Spin Hall Effects in HgTe Quantum Well Structures

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(slides with unpublished results have been removed!)
Anomalous Quantum Hall Effect

in dilute magnetic semiconductor quantum wells

Interplay of Rashba, Zeeman and Landau splitting in a magnetic two-dimensional electron gas

Y. S. Gui(*), C. R. Becker(**), J. Liu, V. Daumer, V. Hock, H. Buhmann and L. W. Molenkamp

Spin Interference Effect

Direct Observation of the Aharonov-Caser Phase

M. König, AT, EMH, JS, VH, MS, CRB, HB, and LWM, PRL 96, 076804 (2006).

In the work, it was shown that a quantum-mechanical system obeys a geometric phase for a cyclic evolution of a parameter even if the parameter change is not connected to any physical process. The presence of a geometric phase in a quantum-mechanical system has been predicted by Berry [1] and has been observed experimentally for cold atoms in a magnetic field [2]. The Aharonov-Casher phase is a geometric phase that arises in the following situation: A particle (e.g., an electron) moves in a two-dimensional potential with an induced magnetic field. The particle experiences a geometric phase if it is transported around a loop in parameter space. This geometric phase is given by the following equation:

$$ \phi = \frac{1}{h} \oint d\zeta \nabla \psi^* \cdot \nabla \psi $$

where $\zeta$ is the change in the magnetic field, $\psi$ is the wave function, and $h$ is Planck’s constant. The geometric phase is independent of the actual path taken in parameter space and is a topological property of the system.

The experimental setup consists of a quantum-mechanical system with a two-dimensional potential and an induced magnetic field. By changing the magnetic field, the system experiences a geometric phase. The phase shift can be measured by observing the change in the observable of the system, such as the transmission probability or the reflectivity.

This work demonstrates the presence of a geometric phase in a quantum-mechanical system and provides evidence for the topological nature of the system.
HgTe-Quantum Well Structures
HgTe

band structure

semi-metal or semiconductor

fundamental energy gap

$E^{\Gamma 6} - E^{\Gamma 8} \approx -300$ meV

D.J. Chadi et al. PRB, 3058 (1972)

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HgTe-Quantum Wells

MBE-Growth

Bandgap vs. lattice constant
(at room temperature in zinc blende structure)
HgTe-Quantum Wells

MBE-Growth Chamber
HgTe-Quantum Wells

VBO = 570 meV

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HgTe-Quantum Wells

Typ-III QW

conduction band

HgCdTe

Γ₆

HgTe

Γ₆

HgCdTe

Γ₈

valence band

inverted

HgCdTe

E₁

HH₁

VBO = 570 meV

normal

band structure

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Band Gap Engineering

4 nm QW

15 nm QW

normal semiconductor

inverted semiconductor

$k = (k_x, k_y)$

$k \parallel (1,0)$

$k \parallel (1,1)$

$k = (k_x, k_y)$

Energy $E(k) (\text{eV})$

Band Gap Engineering

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Rashba Spin-Orbit Interaction

structural inversion asymmetry (SIA)

\[ H_R = \alpha_R (\sigma_x k_y - \sigma_y k_x) \]

\[ E^\pm = E_i + \frac{\hbar^2 k^2}{2m^*} \pm \alpha k_\parallel \]

(for electron and light hole bands)

\[ E^\pm = E_i + \frac{\hbar^2 k^2}{2m^*} \pm \beta k_\parallel^3 \]

(for heavy hole bands)
Rashba Spin-Orbit Splitting

8 x 8 $\mathbf{k} \cdot \mathbf{p}$ calculation

symmetric QW

asymmetric QW

$\Delta R_{\text{max}}$ up to 30 meV

E.G. Novik, HB, et al., PRB 72, 035321 (2005)

Y.S. Gui, HB et al., PRB 70, 115328 (2004)

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Magneto-Transport

nodes in SdH:

SdH-Amplitude:

\[ A \propto \cos(\pi \nu) \quad \nu = \frac{\delta}{\hbar \omega_c} \]


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\[ E^\pm = E_i + \frac{\hbar^2 k^2}{2m^*} \pm \alpha k \parallel \]

(for electron and light hole bands)

\[ E^\pm = E_i + \frac{\hbar^2 k^2}{2m^*} \pm \beta k^3 \parallel \]

(for heavy hole bands)

Y.S. Gui, HB et al., PRB 70, 115328 (2004)
Layer Structure

Carrier densities: \( n_s = 1 \times 10^{11} \text{...} 2 \times 10^{12} \text{cm}^{-2} \)

Carrier mobilities: \( \mu = 1 \times 10^5 \text{...} 1 \times 10^6 \text{cm}^2/\text{Vs} \)

Au

100 nm Si\(_3\)N\(_4\)/SiO\(_2\)

25 nm CdTe
10 nm HgCdTe \( x = 0.7 \)
9 nm HgCdTe with I
10 nm HgCdTe \( x = 0.7 \)
4 - 12 nm HgTe
10 nm HgCdTe \( x = 0.7 \)
9 nm HgCdTe with I
10 nm HgCdTe \( x = 0.7 \)
25 nm CdTe
CdZnTe(001)

symmetric or asymmetric doping
Gated Low Carrier Densities Samples
T = 1.5 K

Q2163
8 nm QW

0V

+5V

-2V

\( V_{\text{Gate}} \)

