The Role of Spin in Ballistic-Mesoscopic Transport

INT Program
Chaos and Interactions: From Nuclei to Quantum Dots
Seattle, WA
8/12/02

CM Marcus, Harvard University

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Spin-Orbit Coupling, Antilocalization, and Parallel Fields in Quantum Dots

D. Zumbühl, J. Miller, J. Folk

Material:
Campman, Gossard, UCSB
weak localization and antilocalization in 2D systems.

\[
\begin{array}{c}
\text{Resistance (}\Omega\text{)} \\
\text{weak localization and antilocalization in 2D systems.}
\end{array}
\]

\[V_g = -240 \text{ mV}\]

\[V_g = +200 \text{ mV}\]

\[T = 300 \text{ mK}\]
spin precision affects phase interference

\(2\pi\) in spin space gives -1 to phase

motion in real space

coherent backscattering

\[\rightarrow\] weak localization

motion in spin space

coherent backscattering + spin rotation

\[\rightarrow\] antilocalization
Spin-Orbit Coupling in 0-D (Quantum Dots)

Statistics of Conductance

$V_{\text{shape1}}$

$V_{\text{shape2}}$

$g (e^2/h)$

$B$ (mT)

Single trace for each shape
Average of ~200 traces

low density, “large dot” 8 \( \mu m^2 \)

low density
weaker SO coupling
weak localization (WL)

dots are on different wafers

high density, “large dot” 8 \( \mu m^2 \)

high density
stronger SO coupling
antilocalization (AL)

CEM2385

\( n = 2.0 \times 10^{15} m^{-2} \)

SY4

\( n = 5.8 \times 10^{15} m^{-2} \)

\( < g > \) (e\(^2\)/h)

\( -1.0 \)
\( 0.0 \)
\( 1.0 \)

Perpendicular Magnetic Field (mT)

average conductance

WL

Perpendicular Magnetic Field (mT)

average conductance

WL + AL

average conductance
Spin-Orbit Coupling in Quantum Dots

\[ H = \frac{p^2}{2m} + \alpha(p_y\sigma_x - p_x\sigma_y) + \rho(p_x\sigma_x - p_y\sigma_y) \]

Rashba \hspace{1cm} Dresselhaus

gauge transformation using \( < v > \longrightarrow 0 \) in quantum dots

(Halperin et al., PRL 86, 2106 (2001))

\[ H' = \frac{1}{2m} \left( \frac{r}{r} - A - a_\perp \frac{\sigma_z}{2} - a_\parallel \right)^2 + \varepsilon \frac{r}{2} \frac{\sigma}{2} - h^{(1)} \]

identify SO terms with different symmetries

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<th>spin-orbit terms</th>
<th>associated energy scale</th>
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<td>( \frac{r}{a_\perp} = \hbar \frac{r \times n_z}{2\lambda_1\lambda_2} )</td>
<td>(SO Berry’s phase keeps ↓ and ↑ correl.)</td>
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<td>( \frac{r}{a_\parallel} = \hbar \frac{r \times n_z}{6\lambda_1\lambda_2} \left( \frac{x_1\sigma_1}{\lambda_1} + \frac{x_2\sigma_2}{\lambda_2} \right) )</td>
<td>(provides spin flips)</td>
</tr>
<tr>
<td>( h^{(1)} = -\frac{\varepsilon Z}{2} \left( \frac{l_1x_1}{2\lambda_1} + \frac{l_2x_2}{2\lambda_2} \right) )</td>
<td>(spin-orbit + ( B_{\parallel} ))</td>
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IL Aleiner and VI Falko, PRL 87 256801 (2001)
$B_{\parallel}$ field scales

- Zero field
- Intermediate field
- Large field
Effects of S-O coupling suppressed in small quantum dots

