Topological physics in HgTe based Quantum Devices

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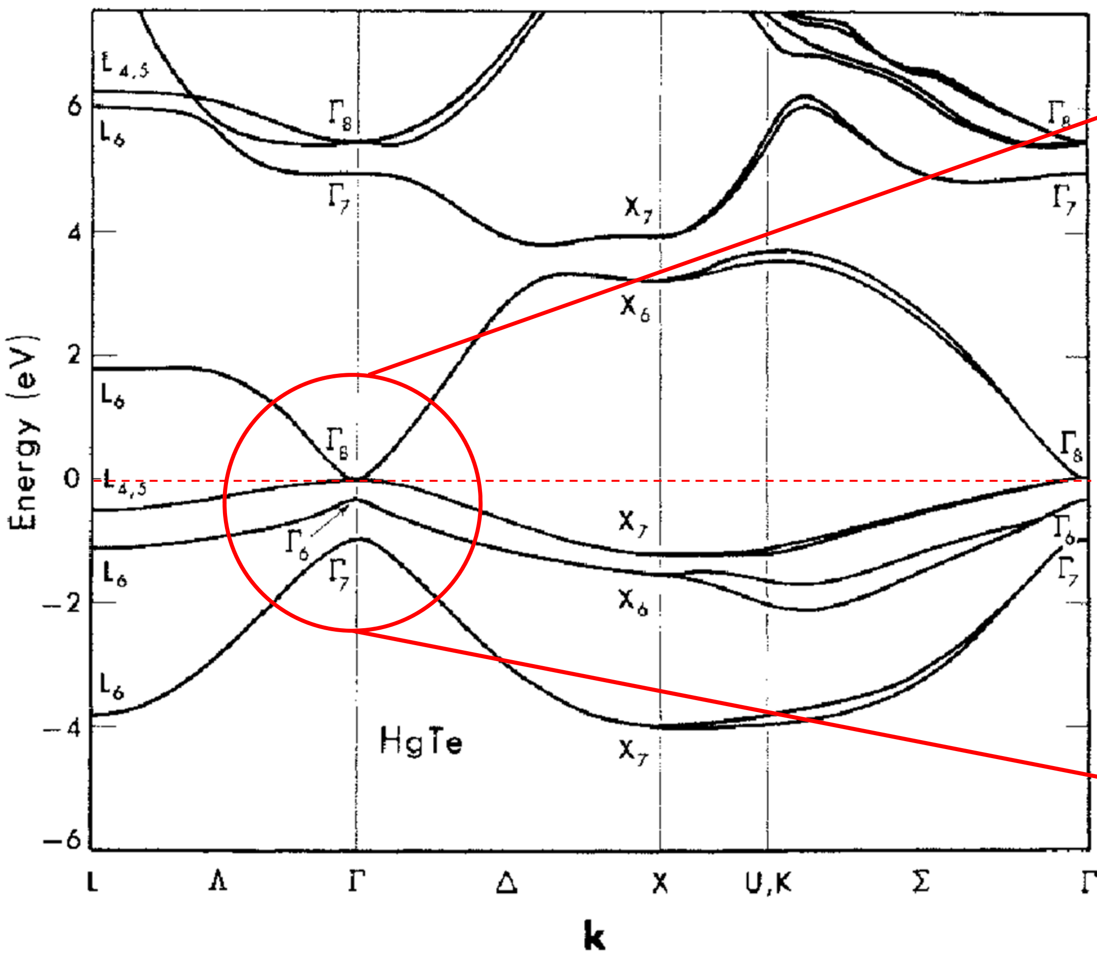
Overview

- HgTe/CdTe bandstructure, quantum spin Hall effect: 2D TI
- Dirac surface states of strained bulk HgTe: 3D TI
- Topological Josephson Junctions
- Compressive strain: Dirac/Weyl systems

