Quantum Transport in InAs/GaSb

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Outline

• InAs/GaSb heterostructure

• The experiments and results
  – Circular conductivity law in the charge neutrality regime in an InAs/GaSb field-effect-transistor
  – McMillan-Rowell like oscillations in a Ta-InAs/GaSb-Ta junction
  – Giant supercurrent in a Ta-InAs/GaSb-Ta junction

• Summary
InAs/GaSb heterostructure:

Quantum spin Hall effect

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• Summary
Growth structure:

- air
- InAs 20A (or GaSb 20A)
- AlSb 500A
- GaSb QW 50A
- InAs QW 150A
- AlSb 1um
- GaSb 1um
- GaSb substrate (p-doped)

Field-effect transistor:

Electron transport at zero magnetic field:

- $R_{xx} (\text{k}\Omega)$
- $V_g (\text{V})$
- $B = 0 \text{T}$
- $T \sim 25 \text{ mK}$

Diagram showing $E_g_0$, $E_1$, and $\Delta$.
$G_{xx}$ ($e^2/h$)

$V_g$ (V)

$T \sim 25 \text{ mK}$
$B = 0 \text{ T}$

$4e^2/h$
\( \sigma_{xx}^{th} \approx \frac{e^2}{h} \times \frac{E_{g0}}{\Delta} \)


\( E_{g0} \sim 15 \text{ meV} \)

\( \Delta \sim 1 \text{ meV} \)

\( \sigma_{xx}^{th} \approx 15 \frac{e^2}{h} \)

\( G_{xx}^{th} = 5 \frac{e^2}{h} \sim 4 \frac{e^2}{h} \)
$G_{xx} = 3.97 + 0.10 \times \log (T)$

Electron transport at low magnetic fields:

\[ R_{xx} \text{ (arb. units)} \]

\[ V_g \text{ (T)} \]

\[ B = 2 \text{ T} \]

\[ \nu = 16 \]

\[ 22 \]

\[ 28 \]

\[ 34 \]
At charge neutrality point CNP \((n + p = 0)\), 
\[|n| = |p| \sim 0.6 \times 10^{11} \text{ cm}^{-2}\]
\[ \sigma_{xx}, \sigma_{xy} \left( e^2/h \right) \]

- \[ B = 5T \]

- \[ \nu_h = -2 \]

- \[ \nu_e = 12 \]
Electron transport at high magnetic fields:

\[ \sigma_{xx}, \sigma_{xy} \text{ (e}^2/\text{h}) \]

\[ V_g \text{ (V)} \]

\[ B = 20 \text{ T} \]

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

\[ \nu_e = 3 \]

\[ \nu_h = 2 \]

\[ \nu = 1 \]

\[ \nu = 0 \]

\[ \nu = -1 \]

\[ \nu = -2 \]
\[(\sigma_{xx} - N)^2 + \sigma_{xy}^2 = N^2\]
Semi-Circular conductivity law in quantum Hall plateau transition

\[ (\sigma_{xy} - \nu/2)^2 + \sigma_{xx}^2 = (\nu/2)^2 \]

independently of \(\rho_{xx}\)

\[(\sigma_{xx} - N)^2 + \sigma_{xy}^2 = N^2\]

\[\rho_{xx} = \frac{h/e^2}{2N}\]

$B = 20 \text{ T}$

$T \sim 30 \text{ mK}$
The circular conductivity law due to co-existence of both electrons and holes and their interactions

- In the CN regime, electron density and hole density low.
- Landau level filling factors for electrons and holes small
- Without e-h interactions, 2D electrons and holes in high magnetic field induced insulating phase, $\sigma_{xx} = 0$ and $\sigma_{xy} = 0$. 
• Breakup of perfect dissipationless edge states due to disorder and e-h interactions.

• Breakup of stable orbits can give rise to chaotic motions.


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• Summary
8-band k.p calculations with QW widths (GaSb 5 nm; InAs 10 nm)

K. Chang, unpublished
Density \( n = 1.8 \times 10^{11} \text{ cm}^{-2} \)

Mobility \( \mu = 1.2 \times 10^5 \text{ cm}^2/\text{Vs} \)

\( E_F = 18.7 \text{ meV} \)

\( l_{\text{mfp}} = 0.8 \mu \text{m} \)

\( V_F = 5.4 \times 10^5 \text{ m/s} \)
Ta-InAs/GaSb-Ta junction

- Junction: W=10 µm L=2 µm

\[
\begin{align*}
&\text{Ta} \\
&240 \text{ nm} \\
&\text{InAs} \ 2 \text{ nm} \\
&\text{AlSb} \ 50 \text{ nm} \\
&\text{GaSb} \ 5 \text{ nm} \\
&\text{InAs} \ 10 \text{ nm} \\
&\text{AlSb} \ 50 \text{ nm} \\
&\text{Ta} \\
&240 \text{ nm}
\end{align*}
\]

\[R (\Omega) \quad T (K)\]

\[T_c = 1.55 K\]
Zero bias conductance peak + multiple equally spaced dips
McMillan-Rowell like Oscillations

\[ V_n = V_0 + n \times \frac{hV_F}{4d_N} \]
One serious issue with MRO explanation:

From the slope of MRO plot, a Fermi velocity of $V_F = 1.3 \times 10^7$ m/s is obtained.

This value is much larger than that ($V_F = 5.4 \times 10^5$ m/s) obtained from SdH oscillations.
Giant super-current in $\text{Ta-InAs/GaSb-Ta}$ junction
Giant super-current observed
A couple of details:

1) Very large $J_c$, $J_c = 350 \text{nA/\mu m} \gg \sim 15 \text{nA/\mu m}$ reported by other groups.
   (considering $L = 2\mu \text{m}$, $\xi_{sc} \sim 80\text{nm}$ (bulk Ta) and $l_{mfl} = 0.8\mu \text{m}$)

2) Large number of flux per lobe $\sim 300 \Phi_0 \gg 1$.
   A large value of flux per lobe was also observed in S-GaAs-S junction by Rokhinson et al.
Summary:

(1) Well-developed integer quantum Hall effect states at Landau level fillings \( \nu = 1, 2 \) in the hole regime and \( \nu = 1, 2, 3... \) in the electron regime.

(2) Chaotic quantum transport behavior at extremely high magnetic fields around the charge neutrality point.

(3) Circular conductivity law in \( \sigma_{xx} \) versus \( \sigma_{xy} \).

(4) MRO in Ta-InAs/GaSb-Ta junction device

(5) Giant supercurrent in Ta-InAs/GaSb-Ta junction
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