The Quantum Spin Hall Effect in HgTe/CdTe Quantum Wells

German National Academic Foundation, Summer Academy Salem 2012

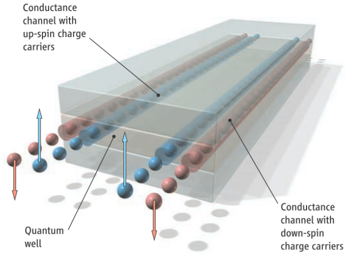
Daniel Guterding

August 23, 2012

Phenomenology of the QSHE

Characterization

- two currents with opposite spin-polarization counterpropagate at each edge of a 2D bulk insulator ('helical' edge states)
- edge states are protected by time-reversal symmetry, no elastic scattering occurs

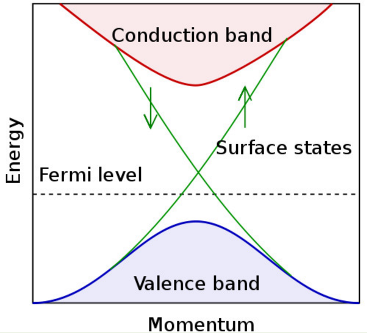


Schematic of the spin-polarized edge channels in a quantum spin Hall insulator.

Search for Materials showing QSHE

Prerequisites

- transport properties demand metallic behavior of edge states
- t-invariance demands crossing of edge states as both $\vec{k}$ and $\vec{s}$ are odd under $t \to -t$
- high carrier mobility to avoid inelastic processes
- spin-orbit split-up bands could serve as insulating regime at very low temperatures



Search for Materials showing QSHE

First idea: Graphene

- spin-orbit effects in graphite known for a long time
- high carrier mobilities possible
- temperature regime for opening of bulk charge excitation gap between spin-orbit split-up bands not accessible

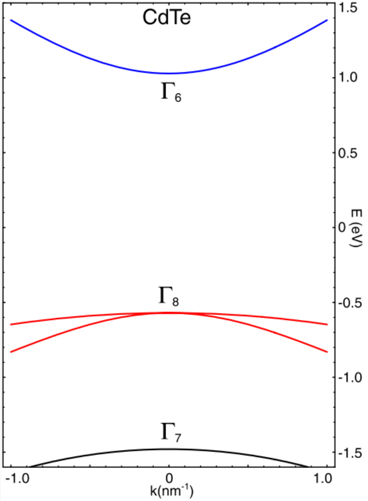
Second idea: Semiconductor heterostructures

- have been used to show QHE, high carrier mobilities possible
- multitude of materials available, bandstructure engineering possible
- success with HgTe/CdTe heterostructures

Properties of CdTe and HgTe

Properties of CdTe

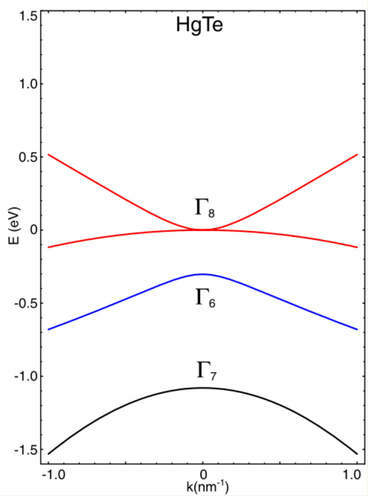
- semiconductor with 1.6 eV gap
- valence band is formed by l=1, J=3/2 hole-like bands (Γ_8, red)
- conduction band is formed by l=0 electron-like band (Γ_6, blue)
- band structure to the right is only depicted schematically near Γ-Point



