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Controlling hole spin dynamics in two-dimensional hole systems at low temperatures

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Abstract.

With the recent discovery of very long hole spin decoherence times in GaAs/AlGaAs heterostructures of more than 70 ns in two-dimensional hole systems, using the hole spin as a viable alternative to electron spins in spintronic applications seems possible. Furthermore, as the hyperfine interaction with the nuclear spins is likely to be the limiting factor for electron spin lifetimes in zero dimensions, holes with their suppressed Fermi contact hyperfine interaction due to their p-like nature should be able to show even longer lifetimes than electrons. For spintronic applications, electric-field control of hole spin dynamics is desirable.

Here, we report on time-resolved Kerr rotation and resonant spin amplification measurements on a two-dimensional hole system in a p-doped GaAs/AlGaAs heterostructure. Via a semitransparent gate, we tune the charge density within the sample. We are able to observe a change in the hole g factor, as well as in the hole spin dephasing time at high magnetic fields.

Keywords: Optical orientation, hole spin dynamics, GaAs heterostructures
PACS: 78.67.De, 78.55.Cr

Regarding possible applications of spins in semiconductors, e.g., quantum computing or semiconductor spintronics [1, 2], mostly electron spin based systems were investigated so far. One reason for the less intense efforts regarding hole spin dynamics were very rapid spin dephasing times (SDT) for holes in bulk semiconductors. For bulk GaAs, this is due to the degeneracy of the heavy-hole (HH) and light-hole (LH) valence bands at k=0, so any momentum scattering can lead to hole spin dephasing [3]. For $k > 0$, valence band mixing also allows for hole spin relaxation during momentum scattering [4]. Only in low dimensional structures, the degeneracy of the valence bands is lifted due to the different confinement energies for LH und HH. So, in the last few years, advances in both, materials sciences and spintronics, allowed for the fabrication of semiconductor structures with considerably long hole SDT [5]. Recently, also due to localization of holes at quantum well (QW) width fluctuations at low temperatures, SDT of up to 70 ns in a narrow GaAs/AlGaAs QW could be shown [6]. With hole spins therefore being a viable alternative to electron spins in semiconductors, effective electrical control of the hole g factor and SDT would be useful.

In our measurements presented here, the sample used is a 4 nm wide p-modulation-doped GaAs quantum well (QW) embedded in $Al_{0.3}Ga_{0.7}As$ barriers, with a doping density $p = 1.1 \times 10^{11}$ cm^{-2}. A semitransparent NiCr gate is evaporated on top of the sample and both the quantum well and the gate are contacted electrically. The gate is held at ground potential, while a voltage can be applied to the quantum well. For photoluminescence (PL) measurements, the sample is mounted in an optical cold finger cryostat, allowing for temperatures down to 4 K. For time-resolved measurements, it is mounted in an optical cryostat with a ^{3}He insert, allowing for sample temperatures below 500 mK and magnetic fields of up to 10 Tesla in the sample plane. The techniques used are time resolved Kerr rotation (TRKR) and resonant spin amplification (RSA) [7]. The optical experiments are performed using a pulsed Ti-Sapphire laser system, details of the experiment are published elsewhere [6, 8].

For characterization of the gated samples, PL spectroscopy is used. Figure 1 (a) shows PL spectra at T=4.5 K as a function of the applied gate voltage V_G. The sample was excited off-resonantly at a wavelength of 726 nm and an excitation density of 100 $\frac{\mathrm{W}}{\mathrm{cm}^2}$. For V_G up to -1 V, the sample shows neutral excitonic behavior. With increased V_G and therefore increased charge density, the PL shifts upwards in wavelength and the sample shows positively charged excitonic behavior up to a gate voltage of V_G=1 V. For $V_G > 1$ V, the PL broadens and shifts again to the red, which is attributed to a change into a 2D hole gas (2DHG) regime.

