Drift transport of helical spin coherence with tailored spin-orbit interactions

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Friday Afternoon Meeting-Talk
Mar 18\textsuperscript{th} 2016
Persistent Spin Helix

J. Schliemann et al., PRL 90, 146801 (2003)
J.D. Koralek et al., Nature 458, 610 (2009)
Persistent Spin Helix

\[ H_{SO} = \alpha (\sigma_x k_y - \sigma_y k_x) + \beta (\sigma_x k_x - \sigma_y k_y) \]

Effect on spin polarization:
• Rotation of z-component of spin only in one plane
• Robust against spin dephasing and spin relaxation

\[ L = v_F t \]
\[ \theta = \omega_L t = \frac{eg}{2m^*} B_{SO} t \]
\[ L = L_{SO} = \frac{\hbar^2 \theta}{2m^* |\alpha \pm \beta|} \]
Excitation of spins by circularly polarized light from a continuous wave laser (→ pump)

- Linearly polarized light probes the angle of spins (→ probe)

→ Kerr microscopy

- Pure diffusion of spins in a wafer (12nm) with α~β

- Observation of PSH pattern

- Decay of pattern due to:
  - non perfect α=β
  - Cubic Dresselhaus term

- PSH no longer visible after ~10-15μm

\[ L_{SO} \sim 7-8 \mu m \]
Setup/concept of measurements

- Sample:
  - AlGaAs/GaAs/AlGaAs QW
  - Ohmics: AuGe/Ni (260/30nm)
  - Gate: Au (7nm)
  - 25nm $\Rightarrow$ $\alpha$ ~ $\beta$
  - 15nm $\Rightarrow$ $\alpha$ < $\beta$

- Experiments (T=8K):
  - Excite spins with laser and scan across sample $\Rightarrow$ measure spin polarization
  - Apply in-plane electric field $\Rightarrow$ drift AND diffusion of electron spins
  - Asymmetric spin drift diffusion (SDD) in Vx
  - PSH visible up to $\sim$100um
Remarks: SOI drift field

- Only part of 2DEG is spin polarized: \((k_{F}^\uparrow)^2 - (k_{F}^\downarrow)^2)/(k_F^2)\) → only net spin polarization is of interest
- For in-plane electric field → shift of spin polarized area by \(\delta k\) → integrate! → Drift SOI field (here only Dresselhaus)

\[
B_{df,D} = \frac{1}{A} \int_{k_{F,\downarrow}}^{k_{F,\uparrow}} r \, dr \int_{0}^{2\pi} d\theta \, \vec{B}_D(\vec{k} + \delta \vec{k})
\]

\[
= \frac{2\gamma(-\langle k_z^2 \rangle + \frac{1}{4}(k_{F,\downarrow}^2 + k_{F,\uparrow}^2))}{g\mu_B} \begin{pmatrix} \delta k_x \\ -\delta k_y \end{pmatrix}
\]

- Average field experienced by the polarized electron spins
- Change of Dresselhaus parameter:

\[
\beta \rightarrow \beta_{eff} = 2(\beta_1 - 2\beta_3)
\]

\[
= \frac{1}{2} \pi \gamma n \quad \text{depends on density!!!!}
\]

M.Studer et al. PRB 82, 235320 (2010)
See also FMM Pirmin 17.5.2013
Experiments

- decay of PSH:
  \[ \theta_K = \exp\left(-\frac{d}{l_s}\right) \cos\left(2\pi\frac{d}{L_{SO}^{[110]}/[1\bar{1}0]}\right) \]
- \(l_s\) \rightarrow spin decay length due to diffusion and/or decoherence
- \(d\) distance from the origin
- both directions can be probed!
- good agreement with simulations

\[
\begin{align*}
\alpha &= \frac{\pi \hbar^2}{2m^*} \left( \frac{1}{L_{SO}^{[110]}} + \frac{1}{L_{SO}^{[1\bar{1}0]}} \right) \\
\beta &= \frac{\pi \hbar^2}{2m^*} \left( \frac{1}{L_{SO}^{[110]}} - \frac{1}{L_{SO}^{[1\bar{1}0]}} \right)
\end{align*}
\]

From fit to spin profile
Extract \(L_{SO}\) \rightarrow yields \(\alpha\) and \(\beta\)

