Electron Spin Relaxation in Bilayer Graphene and Monolayer MoS_2

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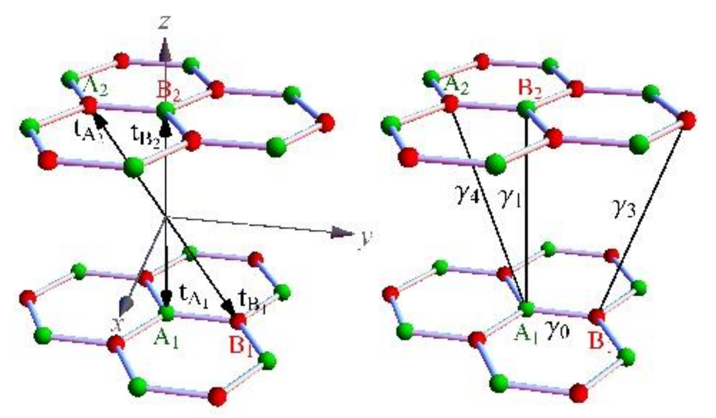
Introduction

Very recently, some attention has been devoted to the spin relaxation in bilayer graphene (BLG). Experimentally, the spin relaxation times (SRTs) are reported to be of the order of 0.01-1 ns. In the present work, with the electron-electron Coulomb, (both the intra- and intervalley) electron-phonon, and possible short-range as well as long-range electron-impurity scatterings explicitly included, we investigate the electron spin relaxation of the lowest conduction band due to the D'yakonov-Perel' (DP) mechanism in BLG by the kinetic spin Bloch equation (KSBE) approach.

Model

The spinless effective Hamiltonian near the K (K') points:

$$H^{\mu}(\mathbf{k}) = \begin{pmatrix} \Delta+V & \gamma_0 p & \gamma_4 p^* & \gamma_1 \\ \gamma_0 p^* & +V & \gamma_3 p & \gamma_4 p^* \\ \gamma_4 p & \gamma_3 p^* & -V & \gamma_0 p \\ \gamma_1 & \gamma_4 p & \gamma_0 p^* & \Delta - V \end{pmatrix}$$



$p(\mathbf{k}) = -\sqrt{3}a(\mu k_x - ik_y)/2$ μ=1 (-1) for K (K').

By incorporating the spin degree of freedom, the effective Hamiltonian of the lowest conduction band:

$$H_{\mathrm{eff}}^{\mu} = \varepsilon_{\mu\mathbf{k}} + \mathbf{\Omega}^{\mu}(\mathbf{k})\cdot\boldsymbol{\sigma}/2$$

Group C_3: $\Omega_x^{\mu}(\mathbf{k}) = \alpha_1(k)\sin\theta_{\mathbf{k}} + \mu[\alpha_2(k)\sin 2\theta_{\mathbf{k}} + \alpha_3(k)\sin 4\theta_{\mathbf{k}}]$,

$$\Omega_y^{\mu}(\mathbf{k}) = -\alpha_1(k)\cos\theta_{\mathbf{k}} + \mu[\alpha_2(k)\cos 2\theta_{\mathbf{k}} - \alpha_3(k)\cos 4\theta_{\mathbf{k}}],$$

$$\Omega_z^{\mu}(\mathbf{k}) = \mu\beta_1(k) + \beta_2(k)\cos 3\theta_{\mathbf{k}}.$$

Konschuh *et al*., PRB **85**, 115423 (2012)

KSBEs

$$\partial_t \hat{\rho}_{\mu\mathbf{k}} = \partial_t \hat{\rho}_{\mu\mathbf{k}}|_{\mathrm{coh}} + \partial_t \hat{\rho}_{\mu\mathbf{k}}|_{\mathrm{scat}}^{\mathrm{intra}} + \partial_t \hat{\rho}_{\mu\mathbf{k}}|_{\mathrm{scat}}^{\mathrm{inter}}$$

$$\partial_t \hat{\rho}_{\mu\mathbf{k}}|_{\mathrm{scat}}^{\mathrm{intra}} = \partial_t \hat{\rho}_{\mu\mathbf{k}}|_{\mathrm{ee}} + \partial_t \hat{\rho}_{\mu\mathbf{k}}|_{\mathrm{ei}}^{\mathrm{LR}} + \partial_t \hat{\rho}_{\mu\mathbf{k}}|_{\mathrm{ei}}^{\mathrm{intra,SR}} + \partial_t \hat{\rho}_{\mu\mathbf{k}}|_{\mathrm{ep}}^{\mathrm{intra}}$$

$$\partial_t \hat{\rho}_{\mu\mathbf{k}}|_{\mathrm{scat}}^{\mathrm{inter}} = \partial_t \hat{\rho}_{\mu\mathbf{k}}|_{\mathrm{ep}}^{\mathrm{inter}} + \partial_t \hat{\rho}_{\mu\mathbf{k}}|_{\mathrm{ei}}^{\mathrm{inter,SR}}$$

