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Review Article

Spin-Controlled Vertical-Cavity Surface-Emitting Lasers

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We discuss the concept of spin-controlled vertical-cavity surface-emitting lasers (VCSELs) and analyze it with respect to potential room-temperature applications in spin-optoelectronic devices. Spin-optoelectronics is based on the optical selection rules as they provide a direct connection between the spin polarization of the recombining carriers and the circular polarization of the emitted photons. By means of optical excitation and numerical simulations we show that spin-controlled VCSELs promise to have superior properties to conventional devices such as threshold reduction, spin control of the emission, or even much faster dynamics. Possible concepts for room-temperature electrical spin injection without large external magnetic fields are summarized, and the progress on the field of purely electrically pumped spin-VCSELs is reviewed.

1. Introduction

Concepts for the use of the electron spin as an information carrier have become an important research field called "spintronics." The goal of spintronic research is to exploit the carrier spin degree of freedom additionally to the charge degree of freedom in order to develop novel devices, which offer new functionalities or a better performance as their conventional counterparts. Semiconductor spintronics in general includes the search for alternative device concepts as well as the investigation of the fundamental physical processes as spin injection, spin transport, spin manipulation, and spin detection. This research area was strongly stimulated by the suggestion of the so-called spin transistor by Datta and Das in 1990 [1]. Although such a spin transistor has yet to be realized even about 20 years after its suggestion, a lot of progress has been made in terms of understanding the above-mentioned fundamental physical processes. Moreover, new spintronic device concepts have been developed which might have a more realistic application perspective than the spin transistor. For example, spin-optoelectronic devices might be very promising. In such devices the direct connection between carrier spin momentum and photon spin momentum upon radiative recombination will be utilized in order to generate a spin-controlled net circular polarization degree for the light emission. While spin light-emitting diodes (spin-LEDs) are already established tools in order to characterize and optimize electrical spin injection [2–9], spin controlled semiconductor lasers (spin-lasers) seem to be more promising for mass applications. Spin-lasers might provide properties superior to those of their conventional counterparts. For example, they promise to have faster modulation dynamics [10–14], to operate with lower threshold [15–20] and to offer a stronger polarization determination than conventional lasers with up to a 100% polarization control [17, 21–26]. However, such spin-optoelectronic device concepts are only attractive for applications if they operate at room temperature and without the need for large external magnetic fields, and if they really provide new or superior properties. Therefore, while earlier reviews have nicely discussed the physical background of spin-optoelectronic devices and the scientific achievements [24, 27, 28], we concentrate on approaches operating at room temperature without the need for superconducting magnets. In particular, we analyze the potential for new and superior performance of spin-controlled lasers.

In this article, we first discuss the fundamentals of spin-optoelectronics and then analyze the concepts for spin injection with respect to their potential for room temperature and low magnetic field operation. Then, we discuss the concepts for spin-controlled semiconductor lasers, namely, spin-controlled vertical-cavity surface-emitting lasers (VCSELs), and analyze which properties are particularly attractive for

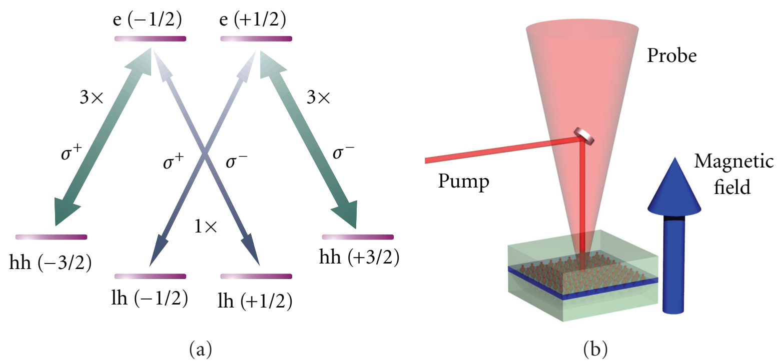


FIGURE 1: (a) Selection rules for optical transitions in direct semiconductor quantum well. The quantum numbers m_j which correspond to the z-projections of the total angular momentum of each Bloch state are printed in brackets. The transition rates and the associated circular polarization states are plotted next to the transition. (b) Vertical geometry for the selection rules in case of quantum well structure.

applications. Finally, we briefly review the state-of-the-art for electrically pumped VCSELs.

2. Fundamentals of Spin-Optoelectronics

2.1. Optical Selection Rules. Spin-optoelectronics is based on the fact that the total spin angular momentum of an electron-hole pair is directly linked to the angular momentum of a photon, which is either absorbed or emitted radiatively. This link is a consequence of the conservation of the angular momentum and is expressed by the so-called optical quantum selection rules for dipole radiation which are shown schematically for direct band-gap semiconductors in Figure 1(a) [29]. This schematic reduces the band structure of a typical direct semiconductor like GaAs in the vicinity of the Γ-point to a 6-level diagram in accordance to usual Bloch states. The Bloch states in Figure 1(a) are denoted by the quantum number m_j which corresponds to the projection of the total angular momentum $\vec{J}$ including orbital and spin momentum onto the positive z axis. The s-like conduction band is represented by two electron (e) levels with opposite spins (+1/2 and −1/2). The p-like valence band is represented by four states: two heavy hole (hh) states with $m_j = \pm 3/2$, and two light hole (lh) states with $m_j = \pm 1/2$. The split-off band is energetically separated by the spin-orbit splitting energy Δ_{SO} and therefore usually not included in the considerations. However, it should be noted that a sufficiently large spin-orbit splitting is a basic requirement for spin-optoelectronic devices otherwise optically induced spin injection as well as optical detection of carrier spin would not be achievable. In bulk GaAs, the hh and lh states are degenerated at the Γ-point. The energetic splitting of hh and lh states in Figure 1(a) appears because we consider a two-dimensional system, for example, a GaAs quantum well (QW), which is mostly used in spin-optoelectronic devices. Here different confinement energies for heavy and light hole states and possible strain contributions lead to a separation of the hole band states. The projection of the angular momentum of circularly polarized photons of the wave vector matches $\pm 1\,\hbar$. From this it follows that optical transitions between conduction and valence band states involving circularly polarized light are allowed for $\Delta m_j = \pm 1$ only. In direct bulk semiconductors, this optical selection rule is valid for all directions, but in the case of lower dimensional active regions like quantum wells or quantum dots (QDs) the situation is a little more complex. In narrow QWs, the transitions depicted in Figure 1(a) are only valid for a vertical geometry, where the carrier spin orientation as well as the light emission is perpendicular to the quantum well plane (Figure 1(b)). Sometimes this geometry is denoted as Faraday geometry, even though a magnetic field is not obligatory in this case. The possible transitions are indicated by arrows in Figure 1(a). Due to the different geometries of the wave functions of the hh and lh states, the transitions involving hh and lh states have different probabilities. In detail, the hh transitions are three-times more probable than lh transitions.

As mentioned above, these selection rules directly link the spin polarization of the carriers and the polarization of the emitted or absorbed light. For example, we assume a spin polarization of 100% in the electron $m_j = -1/2$ state. Then, the emission consists of a part with circular right polarization (σ^+, −1/2 to −3/2) and a part with circular left polarization (σ^-, −1/2 to +1/2), whereas the right polarized part is three-times stronger than the left one. The electron spin polarization is defined as [27]:

$$P_n = \frac{n_+ - n_-}{n_+ + n_-}. \quad (1)$$

Here, $n_\pm$ are the densities of electrons in the +1/2 and −1/2 electron states, respectively. If $I(\sigma^+)$ and $I(\sigma^-)$ are the intensities for the right and left circularly polarized light fields, the circular polarization degree can by described as [27]:

$$P_{\text{circ}} = \frac{I(\sigma^+) - I(\sigma^-)}{I(\sigma^+) + I(\sigma^-)}. \quad (2)$$

In the following we assume that each hole state is sufficiently populated and thus the electron densities are the only limiting factors for optical transitions. Then the equation can be reformed to [27]:

$$P_{\text{circ}} = \frac{I(\sigma^+) - I(\sigma^-)}{I(\sigma^+) + I(\sigma^-)} = \frac{(n_+ + 3n_-) - (3n_+ + n_-)}{(n_+ + 3n_-) + (3n_+ + n_-)} = -\frac{P_n}{2}. \quad (3)$$

From this it follows that the circular polarization degree (CPD) of the light field emitted from an electron spin-polarized QW is always $-1/2$-times the electron spin-polarization degree. In our example with $P_n = -1$ the resulting light field would be right circularly polarized with a CPD of 50%. This correlation is valid as long as we consider both lh and hh transitions. However, the energetic separation of hh and lh states even allows for higher polarization degrees: If the emission or absorption is energy selective, that is, if only the hh-electron transition takes place, a CPD of up to 1 can be obtained for an electron spin-polarization degree of -1.

