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Polarization Stabilization in Vertical-Cavity Surface-Emitting Lasers Through Asymmetric Current Injection

G. Verschaffelt, *Student Member, IEEE*, W. van der Vleuten, M. Creusen, E. Smalbrugge, T. G. van de Roer, F. Karouta, *Senior Member, IEEE*, R. C. Strijbos, J. Danckaert, I. Veretennicoff, *Member, IEEE*, B. Ryvkin, H. Thienpont, *Member, IEEE*, and G. A. Acket

***Abstract*—We present experimental evidence that asymmetric current injection in intracavity contacted vertical-cavity surface-emitting lasers (VCSELs) stabilizes the polarization of the emitted light. Anisotropies in the gain and loss mechanisms introduced by asymmetric current injection are considered to explain this effect. This design scheme opens perspectives to obtain actual polarization control in VCSELs.**

***Index Terms*—Polarization, surface-emitting lasers.**

I. Introduction

INTRACAVITY contacted vertical-cavity surface-emitting lasers (VCSELs) have several advantages due to their unique design. In these VCSELs carriers are injected into the active region via two highly doped contact layers on either side of the active region inside the Fabry–Perot cavity. In this way, the high-resistivity distributed Bragg reflectors (DBR) are bypassed [1], [2]. In this design, an efficient lateral current constriction is needed in order to force the current to pass underneath the top mesa, which is often realized by lateral oxidation of one or two AlAs layers in the active region. However, intracavity contacted VCSELs typically suffer from current crowding on the inner edges of these oxidized AlAs layers, favoring the excitation of higher order modes.

It is well known that VCSELs in general are quasi-symmetric devices with no preferential polarization direction. This makes it difficult to predict, stabilize or control the polarization of the emitted light. With polarization stabilization we refer to the effect of pinning the polarization into an *a priori* known direction, while with polarization control we mean that the polarization of the emitted light can actually be changed via an externally controllable signal or event. In some VCSELs polarization switching with increasing current has been observed [3]. One customary way to stabilize the polarization is through the introduction of loss anisotropy by using anisotropic mesa shapes such as rectangular posts. Mechanisms of polarization control based on the integration in the cavity of electroabsorptive and electrorefractive effects have been proposed [4].

We have introduced a novel design of intracavity contacted VCSELs based on an asymmetric contact layout in order to stabilize the polarization and to avoid current crowding. In these devices the p and n contact metallizations are restricted to opposite sides of the top and bottom mesa (see Fig. 1). In this paper, the first experimental results on the polarization stabilizing effect of the asymmetric current injection scheme are presented.

II. Experimental Polarization Behavior of Intracavity Contacted VCSELs

Our intracavity contacted VCSEL structure (see Fig. 1) was grown by MBE on a (001) GaAs substrate and has 18 pairs AlAs–GaAs top DBR, a 6λ cavity with a top GaAs p-layer and a bottom GaAs n-layer destined for the intracavity contacts. Finally, 28 pairs of AlAs–GaAs form the bottom DBR mirror. The active layer is formed by two quantum wells (QWs) of $In_{0.17}Ga_{0.83}As$, each 8 nm thick and designed to emit light at 980 nm. The active region is surrounded by two AlAs layers, which form a current constriction (CC) aperture after oxidation. The dimensions of the mesas and the oxidation time are chosen such that the oxide aperture is slightly (about 1 μm) smaller than the top mesa. To protect the AlAs of the top DBR against oxidation, the top mesa has to be sealed before the CC layers are oxidized. The sealing method used here follows the procedure described in [5] with the addition of a wet etch dip before the high-temperature anneal step because in our case the top mesa is dry etched. Further details about the fabrication process have been published elsewhere [6]. Symmetrically contacted VCSELs with top mesas of various sizes and shapes (circular, square and rectangular) and square devices with asymmetric current injection were fabricated and interspersed across the wafer. In this way we are sure that our results are not influenced by a systematic shift between gain-peak and cavity mode.

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G. Verschaffelt, J. Danckaert, I. Veretennicoff, and H. Thienpont are with the Department of Applied Physics and Photonics (TW-TONA), Vrije Universiteit Brussel, B-1050, Brussels, Belgium.

B. Ryvkin is with the Department of Applied Physics and Photonics (TW-TONA), Vrije Universiteit Brussel, B-1050, Brussels, Belgium. He also with the A.F. Ioffe Physicotechnical Institute, St. Petersburg 194021, Russia.

E. Smalbrugge, T. G. van de Roer, F. Karouta, R. C. Strijbos, and G. A. Acket are with COBRA - Inter-University Research Institute, Division Telecommunication Technology and Electromagnetics, Eindhoven University of Technology, NL-5600 MB Eindhoven, The Netherlands.

W. van der Vleuten and M. Creusen were with COBRA - Group of Semiconductor Physics, Eindhoven University of Technology, NL-5600 MB Eindhoven, The Netherlands. They are now with the Department of Applied Physics and Photonics, Free University of Brussels, Brussels B-1050, Belgium.

