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Theory of Kerr rotation and resonant spin amplification in p-doped nanostructures

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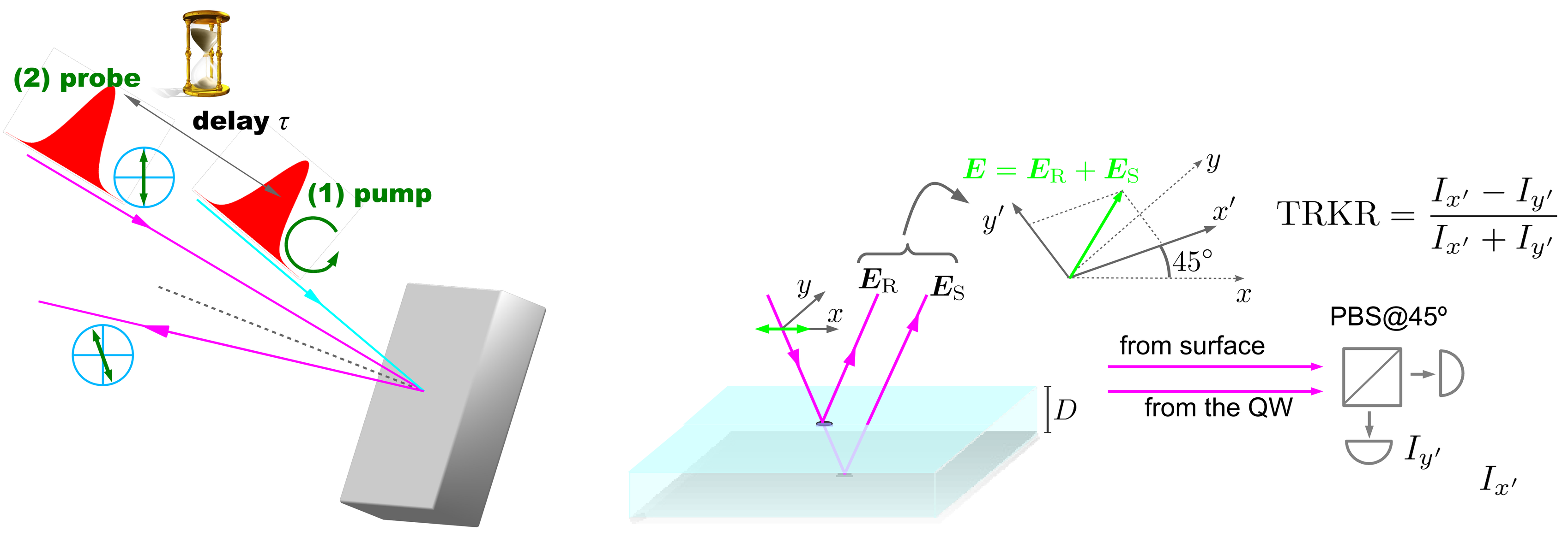
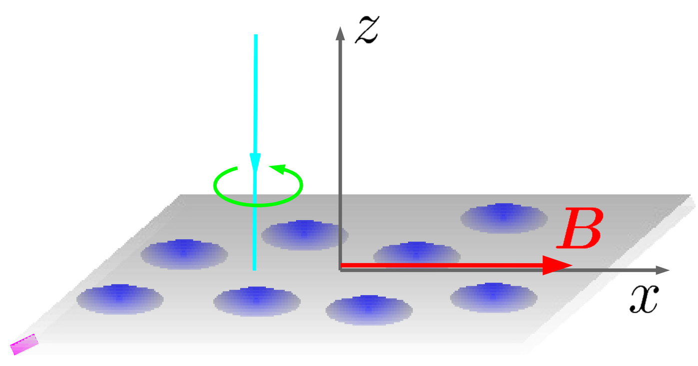
1. Motivation

- Spin dynamics and coherence is crucial for many applications in emerging technologies
  ⇒ growing interest in the studies of spin properties in semiconductors
- Time–resolved Kerr rotation is a very efficient method for the investigation of spin dynamics; interesting experiments have been performed quite recently
- Resonant spin amplification signal shows interesting, still unexplained behaviour for non-resonant excitation, including the formation of the zero-field peak