Properties of CdTe and HgTe

Properties of HgTe

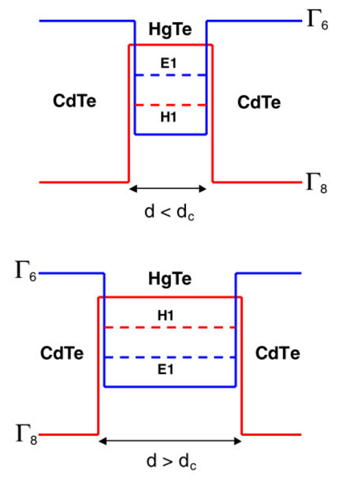
- zero-gap semiconductor
- valence band is formed by heavy-hole subband (Γ_8, red) and now low-lying l=0 band (Γ_6, blue)
- conduction band is formed by light-hole subband (Γ_8, red)
- inverted band structure



Quantum Well Structures

HgTe/CdTe Well structures

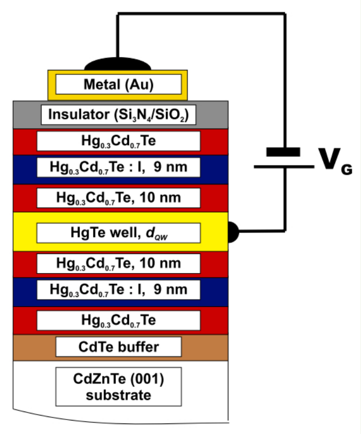
- two regimes separated at critical well width $d_c = 6.3$nm
- for $d_{QW} \to 0$ CdTe behavior must dominate, edge states are gapped, no QSHE
- for $d_{QW} > d_c$ HgTe becomes dominant, band structure in well is inverted, edge states are metallic



Quantum Well Structures

Well fabrication

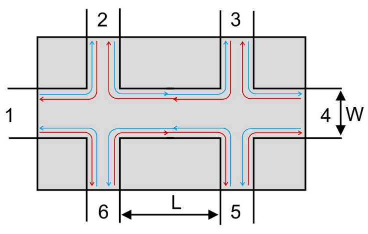
- layers grown with Molecular Beam Epitaxy, control down to monolayer
- $Hg_{0.3}Cd_{0.7}Te$ to compensate lattice mismatch
- modulation doping with iodine supplies charge carriers
- mobilities up to 10^5 cm^2/Vs, elastic mean free path up to several μm



Quantum Well Structures

Well structuring

- temperature has to be kept well below 180°C as HgTe dissociates beyond, also applies for growth process
- combination of optical, electron beam and ion etching techniques
- structures down to 100nm possible
- shaded region is the gate, region within black lines is HgTe, numbers 1 to 6 are leads



Experiments

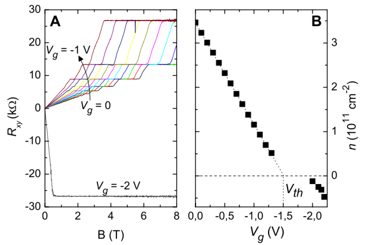
Experimental setup

- gate voltage can be varied between -5V and +5V to adjust Fermi level
- helium cryostat with dilution refrigerator, $T < 30\text{mK}$
- static magnet up to 8T perpendicular to sample
- vector magnet up to 300mT in variable direction

Experiments

High-field characterization, Hall-resistance measurements

- hall-resistance measurements in high fields yield charge carrier concentration
- unusual re-entrant QH state, in between supposed QSH state
- gate voltage adjustment is crucial to establish bulk insulator state

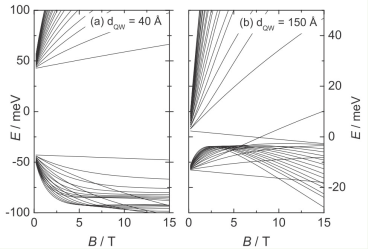


$$\begin{cases} 0V \geq V_g \geq -1.3V & : \text{n-conducting} \\ -1.3V \geq V_g \geq -2V & : \text{insulator} \\ -2V \geq V_g & : \text{p-conducting} \end{cases}$$