Control of both directions!!!
Results

<table>
<thead>
<tr>
<th>$d_{QW}$ (nm)</th>
<th>$V_g$ (V)</th>
<th>15 - 5.0</th>
<th>25 - 4.4</th>
<th>25 - 4.28</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s$ (cm$^2$ s$^{-1}$)</td>
<td>60.8 ± 10.1</td>
<td>40.8 ± 9.2</td>
<td>17.6 ± 8.7</td>
<td></td>
</tr>
<tr>
<td>$l_s^{[1-10]}$ (μm)</td>
<td>29.6 ± 4.0</td>
<td>37.8 ± 6.6</td>
<td>37.5 ± 5.9</td>
<td></td>
</tr>
<tr>
<td>$l_s^{[110]}$ (μm)</td>
<td>21.2 ± 3.4</td>
<td>35.0 ± 4.2</td>
<td>23.2 ± 5.2</td>
<td></td>
</tr>
<tr>
<td>$L_{SO}^{[1-10]}$ (μm)</td>
<td>13.5 ± 0.2</td>
<td>21.5 ± 0.7</td>
<td>18.3 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>$L_{SO}^{[110]}$ (μm)</td>
<td>23.7 ± 1.5</td>
<td>172.9 ± 15.7</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>$\alpha$ (meVÅ)</td>
<td>0.58 ± 0.04</td>
<td>0.74 ± 0.07</td>
<td>0.99 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>$\beta$ (meVÅ)</td>
<td>2.10 ± 0.13</td>
<td>0.95 ± 0.09</td>
<td>0.99 ± 0.02</td>
<td></td>
</tr>
</tbody>
</table>

- 4% change of Dresselhaus field
  - Authors claim change of $<k_z^2>$ but
  - Could be due to density dependence of $\beta_3$
- Decay length becomes smaller at $\alpha=\beta$ along slow axis
- Spin diffusion constant $D_s$:
  - Estimated from broadening of Kerr rotation signal
  - Smaller than in IBM work (≈350 cm$^2$s$^{-1}$) → lower spin density, slower spins?

$$k_F \sim 10 \times 10^7 \text{m}^{-1}$$

$$\langle k_z^2 \rangle \sim \left( \frac{\pi}{W} \right)^2 \approx 1.6 \times 10^{16} \text{m}^{-2}$$

$$\gamma = \frac{\beta}{\langle k_z^2 \rangle - \frac{1}{4} \pi k_F^2} \approx 15 \text{eVÅ}^3$$
Simulation of spin dynamics

\[
\hat{g}_z = \left\{ D_s \left( q_x^2 + q_y^2 \right) \mathbf{E} + i (q_x v_x + q_y v_y) \mathbf{E} + \hat{D} \right\} \hat{\rho} \quad (\dagger)
\]

spin diffusion and drift transport of spins

Matrix \( \hat{D} \) contains the spin rotation (diagonal elements) and relaxation (off-diagonal) terms

Spin distribution \( \hat{\rho} \) from inverse Fourier transform of the solution (\( \dagger \))

For simulation and experiment:

- Extract \( L_{SO} \) and \( l_s \) for each gate config \( \rightarrow \) a changes
- Plot \( l_s \) vs \( L_{SO}(\alpha) \) along
- Curves look similar but are shifted:
  - Neglecting cubic Dresselhaus term
  - and \( \beta \) is fixed in the simulations!

Note:

-according to table 1 range of \( \alpha=[0.74,0.99] \) - doesn't match with the gate voltages!
- Couldn't map data from table 1 to graph!

\[
q_{1/2} = 2m^*(\alpha \pm \beta)/\hbar^2
\]
Modulation of spin transport path

- Apply in-plane AC fields → move spins in x-y direction
- Synchronized laser excitation frequency with $V_{y,ac}$
- Spin pattern stays robust while it oscillates in y-direction
- For faster excitation ~ one period more → time effect!
- Transport of spin polarization in 2DEG plane!

\[ f_{\text{Laser}} = 82.46 \text{MHz}, \quad V_{x,dc} = 100 \text{mV}, \quad V_{y,ac} = 200 \text{mV} \]

Quite large values
Similar to Leons Msc thesis

\[ f = f_{\text{Laser}} \]

\[ f = 2f_{\text{Laser}} \]
Conclusion

• Show spatial and time dependence of the PSH with in-plane DC and AC electric fields
• Probing both directions: [110] and [1-10]
• Neglected density dependence of cubic Dresselhaus term
• Don’t give any relevant standard numbers like density, mobility, $k_z^2$ no determination of $\gamma$ (to compre with other work)

→ Overall: due to the independent control of direction of drifting and diffusing spins, nice new method to extract SOI parameters