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

Spin Relaxation due to Intervalley Relaxation Channel

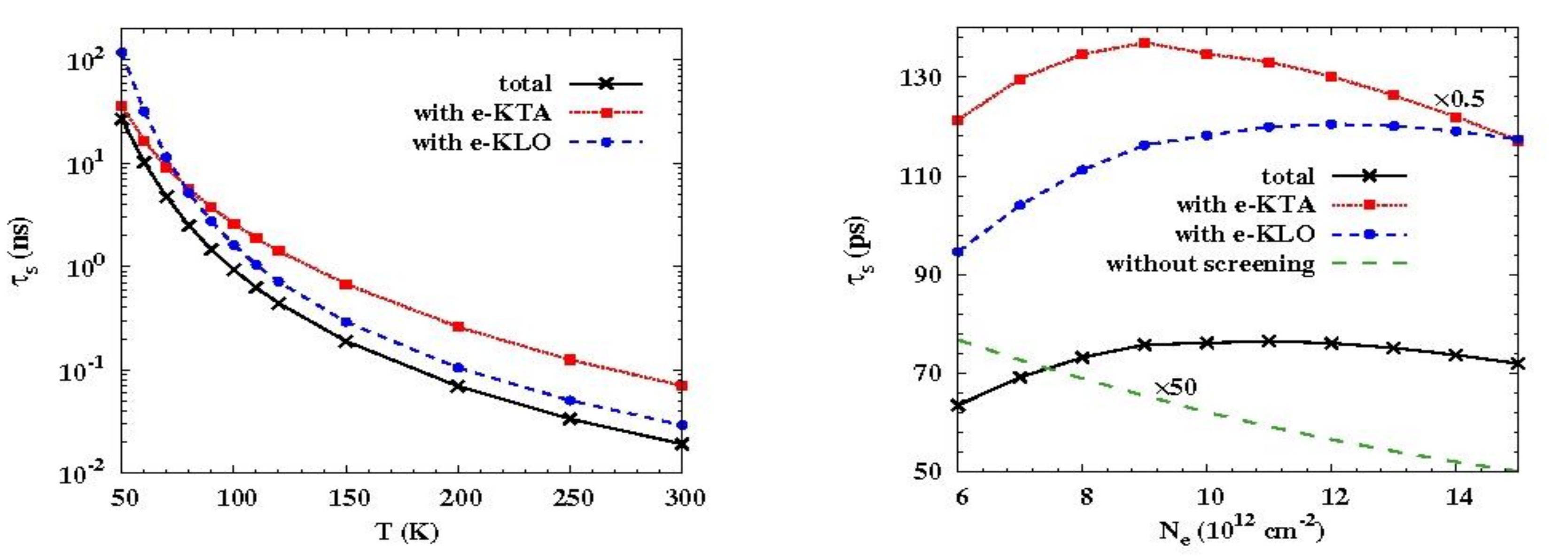
$$\tau_{s_{x,y}}(k) = \begin{cases} \tau_v(k) \text{ weak scattering } [|\beta_1(k)|\tau_v(k) \geq 1], \\ 2/[|\beta_1(k)|^2\tau_v(k)] \text{ strong scattering } [|\beta_1(k)|\tau_v(k) << 1]. \end{cases}$$

$\tau_v(k)$: intervalley momentum scattering time

The system always in the degenerate regime: $\tau_{s_{x,y}}(k) \approx \tau_{s_{x,y}}(k_F)$.

