Subproject A2.3

Spin Injection, Manipulation and Read-Out

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Introduction and Summary

The basic idea of spin-optoelectronics is to explicitly utilize spin in addition to the charge of electrons and holes in optoelectronic devices. Possible major future applications of such devices comprise the area of quantum information processing (QIP) but also devices like fast low-power spin transistors and spin-polarized single photon sources. Information processing relies on quantum mechanical systems (like two-level spin systems) which form the building blocks of QIP devices: quantum bits (qubits) and quantum registers. Basic gate operations are given by logical and coherent operations on individual qubits (single-qubit operations) and controlled coherent interactions between two qubits (two-qubit operations). The realization of a full scale quantum computer is in principle feasible but puts strict requirements on the quantum system as has been formulated by Loss and DiVincenco [1]. In short the system has to show the properties of scalability, ability to be initialized, sufficient coherence, realization of a universal set of gates, addressability of the qubits, interconversion of stationary and flying qubits and faithful exchange of flying qubits. Currently there are intense investigations into a variety of different systems like point defects in diamond [2], ion traps [3], atoms and molecules coupled by cavity QED [4], super-conducting circuits [5], and semiconductor quantum dots (QDs) [6,7]. Although some of these model systems fulfill some of the above mentioned criteria, there is still a long way to go towards a full scale QIP. Gate operations have been demonstrated on the atom and superconducting systems and they have already been developed into nice model systems to study basic properties of QIP. Still, quantum dots based on III–V compound semiconductors show features which make them most promising for the future development of QIP. Semiconductor technology is highly developed and (self-organized) quantum structures are readily available. The relevant compounds like GaAs and InAs are the most important ones for modern optoelectronic devices based on the fact that photons easily couple to their electronic states. This property is also favorable for an easy convertibility of flying (photons) and stationary (electronic spins) qubits. Long coherence times are reported for electron spins in QDs [6], basic qubit operations have been performed [8] and cavity QED (i.e., strong coupling between photons and electronic states) has been demonstrated [9].

The aim of project A2 is to advance a spin-based optoelectronics utilizing spin states in InGaAs QDs. In particular we address the topics of initialization of spin states with high fidelity as well as their storage, addressability and manipulation. Our approach is based on an electrical injection of electron spins into the QDs which are situated in the active region of a light-emitting diode (spin-LED) or transistor. Our collaboration has demonstrated single QD spin-LEDs with the highest spin injection efficiency worldwide proving that concurrent and repeatable initialization of spin-polarized electrons in several InAs/GaAs quantum dots with fidelity near unity is possible by electrical injection (see Sect.1) [A2.3:20]. The same design has recently also been shown to be useful as electrically operated light source for single photons with defined helicity. Indeed, first experiments indicate the highest polarization degree of such a source reported so far (Sect.3). Furthermore, electrical spin injection into QDs has been shown to lead to an efficient, purely electrical driven dynamic nuclear spin polarization (via the hyperfine interaction, see Sect.4) that might be interesting for QIP schemes based on nuclear spins. Replacing the active layer in our devices by a GaInNAs quantum well leads to a promising approach for the realization of circularly polarized light sources in the near infrared which might be useful for fiber telecom applications [A2.3:7]. On the theory side, we could establish a comprehensive understanding of spin relaxation in QDs [10,11] and semimagnetic materials [A2.3:24] which is accepted as standard theory by the community (Sect.5). We have also developed a detailed understanding of the spin relaxation dynamics in our spin devices (Sect.1 and 2) [A2.3:4,A2.3:7,A2.3:16,A2.3:18,A2.3:26,A2.3:31, A2.3:32,A2.3:33,A2.3:35,A2.3:37,12], which paves the way for the current development of transistor-like spin devices (Sect.6). The latter will enable an electrically controlled injection of holes into the QDs independent of the electrons. Thus, a QD can first be filled by an electron with defined spin and read-out optically after a given time delay. This delay can be used to perform spin manipulations (i.e., single qubit operations). In order to realize the latter utilizing electron spin resonance techniques, we have recently established a suitable microwave set-up discussed in Sect.7 together with test measurements. Our approach to realize 2-qubit operations is an optical coupling of QD states via resonant modes in cavity structures [13] which are currently developed in A2.8.

The success of the spin-optoelectronics project results from the uniquely close interplay between high-quality semiconductor epitaxy, world-leading analysis techniques for electron microscopy, excellent facilities for device fabrication, top-level optical spectroscopy, and application-oriented semiconductor theory. In-house we have a strong collaboration with subprojects A2.5 (D. Gerthsen, electron microscopy), A2.6 (young scientist group of D. Schaadt, molecular beam epitaxy) and A2.8. Concerning theory we benefit from the scientific input of E. Tsitsishvili (partly in Karlsruhe as a guest scientist). On spin-relaxation in QDs and their optical properties we have joint projects with A. Reznitsky, A. Klochikhin and S. Permogorov from the Ioffe Institute St. Petersburg [A2.3:17,A2.3:19,A2.3:27,14], on growth and characterization of nitrides there has been collaborative work with the Lischka group in Paderborn [A2.3:8,15]. Finally, we also performed magneto-optical Kerr effect measurements on ferromagnet/superconducting heterostructures [16] in collaboration with H. v. Löhneysen (subproject B2.7).

