polarizations occurs, as well as the existence of such switching itself, depends on the magnitude of the strain and its orientation with respect to the principal crystal axes. This is explained by taking into account a different gain curve for eachof the two polarizations.

1. Introduction

The polarization behavior of Vertical-Cavity Surface-Emitting Lasers (VCSELs) differs from edge emitting semiconductor lasers [1-8]. In VCSELs, the material gain and waveguiding anisotropy are considerably reduced because of their cylindrical symmetry and their surface emission. As a result, polarization switching (PS) between the two orthogonal linearly polarized states in the fundamental mode is often observed [1-4]. Different physical mechanisms have been suggested to explain PS in VCSELs [3,8-11]. The first one, given by Choquette et al [3], relies on the spectral shift of the gain maximum relative to the cavity resonances for the two polarizations caused by current heating. The two linearly polarized modes have slightly different resonant frequencies due to an inherent birefringence in the cavity. Because the mode selection happens according to the higher material gain, the higher frequency state will be lasing on the lower frequency side of the gain curve and vice versa. In such a way, PS from the higher frequency mode to the lower frequency mode ($\nu_H \rightarrow \nu_L$) is predicted. This was designated as type I PS in [9]. More recently, the effect of the photon-energy-dependence of the loss and gain in VCSEL has been invoked to explain type I and type II PS ($\nu_L \rightarrow \nu_H$) happening consecutively in one and the same device [9].

Another explanation takes into account the spin relaxation processes in semiconductor active medium [5,6]. In this spin - flip model (SFM) PS from the lower frequency mode to the higher frequency mode (type II PS) is predicted [6,7]. Also a combination of the thermal mechanism and the SFM has been considered [10].

Alternative explanations rely on the modification of the modal gains for the two polarization states of the fundamental mode [4,8]: the interplay of weak index guiding and spatial hole burning [8] and the thermal lensing effect [4]. This diversity in the explanations of the PS phenomenon in VCSELs is due to the numerous physical effects taking place.

In this paper we report new experimental results on PS in VCSELs, showing that an external mechanical stress applied to the VCSEL package dramatically alters their polarization behavior: depending on the mutual orientation of the stress induced uniaxial strain and the crystal co-ordinate system, PS in the fundamental mode region could take place for one and the same birefringence and substrate temperature [12]. Furthermore, only for uniaxial strain along $[1\bar{1}0]$ direction the current of PS could be widely stress-tuned in the whole region of lasing in the fundamental mode. These experimental results show that the in-plane strain (residual or intentional) leads not only to refractive index anisotropy but to gain anisotropy as well. We propose a qualitative explanation of the observed polarization behavior based on gain anisotropy and birefringence induced by strain and on the red shift of the gain induced by current heating.

2. Experimental Results

In our experiments we use proton-implanted GaAs/AlGaAs quantum-well (QW) VCSELs operating around 850nm. We apply external stress on the VCSEL using a specially designed laser holder [12]. This holder makes it possible to introduce a tensile uniaxial strain in the plane of the VCSEL cavity by bending the metal plate of the laser package on which the VCSEL wafer is glued. All measurements presented here are conducted at fixed substrate temperature of 25°C. We investigate two situations depending on the orientation of the longer side of the laser wafer ($[1\bar{1}0]$ direction) with respect to the direction of the uniaxial strain: it can be either parallel or perpendicular.

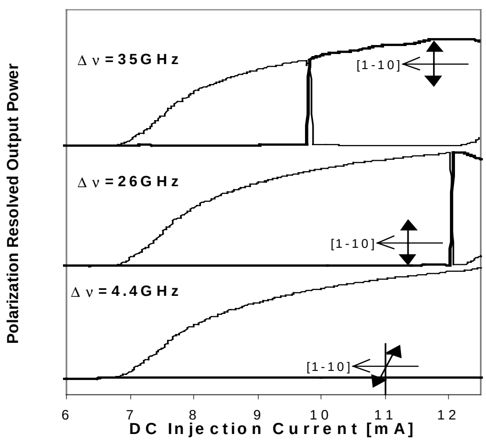

Fig.1. Polarization resolved optical output power versus DC injection current for increasing tensile strain along $[1\bar{1}0]$ crystallographic direction. The higher (lower) frequency mode is shown by the thick (thin) solid line. The orientation of the higher frequency linearly polarized mode is shown schematically together with the $[1\bar{1}0]$ crystallographic direction. The direction of the in-plane tensile strain is always horizontal.