“large dot” 8 $\mu$m$^2$

“small dot” 1.2 $\mu$m$^2$

Dots are on the same wafer.
Variance of Conductance

high density material (SY4)

low density material (CEM)

\[ \text{var g} \left( \left( \frac{e^2}{\hbar} \right)^2 \right) \]

\[ < g > \left( \frac{e^2}{\hbar} \right) \]

8 \( \mu \)m²

Perpendicular Magnetic Field (mT)
Effect of Parallel Magnetic Field on Antilocalization

Parameters fixed by $B_{\parallel} = 0$

$T = 300 \text{ mK}$
$S-O$ coupling asymmetry

\[ \nu_{so} = \sqrt{|\lambda_1/\lambda_2|} \]

\[ \text{range} \quad 1 < \nu_{so} < 2 \quad \text{for 2:1 aspect ratio dot} \]

\[ \delta g (e^2/h) \]

\[ B_{\parallel} (T) \]

\[ 8.0 \, \mu m^2 \]
Parallel Field Effects on Antilocalization and Weak Localization

Time-Reversal Symmetry Breaking by Parallel Field $B_\parallel$

$$\delta g_{\text{wl}}(B_\parallel) = \delta g_{\text{wl}}(0) \left[ 1 + \frac{\gamma_B}{\gamma_{\text{esc}}} \right]^{-1}$$

$$\gamma_B = a \cdot B_\parallel^2 + b \cdot B_\parallel^6$$

$$\gamma_{\text{esc}} = \frac{N\Delta}{h}$$

- effective random $B_\perp$ due to disorder / surface roughness
- inversion asymmetry of heterostructures

J. Meyer, A. Altland, B. Altshuler, cond-mat 0105623
Variance of Conductance dependence on Parallel Magnetic Field

(high density material (SY4) low density material (CEM))

(J. A. Folk et al., PRL 86, 2102 (2001))
Symmetry of Conductance Fluctuations (Movie)

\[ B_{\parallel} = 0 - 5 \text{T} \]

\( 0.4 \text{ V} \)

\( \Delta V_g \)

\( 0 \text{ mT} \) \hspace{1cm} 0 \hspace{1cm} B_{\text{perp.}} \hspace{1cm} +10 \text{ mT} \)
Effect of Temperature in Antilocalization regime

• Increased dephasing at higher T.

• No significant change in SO coupling with T.
Using a center gate to Control spin-orbit coupling
0.7 Structure and a Kondo-like state in Point Contacts

S. Cronenwett, H. Lynch, D. Goldhaber-Gordon, L. Kouwenhoven, N. Wingreen, K. Hirose

Material: Umansky, Heiblum, Weizmann
1D System
0.7 Structure in a Quantum Point Contact
Low Temperature

(a) $g \ (2e^2/h)$

$B = 0$

$B = 8T$

$T = 80 \text{ mK}$

Higher Temperature

(c) $g \ (2e^2/h)$

$B = 0$

$B = 8T$

$T = 1.3 \text{ K}$
Critical Questions:

What is the characteristic time scale on which the spin is oriented in a particular direction?
Nonlinear Transport

- $T = 80\text{mK} \quad B = 0$
- $T = 0.6\text{K} \quad B = 0$
- $T = 80\text{mK} \quad B = 8\text{T}$
Temperature dependence of zero bias anomaly (at various gate voltages)
Kondo-like scaling in a quantum point contact

\[ g = \frac{e^2}{h} \left[ f\left(\frac{T}{T_K}\right) + 1 \right] \]

\[ f\left(\frac{T}{T_K}\right) \sim \left[ 1 + \left(2^{1/S} - 1\right) \left(\frac{T}{T_K}\right)^2 \right]^{-S} \]
In-Plane Field Dependence of Zero Bias Anomaly of a QPC

\[ g \mu B_{||} < T_K \]

\[ g \mu B_{||} > T_K \]
Spin injection and Detection Using Point Contacts and Quantum Dots