The situation would change completely, if split-off band related transitions were involved. If we assume, for example, an excitation with right circular polarized light with a photon energy larger than the band-gap energy E_g plus the spin-orbit splitting energy Δ_{so}, no net spin-polarization degree would be achieved due to the additional split-off transitions. Since split-off-transitions have a transition rate of 2, they equalize the summarized transition rates for right and left circularly polarized light [27]. Correspondingly, in order to achieve a spin-polarization degree for the electrons (and holes) using optical pumping, the excitation photon energy has to be less than $E_g + \Delta_{\text{so}}$. This indicates that spin-orbit coupling is principally necessary for spin-optoelectronics. However, we will see in next chapter that the spin-orbit interaction is also the origin for the most relevant spin relaxation mechanisms which are often obstructive for the development of spin-optoelectronic devices.

These selection rules are the basis for spin-optoelectronics because they directly link optical and carrier spin polarizations. In detail, for spin-optoelectronic devices with electrical spin injection (spin-LEDs or spin-VCSELs) they enable an estimate of the spin injection efficiency from the measured light polarization degree of the optical emission. On the other hand, they can be used also to inject carrier spin polarizations optically, by means of circularly polarized light. This is an important tool in order to investigate spin-dependent effects fundamentally, if electrical spin injection is not available.

2.2. Spin Transport and Spin Relaxation. Unfortunately the carrier spin in a semiconductor is not permanently stable like the electron charge but relaxes to equilibrium within a relatively short time called spin relaxation time. This is often a fundamental challenge for the development of spin-optoelectronic devices especially in case of the spin transport. The spin relaxation is due to many reasons like the Elliot-Yafet (EY) [30, 31], the D'yakonov-Perel (DP) [32], and the Bir-Aronov-Pikus (BAP) [33] mechanisms, and others like the hyperfine interaction. These relaxation mechanisms can basically be described as a result of the interaction between the spin magnetic moments and fluctuating effective magnetic fields, originating mainly from the spin-orbit coupling. This interaction forces a group of aligned electron spins into equilibrium of both allowed spin states. Typical spin relaxation times vary over a huge range from 10 ps up to 100 ns. They are depending on various band structure and environment parameters like lattice symmetry, spin-orbit interaction, confinement, carrier, dopant, defect densities, temperature, and others. A detailed recapitulation of the different spin relaxation mechanisms and their dependencies is beyond the scope of this article. However, a nice overview can be found, for example, in [27]. Here we will concentrate on the fundamentals of spin relaxation important for the development of spin-optoelectronic devices operating at higher temperatures.

Usually, the spin relaxation time strongly decreases with temperature. In semiconductors without inversion symmetry like (100) GaAs and at low hole densities, the DP mechanism is the dominant spin relaxation mechanism at elevated temperature. Here the spin states in the conduction band for $k \neq 0$ are no longer degenerated, resulting in an effective magnetic field $B_{\text{eff}} = f(k)$. Consequently, momentum scattering processes lead to magnetic fields fluctuating in time and inducing a spin dephasing and relaxation process [34]. Typical spin relaxation times for (100) GaAs bulk vary from approximately 100 ns at low temperatures [35] to some tens of ps at room temperature [36]. The confinement energy in low-dimensional active regions is an important factor, too. In (100)-GaAs-QWs at room temperature, the spin relaxation rate exhibits a quadratic increase with increasing confinement energy [37]. Accordingly, typical relaxation times for (100)-GaAs-QWs at room temperature are in the regime of several tens of picoseconds for electron spins. Anyway low-dimensional structures can also provide longer spin relaxation times, because their higher degree of spatial confinement limits the carrier motion and possibly reduces relaxation mechanisms like the DP mechanism. This is the reason for the long spin lifetimes, predicted for quantum dots, which are consequently a very promising material system for spin-optoelectronics [24, 38]. Other possibilities in order to obtain long spin lifetimes are to make use of materials with inversion symmetry like Si or (110)-GaAs, because here the usually dominant DP mechanism is suppressed. Especially silicon, which provides electron spin relaxations times up to 7 ns at RT [38] is a very interesting material system, because of its compatibility with the highly developed complementary metal oxide semiconductor (CMOS) technology. Unfortunately, because of its indirect nature, the development of sufficient spin-optoelectronic devices based on silicon remains a fundamental challenge.

Up to now we have concentrated on the electron spin relaxation only. Hole spins usually relax much faster than electron spins. Typical values at room temperature are in the range of 100 fs [39]. Consequently it is often adequate to assume a statistic contribution of the hole spin even after optical spin injection. Nevertheless there are some concepts for hole spin injection and transport but they suffer from a rather low efficiency [3, 40].

However, even the spin relaxation time of the electrons is typically shorter than the transport time of the carriers through a spin-optoelectronic device, for example, a spin-LED. The selection rules provide a direct link between the polarization of the spin-LED emission and the spin polarization of the carriers when they recombine. However, the longer the time is between the generation of the spin-polarized carriers (by optical absorption or electrical spin injection) the more spins relax before they recombine. This relaxation takes place both on the transport path and within the active region where the carriers recombine radiatively. Consequently, the light polarization emitted by a spin-LED only provides a lower estimate of the spin injection. Presuming a sufficient number of holes for recombination, for example, in a p-doped semiconductor, the spin relaxation within the active region can be accounted using [34]

$$P_{\text{circ, eff}} = \frac{P_{\text{circ}}}{1 + (\tau/\tau_s)}. \quad (4)$$

Here τ_s is the spin lifetime, τ the electron lifetime, and $P_{\text{circ, eff}}$ the effectively measured degree of circular polarization. This has important consequences: the impact of spin relaxation in the active medium is not determined by the spin lifetime alone, but by the electron-to-spin-lifetime ratio τ/τ_s [41] which has to be minimized. This can be accomplished either by a long spin relaxation time or by a short electron lifetime. Furthermore, to ensure a minimized spin relaxation during transport, all transport path lengths in spin-optoelectronic devices should be kept as short as possible. Typical electron spin relaxation lengths for a drift related transport in vertical geometry in n-doped GaAs at room temperature are theoretically predicted to be in the range of 25–50 nm [42]. Recently, these predictions could be verified experimentally using a series of spin-LEDs with varying spin-injection transport path length in vertical drift-based transport geometry by Soldat et al. [43]. The results demonstrate an exponential decrease of the circular polarization degree and thus of the spin-polarization degree in the active region with increasing injection path length. A spin relaxation length of 26 nm at room temperature in undoped GaAs was determined, which corresponds to the lower bound of the theoretically predicted values.

Consequently, the development of electrically pumped spin-optoelectronic devices at room temperature is a huge challenge, because in standard optoelectronic devices in particular lateral carrier transport path lengths easily reach values of several micrometers. In the following section, we briefly review the concepts for electrical spin injection into semiconductors.

2.3. Electrical Spin Injection into Semiconductors. On the long run, spin-optoelectronic devices will only be application relevant if the spin injection can be performed electrically and when the devices operate at room temperature and without the need for high external magnetic fields which would require superconducting magnets. As we will discuss below, this implies that many of the spin injection concepts reported in the literature will never be usable in practical devices. Firstly, we briefly describe the state-of-the-art and the different concepts for spin injection into semiconductors. Again, we are concentrating on concepts which are relevant for the development of room temperature devices.

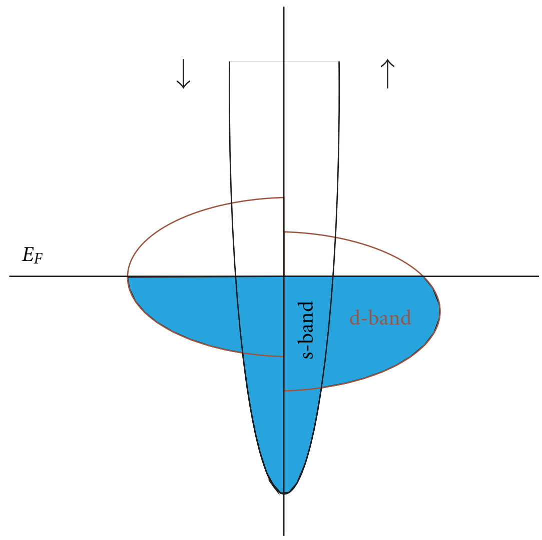


Figure 2: Schematics of the exchange field induced spin-splitting of the d-like density of states in a ferromagnetic metal. E_F denotes the Fermi level (Illustration analogous to [44]).

