Bending the QHE by 90°:

*Novel 1D metallic and insulating phases*

Matthew Grayson

*Walter Schottky Institut, TU München*

preprint
Collaborators

L. Steinke, M. Huber, G. Abstreiter, D. Schuh, M. Bichler
Walter Schottky Institut (Garching)

L. Hoeppel, J. Smet, K. von Klitzing
MPI-Festkörperphysik (Stuttgart)

D. Maude
CNRS - LCMI (Grenoble)

Discussions

Thierry Giamarchi
University of Geneva

Dmitry Polyakov
Karlsruhe Forschungszentrum

Allan MacDonald
University of Texas

Eduardo Fradkin, Eun-Ah Kim
University of Illinois
**Postdoc**: Joel Moser  
**PhD**: Sebastian Roth, Michael Huber, Frank Fischer, Lucia Steinke, Shivaji Dasgupta, Nebile Isik, Emanuele Uccelli  
**Masters**: Felix Erfurth, Sebastian Jakob, Claudius Knaak, Marco Neumair

**Spintronics**  
Heavy holes in (110) GaAs  

**1D Wires**  
Cleaved-edge overgrown quantum wires in AlAs  

**Novel Crystal Growth Techniques**  
MBE-Patterned Etch-Regrowth  
Corner Overgrowth  

**Double Cleave Quantum Wires**  
Modulated potential along wire

**Quantum Hall Edges**  
Edge tunneling spectroscopy  
Intro: QHE

I. Bent quantum well
II. Bending the QHE
   1D Wire bound by QHE gaps
III. T, V - dependence
IV. Discussion + Hartree calculations
QHE Edge states

\( E(x) \)

\[ \nu = 1, 2, 3 \rightarrow \text{Fermi Liquid} \]

\[ \nu = 1/3 \rightarrow \text{Luttinger Liquid} \]

I = \( \frac{\nu e^2}{h} \) V

Chiral 1D

\( \nu = 2 \)

Halperin PRB (82)
Buttiker PRB (85)
X.G. Wen PRB (90)

M.A. Paalanen, et al.
PRL 25 (1982)
(110) Corner overgrowth

(110) substrate

GaAs substrate
(110) Corner overgrowth

(110) substrate

AlGaAs

Si-δ-doping

AlGaAs

GaAs substrate

2DEG

(110) precleave

1 µm

10 nm
(110) Bent Quantum Well

\[ \frac{v_s}{v_p} = \frac{n_s / B \cos(\theta)}{n_p / B \sin(\theta)} = \frac{n_s}{n_p} \tan(\theta) \]

Precleave

T = 350 mK
\( n_p = 1.28 \times 10^{11} / \text{cm}^2 \)

Substrate

T = 350 mK
\( n_s = 1.10 \times 10^{11} / \text{cm}^2 \)
Example 1D Systems

\[ G = \frac{I}{V} \]

\[ \sigma_{1D} = G \cdot L \]

\[ I_{wire} = I_{in} - I_{back} = \frac{\nu e^2}{h} V_{cc} \]

\[ G = \frac{\nu e^2 V_{cc}}{h V_{s}} \]
Tilted field: Uniform $\nu$

$\theta = 51.8^\circ$

![Diagram of tilted field with labels and data points](image)

Graph showing $R_{xx}, R_{cc}$ (Ω) vs. $B$ (T) with marked peaks at 1, 2, 3, 5, 10, 20 T, and labels 10, 8, 6, 5, 4, 3.

30 mK
Tilted field: Uniform ν

Backscattering at corner along 1D Wire

B (T)

Rxx, Rcc (Ω)

30 mK

10 nm < 2 l_B

AlAs

GaAs

1 µm

10 nm

10 nm -
Tilted field: Uniform $\nu$

$\theta = 51.8^\circ$

$G = \frac{\nu e^2}{h} \frac{V_{cc}}{V_s}$
\[ \nu_s : \nu_p = 1:1 \]

\[ \theta = 51.8^\circ \]

\[ G = \frac{\nu e^2}{h} \frac{V_{cc}}{V_s} \]

\[ T = 30 \text{ mK} \]
### Characteristics Table

<table>
<thead>
<tr>
<th>$\nu$</th>
<th>$B$</th>
<th>Conductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
<td>20-23 T</td>
<td>conductor</td>
</tr>
<tr>
<td>1, 2</td>
<td>4-9 T</td>
<td>insulator</td>
</tr>
<tr>
<td>3, 4, 5, 6</td>
<td>0-2.5 T</td>
<td>conductor</td>
</tr>
</tbody>
</table>
Length Dependence

$\nu_s: \nu_p = 1:1$

1D Behavior

$Nl_0 \sim 7 \mu m$

$Nl_0 \sim 27 \mu m$

$G = \sigma_{1D} / L$

$\sigma_{1D} = Nl_0 e^2/h$
## Characteristics Table

<table>
<thead>
<tr>
<th>$\nu$</th>
<th>$B$</th>
<th>conductance</th>
<th>length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
<td>20-23 T</td>
<td>conductor</td>
<td>--</td>
</tr>
<tr>
<td>1, 2</td>
<td>4-9 T</td>
<td>insulator</td>
<td>--</td>
</tr>
<tr>
<td>3, 4, 5, 6</td>
<td>0-2.5 T</td>
<td>conductor</td>
<td>$1/L$</td>
</tr>
</tbody>
</table>
\[ \nu_s : \nu_p = 1:1 \]

\[ \theta = 51.8^\circ \]

\[ B_0 = 90^\circ \]

\[ T = 30 \text{ mK} \]

\[ G (e^2/h) \]