-30000
-20000
-10000
0
10000
20000
30000

\( R_{xy} \) / \( \Omega \)

\( B/T \)

\( n_{\text{max}} = 1.35 \times 10^{12} \text{ cm}^{-2} \)

\( p_{\text{max}} = 3.2 \times 10^{11} \text{ cm}^{-2} \)

\( n \) to \( p \) Transitions

\( E/\text{meV} \)

\( k/\text{nm}^{-1} \)

\( H1 \)

\( H2 \)

\( E1 \)
Magneto-Resistance in the insulating regime

\[ B \neq 0 \]

Presented at the PITP/SpinAps Asilomar Conference in June 2007
Insulator-Metal-Insulator Transition

Landau Levels

E [meV]

insulator  metal  insulator

B [T]


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Insulator-Metal-Insulator Transition

6.5 nm QW

(shifts the LL crossing to lower magnetic fields)

Insulator-Metal-Insulator Transition

6.5 nm QW

p-type

n-type

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Finite conductance in the insulating regime

8 nm QW

$B = 0$

$R_\text{xx} [\Omega]$

$V_{\text{gate}} [\text{V}]$

8 nm QW largest thermal gap

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QSH
insulator
Topological Quantization

Graphene edge states

Conductance: $G = \frac{2e^2}{h}$

C.L. Kane and E.J. Mele, PRL 95, 146802 (2005)
C.L. Kane and E.J. Mele, PRL 95, 226801 (2005)
Bandstructure HgTe

normal insulator state

\[ G_{LR}(\frac{e^2}{h}) \]

\[ E_{gap} \]

\[ d < d_c, \text{ normal regime} \]

\[ d > d_c, \text{ inverted regime} \]
sample layout

![Sample Layout Diagram]

- Width: 20 µm
- Height: 13.3 µm
measurements show that 4-terminal conductance is comparable to 2-terminal
Multi-Terminal Probe

\[
T = \begin{pmatrix}
0 & 1 & 0 & 0 & 0 & 1 \\
1 & 0 & 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 & 0 & 1 \\
1 & 0 & 0 & 0 & 1 & 0 \\
\end{pmatrix}
\]

\[
\begin{align*}
G_{2t} &= \frac{I_{14}}{\mu_4 - \mu_1} = \frac{2e^2}{3h} \\
G_{4t} &= \frac{I_{14}}{\mu_3 - \mu_2} = \frac{2e^2}{h}
\end{align*}
\]

Generally

\[
R_{2t} = \frac{(n+1)h}{2e^2}
\]

\[
\frac{G_{4t,\text{exp}} \approx 1.9 \frac{e^2}{h}}{R_{4t}} \Rightarrow \frac{R_{2t}}{R_{4t}} = 3 \left( \approx 2.6 \right)_{\text{exp}}
\]

X.L. Qi (Stanford Univ.)
Summary 1:

signatures for QSH insulator state for inverted HgTe QW micro-structures

multi-terminal resistance corresponds to expected values for helical edge states
SHE
Spin Hall Effect

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(Received 24 February 1999)

It is proposed that when a charge current circulates in a paramagnetic metal a transverse spin imbalance will be generated, giving rise to a “spin Hall voltage.” Similarly, it is proposed that when a spin current circulates a transverse charge imbalance will be generated, giving rise to a Hall voltage, in the absence of charge current and magnetic field. Based on these principles we propose an experiment to generate and detect a spin current in a paramagnetic metal.

PACS numbers: 72.15.Gd, 73.61.At
Spin-Hall Effect

- extrinsic
  - skew scattering
  - side jump effect
Spin-Hall Effect

2. Intrinsic SHE

Rashba effect

J. Sinova et al.,
Spin-Hall Effect

optical detection


Wunderlich et al. PRL 94, 47204 (2005)
Spin-Hall Effect

electrical detection

SHE⁻¹

Hirsch PRL 83, 1834 (1999)

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Spin-Hall Effect

electrical detection

E.M. Hankiewicz et al. PRB 70, 241301 (2004)
Scaling of H-samples with the system size

Oscillatory character of voltage difference with the system size.

Spin orbit coupling
\( \lambda = 72\text{meVnm} \)

\( n = 1 \times 10^{11}\text{cm}^{-2} \)

Change of voltage \( [\mu V] / L [\text{nm}] \)

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calculated voltage signal for electrons

\[ \Delta V \sim \Delta V(0) [\text{V}] \]

Electrons - linear Rashba

-\( n_{2D} = 10^{12} \text{cm}^{-2} \)
-\( E_F = 77 \text{meV} \)
-\( m_{\text{eff}} = 0.031 m_e \)

-\( d = 180 \text{nm} \)
-\( d = 90 \text{nm} \)

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calculated voltage signal
Holes - cubic Rashba

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more than 10 time larger!
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