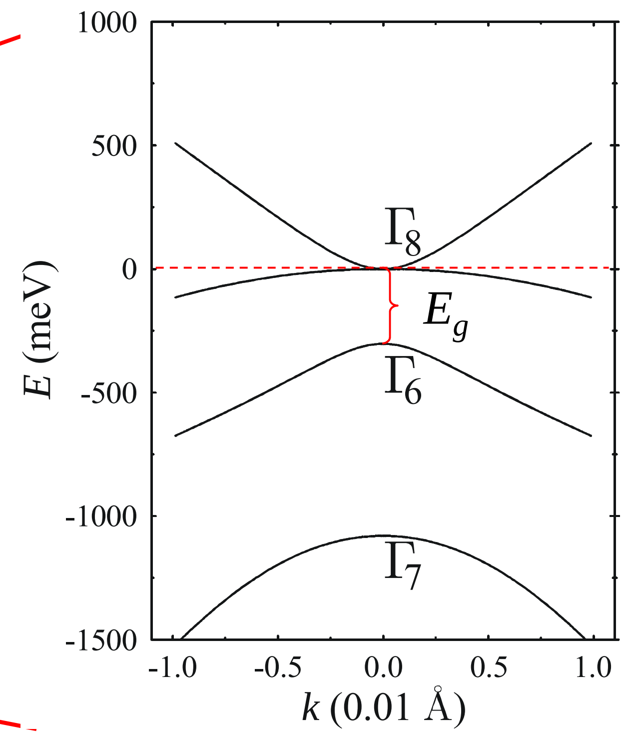
HgTe

band structure



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

semi-metal or semiconductor

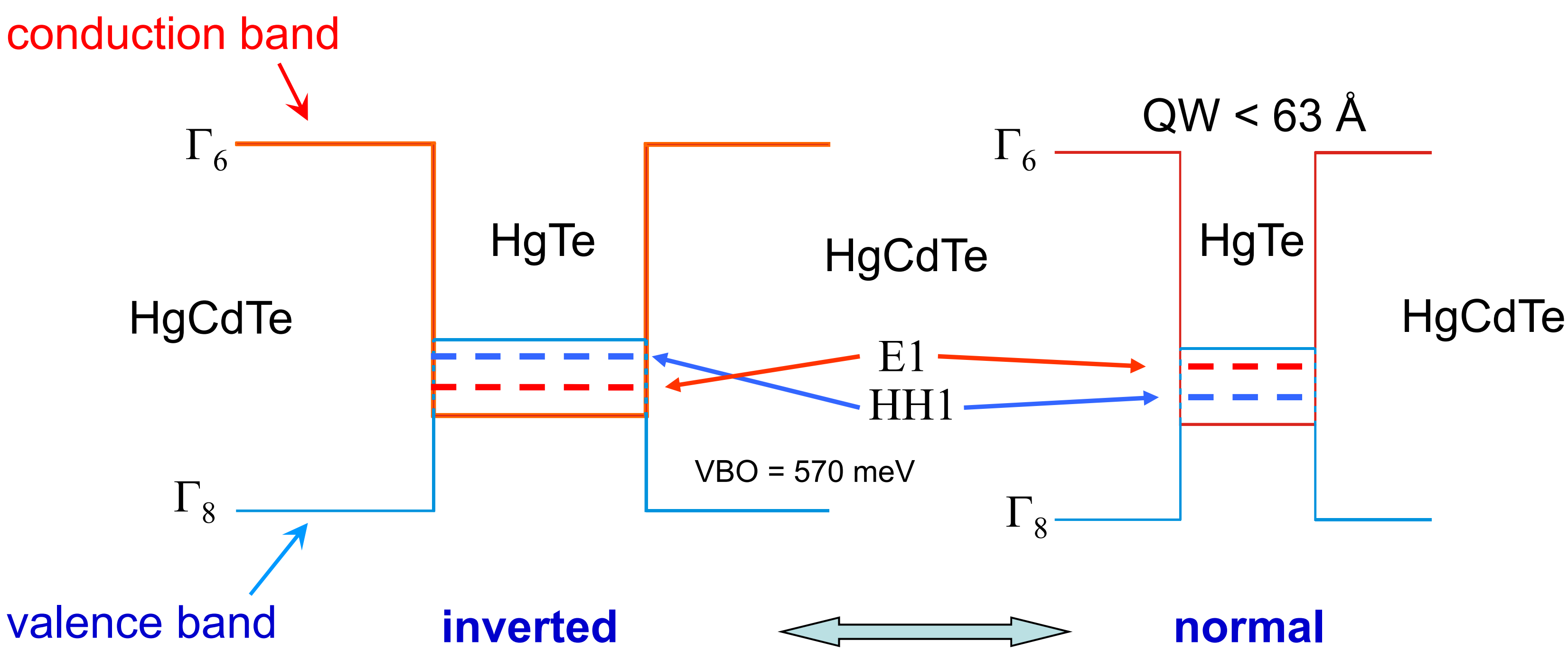


fundamental energy gap

$$E^{\Gamma 6} - E^{\Gamma 8} \approx -300\,\text{meV}$$