1. Electrical Spin Injection into Single Quantum Dots

One of the major achievements of A2.3 is the realization of spin-LEDs which enable the concurrent initialization of electron spin states in QDs and their individual optical read-out through metallic nano-apertures. The realization of such devices required a close collaboration with A2.1 (C. Klingshirn) in the first funding period, A2.2 (M. Hetterich, continued as A2.8), and A2.6 (D. Schaadt) concerning growth and investigation of AlGaAs, InGaAs (QDs), GaInNAs, and combined ZnMn(S)Se/III–V heterostructures (grown in two separate MBE systems) as well as device processing and characterization [A2.3:5,A2.3:7,A2.3:9,A2.3:10,A2.3:11,A2.3:12,A2.3:13,A2.3:14, A2.3:15,A2.3:22,A2.3:23,A2.3:25,A2.3:28,A2.3:29,A2.3:30,A2.3:34,A2.3:40]. Crucial for the performance of our devices is the low defect density of all layers and in particular the high quality of the III-V/II-VI interface [A2.3:1,A2.3:2]. Such excellent material quality is only possible due to the direct feedback by the world-leading characterization and analysis techniques of our electron-microscopy lab (see report of sub-project A2.5). Methods like CELFA (chemical evaluation by lattice-fringe analysis), which have been developed in Karlsruhe, allow a chemical analysis on the length scale of the lattice constant [A2.3:10,17] as well as high-resolution detection of structural defects [A2.3:1,A2.3:25,17].

The tasks of A2.3 are magneto-optical spectroscopy (electroluminescence, EL) of the spin-injection devices as well as their optimization, spin manipulation experiments based on electron spin resonance techniques as well as the development of a theoretical understanding of both our device characteristics and various aspects of spin relaxation processes as such. The latter have been investigated in collaboration with guest scientist Dr. Elena Tsitsishvili (see Sect.5). For the magneto-optical spectroscopy of our electrical spin injection devices we can combine magnetic fields up to 14 T, a high spatial resolution of few 100 nm [18,19] and a sub-ns temporal resolution by using short electrical pulses and time-correlated single photon counting.

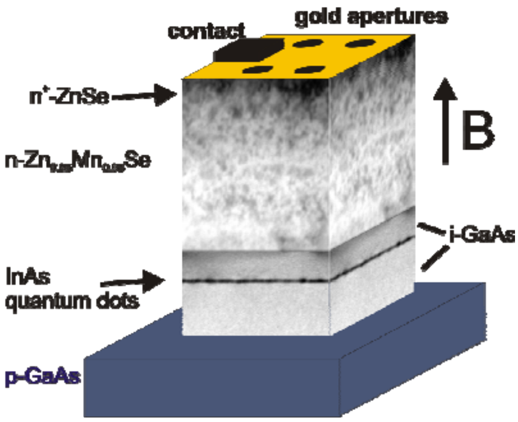

Fig.1: Schematic set-up of a spin-LED. n-type ZnMn(S)Se:Cl is used as a spin aligner for electrons in an applied magnetic field. The optically active InGaAs QDs are embedded in the intrinsic part of the p-i-n structure. The LED is etched from the plane sample as a mesa and contacted by In and a gold wire. The upper surface is covered with a gold layer containing nano-apertures for single-dot spectroscopy [A2.3:20,12].

A typical set-up of a spin-LED is shown in Fig.1. The electrons are injected through the top In contact and a ZnSe contact layer into the actual spin aligner. The diluted magnetic semiconductor (DMS) ZnMnSe is typically used in our devices for this purpose, although some structures contain ZnMnSSe instead. The latter is lattice-matched to GaAs and leads to an improved performance as a consequence of a lower defect density and thus spin scattering at the III–V/II–VI interface [12]. When applying an external magnetic field the conduction band splits into two spin-related sub-bands as a result of the giant Zeeman effect (see Fig.2). The injected electrons relax to the lower Zeeman level (spin initialization) before they are injected into the InGaAs QDs via a GaAs tunnel barrier (spin storage). (In first test structures, InGaAs quantum wells were used instead [A2.3:1,A2.3:2]. Other devices contained GaInNAs quantum wells in order to realize circularly polarized light sources for telecom applications at longer wavelengths, see [A2.3:7] for further details.) Assuming the electrons have preserved their spin polarization they will occupy the *upper* Zeeman-split electron levels in the QDs. This is the case since the dots show an opposite sign *g*-factor for both electrons and excitons compared to the DMS [A2.3:7]. Now the electron spin in the QD is initialized and can be manipulated or read out by a hole injected from the p-side of the junction. The circular polarization degree (CPD) of the photon emitted by the QD as a result of electron–hole recombination directly reveals the degree of electron spin polarization.

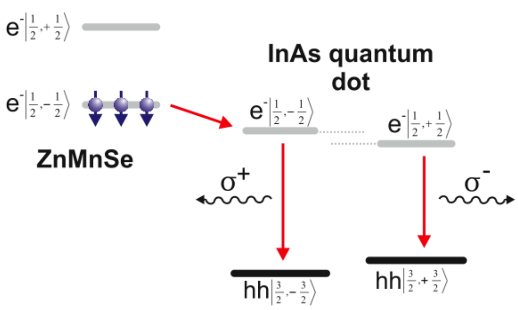

Fig.2: Schematic diagram of the electron levels in the spin aligner and the QDs. Injection of electrons into the dots leads to circularly polarized luminescence. The polarization degree is a function of the spin orientation in the dots.

