Chapter 1

Introduction and Motivation

The high number of different physical effects influencing the polarization[1] of the emitted light is a particularity of vertical-cavity surface-emitting laser diodes (VCSELs) [1, 2]. In gas and solid state lasers the polarization of the emitted electromagnetic radiation is not always well-defined either, but can easily be selected, for example, by inserting a Brewster window into the laser cavity. In semiconductor edge-emitting laser diodes (EEL) the dominant polarization is determined by the cavity and the gain anisotropies [3, 4]. However, the situation is different in VCSELs. Their monolithic cavity with its cylindrical symmetry lacks any anisotropy which could pin the polarization reliably. The same holds for the isotropic gain provided by the quantum wells in standard VCSELs [5]. While the polarization of the individual transverse modes in VCSELs is approximately linear, the orientation of the polarization is a priori unknown, varies from laser to laser [6], and – even worse – changes frequently during operation [7].

These polarization fluctuations lead to very rich and interesting phenomena from the laser physics point of view [8–11]. Concurrently, one of the toughest challenges for laser engineers working on and improving VCSELs is to avoid these polarization fluctuations and to realize VCSELs with a well-defined and stable polarization [12–14]. Great achievements have been made in the design and processing of VCSELs in the last years. Transverse single-mode VCSELs with optical output powers exceeding 6 mW [15, 16] were realized as well as transverse multimode VCSELs with optical output powers of more than 300 mW [17]. Small threshold currents of well below 100 µA [18], large modulation bandwidths exceeding 20 GHz [19], and wallplug efficiencies of above 50 % [20] were achieved as well. However, the issue of polarization control of VCSELs is not yet solved in a satisfactory way.

The first VCSELs were mainly designed for data communication. Meanwhile it turned out that VCSELs are also ideal laser sources for sensing applications like spectroscopy [21] or

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[1] Strictly speaking, the term 'polarization' describes the oscillation of the electric field in the plane perpendicular to the propagation direction of the electric field. This oscillation can occur on a linear, a circular, or an elliptical path with different orientations of its principal axes. Since VCSELs are linearly polarized in a first approximation, the term 'polarization' is frequently used in this thesis as a synonym for 'orientation of the linear polarization'.

for position sensing as needed in optical computer mice. For all these applications, VCSELs with a stable polarization are either highly desirable or even required.

Despite the efforts which have been put into the research and development of methods for polarization control of VCSELs in the last 15 years, an overall satisfactory solution has not been obtained yet. Up to now, the best results were achieved by epitaxial growth on substrates with higher indices in combination with strained quantum wells for VCSELs emitting around 960 nm [22, 23]. However, even with this technique, the suppression of the weaker polarization still decreases during relaxation oscillations. Attempts to apply the same technique to VCSELs with different emission wavelengths have only been partially successful. Furthermore, the performance of VCSELs grown on substrates with higher indices has not yet reached the one of standard VCSELs.

In this PhD thesis, a new approach for polarization control of VCSELs is investigated. The main idea is to monolithically integrate a semiconductor surface grating into the topmost layer of the upper Bragg mirror of VCSELs, resulting in a polarization-dependent reflectivity of the respective mirror. With this approach, two new methods enter the research on and the manufacturing process of VCSELs. Up to now, VCSEL have been mainly simulated in a scalar way and their processing has been based on microtechnology. In contrast, the footing of the research performed for this thesis is rigorous electromagnetic modeling and nanotechnology.

The thesis is organized as follows: First, the fundamentals of VCSELs and their main polarization phenomena are introduced. Subsequently, previous attempts for polarization control are discussed. The concept of surface gratings for polarization control and a fully vectorial, three-dimensional model for electromagnetic simulations of VCSELs [24] are presented in Chap. 3. Using this model, the design of surface grating VCSELs is theoretically investigated in the same chapter, before the fabrication process of grating VCSELs is outlined in Chap. 4. Basic phenomena of polarization-stable single- and multimode grating VCSELs are discussed in Chap. 5 and a detailed analysis of the dependence of the polarization control and the overall performance of grating VCSELs on their grating parameters is performed. The stability of the achieved polarization control is tested in Chap. 6 under demanding conditions. However, studying whether a VCSEL remains polarization-stable under varying temperature, external optical feedback, externally applied stress, and high-frequency modulation still does not provide sufficient quantitative information about the effective strength of the polarization control. A method to measure this strength directly is therefore highly desirable and is presented in Chap. 7. While integrated surface gratings provide an unrivaled polarization control, they can potentially introduce severe optical losses due to diffraction. Therefore, the topic of Chap. 8 is how these diffraction losses can be reduced or be avoided almost completely by an improved grating design. In Chap. 9, a technique for combined mode and polarization control for polarization-stable, single-mode VCSELs is presented, before a summary and a conclusion are given in Chap. 10.

