Dirac Fermions in HgTe

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Overview

- HgTe/CdTe bandstructure, quantum spin Hall effect
- HgTe as a Dirac system
- Dirac surface states of strained bulk HgTe
band structure

semi-metal or semiconductor

fundamental energy gap

$E^{\Gamma_6} - E^{\Gamma_8} \approx -300 \text{ meV}$
HgTe-Quantum Wells

Type-III QW

VBO = 570 meV

HgCdTe

HH1

QW < 63 Å

HgTe

inverted normal

HgTe

valence band

conduction band

Γ₆

Γ₈

E1

HH1

VBO = 570 meV

Γ₆

Γ₈

band structure
Layer Structure

Carrier densities: \( n_s = 1 \times 10^{11} \ldots 2 \times 10^{12} \text{ cm}^{-2} \)

Carrier mobilities: \( \mu = 1 \times 10^5 \ldots 1.5 \times 10^6 \text{ cm}^2/\text{Vs} \)

- Au
- 100 nm Si\(_3\)N\(_4\)/SiO\(_2\)
- 25 nm CdTe
- 10 nm HgCdTe \( x = 0.7 \)
- 9 nm HgCdTe with I
- 10 nm HgCdTe \( x = 0.7 \)
- 4 - 12 nm HgTe
- 10 nm HgCdTe \( x = 0.7 \)
- 9 nm HgCdTe with I
- 10 nm HgCdTe \( x = 0.7 \)
- 25 nm CdTe
- CdZnTe(001)

Graphs:
- \( R_{xx}[\Omega] \)
- \( R_{xy}[\Omega] \)

Symmetric or asymmetric doping
Band Gap Engineering

4 nm QW

normal semiconductor

15 nm QW

inverted semiconductor

$k = (k_x, k_y)$

$- k \parallel (1,0)$

$- k \parallel (1,1)$

Energy $E(k)$ (eV)

$k (0.01 \text{ Å}^{-1})$

$d_{HgTe} (100 \text{ Å})$

$k (0.01 \text{ Å}^{-1})$
Bandstructure HgTe

QSH Insulator
QSHE, Simplified Picture

\[ m > 0 \]
normal insulator

\[ m < 0 \]
QSHE

Entire sample insulating
Experimental Signature

normal insulator state

\[ G_{LR}(\frac{e^2}{h}) \]

\[ E_{\text{gap}} \]

\[ d < d_c, \text{ normal regime} \]

\[ d > d_c, \text{ inverted regime} \]
Observation of QSHI state

Observation of QSH Effect

\[ G = \frac{2 e^2}{h} \]

\[ R_{xx} / \Omega \]

(1 x 0.5) \(\mu\text{m}^2\)

(1 x 1) \(\mu\text{m}^2\)

(2 x 1) \(\mu\text{m}^2\)

(1 x 1) \(\mu\text{m}^2\) non-inverted

\( G = 2 e^2/h \)

Verify helical edge state transport

(a) Multiterminal /Non-local transport samples
Landauer-Büttiker Formalism

\[ T = \begin{pmatrix} -2 & 1 & 0 & 0 & 0 & 1 \\ 1 & -2 & 1 & 0 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 & 0 \\ 0 & 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 1 & -2 & 1 \\ 1 & 0 & 0 & 0 & 1 & -2 \end{pmatrix} \]

\[ G_{2t} = \frac{I_{14}}{\mu_4 - \mu_1} = \frac{2e^2}{3h} \]

\[ G_{4t} = \frac{I_{14}}{\mu_3 - \mu_2} = \frac{2e^2}{h} \]

\[ G_{4t,exp} \approx 2\frac{e^2}{h} \]

\[ \frac{R_{2t}}{R_{4t,exp}} \approx 3 \]

normal conducting contacts ➔ no QSHE
Multi-Terminal Measurements

\[ R_{14,14} = \frac{3}{2} \frac{\hbar}{e^2} \]
\[ R_{14,23} = \frac{1}{2} \frac{\hbar}{e^2} \]

Multi-Terminal Measurements

Configurations would be equivalent in quantum adiabatic regime

Non-Local data on H-bar

Zero gap HgTe well as a Dirac system
Bandstructure HgTe

Dispersion at $d = d_c$ is Dirac-like.

For well thickness $d = 6.3$ nm, the gap closes, especially the conduction band shows a linear dispersion: single Dirac cone.
Large g-factor (g=55) responsible for spin splitting already at low fields.
Hall quantization reflects single valley character of the band structure: a HgTe quantum well at d=6.3 nm is half-graphene.

Landau-fan

Color coded: gate voltage derivative of longitudinal resistivity.
Fits: left – 8-band Kane model, right – Dirac Hamiltonian

Zero mode spin splitting allows to select sample at $d_c$.  

Peak width and mobilities comparable with/better than free standing graphene
Scattering mechanisms: probably mass fluctuations + Coulomb (fit is Kubo model)
Adding a Dirac mass
Changing well width changes Dirac mass
Originally increase in mobility from reduced impurity scattering, then changeover to behavior due to well width (Dirac mass) fluctuations.
Mobility for finite Dirac mass


Modeling by Grigory Tkachov and Ewelina Hankiewicz:
Mass and disorder induce backscattering of Dirac fermions.
Dirac Surface States on strained bulk HgTe
Bulk HgTe as a 3-D Topological 'Insulator'

Bulk HgTe is semimetal, topological surface state overlaps w/ valenceband.


ARPES:
Yulin Chen, ZX Shen, Stanford
70 nm layer on CdTe substrate: coherent strain opens gap
**Bulk HgTe as a 3-D Topological Insulator**

@ 20 mK: bulk conductivity almost frozen out - Surface state mobility ca. 35000 cm²/Vs

Bulk HgTe as a 3-D Topological 'Insulator'

@ 20 mK: same data, plotted as conductivity
3D HgTe-calculations


Red and blue lines: DOS for each of the Dirac-cones with the corresponding fixed 2D-density, Green line: the sum of the blue and red lines
Conclusions

- HgTe quantum wells: normal and inverted gap, linear (Dirac) dispersion
- First observation of Quantum Spin Hall Effect
- At d=dc, a HgTe QW is ideal model system for zero mass Dirac fermion physics
- Can conveniently study Dirac fermions w/ finite Dirac mass
- Strained 3D layers show QHE of topological surface states

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Bastian Büttner, Christoph Brüne, Hartmut Buhmann, Markus König, Matthias Mühlbauer, Andreas Roth, Volkmar Hock

Theory: Alena Novik, Chaoxing Liu, Ewelina Hankiewicz, Grigory Tkachov, Patrick Recher, Björn Trauzettel (all @ Würzburg), Jairo Sinova (TAMU), Shoucheng Zhang, Xiaoliang Qi (Stanford)

Funding: DFG (SPP Spintronics, DFG-JST FG Topotronics), Humboldt Stiftung, EU-ERC AG “3-TOP”, DARPA