The concept of electrical spin injection has the advantage, that many qubits in different QDs can be initialized simultaneously. This would be difficult to achieve with all-optical techniques (e.g., resonant excitation of the dots with circularly polarized light), because the involved electronic transition energies vary from dot to dot. On the other hand, QIP relies on a well-defined optical access to individual QDs/qubits for manipulation and read-out. In order to address single dots in our spin-LEDs with EL, we use gold micro- or nano-apertures on top of our structures fabricated by thermal evaporation and e-beam lithography as well as high spatial-resolution spectroscopy [18,19]. This limits the number of observable QDs so that at low operating currents, single spin states can easily be investigated.

One of the most remarkable results of the described approach is the fact that – after optimization of the device structure, doping etc. [A2.3:1,A2.3:2,A2.3:5,A2.3:7,A2.3:11,A2.3:12,A2.3:14,A2.3:18, A2.3:22,A2.3:37] *polarization degrees close to 100% can be achieved*. This proves that parallel initialization of several separated QDs is indeed possible [A2.3:20]. A representative example for the EL of such a single dot is shown in Fig.3. The injected electrons clearly occupy the higher excitonic (and electronic) Zeeman level of the QD ground state and at B = 6 T. The signal from the lower Zeeman state is negligible which clearly proves spin relaxation within the ground state doublet to be inefficient. We can estimate an upper bound for the spin temperature of the electrons in the QDs to about 132 mK [A2.3:20]. This value is only a little higher than the one observed by continuous optical laser cooling of electronic states in a QD (20 mK) [20].

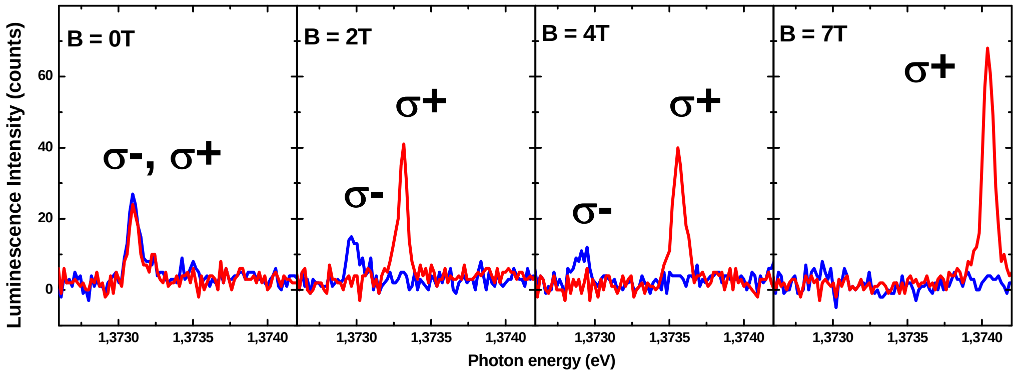

Fig.3: Intensity of the (circularly polarized) electroluminescence from the Zeeman-split ground-state doublet of a single QD. After [A2.3:20].

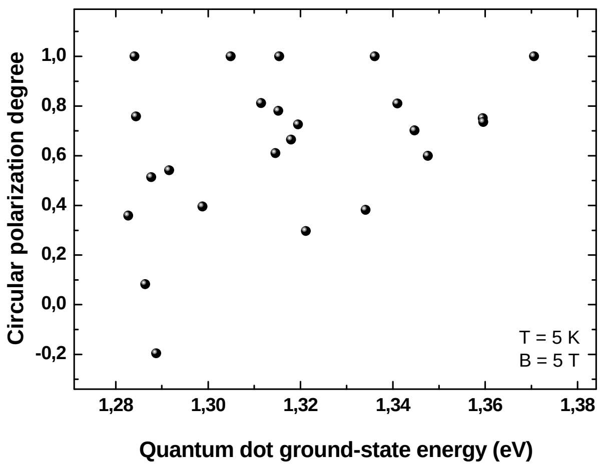

Fig.4: CPD of the EL from several QDs detected through nano-apertures [A2.3:20].

Our experiments further show that electrical spin injection is highly capable to initialize a complete register of QDs: For that we have analyzed the electron spin polarization in many different dots. The resulting polarization for $B = 5$ T is shown in Fig.4 as a function of QD luminescence photon energy. In this example, for five dots emission is found solely from the desired upper spin state. The polarization of all recorded dots, even for the ones with low polarization, was stable over the measurement period of several hours. A clear trend that the multi-dot averaged polarization is lower at the low-energy side can also be seen from Fig.4. This trend has already been observed in experiments on macroscopic ensembles of QDs and is by now well understood [A2.3:4,A2.3:7, A2.3:16,A2.3:18,A2.3:32,12]. Essentially it is caused by two effects, firstly the formation of a two-dimensional electron gas at the DMS/III–V interface which acts as a source for unpolarized electrons that can tunnel into low-energy QD states (below the Fermi edge), and secondly the fact that spin injection into the QD states occurs through a tunnel process. For higher-energy QD states, the effective tunnel barrier is lower. Thus tunneling is faster, i.e., there is less opportunity for spin relaxation processes. Spin relaxation processes within the dots could be shown to be of minor importance, consistent with the results in Fig.3.

