Spin dynamics in p-doped semiconductor nanostructures subject to a magnetic field tilted from the Voigt geometry

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1. Motivation

- Spin dynamics and coherence is crucial for many applications in emerging technologies
- Time–resolved Faraday rotation (TRFR) and resonant spin amplification (RSA) are very efficient methods for the investigation of spin dynamics
- Anisotropy of the hole g-factor makes the evolution in tilted magnetic field nontrivial

2. System

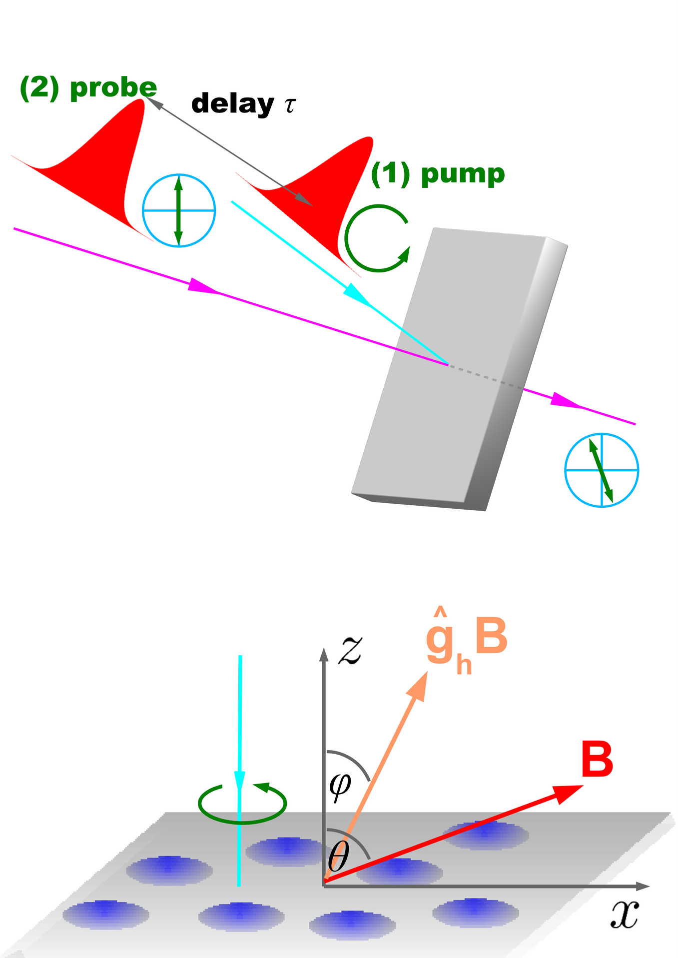
- Holes weakly bound at trapping centers - ensemble of independent hole-trion systems
- Non-magnetic system
- Magnetic field tilted from the exact Voigt geometry
- Pump-probe configuration at normal incidence

3. Model

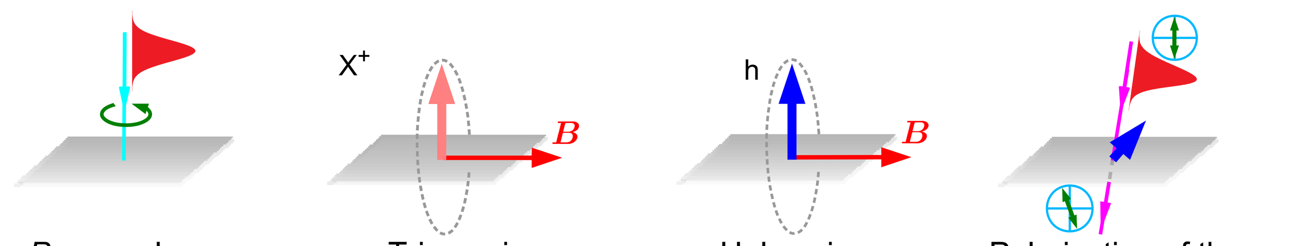
- **Hole–trion system** described by a 4-dimensional density matrix[1]
- **Pump pulse** treated perturbatively – low power limit
- **System dynamics:** Zeeman splitting and precession in the magnetic field
- **System–reservoir interactions:**
  – Trion recombination described by a Lindblad generator
  – Hole spin decoherence described by a Lindblad generator (Markovian, weak coupling limit)
- **Detection:** homodyne formed by the transmitted reference signal and the weak optical signal from the system.

