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Optical Gain and Spin-Controlled Emission of Semiconductor Lasers

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Contents

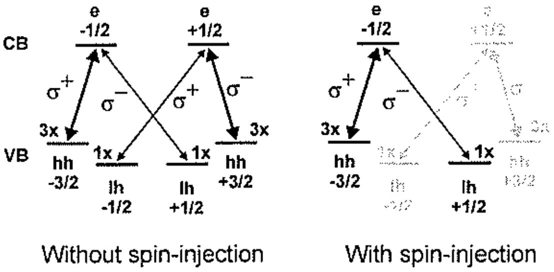
1 Motivation

Today's conventional electronics, beginning with the basic transistor up to the high performance computer, is based almost completely on the control of the charge of electrons in semiconductors. However the electron has another very important property: the spin. The spin is a fully quantum mechanical effect which describes the so-called *internal angular momentum* of a particle. In case of an electron, the spin leads to an additional degree of freedom with only two possible values (*spin down or spin up*) regarding to a fixed direction, defined by the experiment.

The idea to combine the quantum mechanical spin effect with the advantages of semiconductor or metal electronics leads the way to a new field, called spintronics. Spintronics offers fascinating new possibilities for electronic and optoelectronic devices [1, 2] and therefore new possibilities for almost all fields of future technologies. A well known typical example for the potential of spintronics is the Giant-Magneto-Resistance-Effect (GMR) [3], which is already implemented in read heads in modern computer hard drives and which is probably the basic principle for future ultrafast and nonvolatile Magnetic Random Access Memory (MRAM) [4]. Even more important is the perspective of quantum computers. Future large scale quantum computers with quantum bits (qubits) based on the two spin states of electrons in semiconductors [5] should be able to solve certain problems, for example the important factorization of prime numbers, much faster than any classical computer.

In case of using spin effects for future applications, the main challenge is the fast spin relaxation. The degree of spin polarisation of an ensemble of electrons in solid states is therefore, in contrast to the charge of electrons, no longer a constant value in time. The spin information in form of the spin polarisation is disappearing in a very short period of time[1]. This leads to a lot of difficulties for future devices especially at room temperature, where the spin relaxation is extraordinarily fast. Spin effects in devices like spin-transistors, spin-valves or spin-LEDs are very small and the transportation of spin-information is nearly impossible over distances larger than a few μm.

The combination of spin effects and light in so-called spin-optoelectronic devices, especially the combination of spin and optical gain in lasers, offers new possibilities to avoid these drawbacks. In the dissertation "'Optische Verstärkung und Spin-kontrollierte Emission von Halbleiterlasern"' it could be demonstrated, how the development of spin devices can sufficiently be boosted by using spin-controlled lasers, regarding to the enhancement of spin effects and the transportation of spin-information over large distances [6, 7]. Additionally a new concept for electrical spin injection into semiconductor devices was demonstrated for the first time. It is based on Fe/Tb-multilayer contacts, which allow to inject spin polarised currents without external magnetic fields in vertical direction almost up to room temperature [8, 9].



Without spin-injection With spin-injection

Figure 1: Optical selection rules in a direct semiconductor without (left) and with spin injection (right). CB: conduction band, VB: valence band, hh: heavy hole, lh: light hole, σ^+: right polarised light, σ^-: left circular polarised light.

2 Enhancement of spin information with spin-lasers

Spin-optoelectronic devices are based on the correlation between the circular light polarisation and the spin states in direct semiconductors like GaAs. Figure 1 shows the typical optical selection rules for emission and absorption of circularly polarised light in a direct semiconductor. A spin polarisation for the electrons, which is equivalent to an excess of carriers for one spin state in the conduction band, leads to the emission of circularly polarised light. In turn, the excitation of such materials with circularly po-

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[1] The relaxation time constants vary between a few ps an a few μs depending strongly on material and temperature.

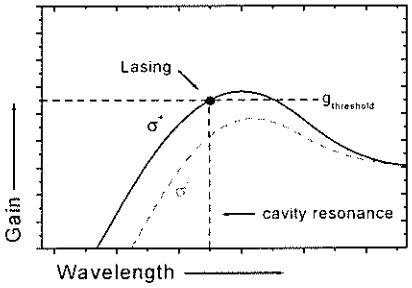

Figure 2: The basic principle of a spin-laser: The spin injection leads to a difference in gain for the left- (σ^-) and right circular (σ^+) polarised laser mode. In a capable pump regime, the laser reaches threshold for the σ^+-mode, only. This leads to a laser emission of right circular polarised light, with much higher degree of circular polarisation as the degree of spin polarisation in the active region.

larised light creates controlled partial spin-alignment of electrons and holes. The use of this correlation between the polarisation of light and spin offers fascinating possibilities to inject and detect spin polarisations in semiconductors and is already implemented in spin light-emitting diodes (Spin-LEDs) to detect electrical spin injection [10]. However the measurable spin effects in such devices are often much too low for realistic applications due to the fast spin relaxation, especially at room temperature.

