Microscopic Theory for the Doppler Velocimetry of Spin Propagation in Semiconductor Quantum Wells

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EP2DS, July 2013, Wroclaw, Poland

Introduction

- Understanding the spin transport phenomena is crucial to the realization of the spintronic devices, whose implementation requires the ability to control and maintain spin coherence over a long distance.
- Transient spin grating spectroscopy has been used to quantitatively study the spin transport in semiconductors by monitoring the temporal evolution of the optical excited spin density wave [1].
- Very recently the effect of the spin drifting was studied with the transient spin grating together with the Doppler velocimity [2].

[1] Weber *et al.*, Nature **437**, 1330 (2005)
[2] Yang *et al.*, Nat. Phys. **8**, 153 (2012)

KSBEs and Analytical Solution to Simplified KSBEs

$$\frac{\partial \rho_{\mathbf{k}}(x,t)}{\partial t} = -eE(x)\frac{\partial \rho}{\partial k_x} + \frac{k_x}{m^*}\frac{\partial \rho}{\partial x} + i[\mathbf{h}_{\rm tot}(\mathbf{k})\cdot\boldsymbol{\sigma}/2, \rho] + \left.\frac{\partial \rho}{\partial t}\right|_s$$

[3] M. W. Wu, J. H. Jiang, and M. Q. Weng, Phys. Rep. **493**, 61 (2010)

When the spin-orbit coupling is weak and the inelastic scattering is neglected, one obtains simplified KSBEs

$$\frac{\partial \mathbf{S}}{\partial t} = D\frac{\partial^2 \mathbf{S}}{\partial x^2} + v_d\frac{\partial \mathbf{S}}{\partial x} - \mathfrak{R}\cdot\mathbf{S} + 2D\bar{\mathbf{h}}\times\frac{\partial \mathbf{S}}{\partial x} + v_d\bar{\mathbf{h}}'\times\mathbf{S}$$

The simplified KSBEs can be solved analytically

$$S_z(x,t) = S_z(q,t)\cos[qx-\phi(t)] = S_z(q,0)\exp[-(Dq^2+1/\tau_s)t]/2$$
$$\times\{e^{-2Dq_0qt}\cos[qx - v_d(q+q_0')t] + e^{2Dq_0qt}\cos[qx - v_d(q-q_0')t]\}$$