FQHE - IQHE

\[ \nu = \frac{1}{3}, \frac{2}{3}, 1, 2, ... \]

\[ \nu \]

\[ 1 \downarrow, 2 \uparrow, 2 \downarrow, ... \]
Temperature dependence

Character of 1D Tuned by gap $\nu$
Voltage dependence

\[
\frac{dI}{dV} (\frac{e^2}{h}) = f(V_{DC})
\]

- 0.010 -0.005 0.000 0.005 0.010
- 0.00 -0.01 -0.02 -0.03
- 30 mK
- 60 mK
- 85 mK
- 120 mK
- 170 mK
- \(\nu = 1/3\)
- \(\nu = 1\)
- \(\nu = 2\)
- \(\nu = 3\)
- \(\nu = 4\)
## Characteristics Table

<table>
<thead>
<tr>
<th>$\nu$</th>
<th>$B$</th>
<th>conductance</th>
<th>length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
<td>20-23 T</td>
<td>metal</td>
<td>--</td>
</tr>
<tr>
<td>1, 2</td>
<td>4-9 T</td>
<td>insulator</td>
<td>--</td>
</tr>
<tr>
<td>3, 4, 5, 6</td>
<td>0-2.5 T</td>
<td>critical</td>
<td>1 / L</td>
</tr>
</tbody>
</table>
Hartree calculation

\[ H = \frac{p^2}{2m^*} + V(x, z) + V_{e-e} \]

- **Hartree (B=0)**
- **2DEG**
- **d = distance from corner**
- **n (10^{11} / cm^2)**
- **substrate**
- **precleave**
- **total density**
- **1D wire density**
- **2D density**
Landau Dispersion

Hartree with B-field

\[ H = \frac{p^2}{2m^*} + V(x, z) + V_{e-e} + \frac{1}{2} m^* \omega_c^2 (x - x_0)^2 \]

Hybrid 1D system
Temperature dependence

Multimode 1D wire
### Characteristics Table

<table>
<thead>
<tr>
<th>$\nu$</th>
<th>$B$</th>
<th>conductance</th>
<th>length</th>
<th>model</th>
<th>interactions?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
<td>20-23 T</td>
<td>metal</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>1, 2</td>
<td>4-9 T</td>
<td>insulator</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>3, 4, 5, 6</td>
<td>0-2.5 T</td>
<td>critical</td>
<td>1 / L</td>
<td>multimode 1D wire</td>
<td>no</td>
</tr>
</tbody>
</table>
Dispersion at various B-fields

$E_0^{1D}$

$E_0^{2D}$

$B = 1 \text{T}$

$B = 2.25 \text{T}$

coupling region

coupling ~ wavefunction overlap

low $B$

hi $B$
Insulator at high B

coupling gap at high B => 1D Insulator
Temperature dependence

Anticrossing gap

Localization in 1D

N.F. Mott and W.D. Twose (1961)
Abrahams, Anderson, Licciardello, Ramakrishnan (1979)
### Characteristics Table

<table>
<thead>
<tr>
<th>$\nu$</th>
<th>$B$</th>
<th>conductance</th>
<th>length</th>
<th>model</th>
<th>interactions?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
<td>20-23 T</td>
<td>metal</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1, 2</td>
<td>4-9 T</td>
<td>insulator</td>
<td>--</td>
<td>level anticrossing</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>localization</td>
<td></td>
</tr>
<tr>
<td>3, 4, 5, 6</td>
<td>0-2.5 T</td>
<td>critical</td>
<td>1 / L</td>
<td>multimode 1D wire</td>
<td>no</td>
</tr>
</tbody>
</table>
1D Metal, $\nu = \frac{1}{3}$

Metal = e- tunnel coupled LL´s

S. Renn, D. Arovas,
PRB 51, 16832 (1995)

C. Kane, M. Fisher,
PRB 56, 15231 (1996)

T. Giamarchi and H. J. Schulz
PRB 37, 325 (1988)

Lo T - decoupled
Temperature dependence

[Graph showing the temperature dependence of various phases in 1D systems.]

Antiwire of chiral Luttinger liquids with e- tunneling
## Characteristics Table

<table>
<thead>
<tr>
<th>$\nu$</th>
<th>$B$</th>
<th>conductance</th>
<th>length</th>
<th>model</th>
<th>interactions?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
<td>20-23 T</td>
<td>metal</td>
<td>--</td>
<td>LL antiwire</td>
<td>YES</td>
</tr>
<tr>
<td>1, 2</td>
<td>4-9 T</td>
<td>insulator</td>
<td>--</td>
<td>level anticrossing localization</td>
<td>no</td>
</tr>
<tr>
<td>3, 4, 5, 6</td>
<td>0-2.5 T</td>
<td>critical</td>
<td>1 / $L$</td>
<td>multimode 1D wire</td>
<td>no</td>
</tr>
</tbody>
</table>
Conclusions

* Demonstrate 1D system bound at corner of bent QHE
* Measure conductance as function of $\nu$
* Measure mean free path $l_0$
* Tune 1D metal – critical – insulator behavior with $\nu$
* Metallic state:
  
  Evidence of 1D metal
Wavefunctions

**B = 1 T**

Strong overlap of counter-propagating channels