Topological Insulators

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1. Introduction
2. Angle resolved photoemission (Hasan)
3. Tentative transport signatures
4. Giant fingerprint signal
5. Insulator and Superconductor
A new class of insulators

Conventional insulator

Top

Surface states are helical (spin locked to $k$)
Large spin-orbit interactn

Bottom

Surface states may cross gap

Topological insulator

Surface state has Dirac dispersion

Fu, Kane '06
Zhang et al. '06
Moore Balents '06
Xi, Hughes, Zhang '09
Protection of helical states

1. Time-reversal invariance prevents gap formation at crossing

\[ \text{cond. band} \quad \otimes \quad \text{valence band} \quad ? \quad \text{cond. band} \quad \otimes \quad \text{valence band} \]

\[ \text{Violates TRI} \quad \text{Kane, Mele, PRL '05} \]

Under time reversal
\[ (k^\uparrow) \rightarrow (-k^\downarrow) \]

2. Suppression of \(2k_F\) scattering

\[ \text{2D Fermi surface} \]

Spinor product kills matrix element
Large surface conductance?
Helicity and large spin-orbit coupling

- Spin-orbit interaction and surface
  \( E \) field \( \rightarrow \) effective \( B = v \times E \) in rest frame

- Spin locked to \( B \)

- Rashba-like Hamiltonian
  \[ H = v_F \hat{n} \times k \cdot s \]

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

Like LH and RH neutrinos in different universes
A twist of the mass (gap)

Doped polyacetylene (Su, Schrieffer, Heeger ‘79)

1. Gap-twist produces domain wall
2. Domain wall traps fractional charge
3. Topological (immune to disorder) Mobius strip like

$H = \begin{bmatrix} pv & \Delta(x) \\ \Delta^*(x) & -pv \end{bmatrix}$

* Domain wall (soliton) traps $\frac{1}{2}$ charge

Mobius strip
Dirac fermions as domain wall excitation

QFT with background mass-twist field

Dirac modes on domain walls of mass field

\[ H = \begin{pmatrix} m(x) & p \\ p & -m(x) \end{pmatrix} \]

Chiral zero-energy mode

Domain-wall fermion

Callan-Harvey: Domain walls *exchange* chiral current to solve anomaly problem

Topological insulator

Chiral surface states?

Vacuum

Jackiw Rebi, PRD '76
Goldstone Wilczek, PRL '81
Callan Harvey, Nuc Phys B '85
Fradkin, Nuc Phys B '87
D. Kaplan, Phys Lett B '92
Fu Kane prediction of topological insulator

Mass twist traps surface Weyl fermions

Mass twist

Bi

Bi$_{1-x}$Sb$_x$

Sb

ARPES confirmation
Hsieh, Hasan, Cava et al.
Nature '08

Confirm 5 surf states in BiSb
Angle-resolved photoemission spectroscopy (ARPES)

20 eV photons

velocity selector

µ

E

Intensity

E

quasiparticle peak

\( E_k^\parallel \)
ARPES of surface states in Bi$_{1-x}$Sb$_x$

ARPES results on Bi$_2$Se$_3$ (Hasan group)

Xia, Hasan et al. Nature Phys ‘09

Large gap ~ 300meV
As grown, Fermi level in conduction band

Se defect chemistry difficult to control for small DOS
Why spin polarized?
→ Rashba term on surface

What prevents a gap?
→ Time Reversal Symmetry

What is expected from transport?
• No $2k_F$ scattering
• SdH
• Surface QHE (like graphene except $\frac{1}{4}$)
• Weak anti-localization

Hsieh, Hasan et al., Nature '09
**Bi$_2$Se$_3$: Typical Transport**

Metallic electron pocket with mobility $\sim 500$-$5000$ cm$^2$/Vs

Carrier density $\sim 10^{19}$ e$^-$/cm$^3$

Roughly spherical Fermi surface (period changes by $\sim 30\%$)
Major problem confronting transport investigation

As-grown crystals are always excellent conductors, \( \mu \) lies in conduction band (Se vacancies).

\[
\rho \ (1 \text{ K}) \sim 0.1-0.5 \text{ m}\Omega \text{ cm}, \quad n \sim 1 \times 10^{18} \text{ cm}^{-3} \\
m^* \sim 0.2, \quad k_F \sim 0.1 \text{ Å}^{-1}
\]

\( n \sim 2 \times 10^{19} \text{ e}^- / \text{cm}^3 \)
Fall into the gap

Hor et al., PRB ‘09
Checkelsky et al., arXiv/09

Solution:
Tune $\mu$ by Ca doping

\[ \mu \]

cond. band
valence band

$1/H$ (T$^{-1}$)

Landau Index

electron
doped

hole
doped

target

$\theta_N (\mu V/ K)$

$\mu_0 H$ (T)

Decrease
electron density

$T = 15$ K
Resistivity vs. Temperature : In and out of the gap

Onset of non-metallic behavior ~ 130 K

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

Non-metallic samples show no discernable SdH

Checkelsky et al., arXiv:0909.1840
Magnetoresistance of gapped Bi2Se3

Giant, quasi-periodic, retraceable conductance fluctuations

Checkelsky et al., arXiv:0909.1840
Magneto-fingerprints

Fluctuations retraceable

Giant amplitude
(200-500 X too large)

Retraceable
(fingerprints)

Spin degrees
Involved in fluctuations

Checkelsky et al., arXiv:0909.1840
Angular Dependence of R(H) profile Cont.