Chapter 2

Polarization Properties and Polarization Control of VCSELs

This chapter starts with a short introduction to VCSELs focussing on those of their properties that have an influence on the polarization of their emitted electromagnetic radiation. Subsequently, the rich polarization phenomena observed in VCSELs are discussed on the basis of some measurements and a literature survey. The survey includes a short presentation of the spin-flip model, the standard theoretical model to describe the polarization dynamics of VCSELs. Although the effects associated with the unstable polarization of VCSELs are not the main topic of this thesis, they are presented to demonstrate why a special polarization control is needed in VCSELs and why such a polarization control is so demanding as the high number of only partially or not at all successful previous attempts for polarization control of VCSELs prove. These attempts are discussed in the last section of this chapter.

2.1 Fundamentals of VCSELs

The basic difference between EELs and VCSELs is the propagation direction of their generated light. While the emission direction of EELs is within the plane of the wafer, it is normal to the wafer surface for VCSELs. This can be seen in Fig. 2.1, which schematically shows the layer structure of a VCSEL. Typical semiconductors on which VCSELs are based are Gallium Arsenide (GaAs) and Indium Phosphide (InP). All VCSELs presented in this thesis are fabricated from the material system Aluminum Indium Gallium Arsenide (AlInGaAs), since such VCSEL structures have been available. However, all techniques described in this thesis are expected to work as well for VCSELs based on InP. On top of a usually n-type substrate and a GaAs-buffer layer, the bottom Bragg mirror is epitaxially grown. Above the bottom mirror, typically three closely spaced quantum wells in one antinode of the optical standing wave inside the VCSEL resonator serve as active gain medium. Another Bragg mirror on top of the quantum wells terminates the laser cavity.

In the simplest case, top-emitting VCSELs have a large-area n-contact on the back side of the substrate and a p-type ring contact on top of the upper Bragg mirror. Thus, in VCSELs, the current flow and the propagation direction of the optical field are parallel to each other, but orthogonal to the plane of the quantum wells. On the contrary, in EELs the propagation direction of the optical field is orthogonal to the current flow and in the plane of the quantum well(s). Accordingly, the ratio of the distance which the light propagates through the gain medium to the effective cavity length is much smaller in VCSELs than in EELs. Consequently, the modal gain is lower in VCSELs than in EELs. Therefore, the outcoupling losses of the mirrors and the internal losses in the non-active layers of a VCSEL have to be very small to achieve lasing operation.

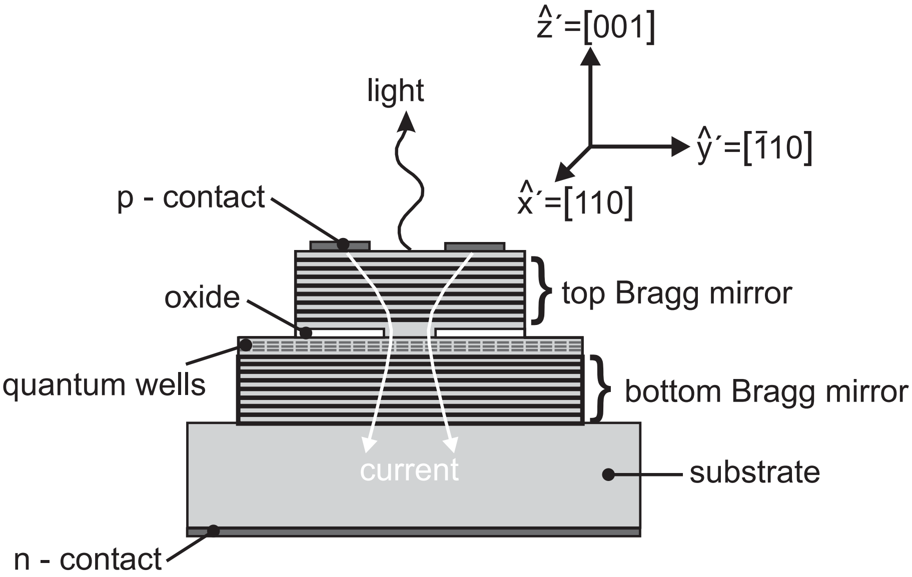

Figure 2.1: Schematic diagram of a typical VCSEL together with the coordinate system and its orientation with respect to the crystal axes as it is used in this thesis.

