Transport Experiments on 3D Topological insulators

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1. Transport in non-metallic Bi$_2$Se$_3$ and Bi$_2$Te$_3$

2. A TI with very large bulk $\rho$ – Bi$_2$Te$_2$Se

3. SdH oscillations to 45 Tesla – Evidence for $\frac{1}{2}$ shift from Dirac Spectrum

4. Is there a Zeeman induced shift at n = 0?

5. Hydrostatic pressure – bulk band structure

Support from
NSF DMR 0819860
DARPA
ARO
Mass (gap) twist in 1D: polyacetylene

Early precursor in solid-state physics

**Doped polyacetylene**

\[ H = \begin{bmatrix} m(x) & v_F(k_x - ik_y) \\ v_F(k_x + ik_y) & -m(x) \end{bmatrix} \]

Dirac \( H \) has an \( x \)-depdt mass term

Traps a kink state at \( m = 0 \) with fractional quantum nos.

Jackiw Rebbi, PRD ‘76
Su, Schrieffer, Heeger PRL ‘78
Goldstone Wilczek, PRL ‘81

Domain wall (soliton) traps \( \frac{1}{2} \) charge
A twist of the gap leads to topological surface states.
1. Mass twist $\rightarrow$ helical state at zero mass

$$H = \begin{bmatrix} m(x) & v_F (k_x - ik_y) \\ v_F (k_x + ik_y) & -m(x) \end{bmatrix}$$

Twist is topologically stable

2. Strong spin-orbit int. $\rightarrow$ giant Rashba term and spin-locking with opposite helicities

$$H_R = v_F \hat{n} \cdot \vec{\sigma} \times \mathbf{k}$$

$n = \text{surface normal}$
Helicity and large spin-orbit interaction

- Surface electron feels surface E-field. In its rest, sees field $B = v \times E$
- Large $B$ (enhanced by SOI) locks spin $s \perp v$
- Rashba-like Hamiltonian

$$H = v_F \hat{n} \times k \cdot s$$

Helical, massless Dirac states with opposite chirality on opp. surfaces of crystal

Suppression of $2k_F$ scattering

Surface conductance

$$G_s = \left( \frac{e^2}{h} \right) k_F l$$

$$R_s \sim 400 \text{ Ohms} \quad \text{if } k_F l = 100$$
In \( \text{Bi}_2\text{Se}_3 \) and \( \text{Bi}_2\text{Te}_3 \)

- Only 1 surface state present
- Massless Dirac spectrum
- Large gaps -- 300 and 200 meV
Difficult to resolve surface states by transport

Onset of non-metallic behavior ~ 130 K

*Bulk* SdH oscillations seen in both n-type and p-type samples

Non-metallic samples show no discernible SdH (disorder from Ca dopants)

**Checkelsky et al., PRL ‘09**

\( \text{Bi}_2\text{Se}_3 \)
Shubnikov de Haas Oscillations in non-metallic Bi₂Te₃

Qu, NPO et al. Science, 2010

Non-metallic crystals

Metallic crystal

SdH oscillations in Hall conductivity

Chemical potentials of samples Q1, Q2, Q3
2D vs 3D Shubnikov de Haas period in bulk Bi$_2$Te$_3$

Non-metallic sample

Metallic sample

Qu, NPO et al. Science 2010

SdH period $S_F$ scales as $\cos \theta$
Hence, 2D

Period $S_F$ deviates from 2D
Hence, 3D ellipsoidal
Temperature dependence of Shubnikov de Haas amplitude

Qu, NPO et al. 2010

SdH amplitude decreases with $T$.

For massless Dirac states, we fit to

$$\Delta\sigma(H,T) \sim \frac{\lambda}{\sinh(\lambda)} e^{-D}$$

$$m_c = \frac{E}{v_F^2}$$

$$\lambda = \frac{2\pi^2 k_BT}{\hbar \omega_c}$$

$$D = \frac{2\pi^2 k_BT_D}{\hbar \omega_c}$$

Fits yield

$m_c = 0.1 \, m_0$

$v_F = 3.7 \text{ -- } 4.1 \times 10^5 \text{ m/s}$

(ARPES gets $4 \times 10^5$).
1. (Panel A) Hall conductivity $\sigma_{xy}$ shows a “resonance” anomaly in weak $H$

2. (Panel B) After subtracting bulk contribution, the resonance is the isolated surface Hall conductivity $G_{xy}$. Peak position yield mobility $\mu$ (~9,000 cm$^2$/Vs) and peak height yields metallicity $k_F\ell = 80$.