For $\delta G$, 29% spin term

For $\ln H$, 39% spin term ($\sim 200 \text{ e}^2/\text{h total}$)

Theory predicts both to be $\sim 1/2\pi$

(Lee & Ramakrishnan), (Hikami, Larkin, Nagaoka)
Universal Conductance Fluctuations

**Quantum diffusion**
Conductance -- sum over Feynman paths

\[ G \approx \sum_{i,j} A_i^* A_j = \sum_i |A_i|^2 + \sum_{i,j} |A_i A_j| e^{i(\theta_i - \theta_j)} \]

**Universal conductance fluctuations (UCF)**

\[ \delta G = e^2/h \]

in a *coherent* volume defined by thermal length \( L_T = hD/kT \)

At 1 K, \( L_T \sim 1 \mu m \)

For large samples size \( L \),

“Central-limit theorem”

\[ \delta G \approx \frac{e^2}{h} \left[ \frac{L_T}{L} \right]^{1/2} \]

UCF should be unobservable in a 2-mm crystal!
\( \delta G_{\text{measured}} \sim \frac{e^2}{\hbar} \)

Taking typical 2D \( L_T = 1 \mu m \) at 1 K,

\[
\frac{L}{L_T} \sim 10^3
\]

For systems size \( L > L_T \) consider \((L/L_T)^d\) systems of size \( L_T\), UCF suppressed as

\[
(L_T / L)^{2-d/2}
\]

For AB oscillation, assuming 60 nm rings, \( N^{-1/2} \sim 10^{-8} \)

\[
L_\phi = \sqrt{D \tau_{\text{in}}}
\]

\[
L_T = \sqrt{D \hbar / k_B T}
\]
Quasi-periodic fluctuations vs T

Fluctuation falls off quickly with temperature.

For UCF, expect slow power law decay $\sim T^{-1/4}$ or $T^{-1/2}$.

AB, AAS effect exponential in $L_T/P$.

→ Doesn’t match!
Non-Metallic Samples in High Field

Fluctuation does not change character significantly in enhanced field
Next Approach: Micro Samples
Micro Samples Cont.

Sample is gate-able

SdH signal not seen in 10 nm thick metallic sample

Exploring Callan-Harvey effect in a cleaved crystal
Desperately seeking Majorana bound state

Surface topological states

Open $\Delta$ at $\mu$ by Proximity effect

Fu and Kane, PRL 08

$\phi = 0$  $\phi = \pi$

$\gamma_{1,2} = \int dx \left[ e^{-i\phi/2} \xi_{1,2}^* (x)c^+ (x) + e^{i\phi/2} \xi_{1,2} (x)c(x) \right]$

Neutral fermion that is its own anti-particle
Intercalation of Cu between layers
Confirmed by c-axis lattice parameter increase and STM data
Crystal quality checked by X-ray diffraction and electron diffraction

Hor et al., arXiv 0909.2890
Diamagnetic Response at low $T$

Typical $M$ for type II: $-1000$ A / m

From $M(H)$, $\kappa \sim 50$

$\chi \sim -0.2$

Impurity phases not SC above 1.8 K ($Cu_2Se$, $CuBi_3Se_5$, $Cu_{1.6}Bi_{4.8}Se_8...$)

Small deviations from Se stoichiometry suppress SC
Cu Doping: Transport Properties

- Not complete resistive transition
- Up to 80% transition has been seen
- Carrier density relatively high

Graphs showing the behavior of $\rho_{xx}$ and $\rho_{yx}$ with magnetic field $B$ and temperature $T$ for different temperatures: 0.35 K, 1.2 K, 1.9 K, 2.5 K, 3 K, 3.5 K, 4 K, and 5 K. The temperature $T_c$ is approximately 3.7 K.
**Upper Critical Field $H_{C2}$**

$H_{C2}$ estimate by extrapolation

Similar shape for $H||_{ab}$

$H_{C2}$ anisotropy moderate

$\xi_c = 52 \, \text{Å} \, , \, \xi_{ab} = 140 \, \text{Å}$
Ca Doping: Conclusions

Ca doping can bring samples from n-type to p-type

Non-metallic samples at threshold between the two reveal new transport properties

\[ G \sim \ln(H) \text{ at low } H \]

\[ \delta G \sim \frac{e^2}{h}, \text{ quasiperiodic} \]

Hard to fit with mesoscopic interpretation

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No LL quantization seen up to 32 T

Metallic nanoscale samples show no LL
Summary

Doping of $\text{Bi}_2\text{Se}_3$ creates surprising effects

Ca doping: Quantum Corrections to Transport become strong

Cu Doping: Superconductivity

Next stage:
1. nm-thick gated, cleaved crystals
2. Proximity effect and Josephson current expt
END