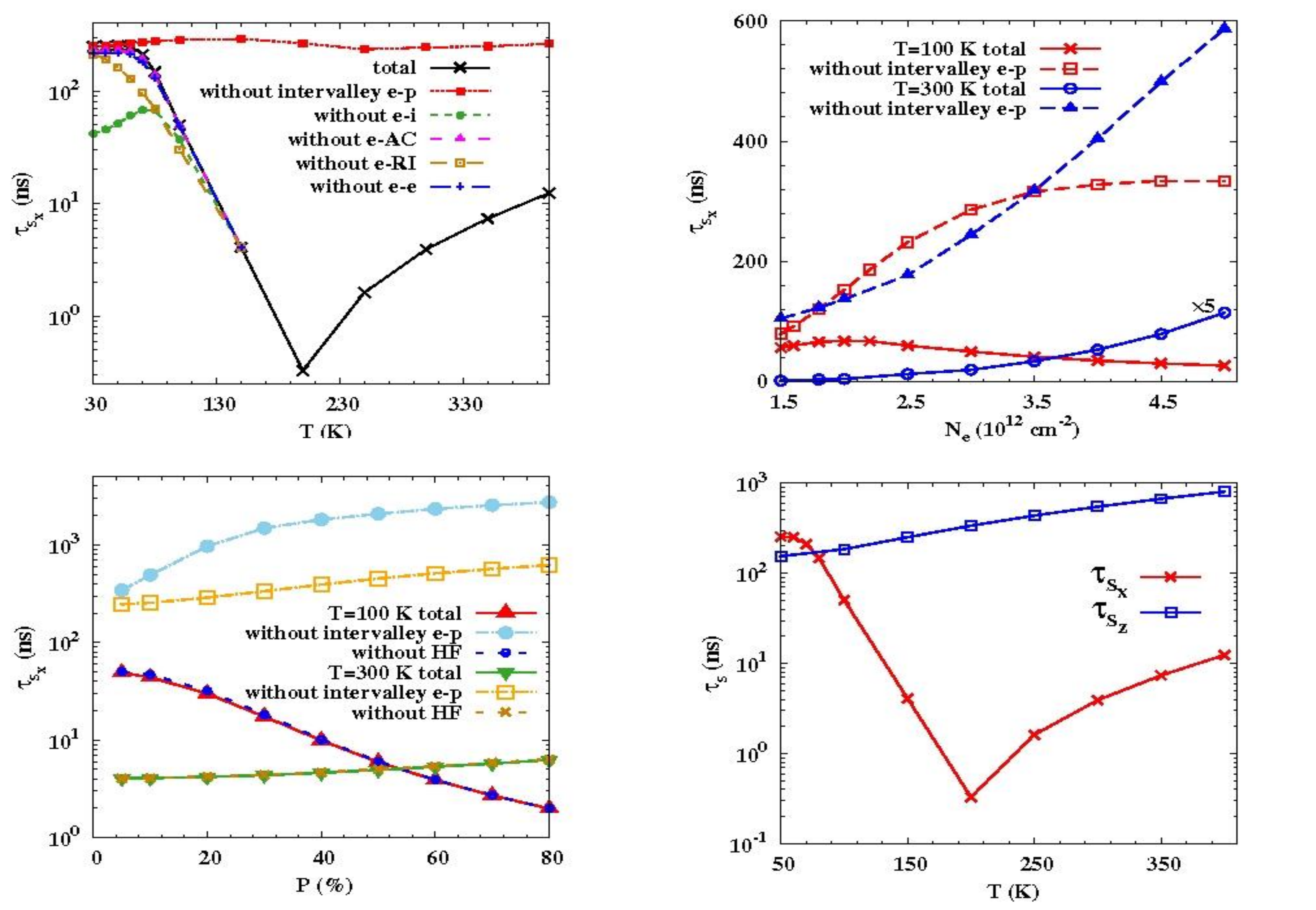
P. Zhang, Y. Zhou, and M. W. Wu, JAP **112**, 073709 (2012)

