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Resonant spin amplification of hole spin dynamics in two-dimensional hole systems: experiment and simulation

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Abstract. Spins in semiconductor structures may allow for the realization of scalable quantum bit arrays, an essential component for quantum computation schemes. Specifically, hole spins may be more suited for this purpose than electron spins, due to their strongly reduced interaction with lattice nuclei, which limits spin coherence for electrons in quantum dots. Here, we present resonant spin amplification (RSA) measurements, performed on a p-modulation doped GaAs-based quantum well at temperatures below 500 mK. The RSA traces have a peculiar, butterfly-like shape, which stems from the initialization of a resident hole spin polarization by optical orientation. The combined dynamics of the optically oriented electron and hole spins are well-described by a rate equation model, and by comparison of experiment and model, hole spin dephasing times of more than 70 ns are extracted from the measured data.

Keywords: Optical orientation, hole spin dynamics, GaAs heterostructures
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Spin dynamics in semiconductor hetero- and nanostructures based on the GaAs material system have been studied intensely in recent years, driven by possible applications in the fields of semiconductor spintronics [1, 2] and quantum information processing [3]. However, electron spin dynamics have been investigated in many more studies than hole spin dynamics. One of the reasons is the rapid dephasing of hole spins in bulk GaAs: here, the heavy-hole (HH) and light-hole (LH) valence bands, which have different angular momentum, are degenerate at $k = 0$, hence any momentum scattering can lead to hole spin dephasing [4]. This degeneracy is lifted in quantum well systems due to the different confinement energies for light and heavy holes. Due to valence band mixing for $k > 0$, which again allows for hole spin relaxation during momentum scattering [5], long-lived hole spin coherence has only been observed at low temperatures [6, 7, 8], where holes can become localized at quantum well thickness fluctuations.

In our study of hole spin dynamics, we use the resonant spin amplification (RSA) technique [9]. In RSA, the interference of spin polarizations created by subsequent laser pulses leads to pronounced maxima in the Faraday rotation angle, which is probed at a fixed time delay between pump and probe pulses, as a function of an in-plane magnetic field. Our sample 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}. For measurements in transmission, the sample is glued to a sapphire support and thinned by selective etching to remove the substrate and leave only the MBE-grown layers. 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. Optical experiments are performed using a pulsed Ti-Sapphire laser system, details of the experiment are published elsewhere [10].

Figure 1 (a) shows a typical RSA trace measured at 400 mK (open dots), compared to simulation (solid line). No RSA maximum is observed in zero field, and for finite fields, the amplitude of the RSA maxima first increases, then decreases again, leading to a butterfly-like shape of the signal, which stems from the complex initialization process of a resident hole spin polarization using optical orientation [10].

The combined dynamics of the optically oriented electrons and holes, as well as the resident holes in the QW, are modelled using two coupled differential equations:

$$\frac{d\mathbf{e}}{dt} = -\frac{\mathbf{e}}{\tau_R} + \frac{g_e \mu_B}{\hbar}(\mathbf{B} \times \mathbf{e}) \quad (1)$$

$$\frac{d\mathbf{h}}{dt} = -\frac{\mathbf{h}}{T_2^*} + \frac{g_h \mu_B}{\hbar}(\mathbf{B} \times \mathbf{h}) + \frac{e_z \mathbf{z}}{\tau_R} \quad (2)$$

Here, $\mathbf{e}$ and $\mathbf{h}$ are the electron and hole spin polarization vectors, τ_R is the photocarrier recombination time, T_2^* is the hole spin dephasing time (SDT), g_e and g_h are the electron and hole g factors. Numerical simulation using these equations allows us to model the RSA measurements precisely and capture all salient features (see simulated trace in Figure 1 (a)), if all relevant parameters are carefully tuned to the measurement. The electron g factor can be precisely measured using time-resolved Faraday rotation (TRFR), and the hole g factor is extracted from the spacing ΔB of the RSA max-

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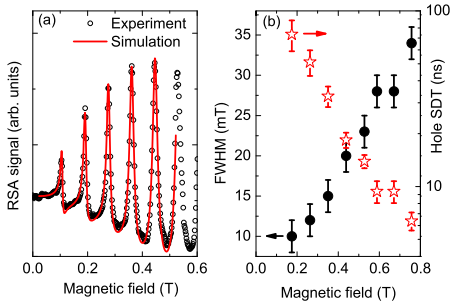

FIGURE 1. (a) Experimental RSA trace measured at 400 mK (black circles) and simulated trace (solid line). (b) FWHM of the RSA maxima extracted from the measurement as a function of magnetic field (black dots) and hole SDT extracted from these values (red stars).