In general, the alignment of spins upon injection into a semiconductor implies the presences of a magnetic layer somewhere in the vicinity of the contact of the spin-optoelectronic device. The straightforward approach would be to use ferromagnetic contacts, for example, iron contacts. In a ferromagnetic metal like iron, the density of states at the Fermi level has both s- and d-character. The exchange interaction in the ferromagnet leads to a spin splitting of the d-states and therefore to a different density of states for spin-up and spin-down states at the Fermi level [44]. The density of states of a ferromagnetic metal is schematically depicted in Figure 2. Since s-electrons have significantly smaller effective masses than electrons in d-states, the current flow in the metal is dominated by the s-electrons. However, due to the splitting of the d-like density of states, spin-up and spin-down electrons have different probabilities for scattering into the d-states which results in different mobilities for spin-up and spin-down s-electrons. Consequently, the current will be dominated by s-electrons in a spin-state with less d-like density of states at the Fermi level. This can principally be used for spin injection in a nonmagnetic semiconductor [44].

But with a normal ohmic contact between the magnetic iron contact and the semiconductor, the large conductivity mismatch [45] leads to nearly negligible spin injection efficiency. Two different solutions of this problem have been suggested: the first is injection by tunnel contacts from a ferromagnetic metal layer into the semiconductor [46, 47] and the second is to use diluted magnetic semiconductors. Spin injection using dilute magnetic semiconductors is either possible with spin injection out of ferromagnetic semiconductors [3] or with spin alignment with paramagnetic semiconductor layers [2]. Though the highest spin injection efficiencies were realized with diluted magnetic semiconductors, these approaches suffer from fundamental drawbacks. Spin aligners for example, a paramagnetic BeMnZnSe layer in the n-doped region of a GaAs/Al-GaAs LED structure, require large external magnetic fields in the order of a few Tesla for spin alignment. Such high fields can only be provided by superconducting magnets. The ferromagnetic semiconductors used for spin injection so far, have Curie temperatures far below room temperature. Consequently, such concepts require cryogenic cooling. Various candidates for ferromagnetic semiconductors with Curie temperatures above room temperature have been suggested and discussed. The most promising materials are GaMnN [48, 49] and MnAs clusters in GaAs environment [50] due to their compatibility to existing optoelectronic semiconductor technology. Materials like ZnCrTe [51], Cr-doped In_2O_3 [52], $CdMnGeP_2$ [53], or ZnMnO [54] offer high Curie temperatures but are far from being compatible with established optoelectronic technology, yet. Actually, efficient spin injection from ferromagnetic semiconductors at room temperature has yet to be demonstrated and it is not clear whether this demonstration will happen at all.

Many ferromagnetic metals, in contrast, have Curie temperatures far above room temperature. But other problems appear for spin injection from ferromagnetic metals. As mentioned above, the conductivity mismatch between metal and semiconductor prevents spin injection via ohmic contacts. This problem can be solved using tunnel contacts either via Schottky contacts or via isolating tunnel barriers as, for example, MgO. In tunnel contacts the tunnel rates for the electrons are proportional to the product of the densities of states of the materials on both sides of the tunnel barriers [44]. Due to the spin splitting of the d-states in ferromagnetic metals discussed above, this enables a robust spin injection from the metal into the semiconductor circumventing the problem of conductivity mismatch.

Spin injection at room temperature has indeed been successfully realized both with Schottky barriers [4, 7] and with isolating tunnel barriers [8, 55]. While the first approaches reached only spin injection efficiencies of a few percent [4], the record value for spin injection from ferromagnetic metals into semiconductors at room temperature is 32% using MgO tunnel barriers [8]. However, as mentioned above, the optical selection rules usually require an orientation of the injected spins perpendicular to the semiconductor surface. Most ferromagnetic contacts, in contrast, have an easy magnetization axis and thus a spontaneous remanent magnetization in the film plane, that is, parallel to the surface. Accordingly, large magnetic fields in the order of 2 Tesla have to be applied in order to turn the magnetization into the required perpendicular orientation. Similar to the spin aligner concept, this induces the need for a superconducting magnet which is not attractive for device applications. This problem can be solved using ferromagnetic materials with perpendicular magnetization even without external magnetic field. Possible candidates include Fe/Tb multilayers [6, 9, 56–58] and alloys, FePt [59], and PtCo [60]. Indeed, room temperature spin injection has successfully been demonstrated in remanence and at room temperature with Fe/Tb-contacts [9, 58] and FePt [59]. The polarization degrees of the spin-LED emission and thus the injection efficiencies were in the few percent region in all cases. One reason for this is that the magnetization orientation of the ferromagnetic contacts is not completely perpendicular to the surface. Typical values for the angle between magnetization direction and surface normal are $\sim 30^\circ$ for FeTb alloys and $\sim 40^\circ$ for FeTb multilayers [57, 58]. Thus, further material optimization is required to ensure perfect vertical alignment of the ferromagnetic contacts in remanence. Then, it can be expected that this efficiency can be increased up to about 30% combining the vertically magnetized ferromagnetic contacts with the optimized injector structure of Jiang et al. [8]. Thus, from the actual point of view, the optimum room-temperature spin-LED would look like it is schematically shown in Figure 3.

However, even this optimized spin-LED will probably not become relevant for applications other than the characterization and optimization of spin injection contacts. This is because LEDs are generally too slow for information technology. Moreover, the injection efficiencies that could be obtained even in the best case are still rather low. In contrast, spin-controlled lasers might offer a much higher application potential. In the following section, we will analyze this potential.

3. Spin-Controlled Vertical-Cavity Surface-Emitting Lasers

The first step on the way to a spin-polarized laser is to identify a qualified laser concept. Principally a choice has to be made, whether an edge- or a vertical-emitting geometry suites best. Figure 4 compares schematically the structures of a vertical-cavity surface-emitting laser (VCSEL) and of a conventional edge-emitting laser. On the first glance, an edge-emitting laser might be more promising. It is obvious from the comparison of both laser structures with the spin-LED in Figure 3 that it would be rather easy to transfer the injector concept of a spin-LED to an edge-emitter while electrical spin injection into the VCSEL is much more complicated due to the larger vertical path length. In addition, an edge-emitting concept would allow for an easy remanent spin injection utilizing the natural in-plane magnetization of the ferromagnetic layers due to the shape anisotropy. But the requirement for the Faraday geometry in spin-optoelectronics implies that lasers with vertical architecture such as VCSELs are the first candidates for spin-controlled lasers. At least for narrow quantum wells the angular momentum of the holes lies in the quantum well plane, and the connection between carrier and photon spin is only straightforward for the vertical geometry as discussed in Section 2.1. In principle, an edge-emitting concept utilizing a bulk active region might still be a possibility. Recent experimental results have demonstrated spin injection in an edge-emitting LED utilizing bulk-like wide GaAs QWs [61]. In a wide QW, the heavy-hole angular momentum can principally lie in the QW plane comparable to the case in bulk semiconductors. However, due to the restriction on bulk-like active systems, an edge-emitting concept for room temperature operation would be

