Spin Orbit Coupling (SOC) in Graphene

MMM, Mirko Rehmann, 12.10.2015
Motivation

Weak intrinsic SOC in graphene:

<table>
<thead>
<tr>
<th>Structure</th>
<th>Spectrum at K</th>
<th>$\Delta_K$</th>
<th>Spectrum at $\Gamma$</th>
<th>$\Delta_{\Gamma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Graphene Structure" /></td>
<td><img src="image" alt="Spectrum at K" /></td>
<td>24 $\mu$eV (refs 84,85) -50 $\mu$eV (ref. 86)</td>
<td><img src="image" alt="Spectrum at $\Gamma$" /></td>
<td>8.8 meV</td>
</tr>
</tbody>
</table>

[84]: Phys. Rev. B 80, 235431 (2009)

Rashba SOC also very weak (5$\mu$eV for $E_{ext} = 1V/nm$)

Observation of spin-orbit effects in graphene

Enhancement of the otherwise weak SOC

Remaining spin-degeneracy due to the absence of broken time & space inversion symmetry

W. Han et al., Nat. Nanotech. 9, 794 (2014)
Different Approaches to induce SOC

Giant Spin-Orbit Interaction due to Rotating Magnetic Fields

Interface-Induced SOC

$\text{WS}_2$

$\text{MoS}_2$


Z. Wang et al., Nat. Commun. 6, 8339 (2015)

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Z. Wang et al., Nat. Commun. 6, 8339 (2015)

Giant SO Interaction due to Rotating Magnetic Fields

The realization of Helical Modes

conducting modes that transport opposite spins in opposite directions

Requirement: lifting of the spin degeneracy

Two possibilities:
1. uniform magnetic field + Rashba spin-orbit interaction (SOI)
2. spatially varying magnetic field

Problem of possibility 1: small intrinsic SOI of graphene

Artificial breaking of the inversion symmetry

$E_{\text{ext}}$ applied perp. to the GNR plane
But: too small for realistic fields (1V/µm)

adatoms which produce local E-fields
But: surface of graphene is in tunnel contact with adatoms
Proposal

Usage of nanomagnets to produce a spatially varying magnetic field

B-field rotating in-plane = GNR with an out-of-plane Rashba SOI + uniform B-field

(mechanism also valid for linearly oscillating fields)

*\( \lambda_n = 200\text{nm} \) \( \Delta_{SO} = 10\text{meV} \)

- No requirement for a perfect periodicity of the field, but it needs a substantial weight of the Fourrier component @ 2\( k_f \)
- The period, not the amplitude of the B-field sets the strength of the induced SOI
Metallic & Semiconducting GNRs

Opening of a gap:

- Uniform B-field perp. to SOI allows transitions between the two spin states
- Intervally scattering (due to impurities or edge disorder) allows transitions between the two isospin states

If \( \mu \) is tuned inside the gap, the system is in the helical regime with nearly perfect polarization, \( <s_x> \approx 0.99 \), in both semiconducting and metallic GNRs
Defects on the edges of a metallic armchair GNR opening of a gap at zero energy

(the valley degeneracy is lifted due to intervally mixing induced by the boundary defects)

E(k) spectrum changes only slightly & qualitative features of a metallic armchair GNRs are maintained helical modes are robust against boundary defects
Summery

• Useage of a spatially varying B-field instead of a uniform B-field + Rashba SOI to lift the spin degeneracy and thus enable the creation of helical states

• Robust against edge defects

• Typical parameter values needed to reach the helical regime:
  - \( \lambda_n = 400 \text{nm} \quad \Delta_{SO} = 5 \text{meV} \)
  - generation of a spatially varying B-field of strength B=0.1-1T (\( \Delta_Z = 6-60 \mu\text{eV} \))
  - required temperature: 50-500mK
Different Approaches to induce SOC

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- Interface-Induced SOC
  - WS$_2$
  - MoS$_2$

References:
Strong Interface-Induced SOI in Graphene on WS$_2$

Ideal substrates for graphene: 
transition metal dichalcogenides

- atomically flat
- Chemically inert

High quality transport properties 
(e.g. $\mu = 50'000$-$60'000$ cm$^2$V$^{-1}$s$^{-1}$, *)

* A. V. Kretinin et al., Nano Lett. 14, 3270 (2014)

Extremely strong SOI:
- x 100 mV valence bands
- x 10 mV conduction band

Graphene on WS$_2$

Multi-terminal Hall bar configuration

Accumulation of electrons at the SiO$_2$/WS$_2$-interface

- Access to conduction band denied due to screening
- Only hole-transport studied
Magnetotransport Measurements