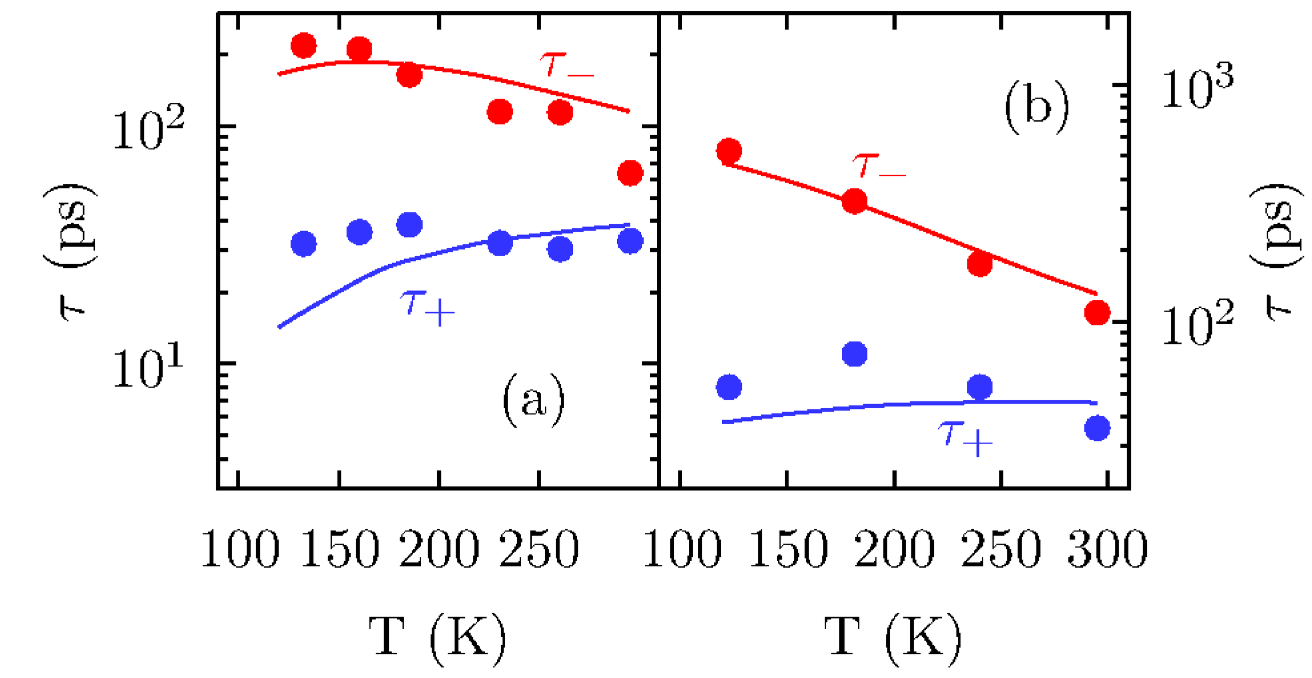
- Without spin drifting $v_d = 0$, the spin density wave decays biexponentially with fast and slow rates.
- With spin drifting but without spin precession the phase shift $\phi(t) = qv_d t$, which is equivalent to a Doppler shift.
- With both spin drifting and coherent spin precession, the phase shift is normal Doppler like at early stage, but deviates from this simple relation and behaviors anomalously at later stage.
- The crossover time from normal to anomalous behaviors is inverse proportional to spin diffusion coefficient, spin-orbit coupling and wave vector.

Conclusion

- We provide a microscopic theory for the temporal evolution of spin density wave and Doppler velocimetry.
- Without spin drifting, the spin density wave decay biexponentially with fast and slow rates, from which the spin diffusion coefficient, relaxation rate can be extracted and spin injection length correctly constructed.
- We analytically show that in the presence of spin drifting and coherent spin precession, the phase shift of the spin density wave is a normal Doppler like at the early stage but becomes anomalous at later stage, with the crossover time inverse proportional to the spin diffusion coefficient, spin-orbit coupling and wave vector of spin den.
- Our numerical results agree every well with the experimental data.
- We point out that the crossover time becomes large at high temperature, one needs longer time to determine the robustness of coherent spin precession. Our numerical results justify that the coherent spin precession is robust up to the room temperature.

Numerical Results for Spin Relaxation

Spin relaxation times as functions of temperature for two wave vectors. The curves are from the theoretical results, the symbols are experimental data from Ref. [1].