[1] P. Machnikowski, T. Kuhn, Phys. Rev. B **81**, 115306 (2010)

Experimental setup



Phenomenology – magnetooptical Kerr effect



Pump pulse generates trion and hole spin polarization | Trion spin polarization precesses and decays due to recombination and spin decoherence | Hole spin polarization precesses and decays due to spin decoherence | Polarization of the *probe* pulse is rotated proportionally to the existing spin polarization

Magnetization (spin polarization) dynamics on picosecond time scales

RSA signal

RSA signal obtained by finding the stationary point of the spin polarization transformation corresponding to one repetition of the pulsed laser:

$$\mathcal{L}_D\,\{\,\mathcal{L}_P\,\{\,\mathbf{S}_{RSA}\,\}\,\} = \mathbf{S}_{RSA}$$

Long time scale decoherence; Pump pulse; Initial spin state being transformed; Final spin state equal to initial one

Inhomogeneous broadening of the hole g-factors is model with the normal distribution.

4. Dynamics

- Pump pulse generates trion and hole spin polarization; the hole polarization survives recombination
- Optical selection rules with respect to the structure axis
- Analytical solution for the precession + decoherence
- **TRFR signal** proportional to the **spin polarization** at the arrival of the probe pulse
- **RSA signal** proportional to the spin polarization generated by subsequent laser pulses, peaks obtained for pulse repetition frequency in resonance with the precession frequency

5. Results – TRFR in tilted magnetic field

- Expression for Faraday signal in tilted magnetic field:

$$\Delta\Sigma^{(\mathrm{Faraday})} = \Sigma_\mathrm{t} - \Sigma_\mathrm{h}$$

$$\Sigma_\mathrm{t}(t) = \Sigma_\mathrm{t}(0)e^{-\gamma t}\left(\cos^2\theta + \sin^2\theta\cos\omega_\mathrm{t} t\right)$$

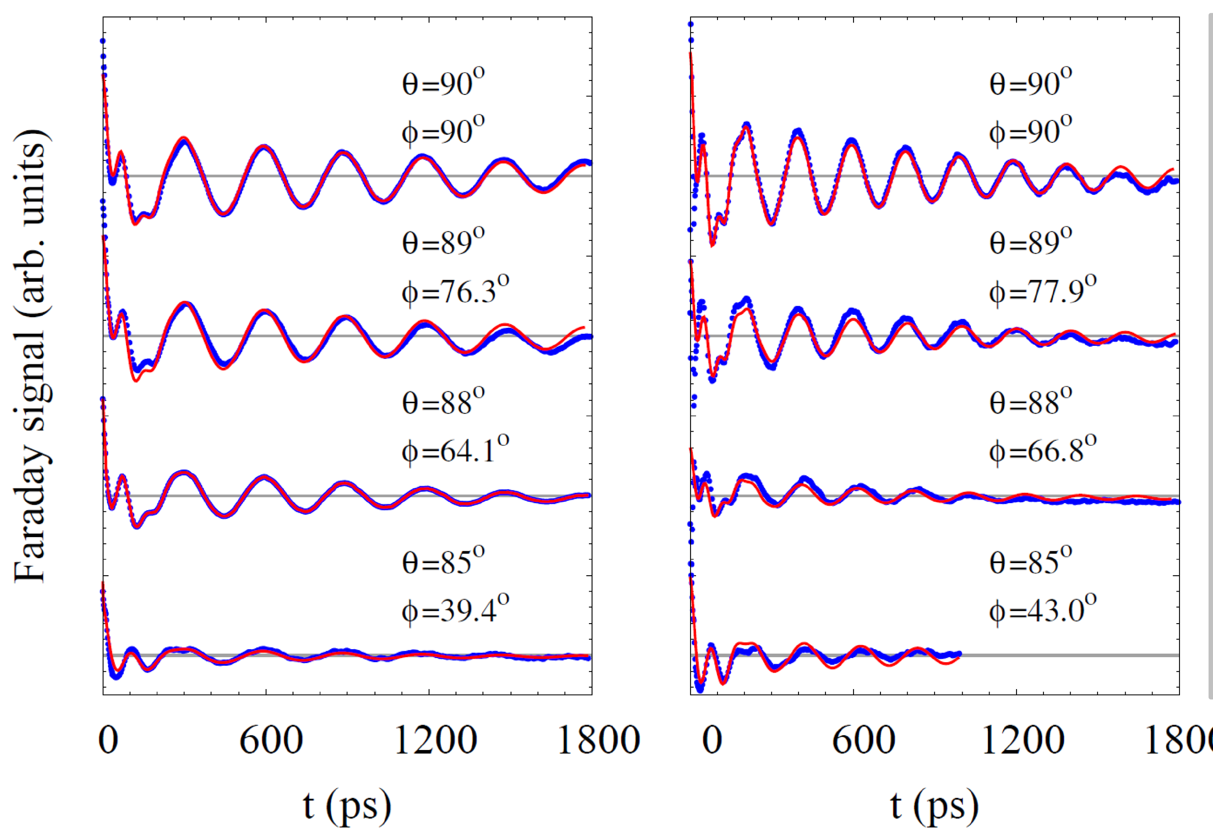
$$\Sigma_\mathrm{h} = A_1 e^{-\gamma t} + A_2 e^{-(\gamma+i\omega_\mathrm{t})t} + B_1 e^{-\kappa_1 t} + B_2 e^{-(\kappa_2+i\omega_\mathrm{h})t} + \mathrm{c.c.}$$