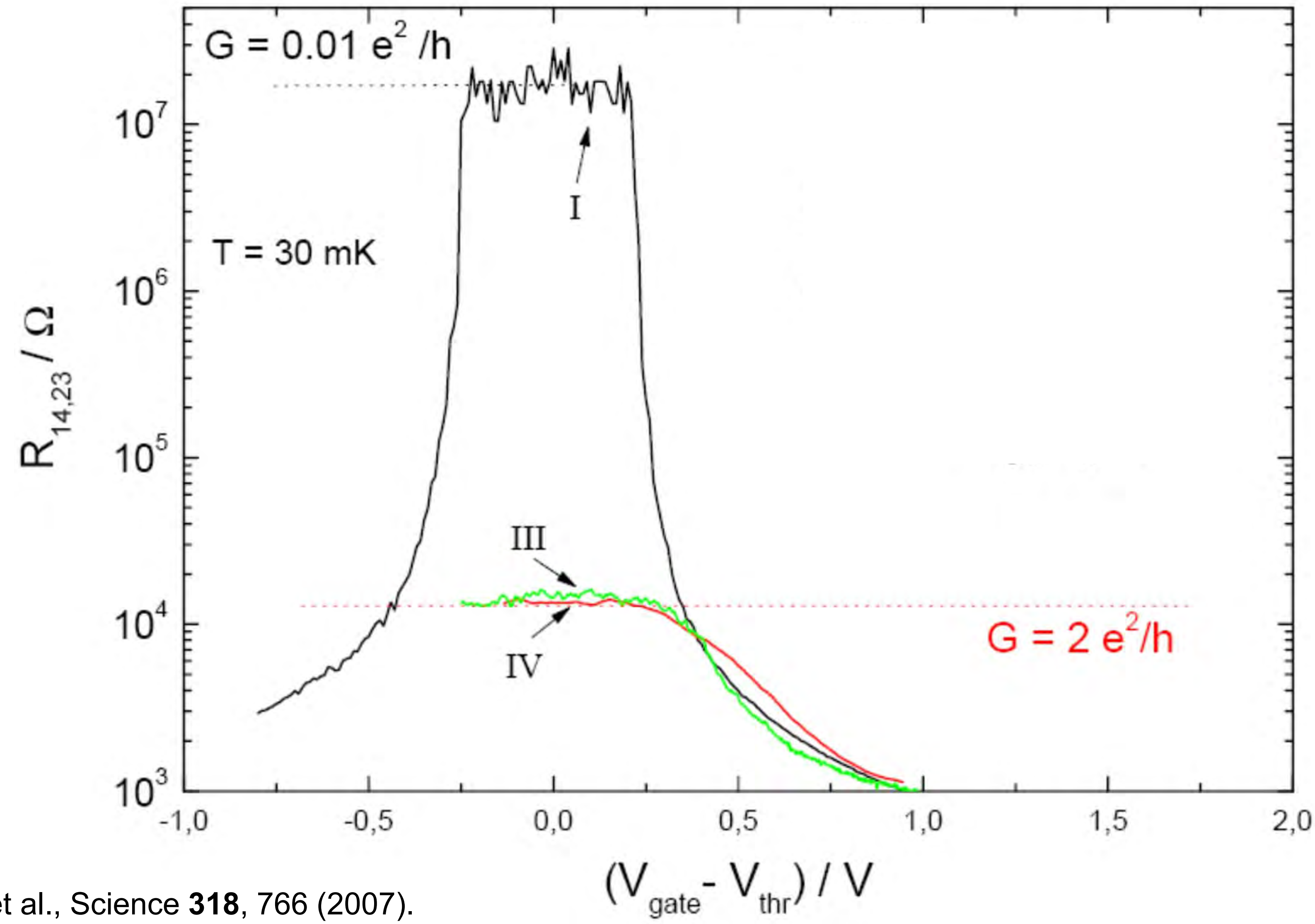
HgTe-Quantum Wells

Type-III QW



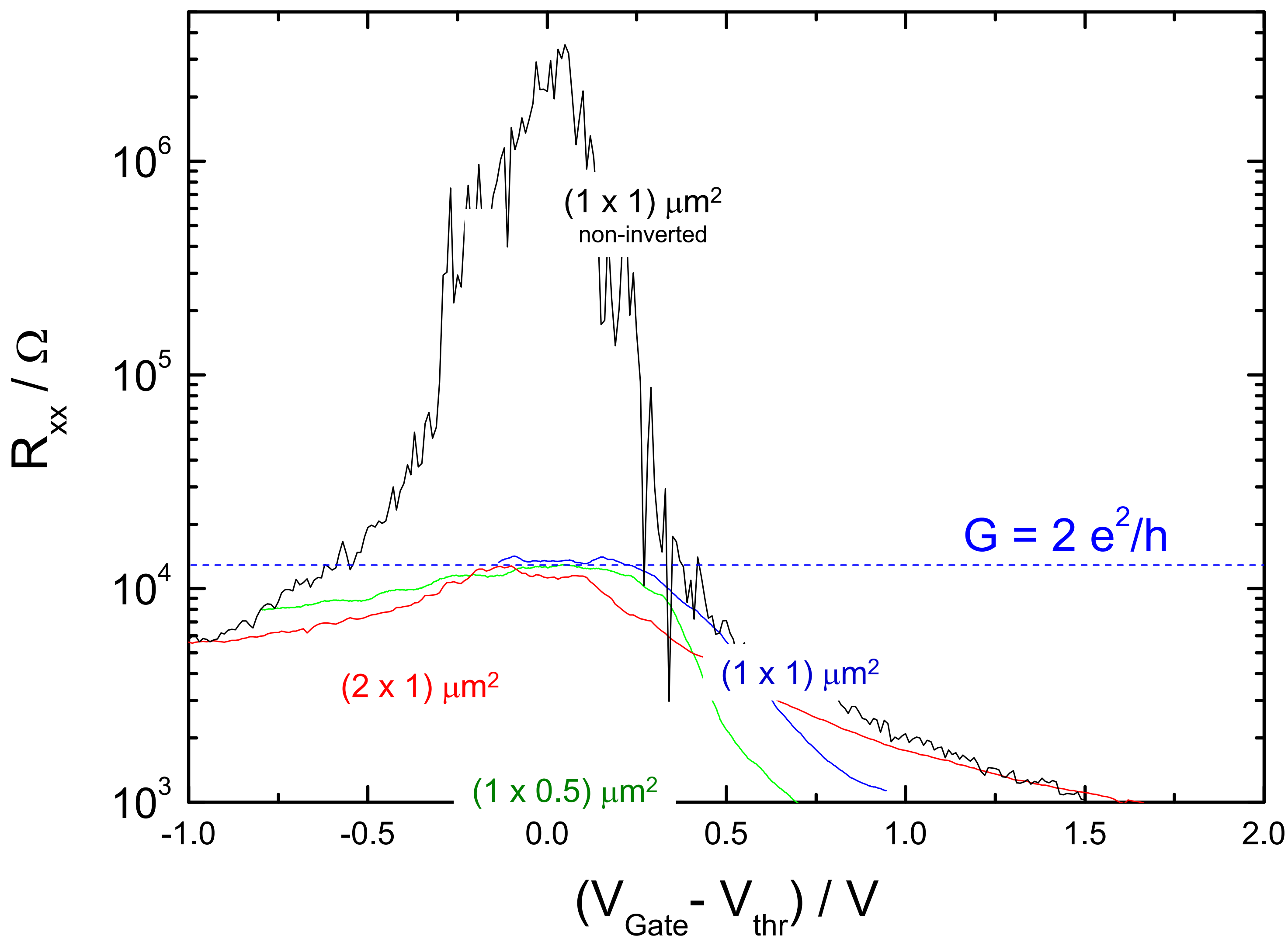
band structure

Observation of QSHI state



M. König et al., Science **318**, 766 (2007).

Observation of QSH Effect



