Topology in HgTe

Laurens W. Molenkamp
Physikalisches Institut, EP3
Universität Würzburg
2005, Postech, Pohang, Korea

2006, NTU, Singapore
Overview

- New experiments on the quantum spin Hall effect: 2D TI

- Dirac surface states of strained bulk HgTe: 3D TI
- Topological Josephson Junctions
- Compressive strain: Dirac/Weyl systems
HgTe

band structure

semi-metal or semiconductor

fundamental energy gap

\[ E_{\Gamma 6} - E_{\Gamma 8} \approx -300 \text{ meV} \]

D.J. Chadi et al. PRB, 3058 (1972)
QSHE, Simplified Picture

\[ m > 0 \]

normal insulator

\[ E_F \]

bulk

\[-w/2 \quad w/2\]

\[ m < 0 \]

QSHE

\[ E_F \]

bulk

\[-w/2 \quad w/2\]

entire sample insulating

Observation of QSHI state

Observation of QSH Effect

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

\[ R_{xx} / \Omega \]

\( 10^3 \)

\( 10^4 \)

\( 10^5 \)

\( 10^6 \)

\( (1 \times 1) \mu m^2 \)

\( (2 \times 1) \mu m^2 \)

\( (1 \times 0.5) \mu m^2 \)

\( (V_{\text{Gate}} - V_{\text{thr}}) / V \)

E-beam voltage reduced to 6 kV
Wet etching...
Wet etching of Nanostructures

Wet etched micron-sized hall bars show strongly improved transport properties; better mobilities and better quantum Hall effect (homogeneity)

K. Bendias et al., Nano Lett. 18, 4831, 2018
Wet etching....

K. Bendias et al., Nano Lett. 10.1021, 2018
Wet etching allows for superconducting side contacts
(no) temperature dependence

Up to ca. 20 K

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

\[ R_{xx} \ \Omega \]

Gate Voltage \( V_g \) \( \text{V} \)

Kalle Bendias, Saquib Shamim
Different – back gated – sample temperature dependence

$R_{XX1}$

$V_{Gate}(V)$

$R_{XX1}(k\Omega)$

Kalle Bendias, Saquib Shamim
Gate training
Why only quantization in small devices?

Can we make larger devices by increasing the gap?

Or are we limited by puddle disorder?

Gap increased by strain engineering

\[ l_{\text{edge}} = 620 \, \mu\text{m} \]

\[ 58 \, \mu\text{m} \]

Lukas Lunczer, Philipp Leubner
Gate Training in large Hall bars

\( l_{\text{edge}} = 620 \, \mu m \)

\( 58 \, \mu m \)

\( 13 \, \mu m \)

Lukas Lunczer, Philipp Leubner
Quantum Point contacts
QPC in 10.5 nm thick HgTe well

$W_{\text{min}} \approx 150 \text{ nm}$

Wang, Meir and Gefen (2017)

Jonas Strunz
n=1 plateau only occurs in wide quantum wells, where the valence band shows prominent camel’s back structure
Fermi level pinning to camel's back in wider well allows Rashba strength $\alpha$ to increase until a spin gap appears.
Quantum spin Hall Effect in (Hg,Mn)Te
Quantised spin Hall conductance in a magnetic TI

- 9 nm thick HgMnTe quantum well, 1.2-1.5% Mn, $\mu_{HB}: 1.9 \times 1.7 \mu m^2$
Band structure: Camel’s Back in Valence Band

Indirect Gap!

D.O.S. in valence band 100x larger than in conduction band and 100x larger than in edge states.
Thermal Activation: Camel’s Back in Valence Band

Higher T:
Transfer of carriers from edge to bulk states, parasitic bulk conductance (but mainly near valence band).
Strain Engineering: Virtual Substrates
Strained Superlattices

Using CdZnTe/CdTe superlattices on a GaAs substrate: can adjust strain from tensile to compressive.
Tensile strain yields semimetal;
Compressive strain yields gap up to 60 meV.

Gamma 8 band develops Dirac/Weyl points.

Compressive strain in bulk HgTe.

Band structure very similar to Cd$_2$As$_3$ and Na$_3$Bi families. Zincblende inversion asymmetry creates Weyl points.
Compressive Strain in bulk HgTe

Large negative MR for B//I: chiral anomaly!

QC0262 HB III Inplane bei 0V Gate

$R_{xx} \Omega$

B [T]

David Mahler
Philipp Leubner
Dirac points and chiral anomaly line up
Surface States disperse through Dirac/Weyl points

No trace of Fermi arcs! But again:
band structure should be very similar to Cd$_2$As$_3$
(and Na$_3$Bi)

Giorgio Sangiovanni
Domenico di Sante
At higher densities: QHE from surface states

B perp to plane
At higher densities: QHE from surface states
Conclusions

- HgTe: can be made into 2D and 3D Topological Insulator
- QSHE: wet etching, strain engineering and puddle optimization
- See clear signs of exotic – topological - superconductivity
- Strain engineering offers larger gaps in 2D, Dirac/Weyl systems in 3D

Collaborators:
Erwann Bocquillon, Christoph Brüne, Hartmut Buhmann, Philipp Leubner, Saqib Shamim, Martin Stehno, Jonas Wiedenmann (Würzburg); Amir Yacoby (Harvard), Russell Deacon, Koji Ishibashi, Seigo Tarucha (Tokyo); Teun Klapwijk (Delft & Würzburg)

Theory: Wouter Beugeling, Ewelina Hankiewicz, Giorgio Sangiovanni, Ronny Thomale, Björn Trauzettel (Würzburg)

Funding: Freistaat Bayern (ENB, ITI), DFG (SFB 1170, ct.qmat CoE, Leibniz project), Humboldt Stiftung, EU-ERC AGs “3-TOP”, “4 TOPS”,