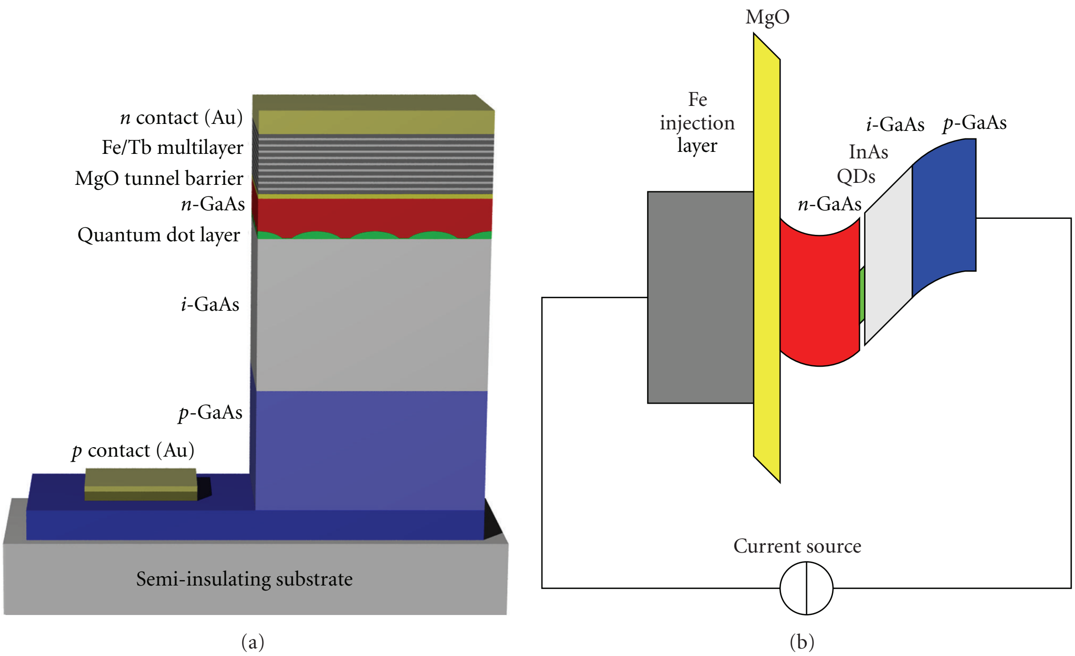


Figure 3: Optimized structure for a room temperature spin-LED. The design combines a Fe/Tb-multilayer contact structure with spontaneous perpendicular magnetization, a highly efficient MgO tunnel barrier for spin injection, a minimized electron path length, and InAs QDs with enhanced spin lifetime at room temperature (a), (b) depicts the schematic energy diagram of the spin-LED in growth direction. Spin-polarized electrons will be injected from the lowest Fe layer of the Fe/Tb multilayer contact into n-GaAs via the MgO tunnel barrier and recombine with unpolarized holes in the QDs.

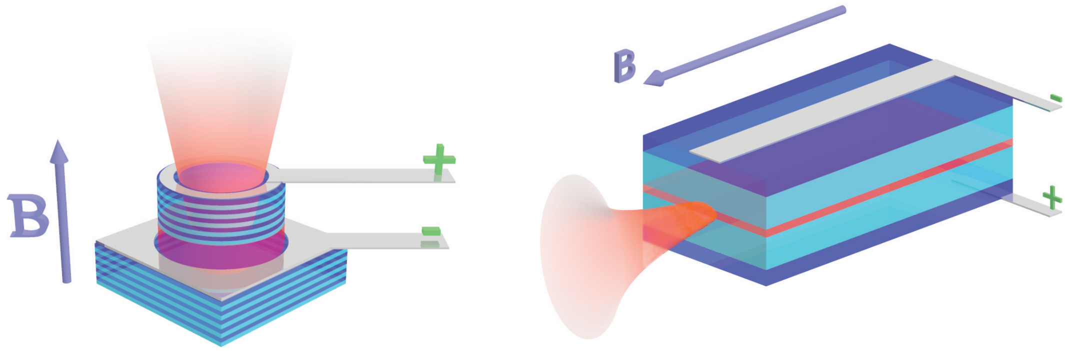
a tough challenge and it remains questionable whether such a concept can be competitive to conventional laser devices. Additionally, waveguide effects have a relevant impact on the polarization state of an edge-emitting laser, usually leading to a linearly polarized laser emission parallel or perpendicular to the waveguide plane. With respect to this, VCSELs have a big advantage, because generally a VCSEL is a laterally isotropic device with nearly perfect circular symmetry, which leads to weak pinning of the polarization state.

Altogether, because of the above-mentioned fundamental disadvantages of edge-emitting concepts a VCSEL seems to be the most qualified concept for a spin-polarized laser at room temperature. Thus, the challenge of a more complicated spin injection concept has to be faced.

As a consequence of the long vertical spin transport path, room temperature spin-VCSELs with electrical spin injection are not available yet. Thus, at this stage, the potential of spin-VCSELs at room temperature has to be analyzed theoretically or with alternative experimental techniques. Since the selection rules shown in Figure 1(a) enable controlled optical spin excitation, most experimental work on this field has been done on spin-VCSELs with optical spin injection. In the following section, we review theoretical and experimental work on room-temperature spin-VCSELs in order to work out the specific advantages spin-VCSELs might deliver for applications.

3.1. Basics and Properties of Spin-VCSELs. The idea that spin-controlled lasers might offer a much higher potential than spin-LEDs arises from the fact that lasers show a dynamical behavior much different from that of LEDs. One important example affects the influence of the spin relaxation in the active region. In spin-LEDs the effective circular polarization degree will be reduced. This reduction is usually accounted for by the factor $1 + (\tau/\tau_s)$ [34] including the electron-to-spin-lifetime ratio (see Section 2.2). At room temperature the ratio is typically very large due to a small spin lifetime, which leads to a small circular polarization degree. In spin lasers, in contrast, the electron lifetime will be reduced significantly due to the strong stimulated emission, resulting in a vanishing electron lifetime to spin lifetime ratio and a correction factor of approximately 1. Accordingly the spin relaxation rate in the active medium should be less important in spin-VCSELs in comparison to spin-LEDs. This is a first fundamental advantage. Nevertheless the spin relaxation during carrier transport remains still an issue.

The dynamic behavior of spin-polarized laser can be investigated theoretically using a spin-dependent rate-equation model. Several different models have been used in the literature for this purpose [12–15, 19, 24, 62, 63]. In the following a common dynamic spin-flip model (SFM) will be used, originally developed by San Miguel et al. in order to describe the polarization switching and bistability in conventional VCSEL devices [64–66]. The SFM is based on a four-energy-level approximation and takes only transitions between electron and heavy-hole states into account. It describes the polarization dynamics for the two hh-related circularly polarized transitions, considering two distinguished carrier densities for spin-up and spin-down carriers [65]. These two carrier reservoirs are coupled by the spin



(a) (b)

Figure 4: Comparison between spin-VCSEL (a) and spin-edge emitter (b).

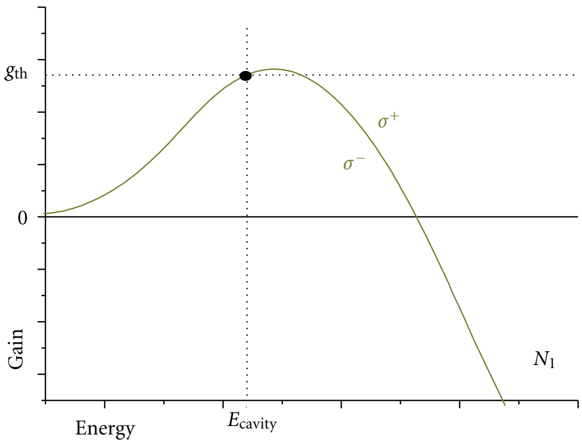
relaxation rate γ_s. The spin relaxation rate γ_s describes all kinds of microscopic spin relaxation processes mentioned in Section 2.2 by means of a single phenomenological parameter [66]. The circularly polarized light fields $E_\pm$ are coupled by the cavity anisotropies birefringence (γ_p) and dichroism (γ_a). The four coupled rate equations are as follows:

$$\begin{aligned}\dot{E}_\pm &= \kappa(1+i\alpha)(N \pm m_z - 1)E_\pm - \left(\gamma_a + i\gamma_p\right)E_\mp \\ &\quad + \xi_\pm\sqrt{\beta\gamma(N \pm m_z)}, \\ \dot{N} &= \gamma[\eta_+ + \eta_- - (1 + I_+ + I_-)N - (I_+ - I_-)m_z], \\ \dot{m}_z &= \gamma(\eta_+ - \eta_-) - [\gamma_s + \gamma(I_+ + I_-)]m_z - \gamma(I_+ - I_-)N.\end{aligned} \tag{5}$$