To realize an emission orthogonal to the wafer on the one hand and to achieve the high required mirror reflectivity on the other hand, distributed Bragg reflectors (DBRs) turned out to be the key element of VCSELs [25–27]. Such Bragg mirrors consist of an alternating sequence of layers with high and low refractive indices and quarter-wavelength[1] ($\lambda/4$) thickness. In a Bragg mirror, the electromagnetic fields reflected at the single interfaces are in-phase which each other due to the optical path difference of a multiple of half the wavelength and the additional phase change of π, which occurs when light is reflected at an optical denser medium. Thus, the reflectivity of Bragg mirrors is virtually only limited by the losses due to absorption and scattering inside the mirrors [28, 29]. For top-emitting VCSELs, the upper mirror usually consists of 20 to 25 layer pairs and the bottom mirror of more than 30. In this way, the reflectivity of both mirrors typically exceeds 99.5 % [28]. Though the reflectivity of Bragg mirrors is slightly higher for incident waves polarized

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[1] In this thesis, the vacuum wavelength is denoted by λ_0. In contrast to that, the term wavelength refers to the material wavelength presented by the symbol λ.

normal to the plane of incidence than for those polarized parallel to this plane [29,30], this neither results in a specific preference of any polarization nor in any specific orientation of the polarization at all, since the reflectivity of a Bragg mirror has a circular symmetry with no preferred crystal axes.

Although VCSELs with quantum dots as gain medium have improved significantly during the last years [31], the gain is still provided by quantum wells in common VCSEL structures. In a quantum well, the strength of a transition from the conduction band to the valence band differs for the transition from the conduction band (C) to the heavy-hole (HH), to the light-hole (LH), and to the split-off (SO) valence band, respectively. The transition matrix elements depend on the relative orientation of the normalized polarization vector $\hat{\sigma}$ to the normalized electron momentum vector $\hat{p}_\mathrm{e}$, which for simplicity is assumed here to be orthogonal to the quantum wells as in a VCSEL. At the band edge, the relative transition strength $|M_\mathrm{T,rel}|^2$ is given for quantum wells in the (001)-crystal plane by [4]

$$\begin{aligned} |M_\mathrm{T,rel,C-HH}|^2 &= \frac{1}{2}\left(1 - |\hat{p}_\mathrm{e}\cdot\hat{\sigma}|^2\right) && \text{for C–HH}\ , && (2.1) \\ |M_\mathrm{T,rel,C-LH}|^2 &= \frac{1}{2}\left(\frac{1}{3} + |\hat{p}_\mathrm{e}\cdot\hat{\sigma}|^2\right) && \text{for C–LH}\ , && (2.2) \\ |M_\mathrm{T,rel,C-SO}|^2 &= \frac{1}{3} && \text{for C–SO}\ . && (2.3) \end{aligned}$$

In the GaAs material system, the splitting between the split-off valence band on the one hand and the light-hole and heavy-hole valence band on the other hand is so large that the split-off band does not contribute to the gain in common semiconductor quantum well lasers [5]. Furthermore, the contribution of the transition from the conduction band to the light-hole valence band is usually negligible in unstrained GaAs/AlGaAs quantum wells [32], because the heavy-hole band possesses the highest energy level in these quantum wells [33]. Thus, only the conduction band–to–heavy-hole valence band transition provides the optical gain. This gain is identical for all orientations of the polarization in the plane of the quantum wells and therefore orthogonal to the current flow, since in that case $|\hat{p}_\mathrm{e}\cdot\hat{\sigma}| = 0$. Consequently, the gain in VCSELs is polarization-independent in the absence of strain and, like the Bragg mirrors, does not select a specific orientation of the polarization.

While the two Bragg mirrors confine the VCSEL cavity in the longitudinal $\hat{z}$-direction normal to the wafer, the transverse size of the laser is a priori undefined, since the VCSEL layer structure initially consists of quasi infinite layers in the $\hat{x}$-$\hat{y}$-plane parallel to the wafer surface. Several techniques for transverse current and optical field confinement have been employed. Among them [34] are a p-contact ring with small outer diameter, proton implantation to strongly reduce the current conductivity outside of an inner circular disk, and etching of the semiconductor layers outside of an inner circle to form either an air-post or to overgrow the structure with a semiconductor material with smaller refractive index, higher bandgap, and reduced conductivity. A further technique for transverse confinement is lateral oxidation, which is the only technique discussed in the following, since oxide-confined VCSELs provide currently an unrivaled performance [35]. Consequently, all VCSELs presented in this thesis are oxide-confined.