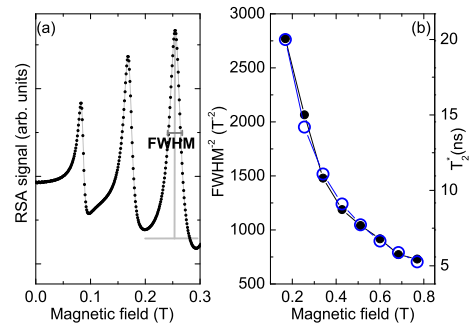

FIGURE 2. (a) Simulated RSA trace. The definition of the FWHM is indicated by the grey lines. (b) Comparison of 1/(FWHM)^2 of the simulated RSA maxima (black dots) to the hole spin dephasing time T_2^* (blue circles) used in the simulation as a function of magnetic field.

ima: $g_h = hf_{rep}/(\mu_B \Delta B)$, where f_{rep} is the laser repetition frequency. Below, we will demonstrate how the hole SDT can be extracted from the full width at half maximum (FWHM) of the RSA maxima. The FWHM of the measured RSA maxima (as defined in Figure 2 (a)) increases monotonously with the applied magnetic field, as Figure 1 (b) shows. This corresponds to a significant decrease of the hole SDT, which is caused by the hole g factor inhomogeneity,Δg_h^*. The inhomogeneous hole spin ensemble dephases more rapidly with increasing precession frequency [11]:

$$T_2^* = \left(\frac{1}{T_2} + \frac{2\pi \Delta g_h^* \mu_B B}{h} \right)^{-1}. \qquad (3)$$

This decrease of the measured ensemble hole SDT with magnetic field makes it difficult to extract the single hole spin coherence time T_2 from high-field measurements like TRFR.

In order to investigate the correlation between the RSA maxima FWHM and the hole SDT T_2^*, we simulate RSA traces using hole SDT calculated with equation 3. Figure 2 (a) shows such a trace for $T_2 = 80$ ns, $\Delta g_h^* = 0.0025$. The FWHM of the RSA peaks, starting at the second peak, is extracted from this trace. In Figure 2 (b), we plot the inverse square of the FWHM as a function of magnetic field (black dots). In the same figure, the hole SDT T_2^* is plotted as a function of magnetic field (blue circles), calculated using equation 3 with the same parameters as the RSA trace. Both sets of data show the same, 1/B-like dependence on magnetic field. This allows us to determine the proportionality constant $\alpha = 7.36 \times 10^{-3}$ ns T^2, $T_2^* = \alpha/(\text{FWHM})^2$. Using this value of α, the hole SDT data shown in Figure 1 (b) are calculated. We observe a maximum hole SDT $T_2^* = 74 \pm 15$ ns for a magnetic field of B$\approx$ 0.2 Tesla. This represents a lower bound for the single hole spin coherence time T_2. From the decay of the hole SDT with magnetic field, we find a g factor inhomogeneity $\Delta g_h^* = 0.003$.

In conclusion, we have investigated hole spin dynamics in a p-doped QW by using the RSA technique. The RSA traces are closely modelled by a system of differential equations. By analysis of the simulated RSA traces, we demonstrate that the hole SDT, T_2^*, at a given magnetic field is inversely proportional to the **square** of the FWHM of the RSA peak at that magnetic field. Using this relation, we extract hole SDTs in excess of 70 ns from the measured RSA traces.

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REFERENCES

1. J. Fabian, *et al., Acta Physica Slovaca* **57**, 565 (2007).
2. M. W. Wu, *et al., Physics Reports, in press* (2010).
3. D. Awschalom, D. Loss, and N. Samarth, *Semiconductor Spintronics and Quantum Computation*, Springer, 2002.
4. D. J. Hilton, *et al., Phys. Rev. Lett.* **89**, 146601 (2002).
5. T. C. Damen, *et al., Phys. Rev. Lett.* **67**, 3432 (1991).
6. B. Baylac, *et al., Solid State Communications* **93**, 57 (1995).
7. M. Syperek, *et al., Phys. Rev. Lett.* **99**, 187401 (2007).
8. M. Kugler, *et al., Phys. Rev. B* **80**, 035325 (2009).
9. J. M. Kikkawa, *et al.,Phys. Rev. Lett.* **80**, 4313 (1998).
10. T. Korn, *et al.,New J. Phys.* **12**, 043003 (2010).
11. D. Yakovlev, and M. Bayer, *Spin Physics in Semiconductors*, Springer,Berlin, 2008, p. 135.