Spin dynamics of electrons and holes in InGaAs/GaAs quantum wells at milliKelvin temperatures

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The carrier spin dynamics in a n-doped (In,Ga)As/GaAs quantum well has been studied by time-resolved Faraday rotation and ellipticity techniques in the temperature range down to 430 milliKelvin. These techniques give data with very different spectral dependencies, from which nonetheless consistent information on the spin dynamics can be obtained, in agreement with theoretical predictions. The mechanisms of long-lived spin coherence generation are discussed for the cases of trion and exciton resonant excitation. We demonstrate that carrier localization leads to a saturation of spin relaxation times at 45 ns for electrons below 4.5 K and at 2 ns for holes below 2.3 K. The underlying spin relaxation mechanisms are discussed.

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I. INTRODUCTION

The spin physics of semiconductor heterostructures attracts considerable attention nowadays due to the emerging fields of semiconductor spintronics, quantum computation and quantum information[1–3]. Understanding the basic mechanisms providing spin orientation, spin relaxation and spin decoherence of electrons and holes as well as manifestation of these mechanisms in various experimental conditions, e.g. external magnetic fields, lattice temperatures, etc., is of great importance in this respect. One of the evident goals is to optimize material properties and heterostructure design to achieve the longest possible spin relaxation time so that sufficient room is left for implementing protocols for spin manipulation and read-out.

Carrier localization quenches the particle orbital motion and is one of the pathways to suppress efficient spin-relaxation mechanisms related to the spin-orbit interaction. It has been shown that the spin relaxation of electrons localized on donors in bulk GaAs can exceed 100 ns[4,5]. Also in (In,Ga)As/GaAs quantum dots the electron spin coherence time can reach 3 μs, while the hole spin relaxation time may exceed tens of nanoseconds[6,7]. In quantum well structures localization of the two-dimensional electrons at liquid helium temperatures is required to demonstrate relaxation times in the order of tens of nanoseconds[8,9]. Under these conditions spin relaxation times of few nanoseconds have been reported for resident holes[10–13]. Very recently a remarkably long hole spin relaxation time of 70 ns has been measured at 400 mK by a resonant spin amplification technique in p-doped GaAs/(Al,Ga)As quantum wells[14]. This time decreases to 2.5 ns with the temperature increase up to 4.5 K. Evidently temperatures below those that can be obtained by pumping ^{4}He (about 1.5 K) are essential for understanding the carrier spin dynamics in quantum wells. However, the available experimental data are very limited in this range, mostly due to the demanding efforts for performing experiments with ^{3}He and the complicated direct optical access to the sample in this case.

In this paper we apply time-resolved Faraday rotation (FR) and ellipticity techniques to study the carrier spin dynamics in n-doped (In,Ga)As/GaAs quantum well. In Sec. II we provide a description of these pump-probe techniques. Experimental features and theoretical modeling of the detected spin polarization are discussed in Sec. III. Two contributions to the Faraday rotation and ellipticity signals due to interaction of the probe beam with the trion and exciton resonances are considered. In Sec. IV we discuss the resident electron spin orientation by the circularly polarized pump. Two mechanisms are suggested for the initialization of the experimentally observed long-lived spin dynamics. In Sec. V we focus on the long-lived spin dynamics of resident electrons measured in the regime of resonant spin amplification (RSA) at very low temperatures down to 430 mK. The characteristic bat-like shape of the RSA signal contains information on the hole spin dynamics, which persists remarkably long at low temperatures. We discuss the mechanisms responsible for electron and hole spin relaxation in the addressed temperature ranges.

II. EXPERIMENTAL DETAILS

We study a heterostructure with two coupled 8 nm thick $In_{0.09}Ga_{0.91}As$/GaAs quantum wells (QWs) separated by a thin (1.7 nm) GaAs barrier. The layer sequence was grown on an undoped GaAs substrate with (100) orientation by molecular-beam epitaxy. It contains a 100 nm n-doped GaAs buffer layer separated by a 100 nm GaAs spacer from the QWs. The doped layer serves as source of resident electrons for the QWs. The