2. Time-Resolved Studies of Electrical Spin Initialization

In order to gain a more detailed understanding of the spin and carrier relaxation processes in our devices and – even more important – as a step towards electrical spin manipulation experiments we have performed time-resolved EL studies of the polarization dynamics (partly also for single dots [A2.3:35]) using pulsed (~20 ns) electrical excitation and time-correlated single photon counting [A2.3:31,A2.3:32,A2.3:33,A2.3:35,12]. Results of these measurements are shown in Fig.5. The CPD is found not to be constant but to show a pronounced maximum at the rising edge of the pulse, while the polarization degrees observed in the plateau region of the traces essentially agree with those obtained in continuous current measurements. The observed feature only appears for confined states (QDs, wetting layer). Furthermore, our experimental analysis shows that also quantum wells exhibit this particular time-dependent feature in pulsed electrical excitation. Since the type of confined state the spin-polarized electrons are injected into is not relevant, we can relate the feature to spin-relaxation processes during electrical transport. In our model electrons are injected though a tunnel barrier inevitably formed at an interface in the spin-LED (as already mentioned in the last section), before they can relax into the confined states. Initially, the QD state population is low and tunneling should be quite efficient. Later on, however, a fraction of the QD states is always filled. Due to this state filling effect, tunneling is hampered and slows down, thus giving more opportunity for spin scattering outside the QDs and resulting in a lower CPD. This effect involves a dependence on the density of states in the target material (QDs, wetting layer), as observed experimentally. It also implies an experimentally observed drop of the CPD with increasing current, which is confirmed experimentally as well. Since these features are typical of spin-LEDs, we expect the effect to be present in all such devices. This implies that the spin-injection efficiency can be increased by using short electrical pulses instead of constant-current excitation. We believe this will be important in a wider context for the realization and optimization of future spintronic devices in which spin-polarized currents are flowing through semiconductor layers, such as a spin transistor.

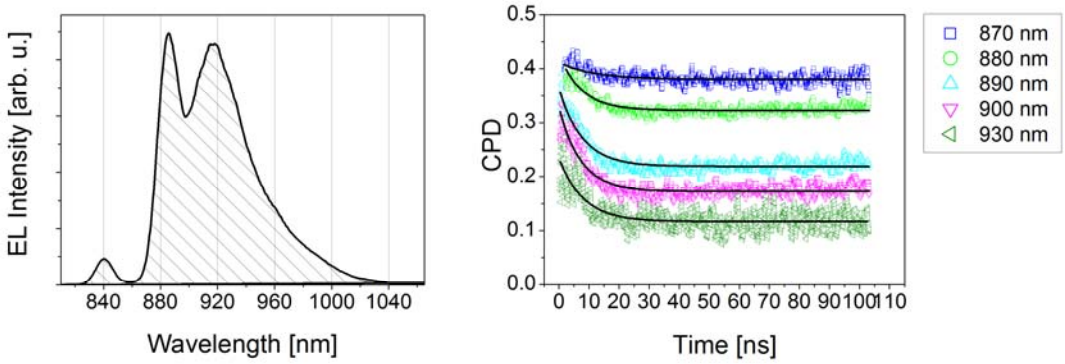

Fig.5: Left: EL spectrum of a spin-LED at T = 5 K. The GaAs-related emission is centered at 840 nm. The wetting layer emission exhibits a peak at 885 nm, the QD emission can be observed at higher wavelengths. Right: Time-dependent CPD (T = 5 K, B = 6 T) for several wavelengths at time t after the beginning of the EL signal. Lower curves represent higher wavelengths. Solid lines are exponential fits [A2.3:32].

3. Demonstration of a Spin-Polarized Single Photon Source

Based on the spin-LEDs developed in this project an electrically operated circularly polarized single photon source was designed. In quantum cryptography implementations, using the two circular polarization states of the emitted photons, quantum states | 0 > and | 1 > could be represented, such that the device could be employed for securely coding and transmitting data. Such a device requires very high circular polarization degrees, as exhibited by the developed structures, and must emit single photons when voltage pulses are applied. In Fig.6 we show that both these prerequisites are fulfilled. The QD exhibits circular polarization degrees (CPD) close to unity, and autocorrelation traces obtained with a newly constructed Hanbury-Brown & Twiss set-up prove the emitted light to be antibunched. This clearly demonstrates that the spin-LED acts as a source for single photons with the highest polarization degree obtained so far, indicating the efficiency of our approach [21].

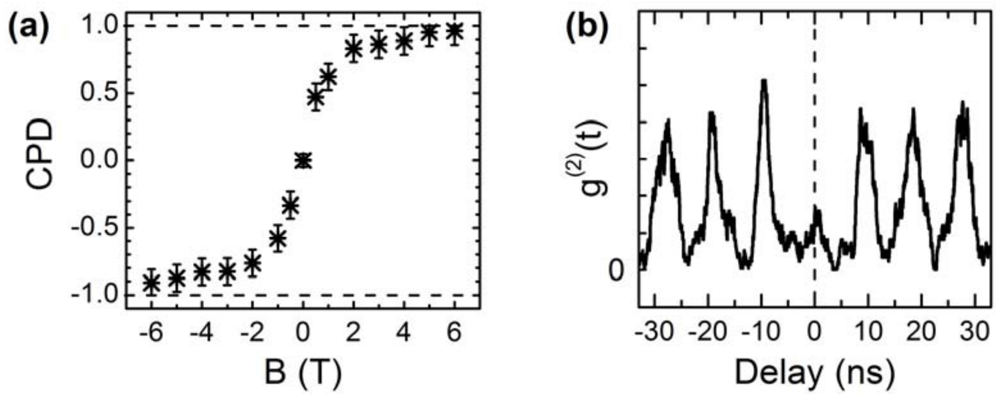

Fig.6: (a) Average CPD of the photons emitted by the QD. At an applied field of +2 T a CPD of 83% is observed, while at +6 T it approaches 96 %. When the field is reversed the helicity of the emitted light changes sign. (b) Autocorrelation measurement of σ^+-polarized photons emitted by the QD at an applied field of +2 T. The sample is excited with sub-nanosecond pulses from a fast electrical pulser. From the zero delay peak area we obtain a value of $g^{(2)}(0)$ = 0.38 for the correlation signal, giving evidence of single photon emission.