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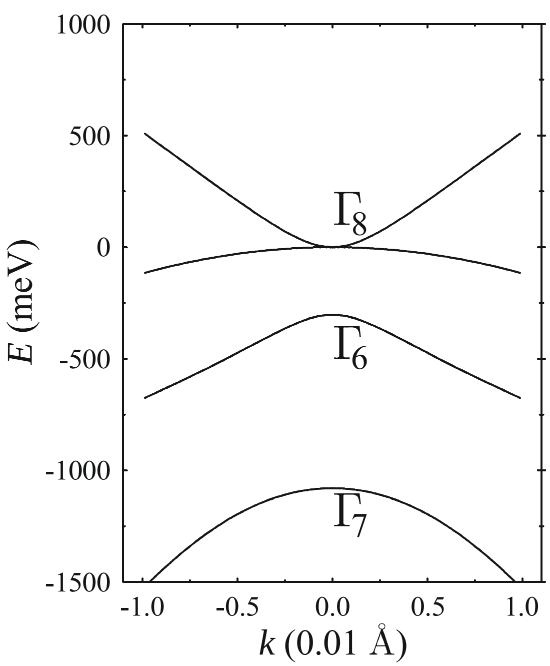
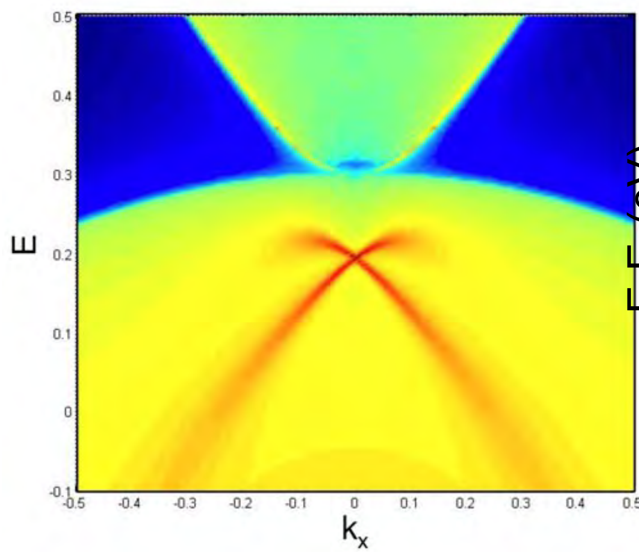
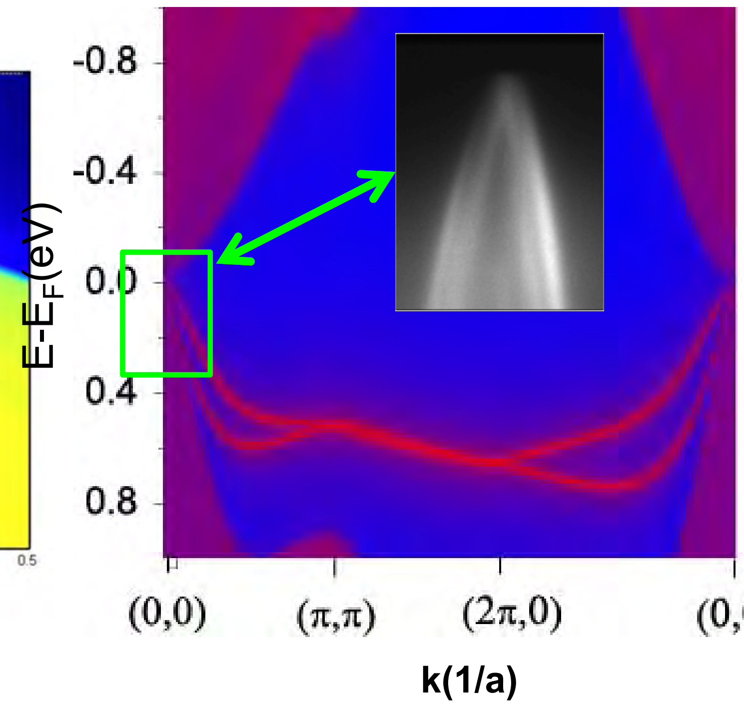
Bulk HgTe as a 3-D Topological ‚Insulator‘

EP 3







Bulk HgTe is semimetal,

topological surface state overlaps with valence band.