Trion Larmor frequency: ω_t
Hole Larmor frequency: ω_h
Radiative decay rate: γ

Hole spin decoherence rates in terms of T_1 and T_2 times for the purely in-plane (x) and purely out-of-plane (z) magnetic field applied:

$$\kappa_1 = \kappa_{1\perp}\sin^2\phi + \kappa_{1\parallel}\cos^2\phi$$
$$\kappa_2 = \kappa_{2\perp}\sin^2\phi + \kappa_{2\parallel}\cos^2\phi$$
$$T_1^{(x)} = \frac{1}{\kappa_{1\perp}},\quad T_2^{(x)} = \frac{1}{\kappa_{2\perp}},\quad T_1^{(z)} = \frac{1}{\kappa_{1\parallel}},\quad T_2^{(z)} = \frac{1}{\kappa_{2\parallel}}$$

- The spin polarization splits into **two parts: non-precessing** along the quantization axis (which coincides with magnetic field axis for the electrons, but, due to the strongly anisotropic hole g-factor, does not for the holes) and **precessing**, perpendicular to this axis.
- TRFR signal is divided into the **short-living component**, decaying with the recombination rate, and the **long-living component**, with its decay rate proportional to the hole spin decoherence rates. This feature comes from the mechanism based on the difference of hole and trion precession frequencies[2].
- As the out-of-plane component of the hole g-factor in the considered structures is larger than the in-plane component, **tilting the magnetic field** from the Voigt geometry results in **an increase of the hole precession frequency**. This does not only shorten the period of the Faraday signal oscillation, but also **changes the dephasing parameters**.
- The **decay rate** of the non-precessing component (inverse of the effective T_1 time) is a **weighted average of the decay rates for purely in-plane and purely out-of-plane magnetic fields**, with weights being the *x* and *z* components of the unit vector parallel to quantization axis. The same holds for the precessing component (i.e. for inverse of the effective T_2 time).
- **Experimental verification of the model**: due to fixed Larmor frequency the reservoir is probed at different angles, but at the same frequency. Therefore the decoherence rates for different angles can be compared. Two series of experimental measurements for two different hole precession frequencies were performed. The fitting parameters used for all angles in a given series were the same.



Experimental details

- Single-side p-modulation-doped $GaAs/Al_{0.3}Ga_{0.7}As$ QW with a width of 4 nm grown by molecular beam epitaxy (MBE)
- Hole density $1.1\times10^{11}\ \mathrm{cm}^{-2}$
- Mobility $1.3\times10^{4}\ \mathrm{cm}^2/\mathrm{Vs}$
- Ti:Sapphire laser generating pulses with 1 ps length and a spectral width of about 2 meV.
- Temperature $1.2\ \mathrm{K}$

[2] M. Syperek, *et. al.*, Phys. Rev. Lett. **99**, 187401 (2007)

