Electron spin relaxation in bilayer graphene and monolayer MoS_2

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Abstract

Electron spin relaxation due to the D'yakonov-Perel' mechanism is investigated in bilayer graphene with only the lowest conduction band being relevant [1]. We construct the spin-orbit coupling $\mathbf{\Omega}^{\mu}(\mathbf{k})$ from the symmetry group analysis where the coefficients are obtained by fitting to the numerical results following the work by Konschuh *et al.* [Phys. Rev. B **85** (2012) 115423] from first principles. Specifically, $\mathbf{\Omega}_x^{\mu}(\mathbf{k}) = \alpha_1(k)\sin\theta_{\mathbf{k}} + \mu[\alpha_2(k)\sin 2\theta_{\mathbf{k}} + \alpha_3(k)\sin 4\theta_{\mathbf{k}}]$, $\mathbf{\Omega}_y^{\mu}(\mathbf{k}) = -\alpha_1(k)\cos\theta_{\mathbf{k}} + \mu[\alpha_2(k)\cos 2\theta_{\mathbf{k}} - \alpha_3(k)\cos 4\theta_{\mathbf{k}}]$ and $\mathbf{\Omega}_z^{\mu}(\mathbf{k}) = \mu\beta_1(k) + \beta_2(k)\cos 3\theta_{\mathbf{k}}$ with $\mu = 1(-1)$ for K(K'). The leading term of the out-of-plane component $\mathbf{\Omega}_z^{\mu}(\mathbf{k})$ serves as a Zeeman-like term with opposite effective magnetic fields in the two valleys. This provides an intervalley inhomogeneous broadening, which leads to intervalley spin relaxation in the presence of intervalley scattering. The intervalley electron-phonon scattering strongly suppresses the in-plane spin relaxation time at high temperature whereas the intervalley short-range scattering plays an important role in the in-plane spin relaxation especially at low temperature. A marked nonmonotonic temperature dependence of the in-plane spin relaxation time with a minimum of several hundred picoseconds is predicted without short-range scatterers. This minimum is comparable to the experimental data. The nonmonotonic behavior is attributed to the crossover between the weak and strong intervalley electron-phonon scattering. In addition, a peak is predicted in the electron density dependence of the in-plane spin relaxation time at low temperature. We also find a rapid decrease of the in-plane spin relaxation time with increasing initial spin polarization at low temperature, which is opposite to the situation in semiconductors and single-layer graphene. Moreover, we carry out a detailed comparison with the existing experiments of Han and Kawakami [Phys. Rev. Lett. **107** (2011) 047207], Avsar *et al.* [Nano Lett. **11** (2011) 2363] and Yang *et al.* [Phys. Rev. Lett. **107** (2011) 047206] in the temperature and electron-density dependences of the spin relaxation time as shown in Fig. 1. Excitingly, our results are comparable to the experimental data at high temperature without short-range scatterers, indicating the importance of the intervalley spin relaxation channel due to intervalley electron-phonon scattering in the in-plane spin relaxation at high temperature. As for low temperature, with the short-range scatterers included, the spin relaxation time from our calculation shows a fairly good agreement with the experimental data.

Similar to bilayer graphene, the intervalley spin relaxation process due to the D'yakonov-Perel' mechanism also exists in the new two-dimensional material, i.e., monolayer MoS_2 [2]. However, in contrast to bilayer graphene, a monotonic decrease of the in-plane spin relaxation time in the temperature dependence is observed since the intervalley electron-phonon scattering is always in the weak scattering limit in monolayer MoS_2. In addition to the intervalley process, the intravalley one due to the D'yakonov-Perel' mechanism is also investigated [3]. From Fig. 2, we find that the intravalley process plays a more important role at low temperature whereas the intervalley one becomes more important at high temperature. At the temperature in between, the leading process of the in-plane spin relaxation changes from the intervalley to intravalley one as the electron density increases. Moreover, we also find that the intravalley process is dominated by the electron-electron Coulomb scattering even with high impurity density. In addition to the D'yakonov-Perel' mechanism, we also take into account the Elliot-Yafet one with the intra- and inter-valley processes included [3]. However, the contribution of the Elliot-Yafet mechanism to the in-plane spin relaxation is negligible compared with that of the D'yakonov-Perel' one due to the marginal interband mixing for in-plane spins.

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References

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[2] L. Wang and M. W. Wu, arXiv:1305.3361.
[3] L. Wang and M. W. Wu, arXiv:1312.6985.

