InAs/GaSb – A New 2D Topological Insulator

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1. Old Material for New Physics
2. Quantized Edge Modes
3. Adreev Reflection
4. Summary

Superconductor Hybrids
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Transport
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ArXiv:1106.5819 (2011)
Quantum Spin Hall Effect in Hg/Te

Quantum Spin Hall Effect

* Bulk charge energy gap

* Gapless edge states – odd number of Kramers pairs

* Helical edge states – four terminal conductance of $2e^2/h$

* Observed in HgTe/CdTe QWs in mesoscopic samples

1. Band parameter
\[ \Delta E = E_1 - H_1 \]
can be tuned by width, x, gates

2. \( \Delta E < 0 \) inverted \(-0.15 \text{ eV} \) to 0

Tunneling mix e-h and opens a gap at finite \( k \)-vector

3. Used as infrared detector and night vision CCD

4. High mobility MBE wafers produced in best industrial labs (1\( \sim \)5 x \( 10^5 \) cm\(^2\)/Vs)
InAs/GaSb as a QSH Insulator

Liu et al, PRL 100, 236601 (2008)
Wafer and Device

ΔE = E₁−H₁
-33 meV -18 meV ~ 0

Eₚ, ΔE can be readily tuned by gates

Simiconductor-TI transition

QSHE

InAs/GaSb/InAs/GaSb… Superlattice
- Helical surface states?
Re-entrant Quantum Hall Effect
Bound Excitons - BEC
Tuning Through Mini Gap in Meso Samples

(Wafer A 1.5 by 0.5um Hall bar)

12.9 kΩ x3?

300 mK

Holes

Electrons

$G'(\phi, L) = (\lambda / L)(2e^2 / h)$

Scattering Length

Sample length
Intrinsic and extrinsic Origins of Bulk Conductivity

\[ \sigma_{on} \approx \frac{3e^2}{h} \frac{E_{g0}}{\Delta} \]

1. Wavefunctions do not 100% overlap -- residual e and h
2. Hybridized e-h not necessary charge neutral
3. Hybridized e-h can break due to impurities

1. Less inverted
2. Narrow QWs
3. Higher mobility

Wafer A \( E_{g0} \sim -33 \text{ mev}, \sigma \text{ (bulk)} > 12 \text{ e}^2/\text{h} \)
Wafer B \( E_{g0} \sim -18 \text{ mev}, \sigma \text{ (bulk)} << 10 \text{ e}^2/\text{h} \)

\( \sigma \text{ (bulk)} \sim 10 \text{ e}^2/\text{h} \) is a “magic” number

Edge modes de-couple from bulk transport

Naveh & Laikhtman, Euro. Phys. Lett. 55, 545
Helical edge modes in four terminal geometry

- For phase coherent samples Landauer-Buttiker formula gives conductance value:
  \[
  G_{14,23} = \frac{4e^2}{h}
  \]

- Longer samples can be modeled by inserting phase breaking probes and applying LB-formula:
  \[
  G_{14,23} = \frac{2e^2}{h} \left( \frac{l_{\phi}}{L} + \left( \frac{l_{\phi}}{L} \right)^2 \right)
  \]
Conclusion

For $\pi$ geometry, the edge conductivity is $\sim$ quantized to $4 \frac{e^2}{h}$.
Robustness of Edge Quantization \textit{vs} Bulk Conduct.

Back gate
To change Inversion

Small inversion

Robustness of Edge Quantization \textit{vs} Bulk Conduct.

- **a)**
  - $R_{xx} (k\Omega)$
  - $V_{\text{front}} (V)$

- **b)**
  - $R_{xx} (k\Omega)$
  - $V_{\text{back}} (V)$

- **c)**
  - $\Delta G (e^2/h)$

- **d)**
  - $\Delta G (e^2/h)$
  - $g_{\text{bulk}} (e^2/h)$

- **b)**
  - Slowly-Prop. Edge Modes
  - $3 \times 10^4 \text{ cm/s}$
“Anomalous” Magnetic Field Dependence

All 300 mK

1. Long samples show stronger positive MR – bulk effect

2. μm samples weaker depend.

3. Edge states does not scatt. into and out of bulk – lack of loop

Decouple from bulk
Opens a Number of Exciting Experiments

1. Edge states extend all the way to the material edge (\(E_f\) pinned above \(E_c\) for InAs)

2. Good interface with superconductors due to low Schottky barrier --- SC Hybrids

Examples

Andreev Reflection

Majorana Bound State (MBS)

Fu & Kane PRB 2008

Non-Equilibrium Josephson Effect Through Helical Edge State

arXiv: 1108.3870

Cleavage STM/STS

Front Gate
1. Can we make Nb/InAs Junction - Test ✓
2. Can we make Nb/InAs-GaSb Junction - New

Multiple Adreev Reflection:
3 sets of peaks: $\Delta_N$, $\Delta_S$, $\Delta_N+\Delta_S$

$\Delta_N/\Delta_S \sim 0.67$

$\Delta_S = 1.31\text{meV} \ ; \ \Delta_N = 0.87\text{meV}$
Andreev Reflection in 3 Regimes

**electron side**

- $V_{\text{front}} = 5V$ (n-type)
- $I_{\text{excess}} = 2.5\mu A$
- $R_N = 2 k\Omega$ or $12.9 k\Omega$
- $\Delta = 1.23 \text{ meV}$
- $e^*_{\text{excess}} R_N/\Delta = 0.365$ or 2.88
- $Z = 0.65$ or 0
- $T = 0.56$ or 1

**In the gap**

- $I_{\text{excess}} = 2.75 nA$
- $R_N = 2 k\Omega$
- $\Delta = 1.23 \text{ meV}$
- $e^*_{\text{excess}} R_N/\Delta = 0.365$ or 2.88
- $Z = 0.65$ or 0
- $T = 0.56$ or 1

**hole side**

- $V_{\text{front}} = -5V$ (p-type)
- $I_{\text{excess}} = 230 nA$
- $R_N = 1.9 k\Omega$
- $\Delta = 1.23 \text{ meV}$
- $e^*_{\text{excess}} R_N/\Delta = 0.365$ or 2.88
- $Z = 0.65$ or 0
- $T = 0.56$ or 1

**Diagram:**

- Width: 1 $\mu$m
- Gate

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$E_R$ (Arb. units)

$E_{\text{go}}$

$k$ (Arb. units)
Andreev Reflection in Nb/(InAs-GaSb)/Nb
Knez, Du, Sullivan  
ArXiv:1106.5819 (2011)
Perfect Andreev Reflection

\[ V_{\text{front}} = 5 \text{V} \]  
Electron side

\[ V_{\text{front}} = -2.1 \text{V} \]  
Hole side
Excess Current Suppressed by Magnetic Fields

- $V_{\text{front}} (V)$, $R_N (\text{k}\Omega)$, $I_{\text{excess}} (\mu\text{A})$
- $B_{\text{perpendicular}} (\text{mT})$
Temperature dependence