4. Nuclear Spin-Polarization by Electrical Injection of a Spin-Polarized Current

For QIP, not only the spin-split electron subbands in semiconductor QDs could be used as two-level systems. Another approach would be to use the nuclear spins of the dots. Via the hyperfine interaction the spin state of the electron and the spin states of the nuclei are interrelated. In order to access the nuclear spin states, an electrically controlled device would be of particular interest. Using the mentioned hyperfine interaction, we can show that nuclear spin states are efficiently spin-polarized by purely electrical injection of spin-polarized electrons [A2.3:39,A2.3:41]. As detection method we employed the Overhauser shift, which results from the effective magnetic field produced by the aligned nuclear spins. This magnetic field results in an additional Zeeman splitting of the emission lines of the QD and is easily accessible with a high-resolution spectroscopic set-up.

In Fig.7 spectral data obtained for different excitation conditions are shown. We were able not only to observe the Overhauser shift during electrical excitation, but also to relate its magnitude to nuclear spin-polarization degrees during photoexcitation. A theoretical model was applied considering spin coherence times of the electrons and nuclei. From data of the photoexcitation, we used this theory to fit the data. We then observed that during electrical excitation the nuclear spins are spin-polarized with a comparable magnitude. During electrical excitation of the spin-LED we obtained spin-polarization degrees of around 50%, demonstrating that efficient nuclear spin polarization in QDs can be achieved by purely electrical means.

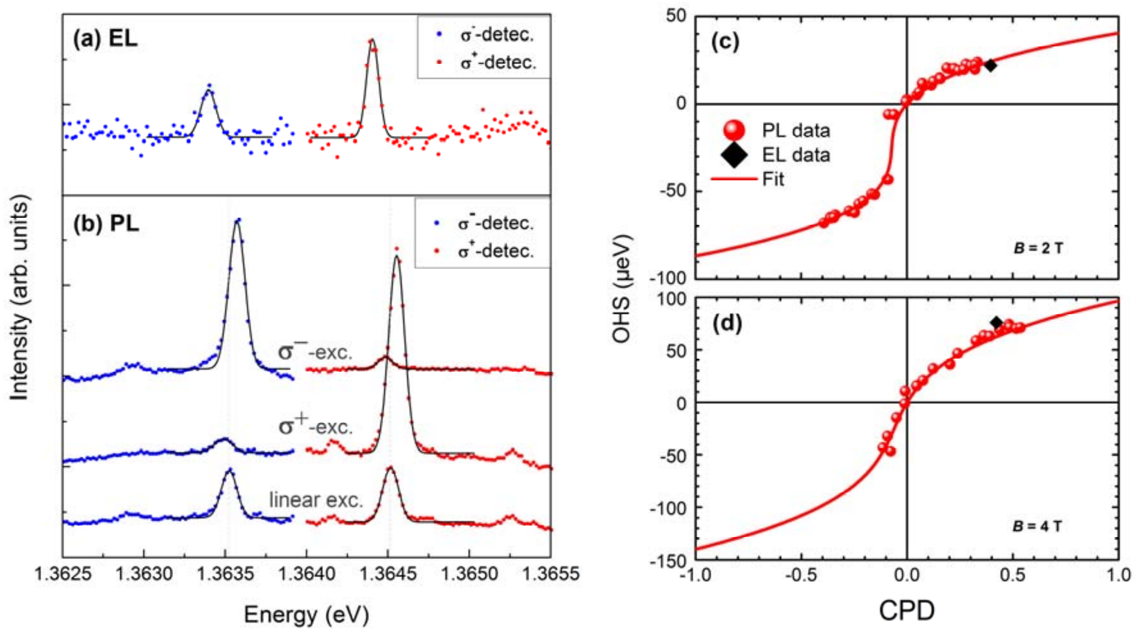

Fig.7: Zeeman-split emission lines (B = 6 T, T = 5 K) from an individual QD showing the Overhauser shift (OHS) for (a) electro- and (b) photoluminescence with Gaussian fits [A2.3:41]. In (b) three curves corresponding to three different excitation conditions are shown (σ^+-, σ^-- and linearly polarized light). The different spectral positions of the emission lines are due to hyperfine interactions / nuclear spin polarization. In (c) and (d) electro- and photoluminescence data from another adjacent QD are shown, along with a fit obtained within a theoretical framework. Different spin coherence times of the nuclei and the electrons result in a hysteretic behavior.

5. Theory of Spin Relaxation in Quantum Dots and Diluted Magnetic Semiconductors

Our experimental efforts are complemented by theoretical studies on spin relaxation processes. In a series of papers starting in the first funding period we give for the first time a comprehensive treatment of excitonic spin relaxation in semiconductor QDs [10,11,22] and DMS compounds [A2.3:3,A2.3:6,A2.3:24,23]. These calculations give valuable information for the design of spintronic devices and are internationally acknowledged as key publications in the area.

In particular we developed a microscopic theory [11] to understand the role of spin–orbit coupling in the spin relaxation of electrons and holes bound within excitons in QDs. This relaxation occurs mainly due to piezoelectric carrier–phonon interaction and is particularly large in flat QDs with weak lateral confinement.