Experimental investigation of SOI:

- Spin Hall & Inverse Spin Hall effect
- Magnetotransport, weak anti-localization (WAL)

WAL-dip as a direct demonstration of SOI

T. Koga, Y. Sekine, NTT Review, 2012
Robust low-T WAL reveals strong SOI

WAL eclipsed by universal conductance fluctuations (UCF)

ensemble averaging procedure:
Low-T WAL in Graphene on WS$_2$

\[ \Delta \sigma = \sigma(B \neq 0) - \sigma(B = 0) \]

\[ \Delta \sigma(B) = -\frac{e^2}{2\pi\hbar} \left[ F \left( \frac{\tau_B^{-1}}{\tau_{\phi}^{-1}} \right) - F \left( \frac{\tau_B^{-1}}{\tau_{\phi}^{-1} + 2\tau_{\text{asy}}^{-1}} \right) - 2F \left( \frac{\tau_B^{-1}}{\tau_{\phi}^{-1} + \tau_{\text{so}}^{-1}} \right) \right] \]

$\tau_{\text{asy}}^{-1}$: breaking of $z/-z$ symmetry  
$\tau_{\text{so}}^{-1}$: total spin relaxation rate  
$\tau_B^{-1}$: phase coherence rate  
$\tau_{\phi}^{-1}$: phase coherence rate

WAL not observed for graphene on SiO$_2$ [1], hBN [2], GaAs [3]

Low-T WAL in Graphene on WS$_2$

- Spin relaxation time from WAL ($\tau_{so} \sim 2.5$ - 5ps)
- Non-local Spin Hall effect
- Elastic scattering time $\tau$

**Open circles:** pristine graphene on SiO$_2$ and hBN (from literature)

**Open triangles:** intervally scattering time (from literature)

**Conclusions:**
- WAL and Spin Hall values in agreement
- $\tau_{so}$ 100-1000 times smaller for graphene/WS$_2$ compared to graphene on SiO$_2$ or hBN
- Spin relaxation mechanism neither Elliot-Yafet ($\tau_{so} \propto \tau$) type nor Diakonov-Perel ($\tau_{so} \propto 1/\tau$)
- Quite well accordance of $\tau_{so}$ and $\tau_{iv}$ related mechanisms?
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[Images and diagrams of WS$_2$ and MoS$_2$ structures, illustrating interface-induced SOC.]


Z. Wang et al., Nat. Commun. 6, 8339 (2015)

Proximity SOC in Graphene/MoS$_2$ devices

First principles methods based on DFT Supercell of 59 atoms:
- 3x3 supercell of MoS$_2$
- 4x4 supercell of graphene

Dirac point slightly below the conduction band edge of MoS$_2$

Enhanced screening $\rightarrow$ increase of the meanfree path in graphene*

Coupled Massless and Massive Electron Gases

Band offsets between graphene and MoS$_2$ tunable by external electric field

For positive fields: $E_F$ crosses valence band of graphene and conduction band of MoS$_2$
Substrate effect on electronic Spectrum

Two effects:
1. Opening of an orbital band gap (due to broken pseudo spin symmetry)
2. Lifting of the spin degeneracy (due to SOC & broken space inversion symmetry)

- Valence states on sublattice B
- Conduction states on sublattice A

Spin texture close to the K-point:

Spin-up
Spin-down
Proximity Induced SO Parameters

Effective Hamiltonian to extract the following parameters:

- \( \Delta \) the orbital proximity gap
- Spin-orbit parameters: \( \lambda_I^A, \lambda_I^B, \lambda_R \)

\(~ 0.5\text{meV} @ \text{zero field}\)
Steep increase due to charge transfer from graphene to MoS\(_2\)

\(~ 0.2\text{meV}\)
About 20 times larger than in pristine graphene*

Strong field dependence of the Rashba parameter \( \lambda_R \)

Optospintronics Experimental Proposal

Creation of spin polarized excitons with circularly polarized light tuned to the band gap of MoS$_2$

Detection:
1. Optically
2. Electrically, FM electrode to measure the Hanle signal

Spin tunneling through graphene:
Sandwich structure MoS$_2$/graphene/MoS$_2$

Excite spins in MoS$_2$ layer 1 with $\omega_1$

Luminescence from MoS$_2$ layer 2 with $\omega_2$
Giant Spin-Orbit Interaction due to Rotating Magnetic Fields

$\Delta_{SO} \sim 10\text{meV}$

$\Delta_{SO} \sim 5\text{meV}$

$\Delta_{SO} \sim 0.2\text{meV}$


Z. Wang et al., Nat. Commun. 6, 8339 (2015)

Thank you for your attention!