Electrical Generation of Pure Spin Currents in a Two-Dimensional Electron Gas

S. M. Frolov, A. Venkatesan, W. Yu, and J. A. Folk

Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada

W. Wegscheider

Institut für Angewandte und Experimentelle Physik, Universität Regensburg, Regensburg, Germany

(Received 2 October 2008; published 19 March 2009)

FMM Talk
Serge Waechter

18.10.2013
Motivation

What can we learn from spin currents?
In general: Spin currents can be used as a probe for interacting electron systems

Many **optical** spin current experiments have been performed

→ spin current is not conserved (in contrast to charge current)
→ Learn about diffusion and relaxation behaviour
→ Learn about relaxation mechanisms

In presence of SOI
Spin precession around spin orbit effective field
→ Learn about spin-orbit interaction
**Motivation**

**Three main issues** of working with spin polarized currents on the example of the spin transistor

**Spin injection**
- optically (polarized light)
- electrically (spin selective contacts)
  - FM material (challenging)
  - tuned QPC contacts in Zeeman split regime

**Spin manipulation**
- SOI
- Spin resonance techniques
- Relaxation issues

**Spin detection**
As for injection
Materials and Methods

• QPC gates on GaAs/AlGaAs heterostructure (2DEG 110nm below the surface)
• Width of channel: 1 micron, length: 100 microns

- Electron density: $1.11 \times 10^{11}$ per cm$^2$
- Electron mobility: $4.44 \times 10^6$ cm$^2$(Vs)$^{-1}$

{Measured at 1.5K}

• Measurements performed in dilution refrigerator

• B-Field properties:
  Lift spin degeneracy but avoid trajectories dominated by skipping orbits

  $B_{\perp}$ is kept below 50mT
  $\rightarrow$ Cyclotron radius $>1$ micron

  $B_{\parallel}$ up to 10T
**QPC as injector of spin**

**Generation of spin polarized current:**
1. Tune QPC to spin selective conductance by adjusting $V_{\text{gate}}$
2. Electrical current is passed through spin-polarizing contact
3. Pure spin diffuses to the right, spin and charge current flows to the ground on the left

---

![Diagram of QPC as injector of spin](image)

**QPC conductance**
- $B=0T$
- $B=10T$

- Both spins allowed to pass
- Spin polarized plateau

- $e^2/h$
- $V_{\text{gate}}$ [mV]
QPCs can also detect non-equilibrium spin populations

Suppose excess of spin-up electrons on the left side of a spin-polarized QPC, chemical potential of spin-up is higher than the average (dash).
Those spin-up electrons will travel through the QPC
→ Spin to charge conversion

Spins in non-Equilibrium (when $\lambda_s > x_{id}$)

Spins in equilibrium (spin reservoir)
Results

3D plot shows non local spin voltage measured for different conductance of injector and detector.

When injector and detector are spin polarized $\rightarrow$ positive spin voltage measured

$$V_{nl} \propto P_{inj} \cdot P_{det}$$

$$P = \frac{(G_{\uparrow} - G_{\downarrow})}{(G_{\uparrow} + G_{\downarrow})}$$

$P = 1$ at the first plateau ($e^2/h$)
$P = 0$ at the second plateau ($2e^2/h$)
$P = 1/3$ at the third plateau ($3e^2/h$)
Results

\[ V_{nl} \propto P_{inj}^* P_{det} \quad P = (G_\uparrow - G_\downarrow) / (G_\uparrow + G_\downarrow) \]

Solve 1-D diffusion equation assuming exponential spin decay

- Spin relaxation length
- Use boundary condition: \( [V_{nl}(L_l) = V_{nl}(L_r) = 0] \)

\[ V_{nl}(x_{id}) = \frac{\rho \Box \frac{\lambda_s}{w} I_{inj} P_{inj} P_{det} \sinh \left( \frac{L_r - x_{id}}{\lambda_s} \right)}{\sinh(L_r/\lambda_s)(\coth(L_r/\lambda_s) + \coth(L_l/\lambda_s))} \]

How to extract spin relaxation length \( \lambda_s \)?