C. Brüne et al., Phys. Rev. Lett. **106**, 126803 (2011).

ARPES:
Yulin Chen, ZX Shen, Stanford

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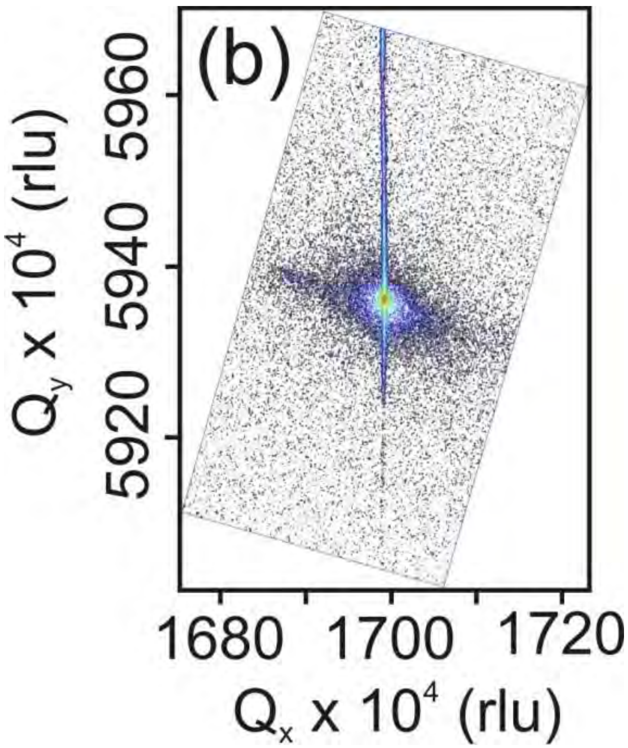