Panel B is a “snap shot” that gives mobility and $k_F\ell$ by inspection.
Fit (semiclassical)

\[ \sigma_{xy} = \sigma_{xy}^b + G_{xy} / t \]

\[ \sigma_{xy}^b = n_b e\mu_b \frac{\mu_b H}{[1 + (\mu_b H)^2]} \]

\[ G_{xy} = \frac{e^2}{\hbar} k_F \ell \frac{\mu_s H}{[1 + (\mu_s H)^2]} \]

\[ \mu_s = \frac{e \ell}{\hbar k_F} \]

\[ \ell = 240 \text{ nm} \quad \mu_s = 8,000 \text{ cm}^2/\text{Vs} \]

- Good agreement with Dingle analysis & 2D massless Dirac state.
- Numbers rule out \( G_{xy} \) as 3D bulk term.
### Comparison of transport parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>$R_{\text{obs}}$ (Ω)</th>
<th>$\rho_b$ (mΩcm)</th>
<th>$\mu_s$ (cm²/Vs)</th>
<th>$k_Fl$</th>
<th>$G_s/G_{\text{bulk}}$</th>
<th>$\mu_s/\mu_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi₂Se₃ (Ca)</td>
<td>0.01</td>
<td>30-80</td>
<td>&lt; 200</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Bi₂Te₃</td>
<td>0.005</td>
<td>4-12</td>
<td>10,000 100</td>
<td>0.03</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Bi₂Te₂Se</td>
<td>300-400</td>
<td>6,000</td>
<td>2,800 40</td>
<td>~1</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>
Topological Insulator with sharply reduced bulk cond. \( \text{Bi}_2\text{Te}_2\text{Se} \)

Xiong, Cava, NPO

*cond-mat/1011.1315*

Also,

Y. Ando et al., PRB '11

**Bulk mobility** \( \mu_b \sim 50 \text{ cm}^2/\text{Vs} \)

**Bulk carrier density**

\( n_b \sim 2.6 \times 10^{16} \text{ cm}^{-3} \)
Band Structure of Bi$_2$Te$_2$Se

Indexing the Landau Levels (LLs)

Applied magnetic field $B$ quantizes density of states (DOS) into Landau Levels

Dirac Landau Levels (LLs) spread out as $B$ increases

Chemical potential $\mu$ approaches $n = 0$ level (Dirac Point)

$\mu$ falls between LLs when $\rho_{xx}$ is a local maximum (at $B_n$)

Landau Level Index $n$ determined by plotting $n$ vs. $1/B_n$
Schrödinger vs Dirac spectrum

Check intercept of index plot in quantum limit $1/B \to 0$

$$\frac{1}{B_n} = (n+1/2)\frac{e}{hn_s} \quad \text{or} \quad \frac{1}{B_n} = \frac{e}{hn_s}n$$

Dirac states have intercept at $n = -1/2$ because states at $n = 0$ LL come from both conduction and valence bands.

Equivalently, effect of Berry phase $\pi$-shift
To approach quantum limit ($n = 0$ Landau Level),

apply very high B field (45 Tesla)
Amplitude of SdH oscillations is 17% of total conductance

Derivatives not needed to resolve SdH oscillations

Bulk resistivity $\rho_b = 4 - 8 \ \Omega \text{cm} \ (\sim 4 \ K)$

Oscillations seen in both $G_{xx}$ and $G_{xy}$
Isolate SdH oscill terms $\Delta G$, $\Delta G_{xy}$

Largest oscillations seen to date in Bi based TI's

Peak-to-peak amplitudes

$\sim e^2/h$ in $\Delta G_{xy}$

$\sim 4e^2/h$ in $\Delta G$

Fit to Lifshitz expression yields

$\mu = 3,200 \text{ cm}^2/\text{Vs}$
Limiting behavior as $1/B_n \to 0$

Intercept $(1/B \to 0)$ at $n = -0.40 \to -0.55$

High-field SdH results support Dirac dispersion
Josephson supercurrent through a topological insulator surface state

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2-probe resistance of exfoliated Bi\textsubscript{2}Te\textsubscript{3}

Incorrect identification of index field $B_n$
Oscillations are actually from bulk carriers
Intense $E$ field applied to sample by ions
As $V_G$ increases to more negative values, resistivity increases. Hall density decreases. Implies surface density decreases.
Liquid Gating Effect on Surface Quantum Oscillations

As $|V_G|$ increases, period of oscillations increases (Fermi Surface cross section decreases).

Also, amplitude of oscillations increases (more uniform density?)

Period increases 7-fold

Energy decreases by 2.6
Tuning SdH oscillations by liquid gating in fields up to 45 Teslas

Sample 2

n = 1/2
Sample 2
Tuning $V_G$ from 0 → -3 V decreases FS area and $n_s$ by ~7

SdH amplitude increases

At 14 Tesla, Lowest Landau Level accessed is $n = 1$!

Intercept in quantum limit $1/B_n \to 0$ gives $n = -1/2$, with much higher resolution.

Strong evidence for Dirac spectrum
$E_F$  

Dirac Point  

$n = 1/2$  

$N = 0$  

(a) Sample 1  

$V_G = 0$  

(b) Sample 1  

$V_G = -2.1$  

(c) Sample 2  

$V_G = -6$  

 integer $n$ vs. $1/B$ (T$^{-1}$)
Experimental Observation of the Quantum Anomalous Hall Effect in a Magnetic Topological Insulator

Cui-Zu Chang, Jinsong Zhang, Xiao Feng, Jie Shen, Zuocheng Zhang, Minghua Guo, Kang Li, Yunbo Ou, Pang Wei, Li-Li Wang, Zhong-Qing Ji, Yang Feng, Shuaihua Ji, Xi Chen, Jinfeng Jia, Xi Dai, Zhong Fang, Shou-Cheng Zhang, Ke He, Yayu Wang, Li Lu, Xu-Cun Ma, Qi-Kun Xue
Quantized Anomalous Hall Effect in Magnetic Topological Insulators

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