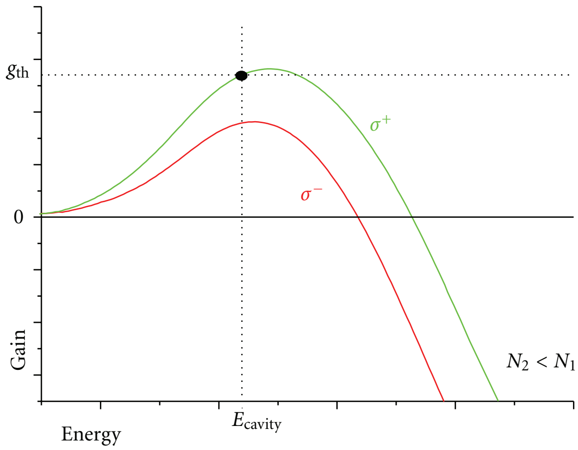
In the SFM the light field is coupled to two population inversion variables [66]. The first variable N is the total carrier population, that is, the sum of the populations of spin-up and spin-down states, normalized to the population at laser threshold. Its decay rate is γ. The second variable m_z is the so-called carrier spin magnetization which represents the normalized value of the population difference between spin-up and spin-down states [63]. The intensity $I_\pm$ of the circularly polarized optical laser modes can be described by the complex amplitudes $E_\pm$ of the circularly polarized light fields via $I_\pm = |E_\pm|^2$. κ is the cavity decay rate which can be related to the photon lifetime using $1/2\kappa$ [66]. α is the linewidth enhancement factor. The influence of the spontaneous emission to the laser mode is considered using the spontaneous emission factor β and the spontaneous emission noise terms $\xi_\pm$ which are usually described by complex Gaussian shaped distributions. Optical as well as electrical pumping can be modelled using the pump terms $\eta_\pm$. The optical gain is implemented in the model by using a simple linear dependence of the population inversion. Since the optical gain for the circularly polarized light intensities $I_\pm$ is proportional to $(N \pm m_z - 1)$, the gain values for I_+ and I_- are unequal in case of a carrier spin polarization. This is one of the fundamental concepts of the spin-polarized VCSEL and will be described later in detail. Gain compression, frequency dependencies or temperature effects are not included in this model. However, since a VCSEL operates spectrally single-mode with a usually small detuning between the cavity mode and the gain mode, the reduction of heavy-hole transitions and neglecting the frequency dependencies are sufficient to describe the main features of conventional and spin-polarized VCSELs. We will use this model in the following in order to discuss the advantages and properties of spin-VCSELs in comparison to spin-LEDs and conventional lasers.

One important difference between a spin-laser and a spin-LED is the nonlinearity of a laser at the laser threshold which enables a kind of amplification of spin information with a spin-controlled carrier injection. Figure 5 shows schematically the gain spectra of a laser with conventional unpolarized pumping in comparison to the case with spin-polarized pumping. Note that only the gain differences at the cavity energy E_{cavity} are relevant for the dynamics so that the spectral dependence of the gain is not considered in our simple model.

The anisotropic pumping leads to a small spin polarization of the carriers in the active region. We assume here a small excess in the occupation of the $e(-1/2)$ state (compare Figure 1) with respect to the $e(+1/2)$ state. This excess is in the regime of a few percent only which is, in principle, accessible by electrical spin injection. This small excess occupation of one spin band leads to a higher inversion in the $e(-1/2)$ state and, accordingly, the corresponding σ^+-transition from $e(-1/2)$ to the hh$(-3/2)$ state sees a higher gain than the σ^--transition from $e(+1/2)$ to hh$(+3/2)$. The transitions to the lh states do not play a role here because they are usually not in resonance with the VCSEL cavity mode and have a lower transition strength. In other words, the spin anisotropic pumping leads directly to a gain anisotropy at the photon energy of the cavity resonance E_{cavity} for the circularly polarized laser modes. We further consider a polarization independent loss level indicated by the horizontal line in Figure 5. In the situation shown in Figure 5(b), the laser is just above threshold for σ^+ emission and still below threshold for σ^- emission, which results in a nearly 100% right circularly polarized laser emission. This behavior has been investigated experimentally by Ando et al. for the first time [21]. They demonstrated that the laser polarization in optically pumped VCSEL structures at room temperature can be



(a) Unpolarized inversion



(b) Spin-polarized inversion

Figure 5: Schematical illustration of the optical gain as a function of photon energy in a VCSEL with conventional unpolarized pumping (a) and for a small spin polarization of the carriers in the active region (b). The spin-polarized pumping leads to separation of the gain spectra for the σ^+ and σ^- transition. This results in a gain anisotropy at the cavity resonance energy E_{cavity}, which marks the relevant photon energy for the laser emission.

controlled via optical spin injection. In an ideal case, even a small excess in the spin polarizations of the electrons in the active region should be efficient in order to generate a 100% σ^+ polarization of the optical emission. Accordingly, it can be expected that a spin-VCSEL, in contrast to a spin-LED, provides a kind of spin amplification, that is, the polarization degree of the optical emission becomes higher than the spin-polarization degree in the active region in the vicinity of the laser threshold. This expectation was confirmed by Hövel et al. [22, 23]. They showed that in an optically pumped spin-VCSEL the circular polarization degree can indeed become higher than the input polarization degree.

In these experiments, a Ti : sapphire laser was taken for optical pumping an InGaAs/GaAs-QW-VCSEL-structure at room temperature. The spin injection was obtained by pulsed excitation with a pulse length of 80 fs. Figure 6(a) shows the measured circular polarization degree of the VCSEL emission as a function of the injected spin polarization of the carriers in the active region. To circumvent the stopband of the VCSEL Bragg mirrors, the excitation was performed with some excess energy leading to excitation of heavy hole- and light hole-transitions in the GaAs barriers. According to the selection rules in Figure 1(a) the maximum spin-polarization degree of the excited electrons is 50%. Accordingly, a circular polarization of 100% leads to an injected carrier spin polarization of 50% at most, if we neglect any kind of spin relaxation in the barriers and in the quantum wells. The results in Figure 6 confirm the expectation of spin amplification with a spin-VCSEL. A circular polarization degree of 100% is already obtained with a spin polarization of 30%, and a spin-polarization of 13% still provides a polarization degree of 50%. The results are in a good agreement with theoretical calculations based on the SFM mentioned above. The simulations also shown in Figure 6(a) were obtained for a spin relaxation time of 40 ps in the active region. Later experimental and numerical work confirmed that spin amplification also works for continuous wave excitation [23]. Nevertheless it has to be noted that both effects, the possibility to control the light polarization by the carrier spin and the amplification of spin information are restricted to a pump region near the laser threshold. In a simple steady-state picture this can easily be understood taking the clamping of the carrier density at the laser threshold into account. If we consider the situation in Figure 5(b), the laser emission with a 100% σ^+ polarization state leads to a clamping of the carrier density in the $e(-1/2)$ electron spin band but not in the $e(+1/2)$ electron spin band. Accordingly, if the carrier density will be increased and the spin-polarization degree is less than 100%, the gain anisotropy will be reduced and the σ^- gain spectrum reaches threshold for a high carrier density, too. Thus the σ^- polarization starts to emit and diminishes the spin control and amplification effects.

Accordingly, a spin-VCSEL has two threshold carrier densities N_{th1} and N_{th2} for the two circularly polarized laser modes. Their difference depends on the spin-polarization degree of the carriers in the active medium. If the device operates in a carrier density regime N with $N_{th2} < N < N_{th1}$, predominantly the electrons with the correct spin-polarization participate in the laser process. From this it follows that less injected carriers are sufficient to reach threshold in a spin-VCSEL in comparison to a conventional VCSEL without spin-control. This spin polarization induced threshold reduction can be seen from the data depicted in Figure 6(b). The laser threshold is significantly reduced for a carrier spin polarization of 50% in comparison to unpolarized pumping. Threshold reduction in spin-VCSELs has motivated a lot of work in the field of spin-lasers, because the direct pumping of only one spin state basically allows reducing the threshold by up to 50% [15]. However this implies 100% spin-polarization degree in the active medium and a sufficiently long spin lifetime, taking simple rate equations into

