Quantum Transport in Ballistic Cavities Subject to a Strictly Parallel Magnetic Field

Cédric Gustin and Vincent Bayot

Cermin,
Université Catholique de Louvain,
Belgium
Collaborators

- Cermin, Univ. Catholique de Louvain, Louvain-la-Neuve, Belgium
  
  Sebastien Faniel
  Benoit Hackens

- Dept. of Electrical Engineering, Princeton Univ., Princeton, NJ, USA
  
  Etienne de Poortere
  Prof. Mansour Shayegan
Motivations for this work

- Interest for ballistic and phase coherent electron dynamics in mesoscopic systems.
- Effect of an in-plane $B$ on the transport properties (universal conductance fluctuations) of an open quantum dot.
- Influence of the 2DEG confinement potential and finite thickness (orbital motion).
Devices Fabrication

- GaAs/Al$_{0.3}$Ga$_{0.7}$As delta-doped Quantum Wells

<table>
<thead>
<tr>
<th></th>
<th>Narrow QW</th>
<th>Wide QW</th>
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</thead>
<tbody>
<tr>
<td>QW thickness</td>
<td>15 nm</td>
<td>45 nm</td>
</tr>
<tr>
<td>Density</td>
<td>$2 \times 10^{11}$ cm$^{-2}$</td>
<td>$3 \times 10^{11}$ cm$^{-2}$</td>
</tr>
<tr>
<td>Location (below surface)</td>
<td>100 nm</td>
<td>150 nm</td>
</tr>
<tr>
<td>Mobility</td>
<td>$6 \times 10^5$ cm$^2$/Vs</td>
<td>$2 \times 10^6$ cm$^2$/Vs</td>
</tr>
<tr>
<td>Occupied Subbands</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

- SEM lithography
- Cr-Au depletion gates
- $3\mu$m$^2$ billiard
Experimental Setup

- Measurements in a 3He refrigerator at 300mK
- Standard lock-in technique at I=1nA

- *In situ* Tilting of the magnetic field
- Second Hall bar on wafer for precise B alignment and tilt angle measurement
Measuring the tilt angle

- Second Hall Bar adjacent to Open dot (150 µm)
- Slope of $R_{xy}$ proportional to tilt angle
- $\Theta=90^\circ$: $R_{xy}$ symmetric in $B$
- Residual $R_{xx}$ at $B=0T$ taken into account
- Precision: 0.01°
- WQW: Drop in $R_{xy}$ around $B=4.5T$
Universal Conductance Fluctuations

- Perpendicular field
- Low-pass filter to isolate UCFs

Narrow Quantum Well

Wide Quantum Well
Tilting the sample: $\theta=90^\circ$

- UCFs under a pure parallel magnetic field
- Fluctuations frequency much smaller in the narrow QW
- Conductance drop in WQW – 4T
- WQW: Comparison with high T curve $\Rightarrow$ looking at high frequencies only $f_{\text{cutoff}}=0.5\text{Hz}$
θ=90° : Temperature Dependence

Narrow Quantum Well

Wide Quantum Well
Fluctuations Statistics : Variance

Wide Quantum Well

- UCFs only: High T (>3K) magnetoresistance removed
- Comparison between Variances at $\theta=0^\circ$ and $\theta=90^\circ$
- Variance decreases as a function of $B_{//}$ (factor 3.5-5) depending on gate voltage

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Possible ingredients

- **2DEG finite thickness**: Electrons “bouncing” on confinement potential walls.

- **Zeeman Energy and SO Coupling**: produce a variance reduction in $B_\parallel$ by a factor of 4
  

- **Orbital effect**: $B_\parallel$ renormalizes $m_{\text{eff}}$, changes $E_F$ (parabolic in $B_\parallel$), lifts the symmetry of the dispersion law $E(k)$.
  

\[
m_{\text{eff}} \rightarrow m_{\text{eff}} \left(1 + \frac{\omega_c^2}{\omega_0^2}\right)
\]

\[
\omega_c = \frac{eB_\parallel}{m_{\text{eff}}}
\]
Subband depopulation – simple model

- Simple Model:
  1. Constant density
  2. 2DEG only
  3. Parabolic confinement potential
  4. No thermal smearing

- Self-Consistent:
  WQW: Upper subband depopulation first
Wide Quantum Well: From 2 to 1 subband

**1 subband:** variance is constant and equal to the value at high $B_{\parallel}$ for 2 subbands.

**No variance reduction with 1 subband**

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**Graph:**

- **$v_{\text{back}} = 0\text{V}$**
- **$v_{\text{back}} = 250\text{V}$**

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UCFs at Intermediate Angles

Wide Quantum Well

- Intermediate tilt angles: subband depopulation
- High tilt angles: No apparent decrease in UCFs frequency
UCFs at Intermediate Angles (2)

Narrow Quantum Well

- Approaching 90°: oscillations frequency decreases
- Near 90°: both frequency and amplitude saturate
Angle from Power Spectrum

- Evaluation of correlation field $B_c$ at intermediate tilt angle

\[ S(f) = S(0) \ e^{-2\pi B_c f} \]

- Comparison with $B_c$ at $\theta=0^\circ$ (perpendicular field)
  - Influence of $B_{//}$ on UCFs statistics
Narrow QW: saturation around $\theta = 89.9^\circ$

Wide QW: saturation below $\theta = 89^\circ$

WQW - 90°: factor 100 in Bc (possible orbital effect)

NQW - 90°: factor 1000 in Bc (not consistent with an orbital effect...
Variance as a function of field: Wide QW

1. M going from 2 to 1 $\Rightarrow$ reduction in variance by a factor of 4: Zeeman and SO coupling might play a role BUT with 1 occupied subband, no further variance reduction is observed!

2. Uncoupled subbands: complete depopulation of upper subband at B=7T. Only lower subband contribute to variance.

3. Why such a large contribution from the upper subband?

4. Could be consistent with finite thickness effect due to semiclassical orbits
Parallel field induced oscillations : Narrow QW

1. Mass renormalization and $E_F$ variation expected to be smaller with narrow confinement potential: lower frequency oscillations induced by $B_{//}$

2. Confinement potential symmetric -> No time-reversal symmetry breaking expected: Variance remains constant

3. Data are not consistent with finite thickness effect due to semiclassical orbits
Conclusions

- Anomalous conductance fluctuations in a parallel magnetic field
- Strong effect of confinement potential
  1. Wide Quantum Well:
     1. Fast oscillating conductance
     2. Variance in pure B$_\parallel$ decreases by a factor of 4 at high field.
     3. One-subband: variance is constant in field
  2. Narrow Quantum Well:
     1. very low frequency oscillations at $\theta=90^\circ$
- Possible ingredients:
  - Semi-classical trajectories
  - Orbital effect with time-reversal symmetry breaking
  - 2DEG subband depopulation