In our recent paper [A2.3:38] we have pointed out a new effective channel for exciton–spin relaxation within the radiative doublet of the exciton ground state in single strongly confining QDs: *second-order exciton–phonon scattering accompanied by an exciton-spin flip*. An intrinsic mechanism for the considered process of longitudinal relaxation is due to the short-range exchange interaction, similarly to the case of the previously studied direct transition between the orthogonally polarized states of the bright exciton. The scattering process considered in [A2.3:38] involves the dipole-forbidden *dark states* as intermediate states and is relevant for both, asymmetrical and symmetrical dots. For dots with no or very small splitting of the bright states (compared to the bright–dark splitting) the proposed process is of paramount importance. The obtained analytical results show that the longitudinal relaxation rate in a single dot depends on the dot composition, shape, and size differing for dots belonging to the various QD structures and varying from dot to dot within the same QD ensemble. An enhancement of the exchange interaction in strongly confining dots (compared to the bulk value) leads to a very strong dependence of the studied process on the dot size. Within a large QD ensemble the observed rates may differ by several orders of magnitude being the larger the smaller a dot is. This result may possibly explain the variation of experimental data on exciton-spin relaxation times in individual dots reported by different authors for similar structures. In any case the longitudinal relaxation in typical structures of InGaAs/GaAs self-assembled QDs is not faster than few tens of nanoseconds at low temperature, as show our numerical estimates. At the same time the spin-flip transition to the dark state in 'small'-size InGaAs/GaAs dots may occur already at the scale of the exciton radiative lifetime. Upon elevation of temperature the proposed process of the longitudinal relaxation is strongly accelerated, especially in 'small'-size dots, where it may be of the order of few nanoseconds at temperatures of few tens of Kelvin.

We further investigated the spin-flip processes of carriers and holes in semi-magnetic systems [23]. In particular we pointed out the importance of direct spin-flip transitions within exciton subbands (split by an external magnetic field) in semi-magnetic quantum wells via the electron–hole exchange interaction (the so-called MAS mechanism [24]). Our theoretical results explain qualitatively a number of experimental findings from the literature like that spin relaxation is strongly suppressed for excitons with a small momentum when the spin-splitting is smaller than the LO phonon energy [25,26]. Our microscopic theory also provides a qualitative understanding of how a magnetic field affects the heavy hole- and exciton-spin-flip scattering (induced by the *sp–d* exchange interaction) in semi-magnetic quantum wells [A2.3:6]. Finally we have explicitly calculated the characteristic time for the direct heating of the Mn spin system by spin-polarized photo-excited holes as well as the relaxation time for a single hole in semi-magnetic quantum wells in an external longitudinal magnetic field [A2.3:24]. Numerical calculations for the example of ZnMnSe-based quantum wells are able to explain the experimental findings of the Dortmund group [27].

6. Spin-Injection Transistors for Electrical Spin-Initialization, Storage, and Read-Out

Having achieved high-fidelity spin initialization and read-out of spin states in single QDs as well as a good understanding of the relevant spin relaxation processes in our devices the next major step will be spin manipulation, i.e., single qubit operations. The latter shall be performed using electron spin resonance (ESR) techniques (see Sect.7). To this end the previously discussed spin-LED design has to be extended such that the injection of spin-polarized electrons and holes can be controlled separately by applied voltages. Thus, a spin state in a QD could first be initialized by injection and storage of a spin-polarized electron, then manipulated using ESR, and finally read out through injection of a hole, optical recombination, and measurement of the polarization state of the emitted photon. The schematic design of the three-terminal device we have been developing for this purpose is depicted in Fig.8 (left), a scanning electron microscopy image and a photograph of the mounted structure are shown in the middle and right part of the same figure, respectively. The upper part of the device is essentially identical to a spin-LED, while the lower part resembles a bipolar pnp transistor (where the upper p layer is thin or even absent in some devices). The n-GaAs base layer is used to electrically control hole injection into the QDs.

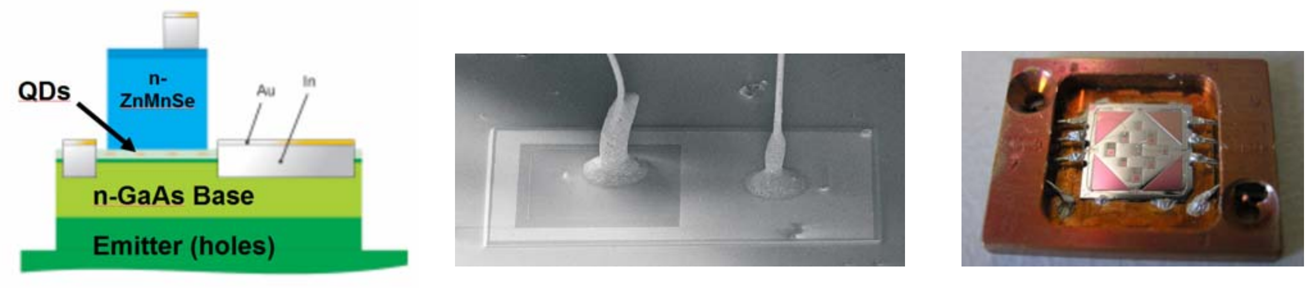

Fig.8: Left: Schematic design of our spin-injection transistor. Middle: Scanning electron microscopy image of contacted structure. Right: Photograph of the mounted device.

Applying suitable (pulsed) biases to the three terminals, configurations for injection of spin-polarized electrons, storage (manipulation), and optical read-out of spin states, respectively, can be realized. This is illustrated by first experimental results shown in Fig.9.