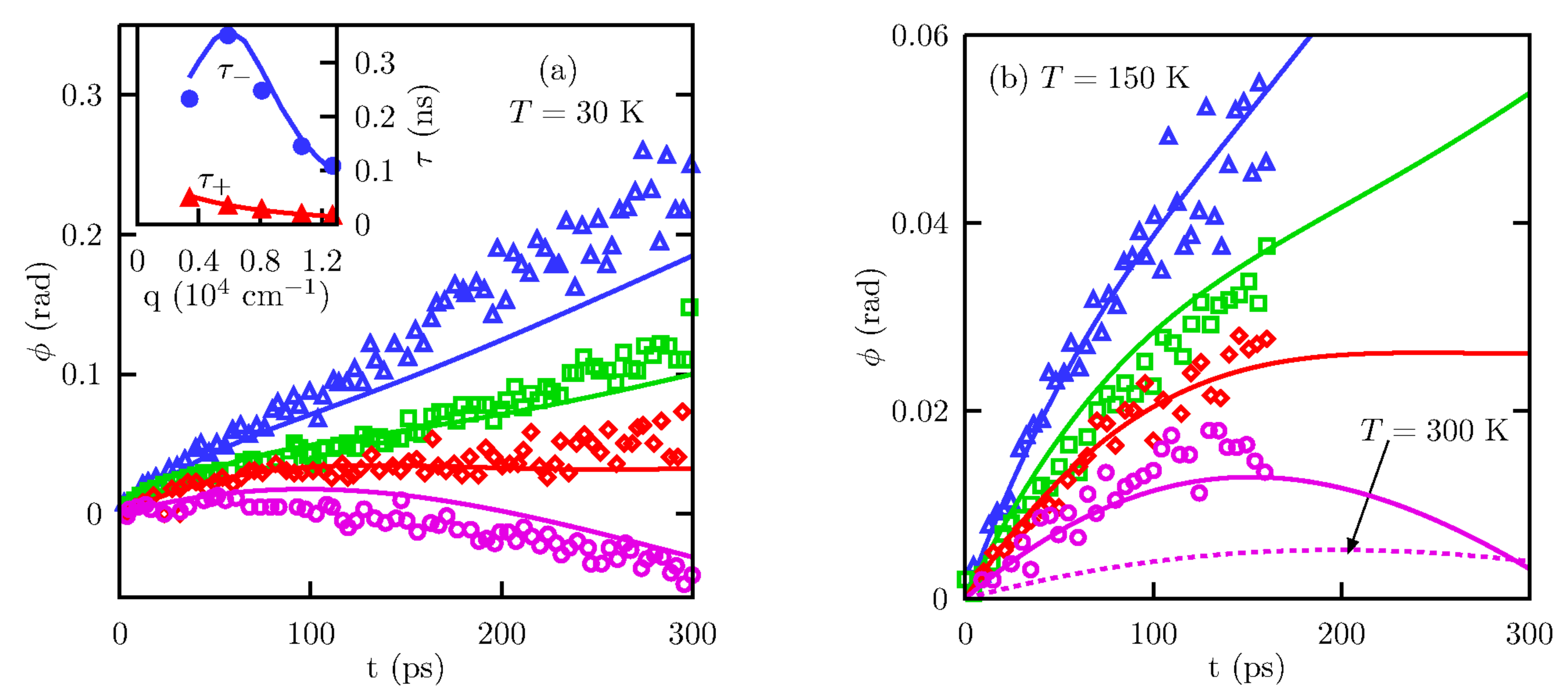
- Numerical calculations justify that spin density wave decays biexponentially with fast and slow rates.
- The average of the two rates can be well fitted by a quadratic function of the form $D_s q^2 + 1/\tau_s$, with D being the spin diffusion coefficient. The difference of the rates can be fitted by a linear function of the form $cq + d$.
- The spin diffusion is smaller than the charge diffusion coefficient due to the spin Coulomb drag.
- The correct spin diffusion length $L_s = 2D_s/\sqrt{|c^2 - 4D_s(1/\tau_s - d)|}$ which can be quite different from $L_s = \sqrt{D_s\tau_s}$ commonly used by the society.

Numerical Results for Phase Shift

Doppler phase shift under an applied electric field of 2 V/cm at (a) T=30 and (b) 150 K for different wave vectors:

- q=0.34× 10^4cm^{-1}
- q=0.59× 10^4cm^{-1}
- q=0.81× 10^4cm^{-1}
- q=1.01 × 10^4cm^{-1}

The curves are from the theoretical calculations. The sysmols are the experimental data from Ref. [2].



- Including all relevant scattering.
- No free parameters: All material and structure parameters are directly from experimental data or from fitting other experimental results.
- The numerical results agree very well with the experimental data.
- Contradict to the conclusion of Ref. [2], the coherent spin precession is robust up to the room temperature.

References:
M. Q. Weng, M. W. Wu and H. L. Cui, JAP **103**, 063714 (2008)
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