2. System

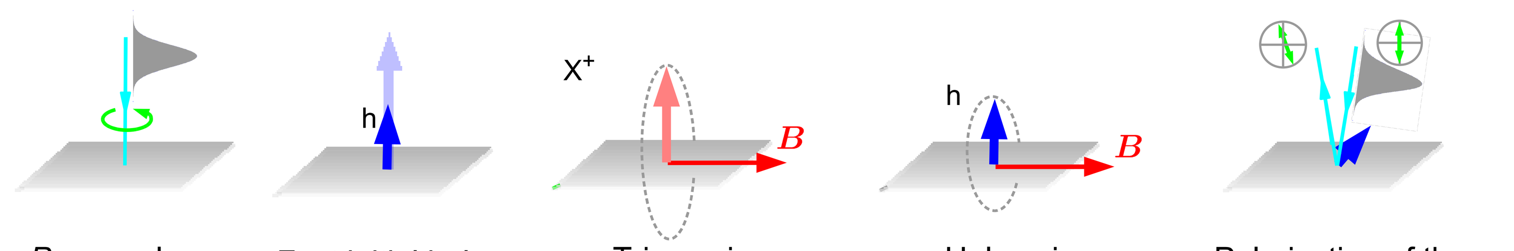
- Holes in a 2DHG weakly bound at trapping centers
  ⇒ ensemble of independent hole-trion systems
- Non-magnetic system
- Exact Voigt geometry
- Pump-probe configuration
- Pump pulse at normal incidence; probe pulse slightly tilted



3. Model

- **Hole–trion system** described by a 4-dimensional density matrix
  [P. Machnikowski, T. Kuhn, Phys. Rev. B **81**, 115306 (2010)]
- **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 reference signal reflected from the surface and the weak optical signal from the system

Phenomenology – magnetooptical Kerr effect



Pump pulse generates trion and hole spin polarization	Fast initial hole spin decoherence	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 calculated by finding the stationary point of the spin polarization transformation corresponding to one repetition of the pulsed laser:

$$\underbrace{\mathcal{L}_{LD}}_{\text{Long time scale decoherence}} \{ \underbrace{\mathcal{L}_{FD}}_{\text{Fast decoherence}} \{ \underbrace{\mathcal{L}_{P}}_{\text{Pump pulse}} \{ \underbrace{\mathbf{S}_{RSA}}_{\text{Initial spin state being transformed}} \} \} \} = \underbrace{\mathbf{S}_{RSA}}_{\text{Final spin state equal to initial one}}$$

The inhomogenous broadening of the hole g-factors is included (Gaussian distribution)

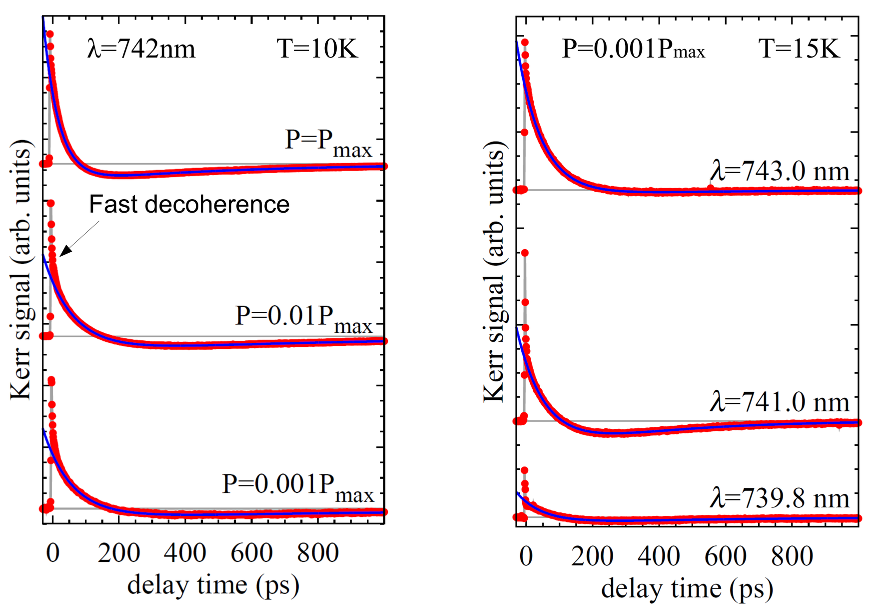
4. Dynamics

- Pump pulse generates trion and hole spin polarization; the hole polarization survives recombination
- Optical selection rules with respect to the structure axis
- Fast initial spin decay takes place on a picosecond time scale after the excitation
- Analytical solution for the precession + dephasing
- **TRKR signal** proportional to the **spin polarization** at the arrival of the probe pulse
  [P. Machnikowski, T. Kuhn, Phys. Rev. B **81**, 115306 (2010); I. A. Yugova *et al.* Phys. Rev. B **80**, 104436 (2009)]
- **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 - TRKR

