Pulsed Electrical Spin Injection into InGaAs Quantum Dots: Studies of the Electroluminescence Polarization Dynamics

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Abstract. We present time-resolved studies of the spin polarization dynamics during and after initialization through pulsed electrical spin injection into InGaAs quantum dots embedded in a *p*-*i*-*n*-type spin-injection light-emitting diode. Experiments are performed with pulse widths in the nanosecond range and a time-resolved single photon counting setup is used to detect the subsequent electroluminescence. We find evidence that the achieved spin polarization shows an unexpected temporal behavior, attributed mainly to many-carrier and non-equilibrium effects in the device.

Keywords: Spin injection, quantum dots, polarization dynamics, spin-LEDs
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INTRODUCTION

Prerequisites for a potential future spin-based quantum information processing are techniques for the initialization of spin states, their storage and manipulation in quantum dots (QDs), as well as their individual read-out [1]. This paper focuses on aspects of the electrical initialization of spin states in self-organized semiconductor QDs embedded in *p*-*i*-*n*-type spin-injection light-emitting diodes (spin-LEDs). As *n*-type material a diluted magnetic semiconductor (DMS) is used, which provides the possibility to electrically initialize the spin states by spin-polarized electrical currents. We already succeeded in proving that initialization of spin states with very high fidelity close to 100% can be achieved for single quantum dots under a constant electrical current in the spin-LEDs [2, 3]. However, in the QD ensemble the spin injection fidelity is limited to significantly lower values by relaxation processes of the spin [2, 3]. In the experiments presented in this contribution, we analyze the initialization of spin states utilizing pulsed electrical excitation of the spin-LED and time-resolved detection of the subsequent electroluminescence. This enables studies of the temporal spin polarization dynamics. Furthermore, initialization by short pulses is the basis for future spin manipulation experiments and more complex operations.

FABRICATION AND EXPERIMENT

The layout of the molecular-beam epitaxy (MBE) grown spin-LEDs is sketched in Fig. 1. Zn-doped *p*-GaAs(001) was used as substrate. For a typical spin-LED, the bottom III–V part consists of $\sim$500 nm GaAs:Be ($p \sim 1 \times 10^{19}$ cm^{-3}), 100 nm *i*-GaAs, the optically active InGaAs QDs, and a 25 nm thick *i*-GaAs spacer. The II–VI part contains a 750 nm $\mathrm{Zn_{0.95}Mn_{0.05}Se:Cl}$ ($n \sim 10^{18}$ cm^{-3}) spin aligner. On top, 200 nm of ZnSe:Cl ($n = 5 \times 10^{18}$ cm^{-3}) were deposited to improve the quality of the In contact. Standard photolithography was used to define individual devices. As has been shown, the band bending and the position of the electronic quasi-Fermi level give rise to a tunnel barrier and often the formation of a two-dimensional electron gas (2DEG) at the III–V / II–VI interface. Further details may be found in [3, 4] and references therein.

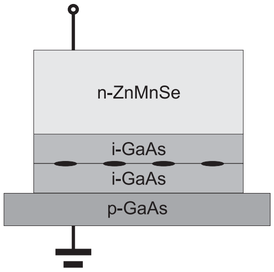

FIGURE 1. Sketch of the spin-LED used in the experiment. InGaAs QDs are located between the two *i*-GaAs layers.

The spin-LEDs were mounted in a magneto-cryostat, and an external magnetic field of 6 T was applied parallel to the growth direction in order to have a spin-polarized current flowing out of the DMS after application of a voltage across the device. We then excited the device at 5 K with current pulses of several nanoseconds width. From the circular polarization degree (CPD) of the emit-

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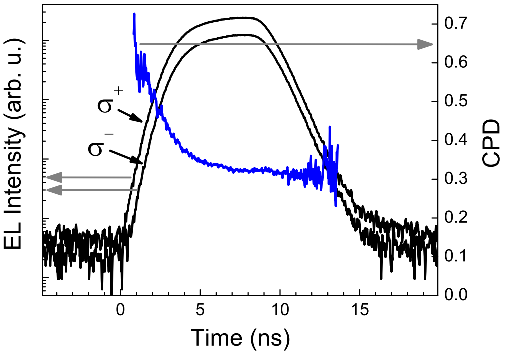

FIGURE 2. Typical temporal evolution of the emission intensity for left and right circularly polarized light at $B = 6\,\mathrm{T}$ of a spin-LED under pulsed electrical excitation, measured at the spectral maximum of 905 nm, and the time-dependent CPD.

ted light at different wavelengths we directly determined the degree of spin polarization [3] in different parts of the spin-LEDs (QDs, wetting layer, GaAs). For the detection of the emitted light, an avalanche photodiode and a time-correlated single photon counting (TCSPC) setup were employed.

RESULTS AND DISCUSSION

For quantum dots emitting at a wavelength of 905 nm the detected intensities of the circularly polarized light components after pulsed electrical excitation and the CPD are shown in Fig. 2. Clearly, the CPD drops from a value higher than 0.6 to a plateau value of 0.3 within the first nanoseconds. A similar behavior was observed for quantum dots emitting at various wavelengths and for the wetting layer, with external magnetic fields ranging from 1 T to 12 T. For the GaAs emission, we never observed such a decrease in the CPD.

A similar drop of the polarization degree on timescales of a few nanoseconds was observed in Ref. [5] for photoexcitation of the carriers, where it was attributed to the hyperfine interaction of the electron spins with the nuclear spins. However, due to the relatively large external magnetic field applied in our experiment this effect should be quenched [6]. Therefore, it can be ruled out as an explanation of our results.

In a further experiment we determined the CPD for several current densities with a constant electrical current flowing through the device. From the analysis of our data we could conclude that the observed CPD decrease with increasing current is also too weak to fully account for the initially increased CPD in the pulsed excitation measurements.

A crucial factor may be the potential barrier at the *n*-ZnMnSe/*i*-GaAs interface, which the carriers have to pass by a (phonon-assisted) tunnelling process [3, 4]. When the carrier density at the beginning of the pulse is still low, spin-polarized electrons can easily tunnel into the empty QD states and retain their polarization. However, as dynamic equilibrium is reached, a certain fraction of the dots will always be filled by electrons. Therefore, tunnelling will only be possible when an empty target state becomes available, i.e., after injection of a hole into an occupied dot and subsequent optical recombination. The resulting retardation should give more opportunity for spin relaxation in the GaAs spacer, which might explain the lower CPD observed under steady-state conditions. The GaAs luminescence would hardly be affected by this mechanism, because many empty states are always available, and tunnelling processes are less important for the majority of electrons contributing to this emission. Further investigations are currently under way.

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