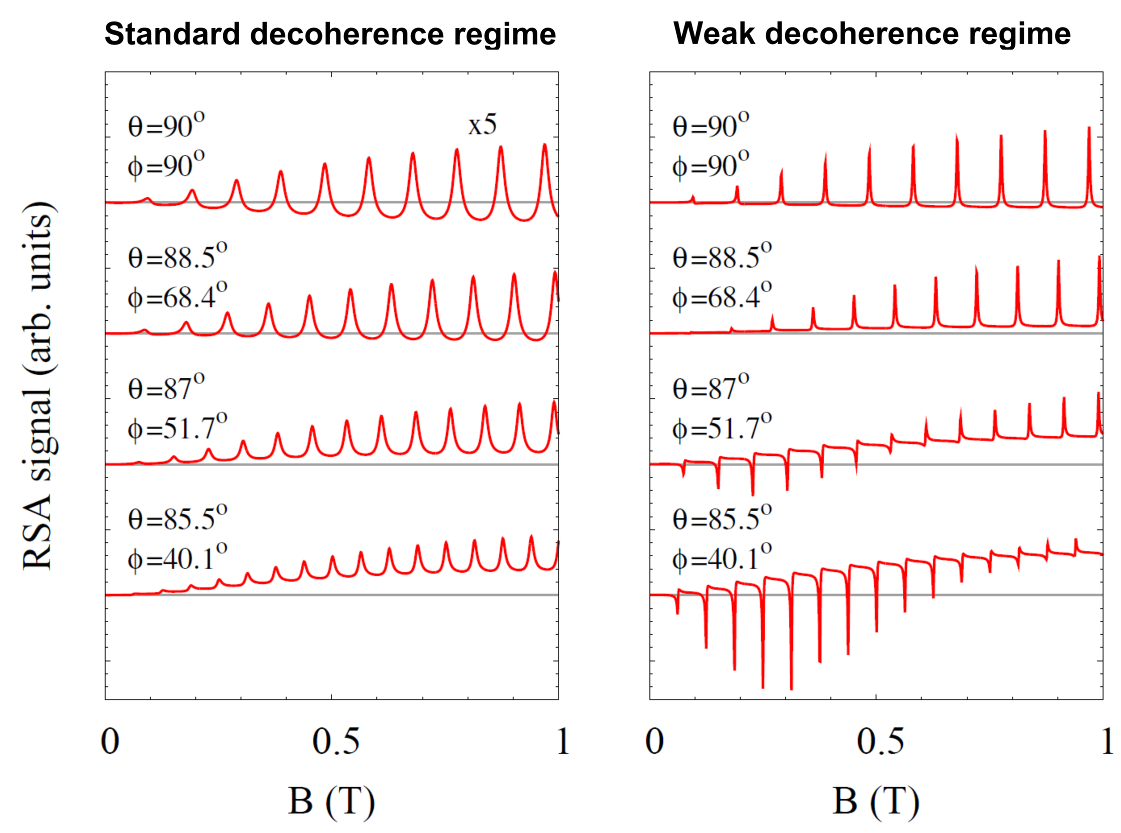
6. Results - RSA

- Expression for resonant spin amplification signal in tilted magnetic field (for small tilt angles):