Figures

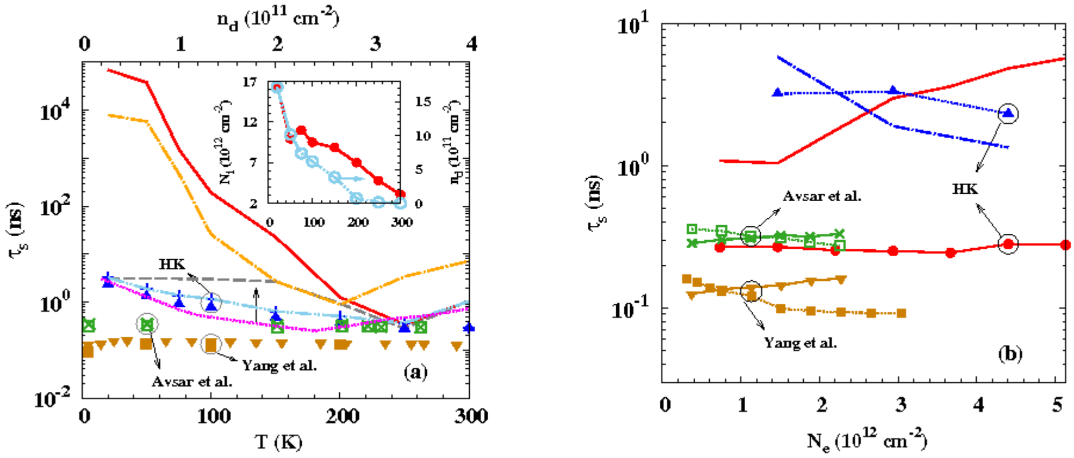

Fig. 1: Comparison of (a) temperature dependence (b) electron density dependence of the in-plane spin relaxation time with the experiment data of Han and Kawakami (HK), Avsar *et al.* and Yang *et al*.. Curves without symbols represent our numerical calculation. (a) Red solid (light blue double-dot-dashed) curve stands for our calculation corresponding to the experiment of HK without (with) short-range scatterers.

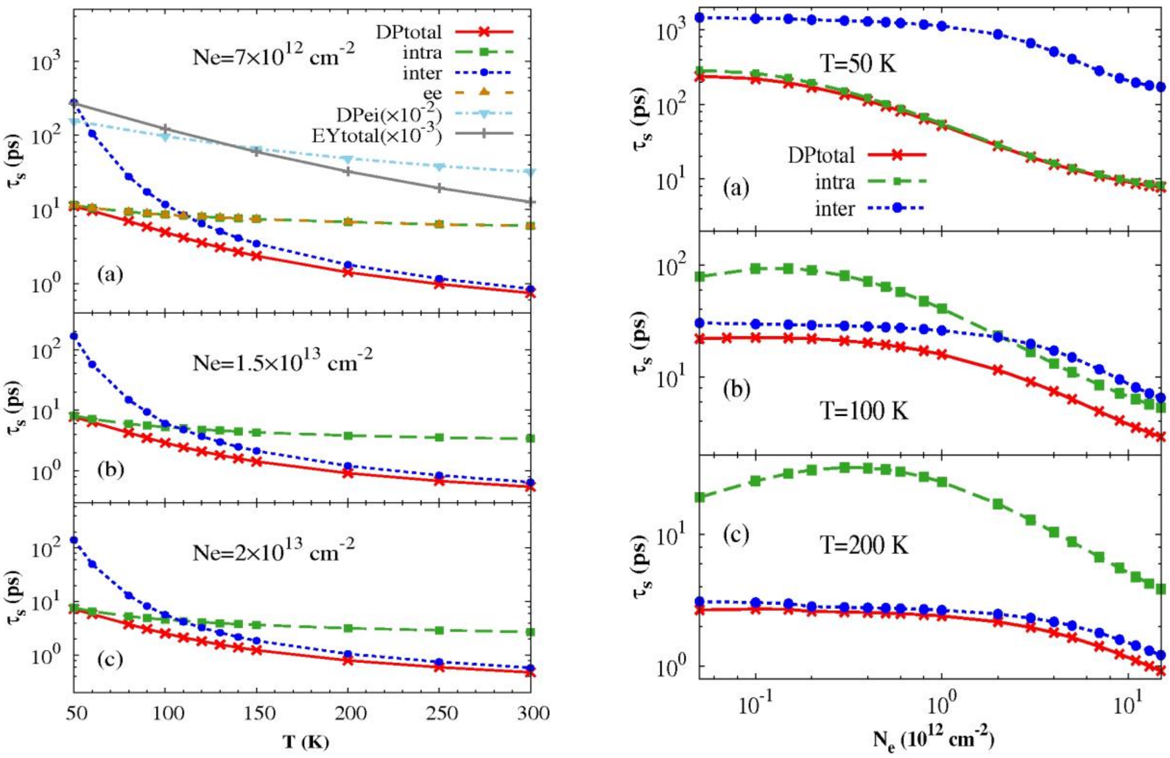

Fig. 2: Left: total in-plane spin relaxation time (crosses) due to the D'yakonov-Perel' mechanism and that calculated with only the intravalley (filled squares) or intervalley process (filled dots) included as function of temperature. In addition, in (a), curve with filled triangle up (filled triangle down) stands for the spin relaxation time due to the D'yakonov-Perel' mechanism with only the electron-electron Coulomb (electron-impurity) scattering whereas the one with plus signs represents the in-plane spin relaxation time due to the Elliot-Yafet mechanism; Right: total in-plane spin relaxation time (crosses) due to the D'yakonov-Perel' mechanism and that calculated with only the intravalley (filled squares) or intervalley process (filled dots) included as function of the electron density. The impurity density N_i=0.1N_e.