Polarization-Resolved Output Characteristics of InAlGaAs VCSELs under Anisotropic Strain

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We present a setup that enables direct examination of the correlation between wavelength, polarization suppression and induced strain in vertical-cavity surface-emitting laser (VCSEL) samples by applying a defined amount of external stress. In addition to measurements on standard oxide-confined VCSELs, devices with a dielectric surface grating have been investigated, showing an outstanding stability of the linear light output polarization.

1. Introduction

Due to anisotropies introduced by the electro-optic effect, the polarization components of most conventional VCSELs are oriented along the [011] or [011] crystal axes [1]. However, the polarization behavior of a VCSEL is also influenced by internal strain, which has various origins and differs from device to device. Since strain modifies the band structure of a crystal material, a change of the material gain in different crystal axes has to be expected [2]. Furthermore, it leads to an anisotropy of the refractive index due to the elasto-optic effect [3].

A strong birefringence, i.e. a splitting between the refractive indices along the [011] and [011] crystal axes, is achieved by applying a tensile strain in the [011] or [011] direction. If strain is induced along the [011] crystal axis, the refractive index in [011] direction will increase while the refractive index along the [011] crystal axis decreases due to the negative elasto-optic coefficient of GaAs [4]. Therefore, the [011] polarization will have a longer wavelength than the [011] polarization. On the other hand, strain applied along the [011] orientation will usually lead to a shorter wavelength of the [011] polarization.

To examine the impact of strain on the polarization behavior of VCSELs, mainly on polarization switches, polarization-dependent measurements under external stress have been performed in the past [5]. In the present work a special holder was designed to create reproducible, external stress in a sample, that enables direct examinations of the correlation between wavelength, polarization suppression and induced strain.

2. Setup for Stress-Dependent Measurements

The left hand side of Fig. 1 shows a sketch of the designed sample holder. The wafer is fixed with a clamp to the bottom plate and it is possible to bend the sample at the edge
Fig. 1: Holder designed to bend a wafer sample in a reproduceable way. The wafer is fixed by a clamp and bent over an edge of the bottom plate.

of that plate. If a force $F$ is applied at a distance $l$ from the edge, the sample is deflected by an amount $b$.

The photograph on the right hand side of Fig. 1 shows the practical realization. On one side, the sample is fixed to the copper holder by a clamp, while the other side is bent by a lever. The lever can be moved from the backside by a micrometer screw or by a piezo mover that is integrated with the screw. Therefore, an exact adjustment of the bending is achieved. To control the temperature of the sample, the backside of the copper holder is connected to a water cooler and to a Peltier element.

3. Results

3.1 Variation of wavelength and output power with anisotropic strain

After suppressing the dominant polarization of the VCSEL by a polarizer, an optical spectrum analyzer is employed to examine the non-lasing polarization mode that occurs due to amplified spontaneous emission. Figure 2 shows the wavelength dependence of the two orthogonal polarizations on the bending $b$ for a 980 nm sample with a thickness of 360 $\mu$m, where strain is applied along the [011] direction. With $l = 6$ mm in Fig. 1, the maximum bending of 73 $\mu$m creates a tensile strain at the surface of the wafer of approximately 65 N/mm$^2$. This strain induces a wavelength splitting of 100 pm between the orthogonal polarization modes. Due to the elasto-optic effect, the wavelength of the [011] polarization increases linearly while the wavelength of the [0\bar{1}1] polarization decreases.

In Fig. 3 the light versus current (LI) characteristics of an adjacent VCSEL on the same sample are shown for different values of the bending $b$. The device has a surface relief with
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Fig. 2: Polarization-resolved emission wavelengths of a VCSEL with an oxide aperture of 7.5 µm diameter and a 5.1 µm surface relief in dependence on the bending $b$ in [011] direction.

A diameter of 9.1 µm to enhance the single-mode output power. When no stress is applied, the VCSEL is polarization-stable within its single-mode regime and the [011] polarization dominates. However, when the sample is bent by 17 µm in the [011] direction, the laser starts to lase in [011] polarization and switches to the [011] polarization at a current of 6.7 mA. This corresponds to a type I switch, namely a switch from the shorter to the longer wavelength. When the bending of the sample increases further, the polarization switch moves to higher currents and the [011] polarized region becomes wider.