Experiments

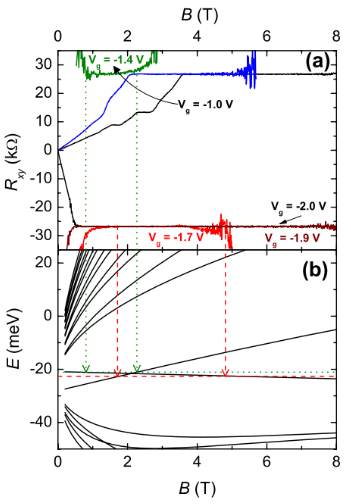
Landau-level dispersion

- anomalous Landau-levels in inverted regime
- calculated LL-crossing can be confirmed by measurements of Hall-resistance

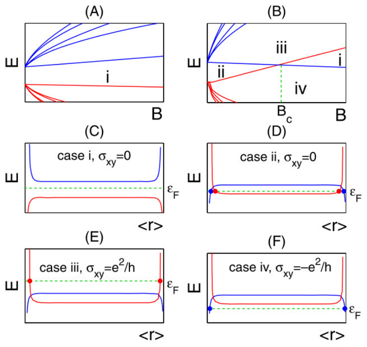


Experiments

Landau-level dispersion



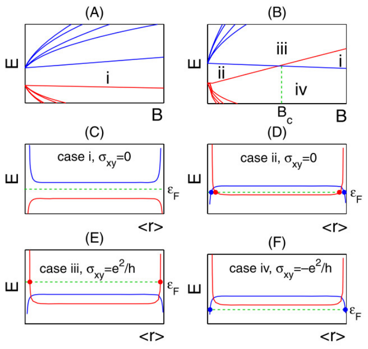
- more than one case for voltage in insulating regime (at B=0)



Experiments

Landau-level dispersion

- case (i) is trivial insulator, band inversion is destroyed by B-field
- case (ii) is QSH state with two pairs of edge states, present for small fields
- case (iii) is n-conducting QH state
- case (iv) is p-conducting QH state
- experiment is consistent with calculated LL-dispersion!



Experiments

Resistance measurements on the Hall bar

- leads are n-type regardless of applied voltage
- leads equilibrate with both spin currents, elastic processes possible
- resistance between leads is finite even in QSH state

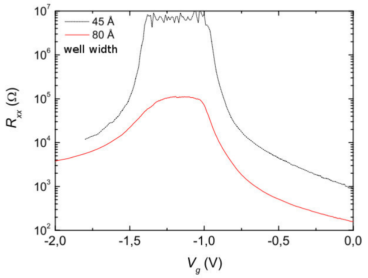
Theoretical resistance: Landauer-Büttiker calculations

- assumes: no inelastic scattering, independent of shape
- for QSHE elastic scattering is also zero
- for four terminals as in our case resistance between neighbouring leads is $R = h/2e^2 = 13k\Omega$
- thus R_{xx} should be $3h/2e^2 = 39k\Omega$

Experiments

Resistance measurements

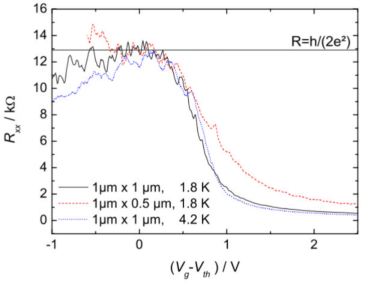
- now measure R_{xx}
- MΩ range is intrinsic resistance of setup, trivial insulator
- finite resistance indicates QSHE, but still far too high
- use smaller sample to avoid inelastic processes
- trivial insulator and QSH insulator now distinguishable



Experiments

Resistance measurements

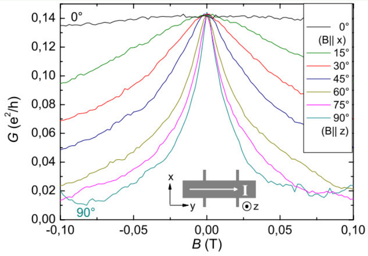
- elastic mean free path of some μm
- obviously QSH behavior of $R = 13k\Omega$ demonstrated, independent of sample size
- resistance must originate in edge states
- p-conducting regime not available, electron lithography charges small sample