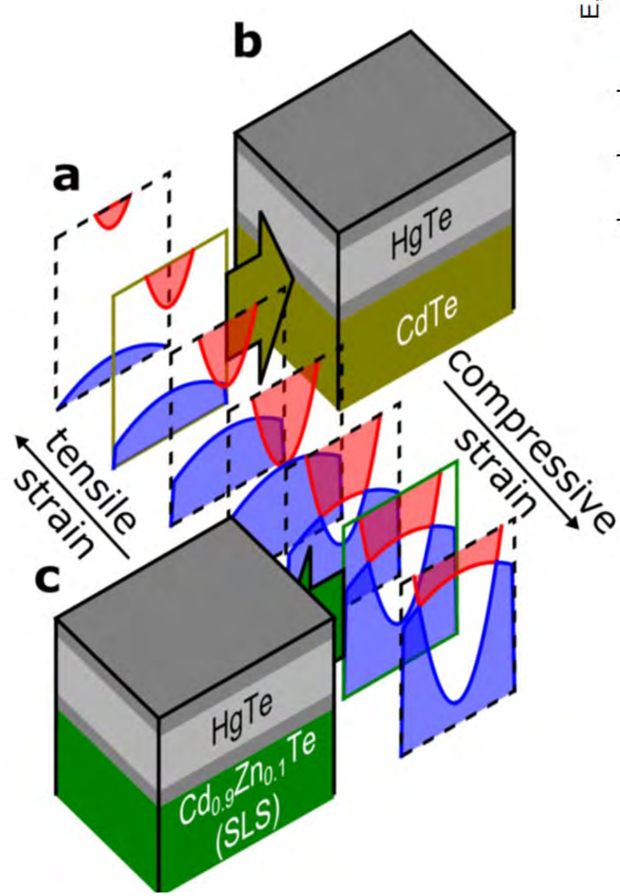
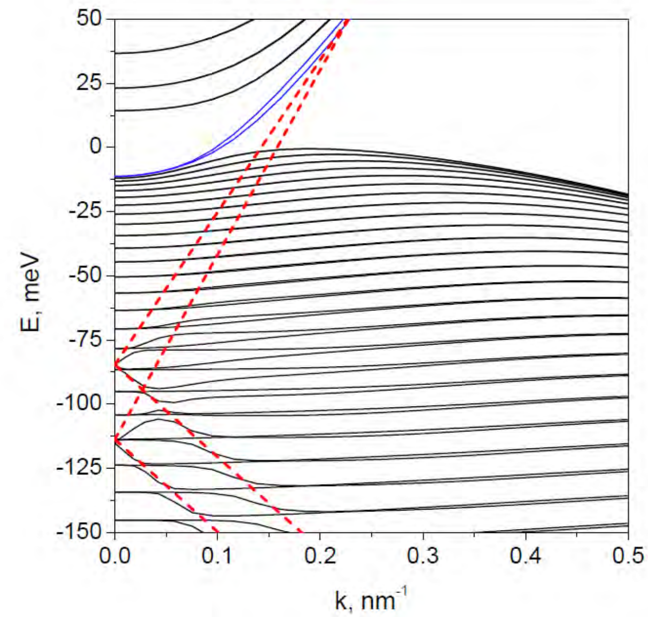
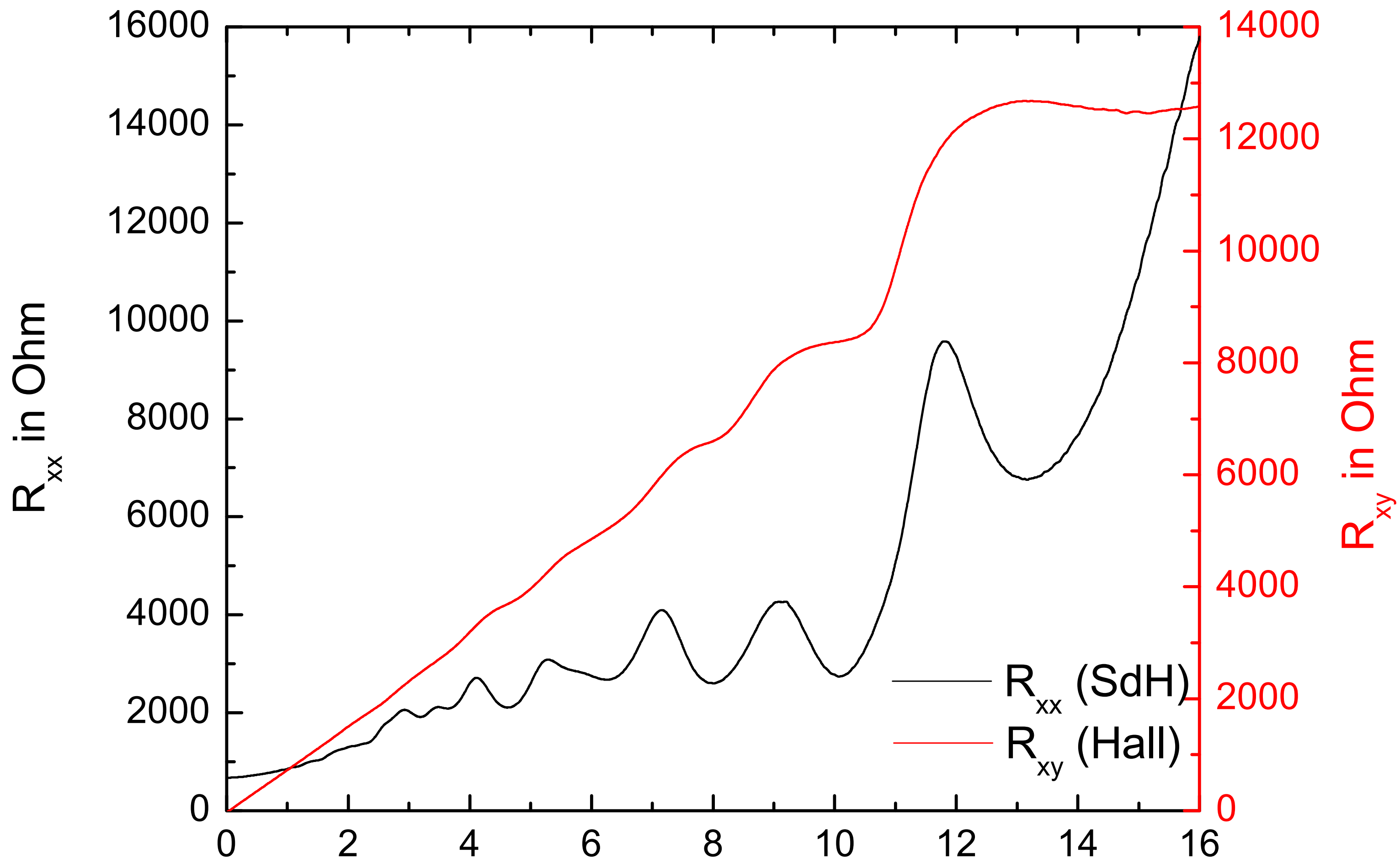
70 nm layer on CdTe substrate: coherent strain opens gap