In this dissertation, the combination of spin and optical gain in semiconductor lasers was investigated. The results demonstrate, that this combination is suitable to enhance the small spin effects in the polarisation of light, even at room temperature. The basic principle of such a spin-laser is discussed in Figure 2. Even a small degree of spin polarisation of electrons in the active layers of such a laser leads to a small difference in optical gain for both circular polarised laser modes. Using the strong nonlinearities at laser threshold, this small amount of spin polarisation can be converted into almost 100% circular polarisation of the output emission when one mode is just above and the other just below laser threshold.

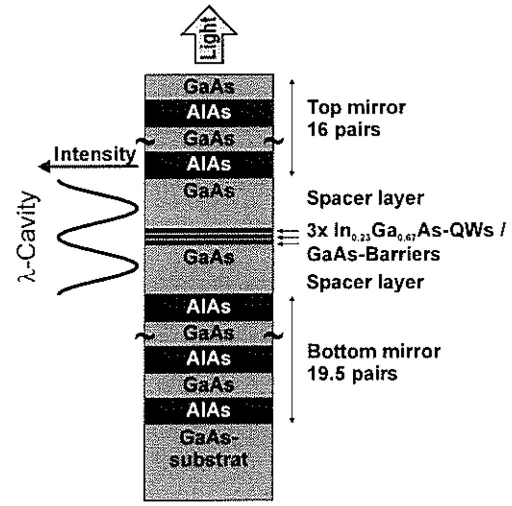

Figure 3: Principle design of the VCSEL structure.

In order to investigate the described behaviour experimentally, it was necessary to design and produce a suitable so-called vertical-cavity surface-emitting laser (VCSEL). The reason is as follows: A functionable laser at room temperature requires low-dimensional layers, for examples quantum wells (QW) as active regions. The optical selection rules, presented in Figure 1, in such QWs are only valid for vertical emission of light[2]. Therefore standard edge-emitting lasers are not suitable for such experiments and a VCSEL had to be developed. The complex structure, composed of over 80 semiconductor layers is shown in Fig-

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[2] This means emission parallel to the growth direction.

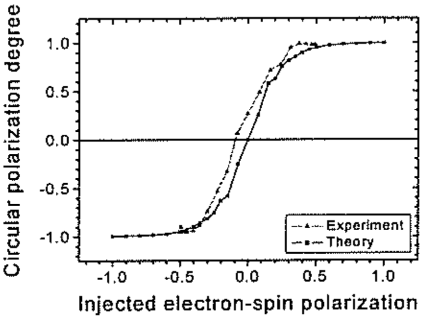

Figure 4: Degree of circular polarisation of the laser emission as a function of the injected spin polarisation. The diagram shows the experimental results for excitation with short light pulses at room temperature in comparison to theoretical calculations.

ure 3. The laser was designed for optical pumping and operation at room temperature [6].

With such a spin-VCSEL, we could demonstrate the enhancement of spin information even at room temperature by means of an optical experiment. In this experiment a controlled spin polarisation was injected by pumping the laser with circularly polarised light, using the selection rules in Figure 1. The circular polarisation of the laser emission was measured as a function of the injected spin polarisation. The experimental results are plotted in Figure 4 in comparison with theoretical calculations by means of a spin-flip-model [7]. Theoretical and experimental results show that a polarisation of the VCSEL emission of 100% can be obtained with less than 30% electron spin polarisation in the active region of the VCSEL. The results demonstrate unambiguously, that it is possible to transform small spin polarisations of the carriers into a large circular polarisation of the laser emission and therefore to enhance spin information in a spin-laser. As we will see in section 4, this could lead to new fascinating possibilities for future spin-optoelectronic devices.

3 Electrical spin injection without external magnetic fields

An optically pumped spin-laser has been used for the experiments described in section 2. For all realistic spintronic applications, not only for spin-lasers, the development of electrically pumped devices is essential. The controlled electrical spin injection into semiconductors has therefore been a field of very active research for more than a decade now. Remarkable progress has been achieved using mainly two approaches: The first approach uses spin alignment of unpolarised carriers in magnetic semiconductors [10], the second uses ferromagnetic metal contacts (e.g. Fe) to inject spin polarised electrons directly via Schottky or tunnel contacts into a nonmagnetic semiconductor [11]. Both concepts suffer from one dramatic drawback. They require strong external magnetic fields in the range of 1-2T or more to achieve a vertical magnetisation in the magnetic semiconductor or metal layers. Unfortunately this vertical magnetisation is absolutely necessary for spin optoelectronic devices with QWs to fulfill the optical selection rules in vertical direction. But realistic devices, requiring external magnetic field with high magnitudes, which have to be generated by liquid He cooled superconducting magnet systems, are not imaginable.

