Electrical Spin Injection into Single InGaAs Quantum Dots

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Abstract. In the context of a potential future quantum information processing we investigate the concurrent initialization of electronic spin states in InGaAs quantum dots (QDs) via electrical injection from ZnMn(S)Se spin aligners. Single dots can be read out optically through metallic apertures on top of our spin-injection light-emitting diodes (spin-LEDs). A reproducible spin polarization degree close to 100\% is observed for a subset of the QD ensemble. However, the average polarization degree is lower and drops with increasing QD emission wavelength. Our measurements suggest that spin relaxation processes outside the QDs, related to the energetic position of the electron quasi-Fermi level, as well as defect-related spin scattering at the III–V/II–VI interface should be responsible for this effect, leading us to an improved device design. Finally, we present first time-resolved electroluminescence measurements of the polarization dynamics using ns-pulsed electrical excitation. The latter should not only enable us to gain a more detailed understanding of the spin and carrier relaxation processes in our devices. They are also the first step towards future time-resolved optical and electrical spin manipulation experiments.

1 Introduction

While in conventional electronics exclusively the manipulation of charge is utilized, the rapidly evolving field of semiconductor spintronics tries to take advantage of the electron’s spin degree of freedom as well. In this context, the prospect of a possible future spin-based quantum information processing is particularly fascinating [1]. It is obvious that the electron spin can be used to code a classical bit by identifying the spin-up (\(|↑\rangle\)) and spin-down (\(|↓\rangle\)) state with a logical “1” and “0”, respectively. Quantum mechanically, however, arbitrary coherent superpositions
\[ |b\rangle = \alpha |\uparrow\rangle + \beta |\downarrow\rangle \]  

(1)

can of course be formed, i.e., spin states can be used to code quantum bits (qubits), the basis of any quantum computer. The main advantage of this approach is the fact, that spin-qubits in semiconductors could be very robust. For instance, coherent electron spin transport over distances in the μm range has been observed [2, 3].

In order to realize a spin-based quantum information processing, suitable concepts for the initialization of spin states and their storage at well-defined sites are needed, as well as techniques to manipulate spins (qubit operations) and finally read out the result of the calculations performed. Some of the steps towards this aim have already been demonstrated: Quantum dots (QDs) – in particular the InGaAs/GaAs dots used in our experiments – could be identified as promising candidates for quantum information storage due to their long spin coherence times for electrons and even excitons [4–7]. (Excitons form for instance when holes are injected into the dots to optically read out the electron spin state, see Sect. 2). Furthermore, the creation of spin-polarized states (i.e., qubit initialization) in quantum dots or wells utilizing electrical spin injection as well as their optical readout could be successfully demonstrated by several groups, using either a diluted magnetic semiconductor or a ferromagnetic metal as spin aligner (see, e.g., [8–20], the references therein, and Sect. 2). A review is given in [21]. However, in most experiments carried out to date, large ensembles of spin-polarized electrons have been measured (although optical spin injection into single self-assembled CdSe/ZnSe quantum dots has recently been demonstrated [22]). On the other hand it is clear, that a future quantum information processing would not only require high initialization fidelities but also the ability to address single spin-qubits stored at individual localized sites.

In our own work summarized below we investigate electrical spin-injection into InGaAs quantum dots using a dilute magnetic ZnMn(S)Se spin aligner. Particularly, the concurrent electrical initialization of several spin-qubits in one device with polarization degrees close to 100% is demonstrated (Sect. 2, [9, 14, 15, 20]). Individual spin states in single quantum dots can be optically addressed and read out through metallic micro- or nano-apertures in a defined and reproducible way. The spin loss mechanisms in our devices and possible design optimizations are discussed in Sect. 3. Finally, we present first time-resolved electroluminescence (EL) measurements of the polarization dynamics using ns-pulsed electrical excitation in Sect. 4. The latter should not only enable us to gain a more detailed understanding of the spin and carrier relaxation processes in our devices. They are also the first step towards future time-resolved optical and electrical spin manipulation experiments.