(a) no bending

(b) $b = 17$ µm

(c) $b = 33$ µm

(d) $b = 50$ µm

Fig. 3: LI characteristics of a VCSEL adjacent to the device in Fig. 2 for different values of the bending $b$ in [011] direction. With increasing strain a polarization switch appears and the width of the [011] polarized region increases. The device has a 10 µm oxide aperture and a surface relief with a diameter of 9.1 µm.

During the experiments, various VCSELs on samples with 980 as well as 850 nm emission wavelength have been examined with stress applied in different directions. It was found for all devices that the polarization parallel to the direction of the stress experiences a strong suppression, in agreement with the example in Fig. 3. Even the polarization of higher order transverse modes can be changed in this way.
3.2 Stability assessment of surface grating induced polarization control

Since the occurrence of polarization switches complicates the use of VCSELs in many applications, there are urgent needs for polarization control. In 2003, the optoelectronics department began to implement dielectric surface gratings in VCSELs, which led to outstanding results with regard to polarization control [6], [7]. To assess the stability of the induced polarization control, the polarization behavior of 850 nm VCSELs with a dielectric surface grating was examined under external induced stress.

Figure 4 shows the wavelength difference between the lasing and non-lasing mode in dependence on the bending of the sample. Positive values of the bending refer to strain in [011] direction, whereas negative values are associated with strain in [011] direction. The 510 µm thick sample was maximally bent by 67 µm, corresponding to an induced strain of approximately 84 N/mm². When the sample experiences strain in [011] direction, the [011] polarization has a higher wavelength, associated with a positive wavelength splitting. By applying strain along the [011] direction, the wavelength splitting becomes negative, in agreement with the elasto-optic effect. The nonlinear relation between bending and wavelength splitting for positive values of the bending may be caused by a weak fixing by the clamp in this measurement.

![Figure 4: Wavelength splitting \( \lambda_{[011]} - \lambda_{[011]} \) versus the bending \( b \) of a surface grating VCSEL sample. A positive bending \( b \) corresponds to strain in [011] direction, negative \( b \) to strain in [011] direction.](image)

Figure 5 shows the LI characteristics of two nominally identical VCSELs on the same sample, 250 µm apart from each other, for stress along the [011] direction. Both VCSELs have an oxide aperture of about 6.5 µm. When no strain is applied (a), the device without a grating on the left hand side, shows a switch in polarization from the [011] to the [011] direction. When the sample is bent by \( b = -33 \) µm, no switch occurs any more and the first two modes start to lase in [011] direction (see Fig. 5(b)). Also for higher order modes a dominance of the [011] polarization is observed that increases further if the strain is increased (see Fig. 5(c)). In agreement with the results of Sect. 3.1, strain along the [011] direction thus leads to a preference of the [011] polarization.
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(a) no bending

(b) bending $b = -33 \, \mu m$

(c) bending $b = -67 \, \mu m$

Fig. 5: Polarization behavior of two VCSELs on a 850 nm sample under strain in [011] direction. The VCSEL on the left hand side has no grating, whereas the VCSEL on the right hand side has a grating in the [011] direction with a period of 0.7 $\mu m$ and a grating depth of 39 nm.

The VCSEL on the right hand side of Fig. 5 has a surface grating in [011] direction with a period of 0.7 $\mu m$ and a grating depth of 39 nm. Without external stress, it shows a strong suppression of the [011] polarization of more than 12 dB until thermal rollover, where 10 modes are lasing.

When strain along the [011] direction is applied, the orthogonal polarization suppression for higher order modes decreases. However, polarization switches can be avoided over the entire operation range. Even if the bending of the sample is increased to $b = -67 \, \mu m$, the polarization of the first two modes is still fixed in [011] direction, although in the reference VCSEL the [011] polarization already dominates (see left hand side of Fig. 5(c)). Therefore, an outstanding stability of the induced polarization control is observed.
4. Conclusion

By applying external stress to VCSELs, a wavelength splitting of up to 100 pm has been induced. In that way, polarization switches can be enforced and the switching current can be varied. A strong preference of the polarization orthogonal to the direction of the induced strain was observed.

To assess the polarization control introduced by a dielectric surface grating, the polarization behavior of VCSELs with and without grating have been examined under external stress. Even for a strong bending, which induced a wavelength splitting of more than 60 pm, the polarization of the fundamental mode as well as that of the first higher order mode was not affected, while the polarization of the VCSEL without grating was already strongly dominated by the orthogonal polarization. Thus, a dielectric surface grating enables a stable, dependable polarization control, even under high anisotropic strain.

References