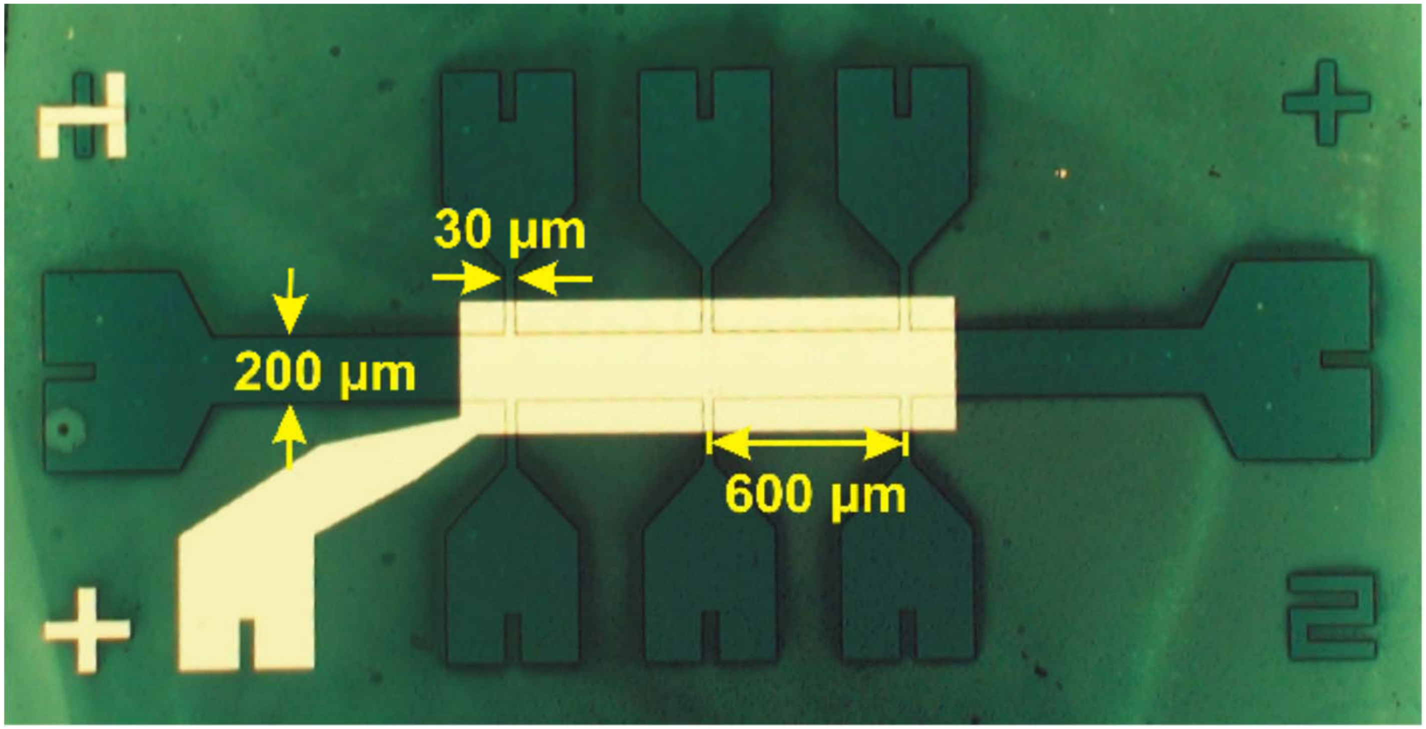
Bulk HgTe as a 3-D Topological ‚Insulator‘