Experiments

Destroying time-reversal symmetry

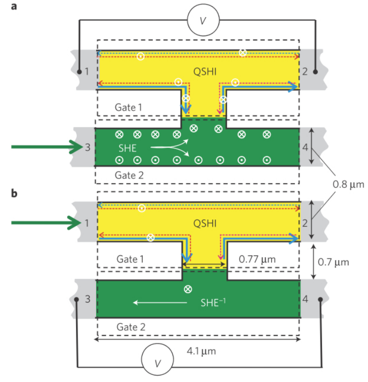
- apply magnetic field at various angles
- measure magneto-conductance G
- for field perpendicular to HgTe-plane huge decrease in conductance, $B_{\mathrm{FWHM}} = 10mT$
- for parallel field only small effect, $B_{\mathrm{FWHM}} = 700mT$



Experiments

Measuring the spin-polarization of the edge channels

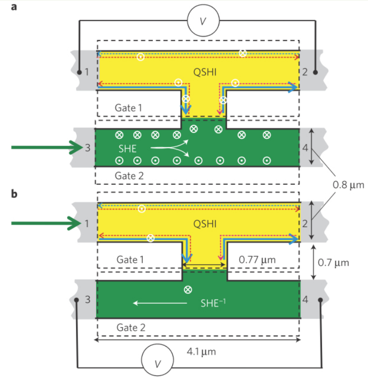
- utilizes split gate technique on HgTe well structures, state can be adjusted independently
- one part in conducting regime, spin hall effect and inverse spin hall effect present
- other part in QSH regime
- interface in the middle of the structure, chemical potentials have to equilibrate



Experiments

Measuring the spin-polarization of the edge channels

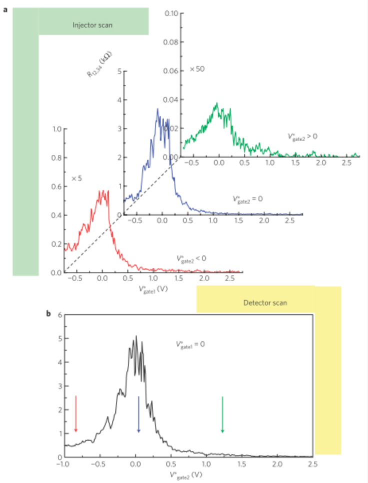
- SHE occurs when current flows through a conducting structure, currents on both sides are spin-polarized
- inverse SHE occurs when spins accumulate on one side of the sample, current flows
- if QSHE is present, spins accumulate at interface, equilibrium condition ensures spins accumulate on conducting side



Experiments

Measuring the spin-polarization of the edge channels

- voltage drop can be measured and used to show spin polarisation
- if no QSHE present, spins will not accumulate, no voltage drop in conducting part
- voltage levels redefined, QSH state at zero
- inverse SHE can be used to detect QSHE and vice versa



Conclusion

Properties of QSH state reproduced in this experiment

- inversion of bandstructure crucial
- transport through dissipation free edge states
- time-reversal symmetry protects edge states
- edge states are spin-polarized

Literature

- König et al.: The Quantum Spin Hall Effect: Theory and Experiment, J. Phys. Soc. Jpn. 77 (2008) 031007
- König et al.: Quantum Spin Hall Insulator State in HgTe Quantum Wells, Science (2007) 318 (5851), 766-770
- Brüne et al.: Spin polarization of the quantum spin Hall edge states, Nature Physics 8, 486 (2012)
- Büttiker: Four-Terminal Phase-Coherent Conductance, Phys. Rev. Lett. 57, 1761–1764 (1986)