- Kerr signal in the absence of a magnetic field

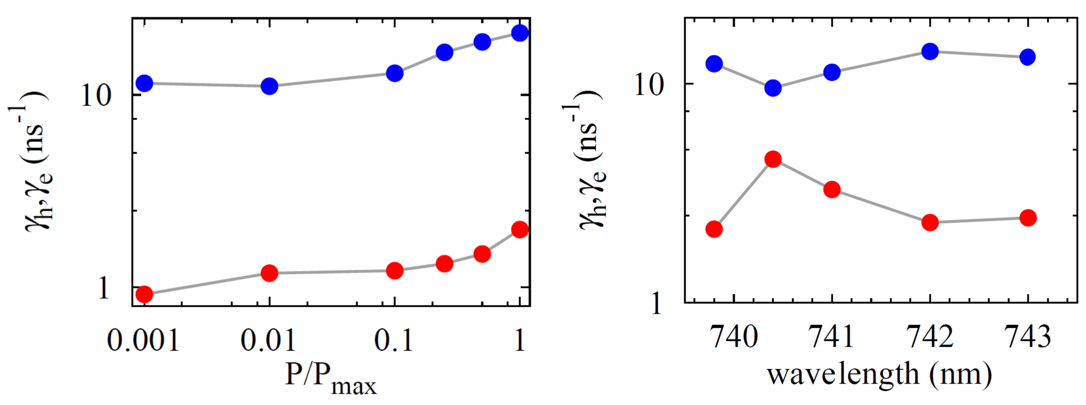
$$\Delta\Sigma = a e^{-\gamma_t t} - b e^{-\gamma_h t} \quad ; \quad a = \left[1 + \frac{\gamma_R}{\gamma_t - \gamma_h}\right]\Sigma_t^{(0)}, \quad b = \left[\Sigma_h^{(0)} + \frac{\gamma_R}{\gamma_t - \gamma_h}\Sigma_t^{(0)}\right]$$



- $\Sigma_h^{(0)}$ - Initial (after the fast decoherence) hole spin polarization
- $\Sigma_t^{(0)}$ - Initial trion spin polarization
- γ_h - Hole spin dephasing rate
- γ_t - Sum of the trion spin decoherence rate and the radiative decay rate: $\gamma_t = \mu + \gamma_R$

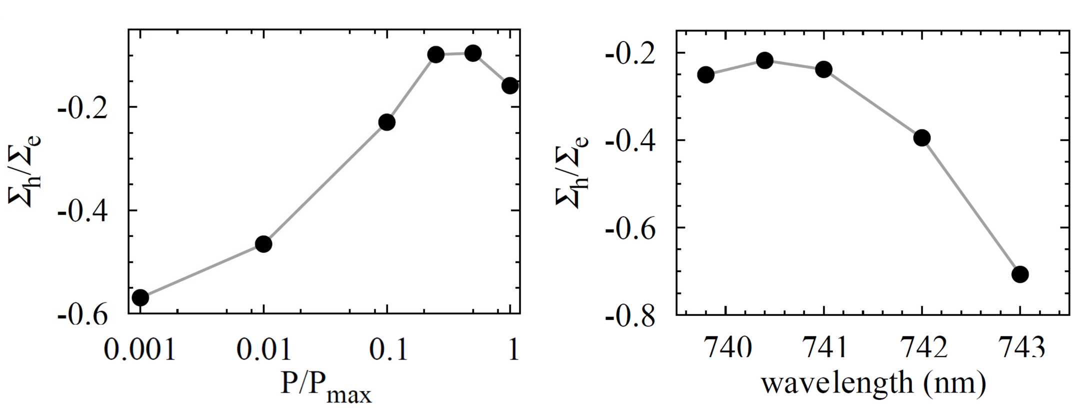
Fitting to the experimental results for Kerr rotation

- Dependence of decay rates



Relatively little dependence on the excitation power and wavelength (except for high powers, probably due to heating). One of the decay rates (blue) is close to the recombination rate, so we link it with the trion and the red one is connected with the hole.