When the uniaxial tensile strain is parallel to the $[1\bar{1}0]$ direction, the laser is emitting in the low frequency mode (ν_L state) at a small external stress. The direction of this linearly polarized state is at about 20° away from the $[1\bar{1}0]$ direction (fig.1a). As shown in fig.1, if one continuously increases the external stress, one first observes a rotation of the direction of linear polarization followed by a stabilization of the polarization along the $[1\bar{1}0]$ direction. In the fundamental mode, type II PS first appears at rather large value of the strain-induced frequency splitting (26GHz in fig.1b) and for quite high current (12mA). As the external stress is further increased, the current of PS continuously decreases (fig.1c). A very broad region of stress – induced type II PS tuning exists (frequency splittings ranging from 25GHz to 60GHz). For larger splittings the laser is emitting in the higher frequency mode only (ν_H state), with linear polarization oriented perpendicular to the direction of the tensile strain.

When the uniaxial tensile strain is along the [110] direction the laser is emitting again in the low frequency mode (ν_L state) oriented at about 15° away from the $[1\bar{1}0]$ direction (fig.2a) at a small external stress. Now, even a very small external stress changes the direction of linear polarization much more than in the previous case. Again, the tuning of the polarization orientation with increasing the external stress is towards the line of the tensile strain (now [110] direction) (fig.2c). However, before reaching this orientation PS II is observed in the fundamental mode in a very restricted domain of external stress (frequency splitting of 4 GHz in fig.2b). Moreover, the polarization eigenstates are now oriented at about 40 degrees with respect to the [110] direction. It is now much more difficult to tune the PS current with the external stress and impossible to infer the direction of this tuning. When increasing the external stress the polarization eigenstates fix along [110] and $[1\bar{1}0]$ directions (fig 2c) and only the ν_H mode is lasing for $\Delta\nu$=4.5GHz and higher.

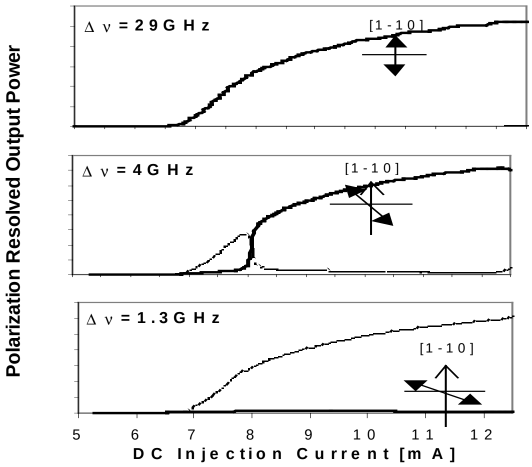

Fig.2. Polarization resolved optical output power versus DC injection current for increasing tensile strain along [110] crystallographic direction. The higher (lower) frequency mode is shown by the thick (thin) solid line. The orientation of the higher frequency linearly polarized mode is shown schematically together with the $[1\bar{1}0]$ crystallographic direction. The direction of the in-plane tensile strain is always horizontal.

3. **Discussion**

In the explanation of PS in VCSELs proposed by Choquette et al. [2,3] the gain depends on the polarization state only via the modal frequency. Our experiments demonstrate that in-plane anisotropic strain (either unintentionally or externally induced) introduces both birefringence and gain anisotropy. Indeed, birefringence cannot be the only relevant parameter, since we observe a completely different polarization behavior for two orthogonal directions of tensile strain corresponding to the same frequency splitting. In our case of in-plane anisotropically-strained QW, an in-plane gain anisotropy exists, i.e. the gain is different for different polarizations in the plane of the QW [14]. In addition, there is a gain difference due to the frequency splitting [3,15], which also results from the stress via the elasto-optic effect. We assume that for tensile strain along [110] and $[1\bar{1}0]$ directions the gain anisotropy has the same principal axes as the index ellipsoid, namely [110] and $[1\bar{1}0]$. Due to the strain-induced gain anisotropy, each linearly polarized state has its own gain curve which it follows as any relevant parameter, e.g. lattice and carrier temperature, carrier density, etc is changed.

As the DC current is increased, the active region heats up and the gain undergoes a red shift faster than the cavity modes. Therefore, when working on the higher frequency side of the gain maximum (as in our experiments) the carrier density should increase in order to keep the gain equal to the losses. Type II PS can occur when the gain of the linearly polarized mode with higher frequency becomes larger and the two gain curves move apart from each other with increasing current [12]. It should be mentioned that in this picture type II PS can be preceded by type I PS around the gain maximum. Indeed, such double PS has been experimentally demonstrated in [9].

4. Conclusion

In conclusion, our experiments reveal that an externally induced in-plane anisotropic strain modifies strongly the polarization behavior of VCSELs. Based on this observation we conclude that the anisotropic in-plane strain leads both to birefringence (via the elasto-optic effect) and to gain anisotropy. Consequently a separate gain curve for each of the two polarization modes has to be considered.

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