Theoretical evaluation of spin coherence length of ambipolar conductor

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The Hall effect measurement of the ambipolar conductor YH_2 under spin injection [1] revealed that the spin coherence length (SCL) of ambipolar conductor is $\sim 10\ \mu m$ which is much larger than the typical spin diffusion length in paramagnetic metals. Investigating the reason behind the ambipolar conductor for having such an extraordinarily large SCL, we have found the presence of two specific modes of spin currents, namely parallel and antiparallel spin current in the form of $\mathbf{J}_s^{(h)} + \mathbf{J}_s^{(e)}$ and $\mathbf{J}_s^{(h)} - \mathbf{J}_s^{(e)}$ respectively. By taking the divergence of these parallel and antiparallel spin currents and employing detailed balance $N_\uparrow^{(h/e)}/\tau_{\uparrow\downarrow}^{(h/e)} = N_\downarrow^{(h/e)}/\tau_{\downarrow\uparrow}^{(h/e)}$, the following equations can be deduced

$$\mathrm{div}\left(\mathbf{J}_s^{(h)} + \mathbf{J}_s^{(e)}\right) = -\frac{2\hbar}{\tau_s}\left(N^{(h)} - \frac{1+\Phi}{1-\Phi}N^{(e)}\right) \times \Delta\mu^{(h)} \qquad (\Phi \neq \pm 1) \qquad (1)$$

$$\mathrm{div}\left(\mathbf{J}_s^{(h)} - \mathbf{J}_s^{(e)}\right) = -\frac{2\hbar}{\tau_s}\Phi\left(N^{(h)} - \frac{1+\Phi}{1-\Phi}N^{(e)}\right) \times \Delta\mu^{(h)} \qquad (\Phi \neq \pm 1) \qquad (2)$$

where Φ is the charge polarization defined by $\Phi = \left(n^{(h)} - n^{(e)}\right) / \left(n^{(h)} + n^{(e)}\right)$, $N^{(h/e)} = \left(N_\uparrow^{(h/e)} N_\downarrow^{(h/e)}\right) / \left(N_\uparrow^{(h/e)} + N_\downarrow^{(h/e)}\right)$ and $\tau_s = (\tau_{\uparrow\downarrow}\tau_{\downarrow\uparrow}) / (\tau_{\uparrow\downarrow} + \tau_{\downarrow\uparrow})$. $N_{\uparrow/\downarrow}^{(h/e)}$ is the density of states at the Fermi level and $\tau_{\nu\bar{\nu}}$ represents the average time for flipping a spin-ν to a spin-$\bar{\nu}$. In deriving Eqs. (1) and (2), we assumed $\tau_{\uparrow\downarrow}^{(h)} = \tau_{\uparrow\downarrow}^{(e)} \equiv \tau_{\uparrow\downarrow}$ and $\tau_{\downarrow\uparrow}^{(h)} = \tau_{\downarrow\uparrow}^{(e)} \equiv \tau_{\downarrow\uparrow}$, equal carrier spin polarization between electrons and holes with nonzero value $\left(P_s^{(h)} = P_s^{(e)} \equiv P_s \neq 0\right)$ and employed it in Gibbs-Duhem relation which gives us a specific relationship between spin splitting of electron and hole chemical potentials i.e. $(1+\Phi)\Delta\mu^{(h)} + (1-\Phi)\Delta\mu^{(e)} = 0$. By expressing parallel and antiparallel spin currents in terms of spin dependent longitudinal conductivities $\sigma_{\uparrow/\downarrow}^{(h/e)}$, the SCLs for the parallel and antiparallel spin currents can be written as [2]

$$l_P = \left[\frac{\tau_s}{4e^2}\frac{\sigma_\uparrow^{(h)} + \sigma_\downarrow^{(h)} - \frac{1+\Phi}{1-\Phi}\left(\sigma_\uparrow^{(e)} + \sigma_\downarrow^{(e)}\right)}{N^{(h)} - \frac{1+\Phi}{1-\Phi}N^{(e)}}\right]^{\frac{1}{2}} \qquad (\Phi \neq \pm 1) \qquad (3)$$

$$l_{AP} = \left[\frac{\tau_s}{4e^2}\frac{\sigma_\uparrow^{(h)} + \sigma_\downarrow^{(h)} + \frac{1+\Phi}{1-\Phi}\left(\sigma_\uparrow^{(e)} + \sigma_\downarrow^{(e)}\right)}{\Phi\left(N^{(h)} - \frac{1+\Phi}{1-\Phi}N^{(e)}\right)}\right]^{1/2} \qquad (\Phi \neq \pm 1) \qquad (4)$$

Eq. (4) shows that effective spin relaxation time $\left(\tau_s' = \frac{\tau_s}{\Phi}\right)$ for antiparallel spin current gets longer when $\Phi \cong 0$, making SCL of antiparallel spin current (l_{AP}) larger whereas the spin coherence length of the parallel spin current (l_P) (Eq. 3) remain at its standard value. So, it can be concluded that the presence of antiparallel spin current in ambipolar conductor makes its SCL larger.

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