The drawback of external magnetic fields can be circumvented using ferromagnetic spin injection contacts with spontaneous perpendicular magnetisation. In this work a

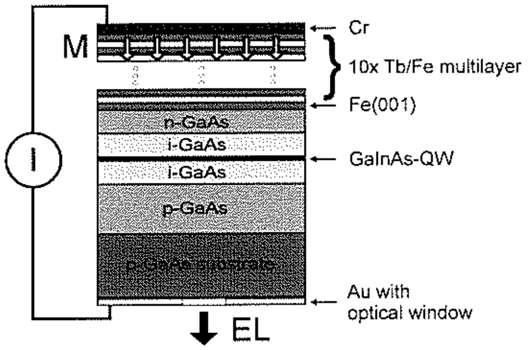

Figure 5: Concept of a spin LED with Fe/Tb-multilayers for the spin injection contact. Using this concept, spin injection in vertical direction without external magnetic field could be demonstrates for the first time.

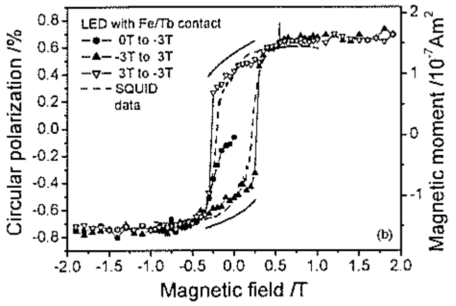

Figure 6: Spin injection with Fe/Tb-contacts in remanence at 90K. The figure shows the degree of circular polarisation as a function of the magnetic field and in comparison to the magnetic moment of the contact layers. Note the nonzero circular polarisation for zero external magnetic field.

new concept for electrical spin injection contacts, based on a Fe/Tb superlattice structure with spontaneous perpendicular magnetisation M is presented. The concept is shown in Figure 5. We used a GaAs-based LED structure with a single GaInAs-QW as an active layer and a Fe/GaAs-Schottky tunnel n-contact for injection of spin polarised electrons. The epitaxially grown Fe(001) layer was capped by a polycristalline Fe/Tb-superlattice structure [8]. Fe/Tb-multilayers are known to exhibit spontaneous out-of-plane magnetisation in contrast to conventional magnetic thin film layers.

Figure 6 shows the experimental results for a temperature of 90K. The degree of circular polarisation of the LED emission, which is linked to the spin polarisation in the QW by the optical selection rules, is plotted as a function of the external magnetic field. The nonzero circular polarisation at zero magnetic field demonstrates for the first time the successful spin injection in vertical direction without external magnetic fields. These results could be reproduced up to temperatures of 260K [9]. Room temperature spin injection will soon be possible with this new concept and an optimised device structure.

4 Transmission of spin information: An outlook

Combining the results for the enhancement of spin information using spin-lasers in section 2 with the first demonstration of electrical spin injection without external magnetic fields in spin-LEDs in section 3, the development of an electrically pumped spin-VCSEL, operating at room temperature comes into reach. Such a device can be used for lots of interesting new applications. These include conventional applications as polarisation stabilised VCSELs with reduced threshold [12], or polarisation switchable lasers in light-wave networks with enhanced bandwidth [13]. But most promising is the demonstrated enhancement of spin information which provides fascinating new possibil-

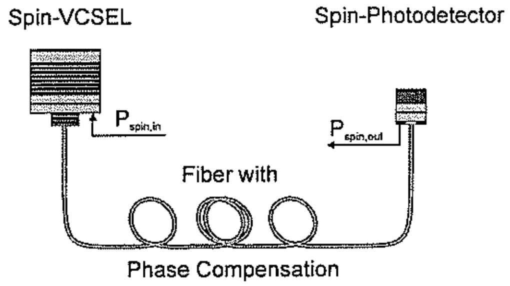

Figure 7: Principle concept of a spin information transmission network consisting of a spin VCSEL for enhancement and conversion of spin information, a phase compensated optical fibre and a spin photodetector for the reconversation.

ities for future spintronics.

An example for such future spintronic applications is a spin information transmission network as illustrated in Figure 7. The transmission network consists of a spin VCSEL in order to transform the spin polarisation into light polarisation and to enhance the containing spin information, a phase compensated fibre for the transport of the polarised light and a spin photodetector based on a spin LED in which the light polarisation will be retransformed into a spin polarisation of carriers. With such a spin information transmission network, it should be possible to transport spin informations over nearly any distance and therefore to solve the basic problem of short spin transport distances due to the fast spin relaxation in solids.

5 Conclusion

In conclusion, this dissertation demonstrates that the development of spin devices can be sufficiently boosted by using spin-controlled lasers. A spin-controlled laser, as the one developed for this work, is able to enhance spin information and therefore represents a realistic spin-optoelectronic device at room temperature. A very important application for such a spin-laser is the spin information transmission network, allowing to transport spin informations over nearly every distance without loss of spin information due to spin relaxation. A realistic application is only imaginable with a concept for electrical spin injection without strong external magnetic fields. In order to solve this basic drawback of conventional spin injection approaches, this work also demonstrates a new concept for spin injection contacts. With this new contact structure it was possible to realise electrical spin injection in vertical direction without external magnetic fields for the first time.

6 Acknowledgment

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