Gives information about relaxation processes which are present in the material
Extraction of spin relaxation length

Function of lambda-gate:
*When undepleted* → right side of the channel is short → right hand spin equilibrium is closer to the detector → short channel
*When depleted* → spin equilibrium is farer away from detector → long channel
Injector and detector properties remain unchanged for both measurement geometries

\[
V_{nl}(x_{id}) = \frac{\rho \frac{\lambda_s}{w} I_{inj} P_{inj} P_{det} \sinh\left(\frac{L_r - x_{id}}{\lambda_s}\right)}{\sinh(L_r/\lambda_s)(\coth(L_r/\lambda_s) + \coth(L_I/\lambda_s))}
\]

\(\lambda_s\) can be extracted in-situ by changing the length of the diffusion channel using the lambda-gate.

→ Extract \(\lambda_s\) from the ratio of the signals for the long and short channel

\[\lambda_s = 30 \pm 10 \, \mu m\] and \[\lambda_s = 50 \pm 10 \, \mu m\] is found for two devices
**Relaxation mechanisms**

\[ \lambda_s = 30 \pm 10 \, \mu m \quad \text{and} \quad \lambda_s = 50 \pm 10 \, \mu m \]

- **Dyakonov-Perel** mechanism arising from SOI is assumed to be the primary source of relaxation.

- Relaxation lengths are **independent of field and temperature** between \( B = 3-10 \, \text{T} \) and \( 50 \, \text{mK}-2 \, \text{K} \).

- From Monte Carlo simulations an upper limit of \( B_{so}[\overline{110}] < 1.5 \, \text{T} \) is found to achieve spin relaxation lengths > 30 microns.

- Simulations suggest that the spin relaxation length should rise to \( >300 \, \mu m \) as B-field is increased to 10T.

→ Other spin relaxation mechanisms such as Elliott-Yafet must play a key role.
Extract g-factor of QPCs

g-factor not necessarily equal for bulk and QPC region as reported in previous work

Polarized current results from spin resolved QPC conductance which is dependent on temperature and B-Field

\[ G_{\uparrow\downarrow}(E_0) = \int \frac{df(E + [-\frac{g\mu_B B_1}{2}, T])}{dE} T(E - E_0)dE \]

Electrons contributing to transport and transmission

\[ T(E) = \frac{1}{1 + e^{-2\pi E/\hbar \omega}} \]
Extract g-factor of QPCs

\[ G_{[\Pi]}(E_0) = \int \frac{df(E + [- \frac{g\mu_B B}{2} + T])}{dE} T(E - E_0) dE \]

\[ P \text{ approaches 1 when } g\mu_B B \text{ is much larger than } k_B T \text{ and } \hbar \omega \]

Temperature dependence of G provides measure of the g-factor

→ Change B-Field and T and use g as fitting parameter

\[ |g| = 0.44 \text{ in bulk} \]

\[ |g| = 0.75 \pm 0.1 \text{ in QPC} \]

→ Increased g-factor in QPC
Nonlocal voltages unrelated to spin accumulation were also observed. Injected current gave rise to temperature difference across detector → Joule heating → appears on 2\textsuperscript{nd} harmonics of Lock-in excitation

$$\Delta V_{\text{Joule}} = S_{\text{det}} \Delta T \propto S_{\text{det}} I_{\text{inj}}^2$$

→ Peltier heating → appears on 1\textsuperscript{st} harmonics of Lock-in excitation

$$\Delta V_{\text{Peltier}} \propto S_{\text{det}} S_{\text{inj}} T I_{\text{inj}}$$

At high B-Fields (>3T) → \(V_{nl}\) is dominated by spin component → measure at 0 field

Peltier signal in a checkerboard pattern that is remarkably reminiscent of spin signal

→ Increased voltage measured near steps of conductance, lower voltage on steps

→ Finite thermopower for injector and detector near the steps in conductance
The 2f signal is proportional to Joule heating → fingerprint of thermal effects

→ 1f signal shows nearly identical gate voltage dependence
  → suggests a thermal effect

\[ \Delta V_{\text{Peltier}} \propto S_{\text{det}} S_{\text{inj}} T I_{\text{inj}} \]

Would make sense since the thermopower \( S \propto d\ln(G_{\text{qpc}})/d\mu \)
→ largest \( S \) between the transitions
Conclusion

• QPCs can be used to both inject and detect spin currents
  → Polarization of QPCs and channel length in-situ tunable by gates

• Spin relaxation length of 30-50 microns extracted

• This length is one order of magnitude smaller than expected from simulations
  → Other spin relaxation effects must be present beside DP

• Landé g-factor is enhanced in the QPC compared to the bulk region

• Signal arising at B=0 was identified as Peltier heating

Frolov et al.