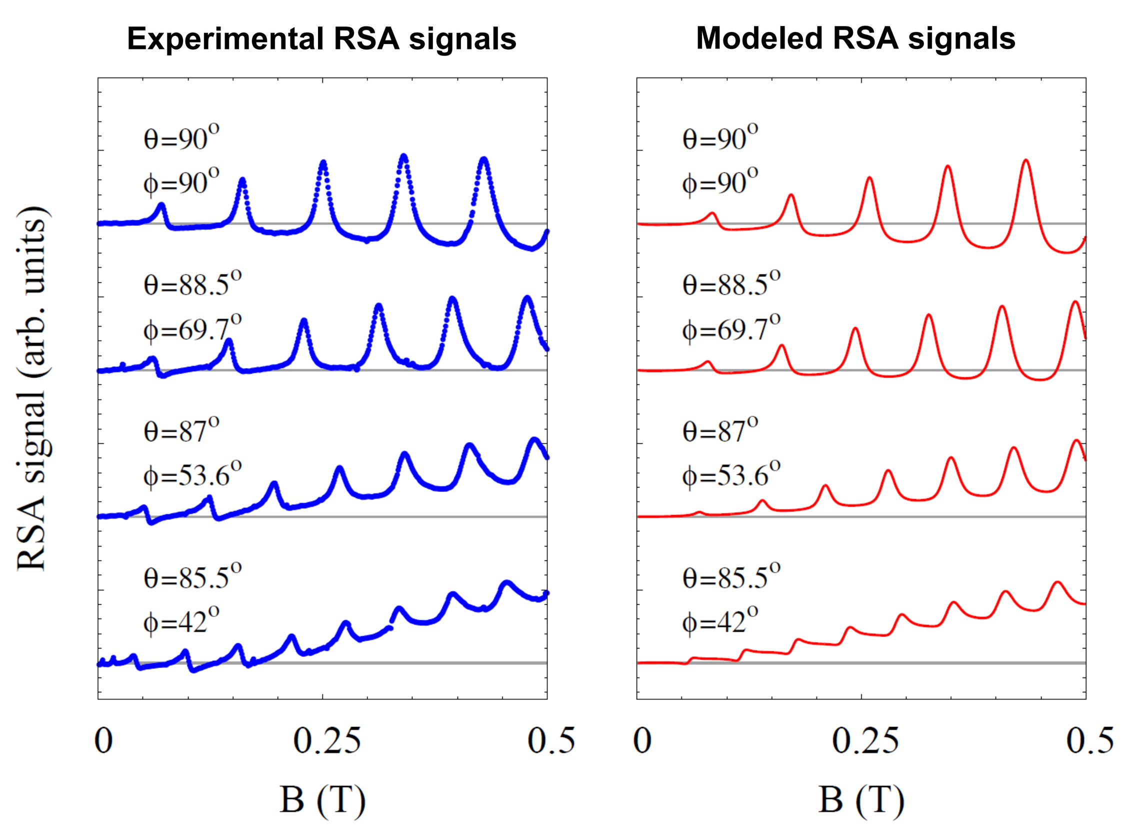
$$\Delta\Sigma^{(\mathrm{RSA})} = \frac{\sum_{i=1}^{3} A_i e^{-\lambda_i t_\mathrm{r}} - \sum_{i=4}^{5} A_i e^{-\lambda_i t_\mathrm{r}} + \mathrm{c.c.}}{Q\left(\left(\sum_{i=1}^{3} e^{-\lambda_i t_\mathrm{r}} - \sum_{i=4}^{5} e^{-\lambda_i t_\mathrm{r}} + \mathrm{c.c.}\right) - 1\right)}$$

$$\lambda_1 = \kappa_1,\quad \lambda_2 = \kappa_1 + 2\kappa_2,\quad \lambda_3 = \kappa_2 + i\omega_\mathrm{h},$$
$$\lambda_4 = 2\kappa_2,\quad \lambda_5 = \kappa_1 + \kappa_2 + i\omega_\mathrm{h}$$

- **Two regimes**: standard decoherence regime and weak decoherence regime.
- In both regimes **tilting the magnetic field** from the Voigt geometry results in **decrease in the spacings of the RSA peaks** (due to growing hole Larmor frequency) and the **positive drift of the average value of the signal together with the decrease of the oscillation amplitude** with growing magnetic field. The latter effect comes from the higher survival rate of the non-precessing component of spin polarization compared to the precessing one due to the removal of holes with more evenly distributed spin directions by trions with a larger Larmor frequency.
- For **larger decoherence rates** the RSA peaks become broader (their **halfwidths increase**) and their **heights get smaller** (similarly to the Voigt conguration).



Due to the complex interplay of numerator and denominator in the expression for RSA signal in the **weak decoherence regime**, the sign of the signal oscillations can change for magnetic fields up to some field B_0 (growing with the tilt angle), resulting in the **emergence of the inverted peaks.**



Experimental verification of the model: experimental details as in the TRFR case and the repetition rate of the laser system is 80 MHz. All the parameters of the model, apart from the tilt angle, are the same for all modeled curves. Also, to account for the inhomogeneous ensemble broadening of the hole g-factors, the modeled result was averaged according to a Gaussian distribution of g-factors.

7. Conclusions

- The obtained expressions for the angular dependence of decoherence rates allow to get insight into the effective T_1 and T_2 times for magnetic field applied along any axis by performing TRFR measurement in tilted magnetic field.
- The analytical expression for the RSA signal in tilted magnetic field allows to use the RSA technique for investigating the spin dynamics not only limited to the Voigt geometry.
- We predict that for long enough hole spin dephasing times it should be possible to observe inversion of the RSA peaks induced by tilted magnetic field.

See also: arXiv:1105.1338

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