J. A. Folk, R. M. Potok

Material: Umansky, Heiblum, Weizmann
QUANTUM POINT CONTACTS AS SPIN INJECTORS AND SPIN DETECTORS

R. M. Potok, J. A. Folk, C. M. Marcus, V. Umansky
cond-mat (2002).

\[ V_c \propto \frac{\hbar}{2e^2} I_e (1 + P_e P_c) \]

\[ P_c = \frac{(T_\uparrow - T_\downarrow)}{(T_\uparrow + T_\downarrow)} \]

\[ P_e = \frac{(I_\uparrow - I_\downarrow)}{(I_\uparrow + I_\downarrow)} \]
QUANTUM POINT CONTACTS AS SPIN INJECTORS AND SPIN DETECTORS

(a) T = 300 mK

Peak Ratio (0.5 : 0.5) / (2 : 2)

(0.5 : 0.5) / (2.2)

(0.5 : 2) / (2.2)

(2 : 0.5) / (2.2)

B\parallel (T)

0 1 2 3 4 5 6 7

1.0 1.2 1.4 1.6 1.8 2.0

(b) Peak Ratio (0.5 : 0.5) / (2 : 2)

5 T

7 T

8.5 T

model

Peak Ratio (0.5 : 0.5) / (2 : 2)

1.0 1.2 1.4 1.6 1.8 2.0

T (K)

3 4 5 6 7 8 9 10

(b) Peak Ratio (0.5 : 0.5) / (2 : 2)

B\parallel = 6\text{T}

B\parallel = 0\text{T}

g(e^2/h)

0.0 0.5 1.0 1.5 2.0

V_g (mV)

-580 -560 -540 -520 -500 -480 -460

0.0 0.5 1.0 1.5 2.0
SPIN EMISSION FROM A POLARIZED QUANTUM DOT

\[ V_c \propto \frac{\hbar}{2e^2} I_e (1 + P_e P_c) \]
\[ P_c = \frac{(T_\uparrow - T_\downarrow)}{(T_\uparrow + T_\downarrow)} \quad \text{QPC Collector} \]
\[ P_e = \frac{(I_\uparrow - I_\downarrow)}{(I_\uparrow + I_\downarrow)} \quad \text{QD Emitter} \]

J. A. Folk, R. M. Potok, C. M. Marcus, V. Umansky (in preparation)
Injector: PC at 2e²/h
Collector: PC at 0.5 e²/h

No dependence of $V_{BC}$ on $V_{gate}$

Injector: DOT at 2e²/h, 2e²/h
Collector: PC at 0.5 e²/h

Fluctuation of $V_{BC}$ when the dot is completed and a parallel field is applied
QUANTUM DOT AS SWITCHABLE SPIN FILTER
Mesoscopic Spin Fluctuations

collector QPC not spin selective
no Zeeman splitting

all configurations show UCF
Statistics of Fluctuating Polarized Current from a Quantum Dot

\[ p = \frac{G_{\uparrow} - G_{\downarrow}}{G_{\uparrow} + G_{\downarrow}} \]

\[ E_Z = g\mu_B B \gg \Delta \]

\[ P(p) = \frac{1}{(1 + |p|)^2}, \quad -1 < p < 1 \]

\[ \langle p \rangle = 0 \]

\[ \langle p^2 \rangle = 3 - 4 \ln 2 \approx 0.23 \]

with P. W. Brouwer
SUMMARY

Spin-Orbit Coupling Antilocalization and Parallel Fields in Quantum Dots

- Antilocalization in QD.
- Comparison to new random matrix theory that includes SO and parallel magnetic field.
- Asymmetry of SO is measured.
- Gate control of SO coupling.

Spin-Orbit Coupling Antilocalization and Parallel Fields in Quantum Dots

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- New theory allows voltage to read out spin polarization.
- Demonstrate > 80% polarization in a QPC
- Quantum dot as a gate-tunable spin filter with ~25% filtering and adjustable polarization.

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