When applying a constant collector–emitter voltage U_{CE} = 2V to the device, the current flowing through the ZnMnSe spin aligner injects spin-polarized electrons into the QDs. However, for a low base–emitter voltage U_{BE} = 0.4 V, only GaAs EL from the BE-region is observed, i.e., the dots are filled only with electrons, while hole injection is blocked. When rising the base potential to U_{BE} = 1.4 V, QD luminescence is clearly observed, i.e., holes are injected for optical read-out. This proves, that hole injection can indeed be controlled via the base–emitter voltage. The highest circular polarization degree achieved so far in these structures is 40%. However, further technological progress (in particular concerning base layer contacting, reduction of leak currents, and improvement of the technology steps in order to achieve a better III–V/II–VI interface) will be required to ensure reliable and predictable operation of the devices, a prerequisite for their application in ESR spin manipulation experiments.

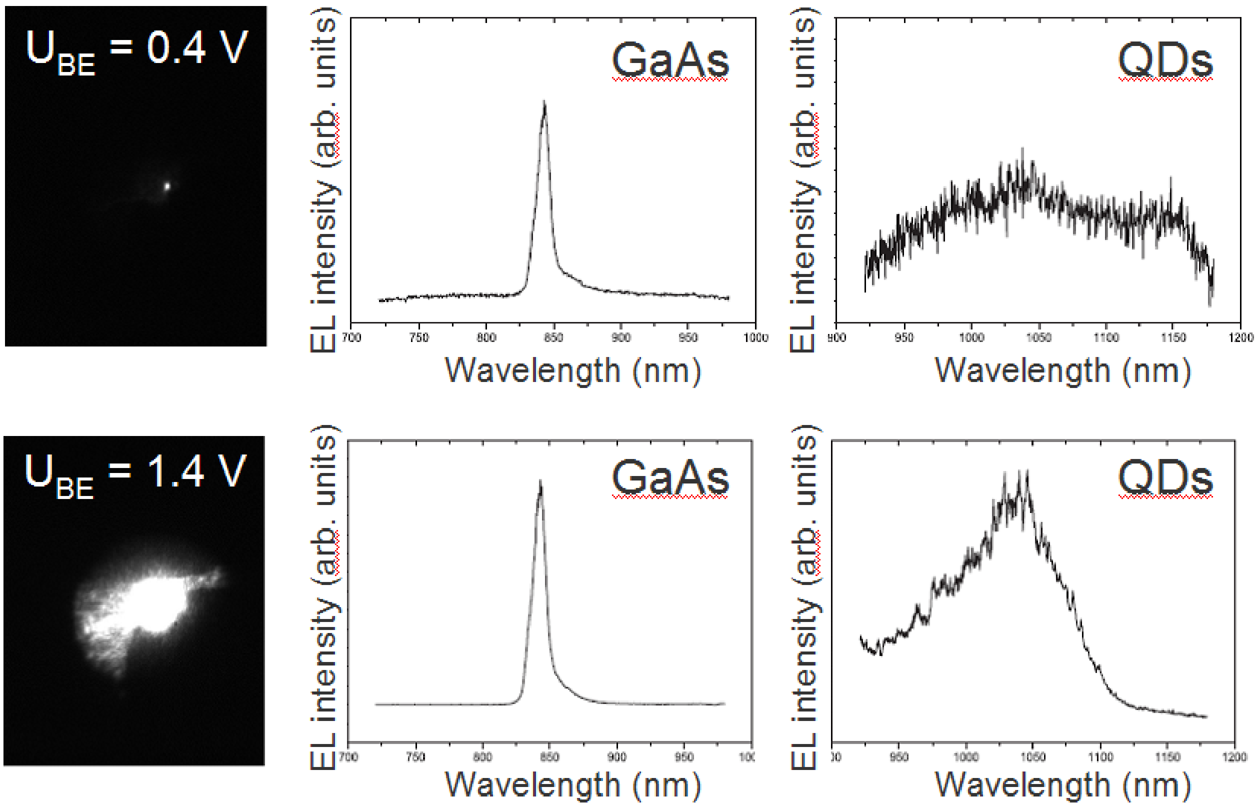

Fig.9: Low-temperature (T = 5 K) electroluminescence of a spin-injection transistor: CCD images (left) and corresponding spectra in the wavelength range of GaAs (middle) / QD emission (right). The top and bottom row show results for two different base–emitter voltages U_{BE}. The collector–emitter voltage was fixed at U_{CE} = 2V.

7. Electron Spin Resonance (ESR) Set-Up for Microwave Spin Manipulation

For the intended spin manipulation experiments already mentioned above we built a microwave set-up for ESR. Resonant coupling to the Mn and QD spin states requires utilization of high frequencies (53 GHz) from a tunable high-power microwave source. Therefore, a Gunn diode is used, which is amplified by a specially designed power combiner using IMPATT devices (Fig.10).

In order to make ESR possible in our existing experimental set-up (magneto-cryostat, spectroscopy), investigations into a microwave resonator solution and a better sample preparation have been done. Possible cylindrical resonator geometries were simulated with CST microwave studio to explore field distribution and power to optimize the set-up. Tunable microwave resonators were built (Fig.11, left) and their characteristics improved. Due to the significant influence of the sample (mounted on a quartz rod in the center of the cavity) on the resonator properties, our spin-devices had to be processed: the thickness of the sample was reduced from 400 μm down to 50 μm (by polishing) to avoid perturbing influences on the field distribution and heating effects of the highly doped substrate. For electrical operation the samples were contacted via gold leads deposited along the quartz rod. In contrast to standard ESR resonators our resonator provides a detection hole for optical excitation and detection. This set-up allows for both optical detection of magnetic resonance (ODMR) as well as standard ESR experiments.