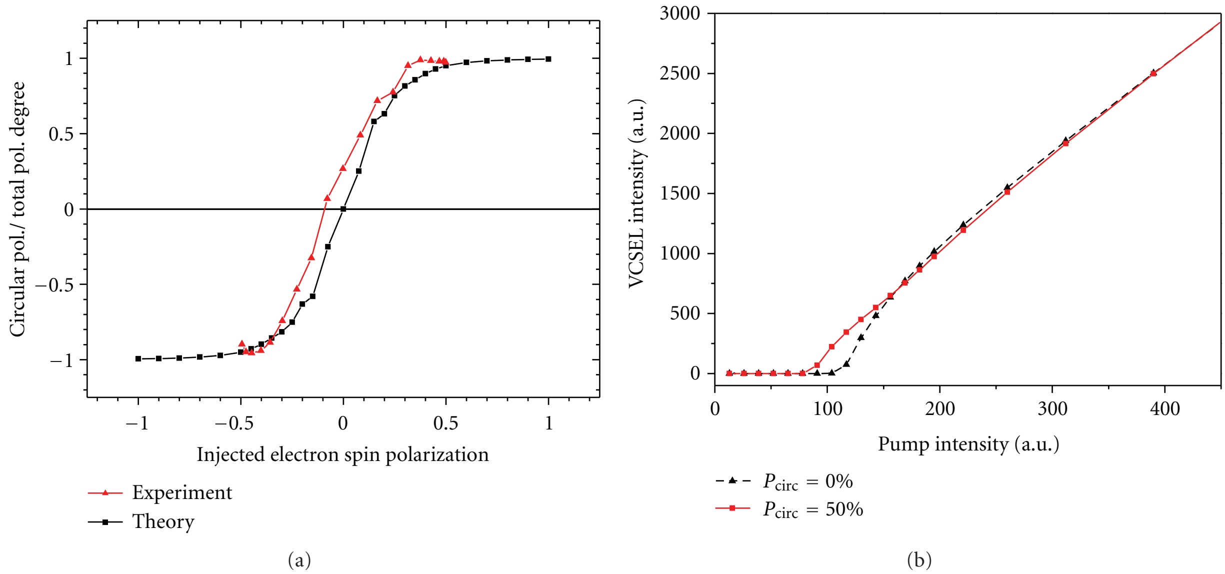


Figure 6: Circular polarization degree as a function of the carrier spin polarization in the active region (a). The experiments have been obtained at room temperature for pulsed excitations and show a good agreement with theoretical results based on the SFM for a spin relaxations time of 40 ps. (b) shows the calculated laser characteristics for a carrier spin polarization of 0% and 50%.

account. This threshold reduction was indeed observed. At low temperatures, Rudolph et al. have reported a threshold reduction of 23% in optically pumped devices [15], while at room temperature still a reduction of 2.5% was observable [16]. Recent theoretical work about threshold reduction even predicts threshold reductions significantly higher than 50% depending on several device parameters like nonradiative recombination [18], hole spin relaxation [67], and valence-band mixing [20] Anyway, the best result for electrically pumped devices so far is a threshold reduction of 14% at 200 K [68]. However, even though threshold reduction is an important property of spin-VCSEL, its efficiency depends strongly on the spin lifetime and it is still questionable whether in terms of threshold reduction a spin-VCSEL will be ever competitive with optimized conventional devices at room temperature. This spin-induced threshold reduction will probably be overcompensated by the additional effort needed for spin injection by using ferromagnetic contacts, for example.

A closer look onto the experimental details of the work done on purely optically pumped spin-VCSELs indicates problems that might occur in electrically pumped devices, too. In order to obtain the effects like spin amplification and threshold reduction great care had to be taken to ensure a perfectly circularly symmetric pump spot. Otherwise additional anisotropic carrier density and temperature effects introduce parasitic anisotropies into the cavity, which lead to a coupling of both circular polarized laser modes and result in linearly polarized laser emission. Such cavity anisotropies like birefringence and dichroism are known to have an enormous impact on the polarization dynamics of electrically pumped VCSEL [69–71]. The anisotropies, caused for example, by the internal electric fields and anisotropic strain induce a pinning of the polarization mode to a certain linearly polarized state and thus are the origin of chaotic polarization behavior in electrically pumped VCSEL devices [64, 70–74]. Accordingly, for the development of electrically pumped spin-VCSELs the role of cavity anisotropies on the laser dynamics is an important issue and might in the worst case be stronger than any spin-induced effects. Hövel et al. have investigated whether the influence of cavity anisotropies can be overcompensated by the spin in electrically pumped devices [25]. The experiments were performed using a special hybrid pumping scheme for a conventional electrically pumped VCSEL structure. The VCSEL was pumped electrically with a continuous spin unpolarized current in the vicinity of the electrical threshold. Additionally, a short circularly polarized light pulse with 3 ps pulse length was used to inject a small amount of spin-polarized carriers in the active region. The experimental setup shown in Figure 7 was used for these experiments. Just, instead of the streak camera shown in Figure 7, a time integrating photodetector was used to analyze the time averaged output of the VCSEL. The results indeed confirmed that spin control and spin amplification are also feasible in electrically pumped VCSEL devices. In other words, the spin effects are strong enough to overcompensate the above-mentioned cavity anisotropies at least for time-integrated measurements [25].

So far, we have only discussed time averaged stationary effects. But, besides spin amplification, spin control, and threshold reduction in continuously operating spin-VCSELs, dynamical effects might be even more promising. For example, it was predicted that spin-VCSELs might be considerably faster than their conventional counterparts. First fundamental investigations by Hallstein et al. confirmed this potential [10]. They investigated an optically pumped VCSEL structure at low temperature and in a high magnetic field and observed a fast modulation of the VCSEL polarization

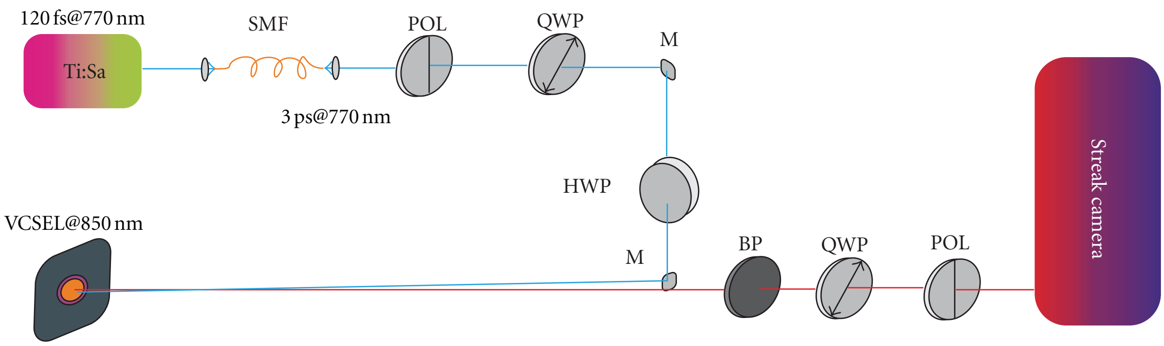


Figure 7: Setup for hybride excitation and spin control of a commercial VCSEL device. (SMF) single mode fiber, (POL) linear polarizer, (QWP) quarter wave plate, (M) mirror, (HWP) half wave plate, and (BP) bandpass.

due to spin precession of the carriers in the magnetic field with modulation frequencies up to 120 GHz [10, 11]. But also under realistic device conditions, strong indications for improved dynamical performance of spin-VCSELs have been found. Li et al. investigated an electrically pumped commercial VCSEL device with additional optical spin injection at room temperature [14]. Now, the entire experimental arrangement shown in Figure 7 was used for these experiments. Instead of the time integrated detection used by Hövel et al. [25], a time and polarization resolved analysis of the VCSEL emission was performed with a streak camera synchronized to the exciting Ti : sapphire laser. The time-resolution of the setup was approximately 3 ps. Again, the above-mentioned hybrid excitation scheme for the electrically pumped VCSEL was used and the VCSEL was operated in the vicinity of the threshold.