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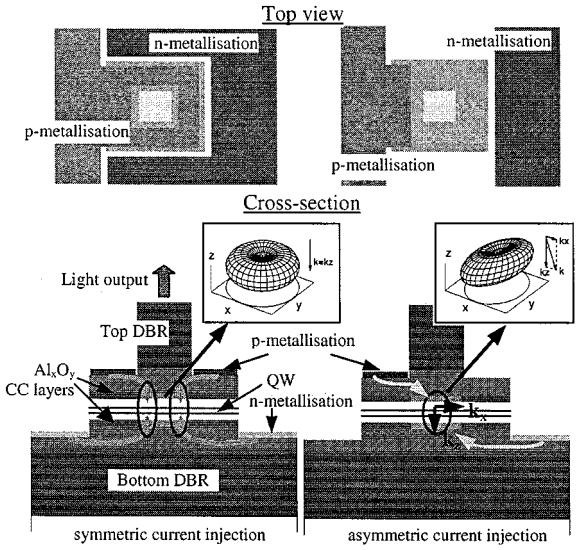

Fig. 1. VCSEL with symmetric (left) and asymmetric (right) current injection, illustrating that devices with symmetric current injection will suffer more from current crowding effects. Asymmetric current injection also results in $k_t = k_x \neq 0$. The surfaces in the insets represent the dependence of the optical transition probability on the crystal momentum $\boldsymbol{k}$ and the polarization direction $\boldsymbol{E}$ of the emitted light, while the contours indicate the transition strength for the polarization directions in the plane of the QWs. Here x is along [1–10] and y along [110].

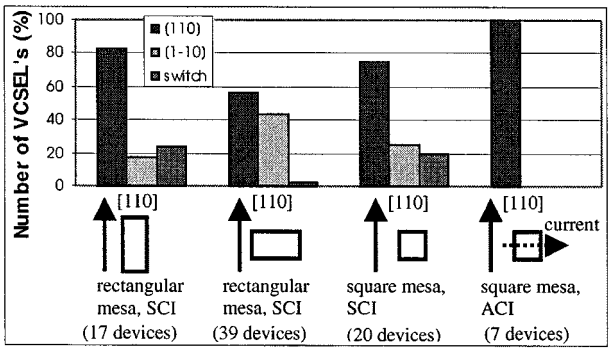

Fig. 2. Polarization of the emitted light for different device shapes. "Switch" indicates polarization switching with current. SCI (ACI) denotes symmetric (asymmetric) current injection.

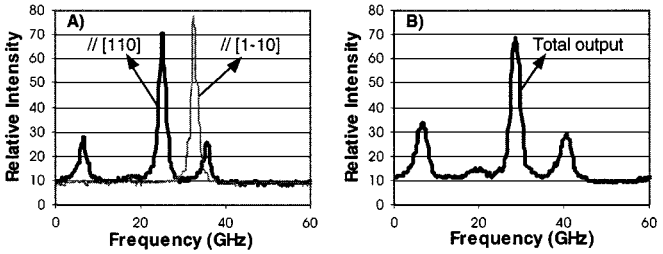

Fig. 3. Spectrum of the devices with asymmetric current injection at 18 mA. (a) Polarization resolved spectrum (with the spectrum for the polarization along [1–10] magnified). (b) Total spectrum. The largest peak in spectrum B corresponds to a wavelength of 970 nm.

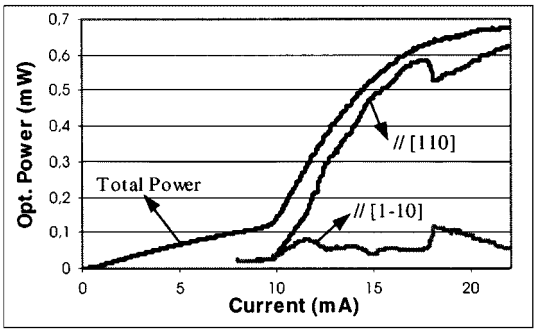

Fig. 4. Total and polarization resolved P–I curve of a device with asymmetric current injection.

Fig. 2 gives an overview of the polarization properties of these devices. From the data of the square devices with symmetric current injection, a general preference for a polarization along the [110] crystallographic direction is observed. This preference can also be derived from the polarization behavior of the rectangular devices. The rectangular shape of the top mesa should favor a polarization along the longer mesa side [7], but from Fig. 2 it is clear that the effect of this kind of asymmetry was not large enough to stabilize the polarization direction completely. This is probably due to the relative large mesa sizes of the fabricated VCSELs, since the smallest device implemented had top mesa dimensions of $8 \times 7\ \mu\text{m}^2$.