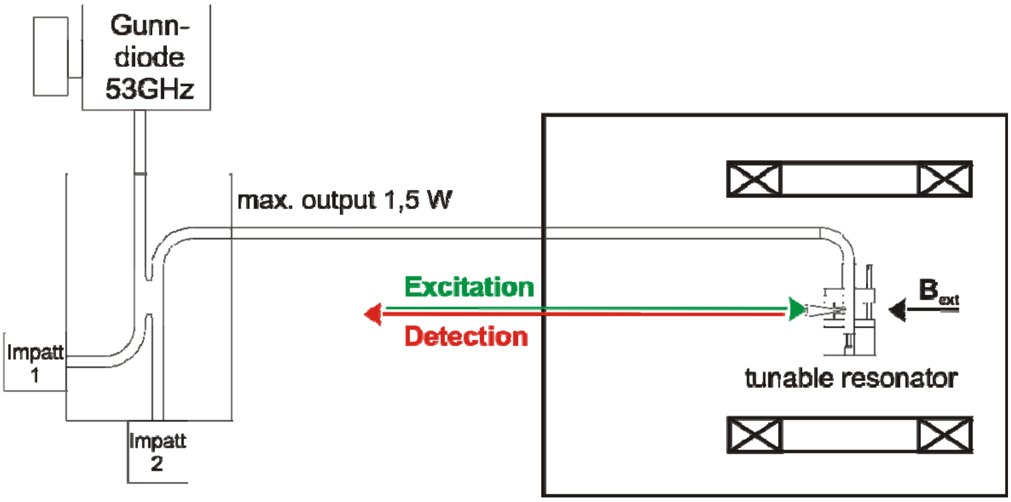

Fig.10: Microwave source and cryostat with resonator. The radiation from the amplified Gunn source at 53 GHz is guided into the cryostat where the external magnetic field is applied. Optical access to the sample is provided by a detection hole in the microwave resonator.

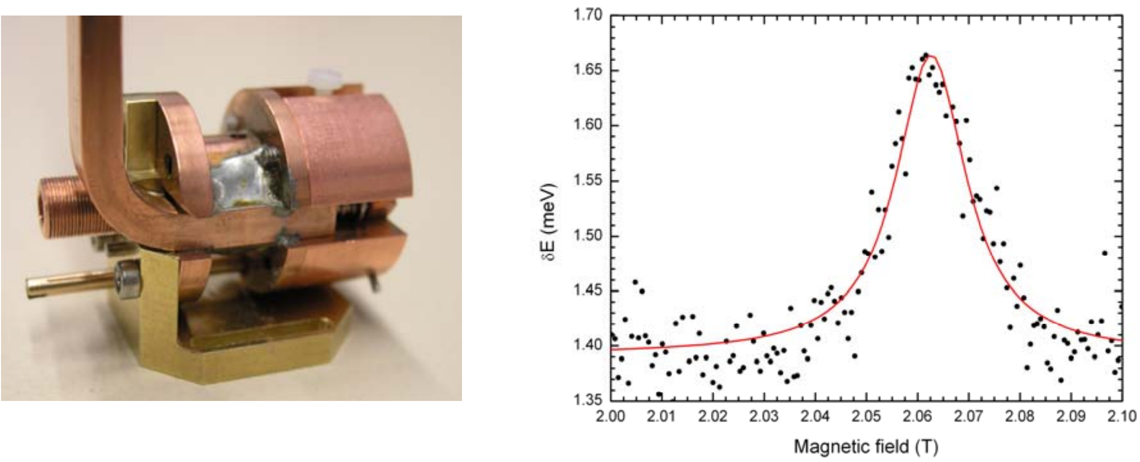

Fig.11: Left: 53 GHz resonator with optical detection hole and WR-15 waveguide. On the left side the cavity and coupling tuning screws are visible. Right: Microwave-induced energy shift of the $Zn_{0.984}Mn_{0.016}Se$ photoluminescence at $T \sim 10$ K versus magnetic field around the ESR resonant field. In resonance, the Mn spins aligned by the magnetic field partly flip (i.e., heating of the Mn spin system occurs) thus reducing the giant Zeeman splitting.

First ODMR results show the resonance of the Mn^{2+} spins [28] in a $Zn_{0.984}Mn_{0.016}Se$ layer at B = 2.062 T (Fig.11, right). The orientation of these spins in the applied magnetic field is responsible for the giant Zeeman splitting used to spin-polarize the conduction band electrons in our devices. Resonant excitation of these states leads to spin flip processes (i.e., a heating of the spin system occurs) thus reducing the giant Zeeman splitting and shifting the energetic position of the photoluminescence peak. Apart from testing the set-up and determination of the microwave power at the sample position these studies might enable future experiments where a defined manipulation of the Mn spin orientation is used to achieve spin initialization in the QDs with predefined polarization.

8. Future Perspectives

The recent progress concerning ESR and ODMR using the microwave set-up described in Sect.7 should make spin manipulation experiments in the near future possible. First experiments will be performed on well-characterized spin-LEDs involving Mn-spin manipulation during continuous or pulsed excitation of the sample. In a further step, spin manipulation experiments of electrons captured in QDs is planned. For these experiments, the transistor structures discussed in Sect.6 or similar devices capable of storing electrons for longer time scales shall be utilized. This will be of considerable interest to the scientific community, as several groups are working on microwave spin manipulation of the electron spin in a QD. These experimental investigations will be among the central activities of the remaining time of the funding period.

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