Electron Spin Relaxation in Monolayer MoS_2



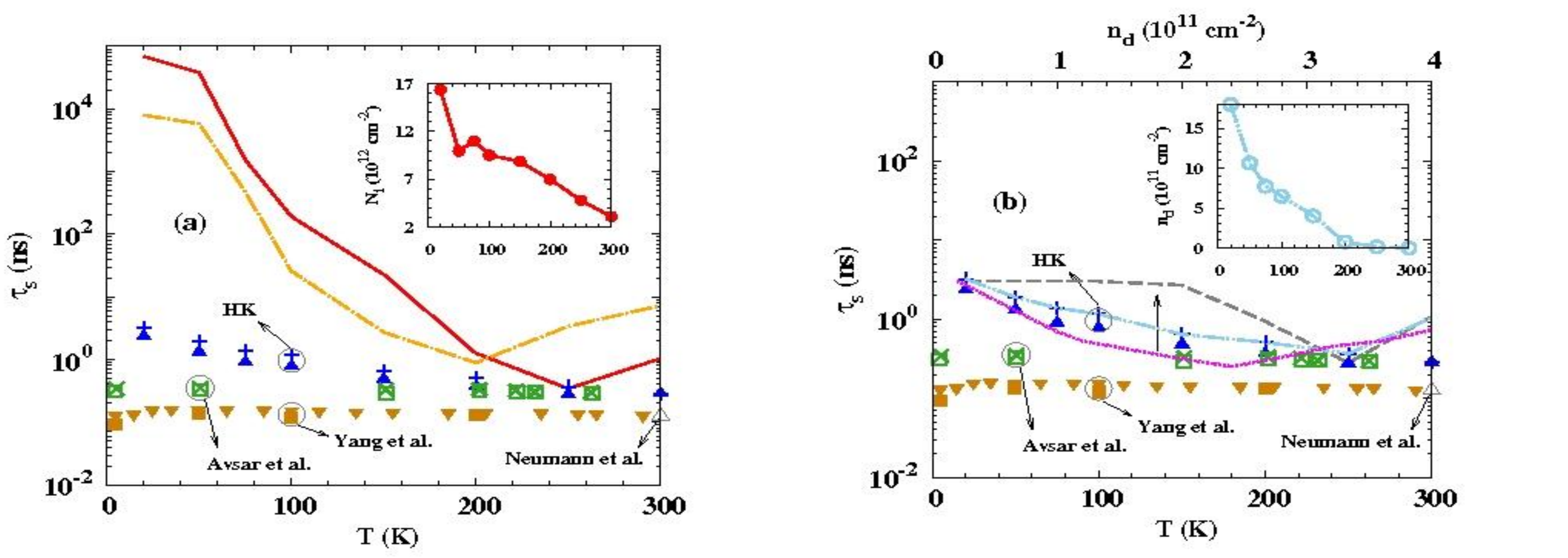
$$\mathbf{\Omega}^{\mu} = (0, 0, 2\lambda\mu) \qquad \tau_s = \tau_v \text{ weak intervalley scattering}$$

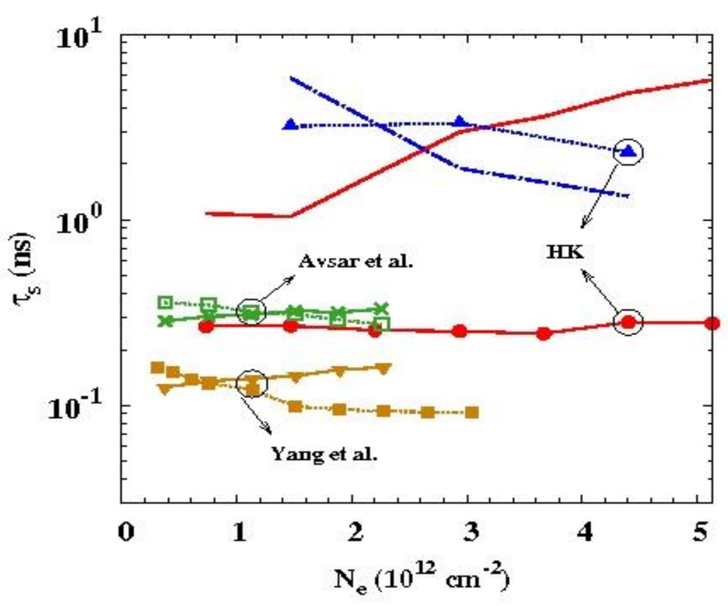
Spin Relaxation with High Mobilities in BLG



- A minimum down to several hundred picoseconds, which is comparable to the experimental data, is obtained in the temperature dependence of the in-plane SRT.
- In-plane SRT decreases rapidly with increasing initial spin polarization at low temperature, which is very different from the previous studies in both semiconductors and single-layer graphene.

Comparison with Experiments





- SRT from our calculation without short-range scatterers is comparable to the experimental data at high temperature.
- With the inclusion of the short-range scatterers, our result agrees fairly well with the experimental data.

Yang *et al*., PRL **107**, 047206 (11); Han and Kawakami, PRL **107**, 047207 (11); Avsar *et al*., Nano Lett. **11**, 2363 (11); Neumann *et al*., Small **9**, 156 (13)

Conclusion

- We have investigated the electron spin relaxation due to the DP mechanism in both BLG and monolayer MoS_2.
- The out-of-plane component of the SOC supplies a Zeeman-like term in the two valleys, which opens an intervalley spin relaxation channel together with the intervalley scatterings. This intervalley spin relaxation channel greatly suppresses the in-plane SRT.
- Our result is comparable to the experimental data at high temperature without short-range scatterers. With the inclusion of short-range scattering, our result agrees fairly well with the experimental data.

References:
L. Wang and M. W. Wu, PRB **87**, 205416 (13) (BLG);
arXiv:1305.3361 (MoS_2)

http://wu.ustc.edu.cn/