The results for a pulsed spin injection into the $e(-1/2)$ electron spin band are presented in Figure 8. While the intensity dynamics exhibits a typical short pulse response, followed by some relaxation oscillations, the dynamics of the circular polarization degree perform a very fast oscillation within the first VCSEL pulse. The corresponding oscillation frequency is in the range of 10 GHz and thus much faster than the relaxation oscillation in the device for the same pump conditions. Accordingly, even in electrically pumped devices at room temperature, the combination of the spin dynamics with the photon dynamics in a laser cavity obviously leads to an improved speed of spin-VCSEL devices in comparison to conventional devices. The results are in a good agreement with simulations utilizing the rate equation spin-flip-model discussed before (Figures 8(c) and 8(d)) [14, 75]. A detailed analysis based on the SFM additionally revealed that the observed dynamics are a consequence of an interplay between the spin dynamics of the carriers and the birefringence in the laser cavity which can be described as follows: in case of a zero spin polarization as in a conventional VCSEL, only one linearly polarized mode is lasing. In case of spin injection, we have an imbalance of the spin band populations, which results in laser emission with a nonzero circular polarization degree. This corresponds to a simultaneous emission of two orthogonal linearly polarized laser modes. Due to the birefringence in the cavity, their frequencies are different [70]. The resulting beating of both modes leads to an oscillation of the circular polarization degree [76]. The polarization oscillations feed back into the carrier spin dynamics and can stabilize the dynamics which potentially results in a long oscillation lifetime. The damping of polarization oscillations depends on the effective dichroism in the cavity and the oscillations are sustained the longer, the smaller the dichroism is. Since the effective dichroism and thus the damping of the oscillations can be controlled by the current, this allows for both very long and very short oscillation lifetimes. This is potentially interesting to stabilize spin information, as well as for the generation of short polarization bursts which are interesting for information transmission. This concept has been verified experimentally very recently by Gerhardt et al. [76]. They demonstrated polarization oscillations with a frequency of 11.6 GHz for a device with a modulation bandwidth of only less than 4 GHz at room temperature. The oscillation lifetimes could be controlled by the current in the vicinity of a polarization switching point significantly above threshold, where the effective dichroism is minimized. It should be added that while the damping of the oscillations is current dependent the oscillations themselves are not restricted to any current region. In comparison to the other spin effects in VCSELs this is an important advantage for applications and will be discussed later. At the polarization switching point, oscillation lifetimes of at least 5 ns could be demonstrated which is 200-times longer than the estimated spin lifetime in the device [76]. The oscillation frequency is determined by the linear birefringence and small corrections due to nonlinear spin effects only and is principally independent of the carrier dynamics. Hence, by tuning the birefringence, for example, by applying additional strain, the oscillation frequency can possibly be enhanced significantly. It is not restricted by conventional relaxation oscillations. Since strain-induced birefringence values of 80 GHz have already been reported in the literature [77] this concept has a strong potential for future ultrahigh bandwidth lasers in the 100 GHz region [75, 76].

The ability for enhance speed and modulation bandwidth is a very promising advantage of spin-VCSELs, which is attractive for a lot of applications, for example, high-speed optical data communication technology. Accordingly, a lot of work has been concentrated on this issue, and

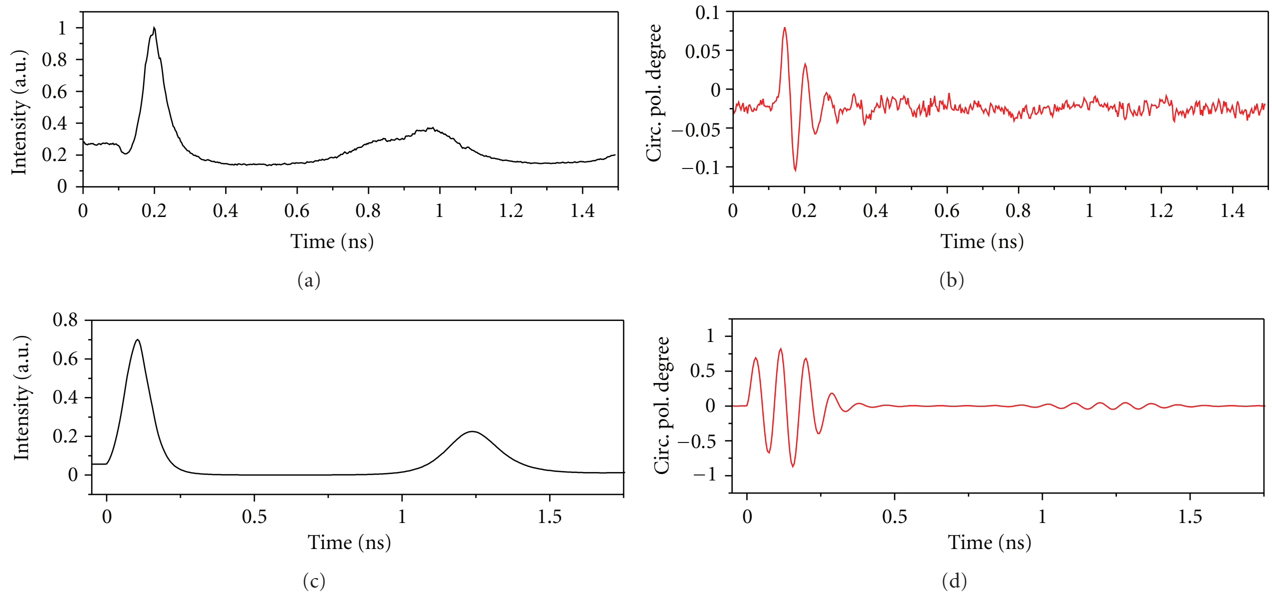


Figure 8: Dynamics of the total intensity (a) and the circular polarization degree (b) of an electrically pumped VCSEL after additional spin injection using a short right circularly polarized light pulse. Theoretical calculations based on the SFM are depicted ((c), (d)).

several other concepts have been presented, recently. Lee et al. investigated the small-signal modulation properties of both circularly polarized laser modes in a spin-polarized VCSEL, theoretically [13]. They predict that the modulation bandwidth can be enhanced for the favored circularly polarized laser mode as compared to conventional devices, due to spin injection. This concept is directly correlated to the threshold reduction for this laser mode and accordingly restricted to this current region close to threshold. In another recent publication Saha et al. have studied both the small-signal and the large signal modulation properties using a rate equation model [12]. The results for small-signal modulation support the reported prediction of Lee et al. and emphasize that the laser dynamics can be improved, when only one circularly polarized mode is operating. Additionally, they demonstrate experimentally using an electrically pumped InAs-QD-based spin-VCSEL that the amplification of spin information and the polarization control can significantly be enhanced for pulsed operation (see Section 3.3).

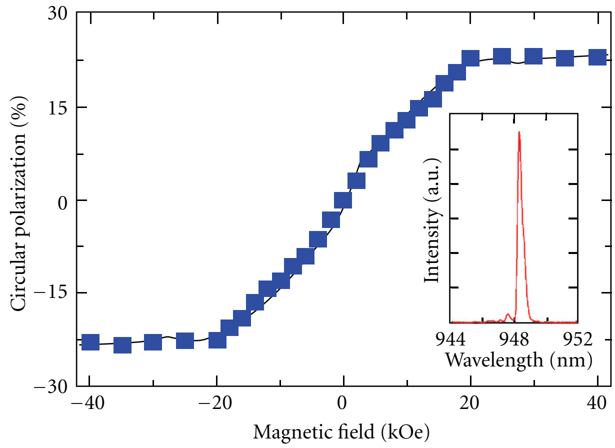
However, even though a lot of progress has been made in emphasizing the advantages of spin-polarized laser devices in comparison to conventional ones and a lot of promising properties have already been identified, a device with superior performance in comparison with conventional devices is still missing. One important challenge which has to be solved is the realization of efficient electrically pumped spin-VCSELs at room temperature. The current state of technology for electrically pumped VCSELs will be discussed in the next section. However, another important problem is that most concepts for spin-VCSELs are restricted to an operation near the laser threshold. This can be an important drawback on the way to realistic applications, because here the efficiency and the power of a laser are low and the laser dynamics is inherently slow. Accordingly, the search for other spin-dependent properties which are not restricted to this current region is one of the most relevant tasks in the near future. Anyway, the usable current region can be significantly enhanced by improving the spin polarization degree. Here the development of spin-VCSELs using (110) GaAs quantum wells might deliver an important progress due to the long spin relaxations time in this material. Recently the first optically pumped spin-VCSEL grown on (110) GaAs substrate and operating at room temperature could be demonstrated by Iba et al. [26]. They reported circularly polarized lasing with a circular polarization degree of 0.96 at room temperature using pulsed excitation. The spin lifetime in the active region was estimated to be 0.7 ns which is significantly larger than in conventional (100) GaAs QWs. First transient investigations using a (110) GaAs-based VCSEL with an (110) InGaAs active region operating at 77 K additionally demonstrate optically induced switching of the circular polarization mode in the GHz range [78]. Even though these results are very promising, the realization of exceptional (110) based electrically pumped devices is still a big challenge. This is because "standard" all electrically pumped spin-VCSELs on conventional (100) oriented substrates already induce severe technological difficulties which have not yet been solved completely. We will review this work in the next section.