However, for all square devices with asymmetric current injection the emitted light is polarized perpendicular to the direction of current injection, proving that asymmetric current injection can be used to stabilize the polarization of the emitted light in intracavity contacted VCSELs. Usually, the higher order transverse modes appear with a polarization perpendicular to that of the fundamental mode. Nevertheless the spectra of the asymmetric injected devices depicted in Fig. 3 show that most of the optical power is polarized perpendicular to the direction of current injection even though these devices feature higher order transverse modes.

We have also recorded the polarization resolved PI-curve of the devices with asymmetric current injection (see Fig. 4). Again these measurements confirm that most of the emitted light is polarized perpendicular to the current path. The polarization contrast, defined as the ratio of the optical output power of the two orthogonal polarizations, becomes even larger for higher values of the injected current.

The polarized resolved PI-curve is not smooth due to the appearance of higher order transverse modes. We expect that reducing the size of the devices with asymmetric current injection will result in single mode operation and hence a further increase of the polarization contrast. From Fig. 4 one can also see that the efficiency of the devices is rather low, due to imperfections in the growth of the structure.

III. Polarization Effects of Asymmetric Current Injection

To explain the effect of asymmetric current injection on the polarization of the emitted light, we look for anisotropies introduced in the gain and loss. First of all, the asymmetric current injection results in an anisotropy in the gain g for the two orthogonally polarized modes. As shown in Fig. 1, it indeed induces a nonzero transverse component of the crystal momentum (k_t) of the injected carriers in the active layer. Because the active layer consists of compressively strained quantum wells, it is essentially the transition between the conduction and heavy hole

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band that will determine the laser output. The polarization dependence of this transition is well known and given by [8]

$$\text{Transition probability} \sim 1 - |\hat{\boldsymbol{k}} \cdot \hat{\boldsymbol{E}}|^2.$$

As depicted in the inset of Fig. 1, this electron-hole transition probability depends on the relative orientation between the crystal momentum of the injected carriers (unity vector $\hat{\boldsymbol{k}}$) and the electric field of the emitted electromagnetic wave (unity vector $\hat{\boldsymbol{E}}$) and will be maximal when the optical field is polarized perpendicularly to the transverse component of the crystal momentum. If we define $g^{//}$ ($g^{\perp}$) as the gain of the mode polarized parallel (respectively perpendicular) to the current direction, the former means that $g^{//} < g^{\perp}$.

Second, the asymmetric current injection will also cause a definite direction of the transverse component of the electric field in the plane of the contact layers. This results in a less well-known polarization dependence of the optical loss α, which can in principle be used for polarization selection [4]. A first contribution to the polarization dependence of the loss is determined by the electroabsorption effect (e.g., Franz–Keldysh effect). This polarization dependence was tested experimentally in semi-insulating GaAs at room temperature in [9]. We have measured the polarization dependence of the electroabsorption in intrinsic GaAs using a metal–semiconductor–metal (MSM) structure. By applying a voltage across the metal fingers of the MSM structure, an electric field is generated in the GaAs between the fingers in a similar way as between the asymmetric contacts of the VCSEL structure. The responsivity of this device (measured at 980 nm) for two different polarizations of the input light beam is a measure for the electroabsorption in the GaAs layer. This experiment showed that the electroabsorption is larger for light polarized along the direction of the applied electric field, resulting in $\alpha^{//} > \alpha^{\perp}$. Here $\alpha^{//}$ ($\alpha^{\perp}$) is the loss of the VCSEL mode polarized parallel (respectively perpendicular) to the current direction.

Another contribution to the loss is the free carrier absorption occurring in the p-doped contact layers due to transitions between the heavy hole and split-off valence bands. Theory [10] predicts for these transitions a larger probability for light polarized perpendicular to the transverse component of the electric field in the contact layers, yielding $\alpha^{//} < \alpha^{\perp}$.

Of the three mechanisms described here (gain, electro-absorption and free carrier absorption), the first two would predict a polarization of the emitted light perpendicular to the current path while free carrier absorption would favor a polarization parallel to the current path. The anisotropy introduced by each of these three mechanisms is difficult to estimate quantitatively, as each of them will be small. However, it is known that the polarization state of VCSELs is determined by relative anisotropies as small as 10^{-4}–10^{-5} [3], [7]. Our experiments indicate that for our structure, the anisotropies in the gain and electroabsorption are more important than the one of the free carrier absorption.

IV. Conclusion

Intracavity contacted VCSELs with asymmetric and symmetric contacts have been fabricated and characterized. The square devices with asymmetric current injection emit light polarized perpendicular to the direction of the current injection, also in the higher order transverse mode regime. However, more quantitative estimations of the gain and loss anisotropies due to asymmetric current injection are necessary to pin down the polarization stabilization mechanism(s). Moreover, incorporating two orthogonal and separated current paths in one device could prove the feasibility of asymmetric current injection for electrical polarization control, which could be very useful to realize fast reconfigurable interconnects [11].

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