- The ration of the hole-to-trion spin polarization just after the fast initial decay

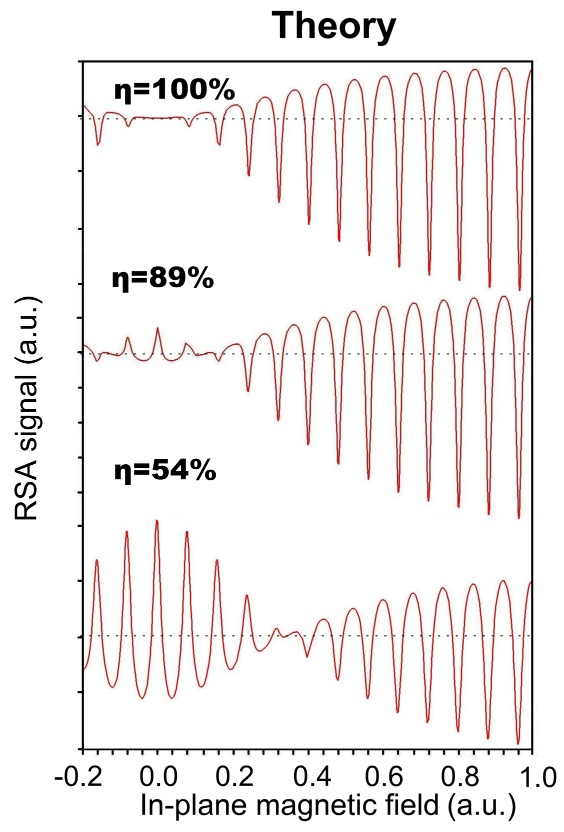


The absolute value of the ratio drops down for more detuned pulses and for higher powers. This leads to a negative total spin polarization at these conditions and is essential for the formation of the zero-field RSA peak. We attribute this effect to the supply of excess energy caused by a blue-shifted or high-power pump pulse.

