Electron spin relaxation in bilayer graphene

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We investigate the electron spin relaxation due to the D'yakonov-Perel' mechanism in bilayer graphene with only the lowest conduction band being relevant. The spin-orbit coupling $\mathbf{\Omega}^{\mu}(\mathbf{k})$ is constructed from the symmetry group analysis with the parameters obtained by fitting to the numerical calculation according to the latest report by Konschuh *et al.* [1] from first principles. Its three components can be written as $\Omega_x^{\mu}(\mathbf{k}) = \alpha_1(k)\sin\theta_{\mathbf{k}} + \mu[\alpha_2(k)\sin 2\theta_{\mathbf{k}} + \alpha_3(k)\sin 4\theta_{\mathbf{k}}]$, $\Omega_y^{\mu}(\mathbf{k}) = -\alpha_1(k)\cos\theta_{\mathbf{k}} + \mu[\alpha_2(k) \times\cos 2\theta_{\mathbf{k}} - \alpha_3(k)\cos 4\theta_{\mathbf{k}}]$ and $\Omega_z^{\mu}(\mathbf{k}) = \mu\beta_1(k) + \beta_2(k)\cos 3\theta_{\mathbf{k}}$, with μ standing for the two valleys. The leading term of the out-of-component $\Omega_z^{\mu}(\mathbf{k})$ shows a Zeeman-like term with opposite effective magnetic fields in the two valleys. This Zeeman-like term opens a spin relaxation channel in the presence of intervalley scattering. The intervalley electron-phonon scattering, which has not been reported in the previous literature, 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 in the absence of short-range scatterers. This minimum is comparable to the experimental data. The nonmonotonic behavior originates from the crossover between the weak and strong intervalley electron-phonon scattering. Moreover, a peak in the electron density dependence of the in-plane spin relaxation time at low temperature is predicted. We also find a rapid decrease in the in-plane spin relaxation time with increasing initial spin polarization at low temperature, which is opposite to the situation in both semiconductors and single-layer graphene. A strong anisotropy between the out-of- and in-plane spin relaxations at high temperature is also revealed. Detailed comparisons of the temperature and electron density dependences of the spin relaxation with the existing experiments of Han and Kawakami [2], Avsar *et al.* [3] and Yang *et al.* [4] are reported. Our result is comparable to the experimental data at high temperature in the absence of short-range scattering, indicating that the intervalley electron-phonon scattering plays an important role in the in-plane spin relaxation at high temperature. As for low temperature, with the inclusion of the short-range scattering, the spin relaxation time from our calculation agrees fairly well with the experimental data.

[1] S. Konschuh, M. Gmitra, D. Kochan, and J. Fabian, Phys. Rev. B **85**, 115423 (2012).
[2] W. Han and R. K. Kawakami, Phys. Rev. Lett. **107**, 047207 (2011).
[3] A. Avsar, T.-Y. Yang, S. Bae, J. Balakrishnan, F. Volmer, M. Jaiswal, Z. Yi, S. R. Ali, G. Güntherodt, B. H. Hong, B. Beschoten, and B. Özyilmaz, Nano Lett. **11**, 2363 (2011).
[4] T.-Y. Yang, J. Balakrishnan, F. Volmer, A. Avsar, M. Jaiswal, J. Samm, S. R. Ali, A. Pachoud, M. Zeng, M. Popinciuc, G. Güntherodt, B. Beschoten, and B. Özyilmaz, Phys. Rev. Lett. **107**, 047206 (2011).
[5] L. Wang and M. W. Wu, arXiv:1302.5880.