Figure 2 (a) shows the effective in-plane hole g factor extracted from the peak spacing of RSA measurements as shown in Figure 1 (b). The sample was resonantly excited at a pump beam power of 1.7 $\frac{\mathrm{kW}}{\mathrm{cm}^2}$. For V_G from -20 V to 0 V, no change in neither the signal nor the g factor is to be seen. For V_G above about 1 V, the hole spin signal vanishes abruptly. Only in the region where the PL shifts from positively charged excitonic to 2DHG behavior, the g factor shows a distinct decrease from 0.06 down

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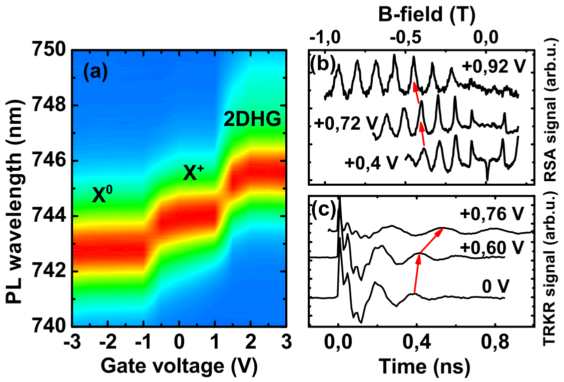

FIGURE 1. (a) Gate voltage dependent PL spectra at T=4.5 K. (b) RSA curves taken at T=1.2 K for different gate voltages. (c) TRKR curves taken at T=1.2 K and B=6 T for different gate voltages (The red arrows visualize the changed precession frequency.).

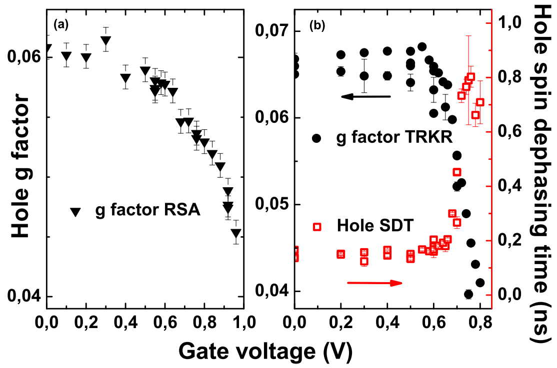

FIGURE 2. (a) Effective hole g factor versus applied gate voltage as extracted from RSA data at T=1.2 K. (b) Effective hole g factor (black circles) and hole spin dephasing times (red squares) at B=6 T and T=1.2 K for different applied gate voltages extracted from TRKR measurements.

to 0.045. Complementary data extracted via damped cosine fits from TRKR measurements - as shown in Figure 1 (c) - is shown in Figure 2 (b). Here, the g factor (black circles) was extracted from the precession frequency at B=6 T. The behavior from the RSA measurements is reproduced, showing a decrease of more than 30 % from 0.065 to 0.04. The small deviations in the absolute values from RSA to TRKR measurements might stem from a slight change of sample position.

The shift in the hole g factor can be explained due to the shift of the wave function position and symmetry within the quantum well due to the changed external electrical potential [6].

The red squares in Figure 2 (b) show the evolution of the hole SDT at B=6 T with applied gate voltage, again extracted from damped cosine fits to the TRKR data. Here, with increasing V_G, the SDT increases by a factor of 5 from initially $\sim$ 150 ps at $V_G = 0$ V to $\sim$ 750 ps at $V_G = 0.75$ V.

Taking into account the RSA data at small magnetic fields, where no SDT change on this order of magnitude takes place with applied gate voltage, this behavior can be explained: As the holes are localized, each hole sees a slightly different enviroment. The resulting g factor inhomogeneity leads to ensemble dephasing with applied magnetic field. This is observed as a characteristic 1/B-dependence of the SDT in 2D hole systems [8]. With increased carrier density close to the 2DHG regime, increased averaging over all holes occurs, leading to a decreased g factor inhomogeneity. This leads to a longer SDT at high magnetic fields, as observed in TRKR measurements above, while the SDT at small magnetic fields stays the same. This can also be seen in the RSA curves, where the FWHM of the RSA maxima and therefore the SDT stays roughly the same at low magnetic fields, regardless of the gate bias. At higher fields, the peaks vanish for low gate bias, while more and more peaks appear at high magnetic fields with increased gate bias, indicating less rapid spin dephasing due to reduced g factor inhomogeneity.

In conclusion, we have investigated hole spin dynamics in a gated, p-doped QW by using PL, TRKR and RSA techniques. The RSA and TRKR techniques deliver matching data, which in combination with the PL spectra show a distinct shift of the hole g factor at the boundary between charged excitonic and 2DHG behavior. This is accompanied by an increase of the hole SDT at B=6 T by a factor of 5, which can be consistently explained by a reduced g factor inhomogeneity.

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