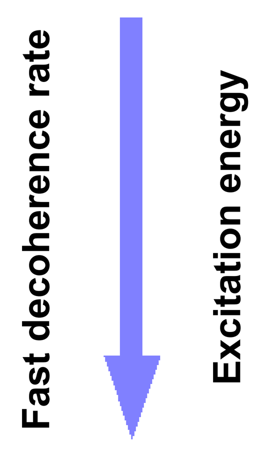
6. Results - RSA

- Forming of a zero-field peak

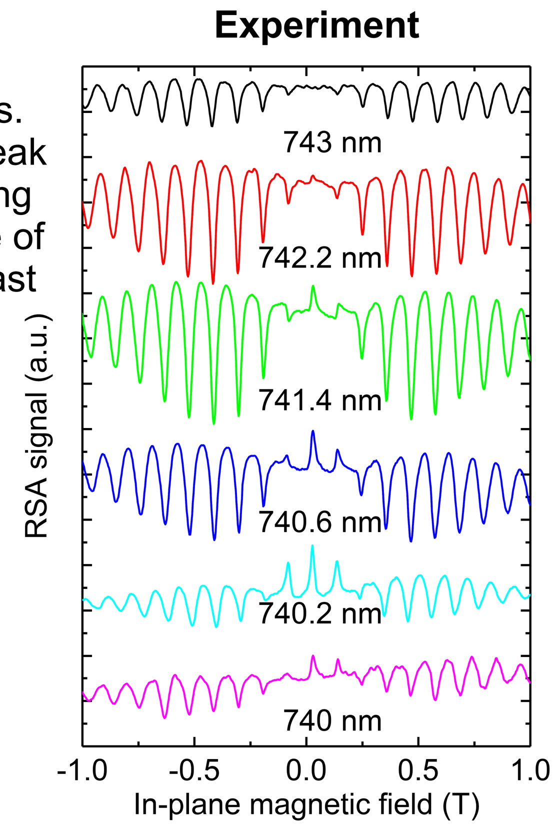
Theory



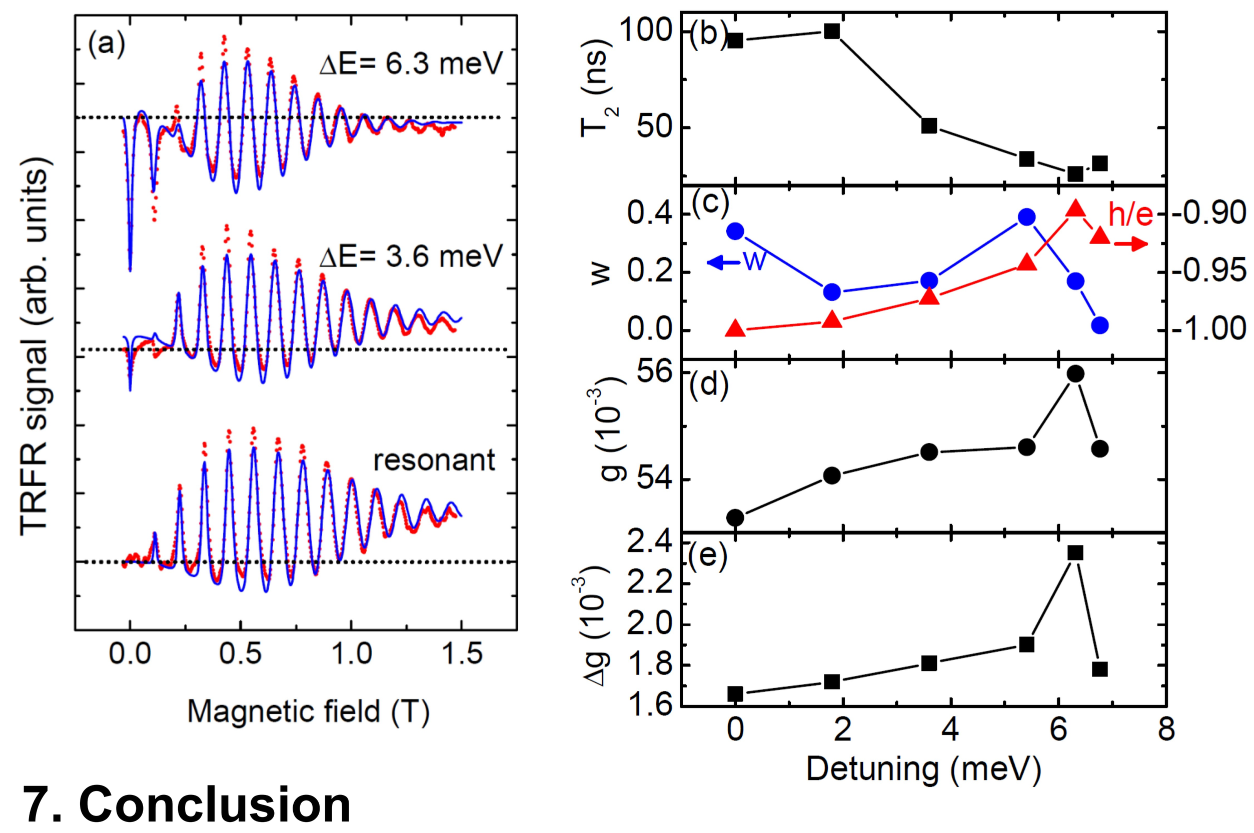
RSA signal obtained from analytical formula vs experimental measurements. Formation of the zero-field peak can be seen due to increasing fast decoherence (η - degree of hole spin polarization after fast decoherence).



Experiment



- Parameters relevant to the hole spin dynamics extracted from the best fits to the experimental data



Intrinsic (homogeneous) spin coherence time

The ratio of hole and electron spin polarizations after optical orientation

g-factor distribution in the ensemble: mean value and the standard deviation

7. Conclusion

- The Kerr signal decay in the absence of magnetic field consists of two parts: trion radiative decay and hole spin decoherence
- The negative Kerr signal observed in the experiment for nonresonant excitation is related to the ratio of the hole-to-trion polarization after the fast initial decay
- The initial hole-trion spin imbalance (due to fast decoherence) may lead to the formation of the zero-field peak in RSA signal
- Detuning does not directly contribute to the RSA signal. Its role in the appearance of the zero-field peak may be to provide excess energy that increases the initial dephasing
- Off-resonant excitation conditions in low magnetic fields at low temperatures assure a long lifetime of the optically oriented hole spins

See also: Phys. Rev. B **84**, 085327 (2011)