3.2. Electrically Pumped Spin-VCSELs. All electrically pumped spin-polarized VCSEL devices published so far have been developed at the University of Michigan, USA. The first device was presented in 2005 by Holub et al. [40]. Here a GaMnAs spin aligner, located intracavity underneath the top mirror was used for electrical spin injection. Because GaMnAs is an intrinsically p-doped material, the spin-VCSEL concept based on hole spin injection, accepting the associated ultrafast spin relaxation. Five $In_{0.2}Ga_{0.8}As$

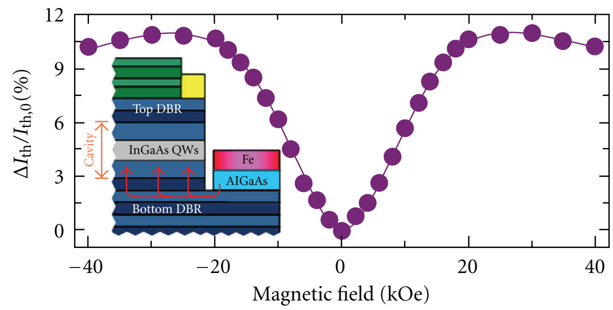
quantum wells served as active gain media. Polarization measurements as a function of the magnetic field revealed a maximum circular polarization degree 4.6% at 80 K. The concept to implement the spin-injection contact directly into the cavity of the VCSEL, which displays a direct transfer of a spin-LED concept to spin-VCSELs, has the advantage that the lateral transport length equals zero whereas the vertical transport length could be minimized to ~0.25 μm [40]. Unfortunately, the intracavity spin-aligner layer has a critical impact on the cavity quality and induces additional magnetic circular dichroism (MCD). The latter has a potentially strong influence on the polarization state of the emission, depending on the number of reflection within the laser cavity [24]. Accordingly, due to the impact of the MCD and the utilized hole spin injection, the results have been critically discussed in the literature [79, 80]. However, a small amount of circular polarization degree of approximately 1% has finally been stated to be due to the injection of spin polarized holes [24, 80], thus demonstrating the first realization of purely electrically pumped spin-polarized VCSEL.

Taking the difficulties due to hole spin injection and MCD in the cavity into account, the next concept for an electrically pumped spin-VCSEL consequently based on electron spin injection contacts. This concept was realized by Holub et al. in 2007 [17] using a Fe/$Al_{0.1}Ga_{0.9}As$ Schottky tunnel barrier for electron spin injection in combination with an n-doped intracavity contact. The VCSEL design is depicted in the inset of Figure 9(b). Again, an active region containing five compressively strained $In_{0.2}Ga_{0.8}As$ QWs was used for the laser operation. One important advantage of this concept is the utilization of a magnetic layer free cavity, reducing the impact of MCD to a minimum. However this led to a significantly increased average electron spin transport length of ~4.5 μm for a circular post VCSEL with a mesa diameter of 15 μm. Nevertheless laser operation with a maximum CPD of 23% at 50 K and for an external magnetic field of 2.2 T could be realized with this device (Figure 9(a)). Additionally, threshold reduction in electrically pumped spin-VCSELs could be demonstrated for the first time, showing a maximum value of 11% at 50 K (Figure 9(b)) [17, 81]. Using this value, a cavity spin polarization degree of 16.8% was estimated for the barrier layers using a spin-dependent rate equation model comparable to the model used by Rudolph et al. [15, 16]. This value is significantly higher than the carrier spin polarization in the InGaAs-QWs estimated to be 7%. However, the circular polarization degree of the laser is stated to be dominantly determined by the cavity spin degree, while the spin polarization in the active region is less important due to the short carrier lifetime. Comparing the 16.8% cavity spin polarization with the maximum value of 23% for the CPD, the results nevertheless demonstrate the predicted amplification of the spin information.

In order to optimize the spin-VCSEL concepts for an operation at elevated temperatures, the next concept published by Basu et al. in 2008 based on InAs/GaAs quantum dots as active gain medium [68]. Electron spin injection was obtained using a MnAs/$Al_{0.1}Ga_{0.9}As$ Schottky tunnel contact in a comparable VCSEL design comparable to that



(a)



(b)

FIGURE 9: Circular polarization degree (a) and threshold current reduction (b) as a function of the magnetic field in an electrically pumped spin-VCSEL at 50 K. The VCSEL design is displayed in the inset of (b). The spin-VCSEL based on electron spin injection utilizing a Fe/AlGaAs Schottky tunnel contact design. (from [17]).

displayed in the inset of Figure 9(b)). The active region contains 10 layers of self-organized QDs grown by molecular beam epitaxy (MBE) with a QD density of 3×10^{10} cm^{-2}. The utilization of InAs-QDs represented an important progress, allowing to increase the operation temperature of the laser up to 200 K. Here a CPD of 8% and a maximum threshold reduction of 14% could be demonstrated for external magnetic fields of approximately 2 T, using a device with 15 μm mesa diameter. A following publication based on comparable devices showed values of ~15% CPD and ~8% threshold reduction at 200 K and demonstrates the electrically controlled modulation of the output polarization in the vicinity of the threshold for the first time [19]. The issues of polarization control and high-frequency dynamics in such devices have been addressed recently in 2010 by Saha et al. [12]. They investigated the transient characteristics of an electrically pumped spin-VCSEL structure, comparable to the devices in [19, 68] but with mesa diameters down to 10 μm. The operation temperature could be increased to 230 K and an average CPD of up to 55% could be realized for pulsed bias conditions with a pulse length of 3 ns. These results were obtained for an estimated spin polarization in the active region of ~6%, demonstrating a significant amplification process for the spin information, due to the stimulated emission in spin-VCSELs.

Though impressive progress has been made concerning the development of electrically pumped spin-VCSELs, a device operating at room temperature is still missing. However, the realization of this goal is absolutely necessary to develop spin-VCSELs in order to benefit from the potential for superior performance in comparison to conventional devices in the near future. Thus, additional intensive research effort is required in this field in the next years. But the already demonstrated results are encouraging and raise the hope that this goal can be reached soon.

4. Conclusions and Outlook

In this paper we review the state-of-the-art of spin-controlled VCSELS with a particular focus on the most promising concepts for real devices. After discussing the fundamentals of spin-optoelectronics we discuss the concepts for electrical spin injection into semiconductor light-emitting diodes (LEDs). However, spin-controlled lasers are generally more attractive for applications than spin-controlled LEDs. Lasers have much faster dynamics than LEDs and the nonlinearity of the laser at threshold potentially enables a strong amplification of spin-dependent effects. Among the different concepts for semiconductor lasers, VCSELS are most attractive for spin-control because of their vertical device architecture and circular symmetry. Fundamental studies confirm that spin-VCSELs promise to have lower thresholds than their conventional counterparts and that they enable spin-control of the output polarization. But their most promising advantage is that they might be much faster than their conventional counterparts. For practical applications, the interaction of the spin effects with cavity anisotropies like birefringence and dichroism might enable enormously high modulation frequencies. Recently, Li et al. and Gerhardt et al. [14, 76] have reported spin-induced oscillations much faster than the relaxation oscillation frequency which, in conventional devices, roughly determines the upper modulation frequency limit. Since the damping of the spin induced oscillations and thus their lifetime can be tuned by the current, this concept is interesting for many applications like high-bandwidth data communication or spin information storage. However, in order to realize a device with superior performance, this concept has to be further analyzed in detail. In particular, a clever cavity design with careful engineering of the birefringence might open the door to modulation frequencies significantly above 100 GHz. While most spin-induced effects work only in the vicinity of threshold, such polarization oscillations can be utilized at higher pump levels. This is potentially an important breakthrough, because the usual restriction to an operation near the laser threshold is a major drawback for applications.

The greatest challenge in the field of spin-VCSELs still remains the realization of room temperature operation with pure electrical spin injection. Further massive effort will have to be invested into the engineering of appropriate spin injectors, injection paths in the semiconductor, and of materials with weak spin relaxation such as (110) GaAs, for example. Additionally a successful integration of efficient spin injection contacts with perpendicular magnetization, providing low switching fields would be an important issue towards realistic applications. However, there has been considerable progress in this area of electrically pumped VCSELs in the past few years. Together with the above-mentioned high potential of spin-VCSELs it can thus be expected that spin-controlled VCSELs remain a scientifically stimulating research area with growing application potential within the next decade.

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