C. Brüne et al.,
Phys. Rev. Lett. **106**, 126803 (2011).

@ 20 mK: bulk conductivity almost frozen out - Surface state mobility ca. 35000 cm^2/Vs

Experiments on a gated Hallbar



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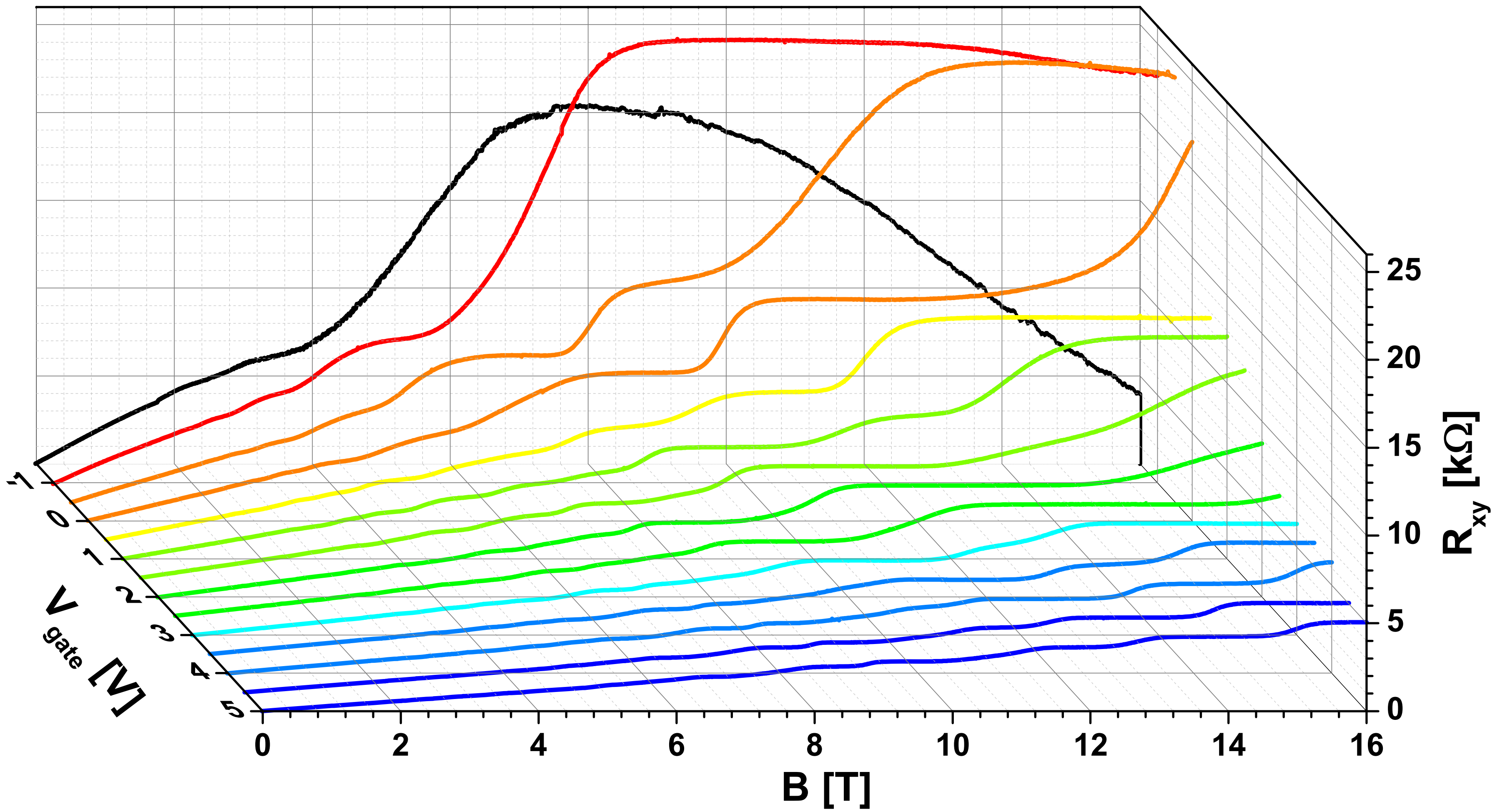
Rxy from -1.5V to 5V

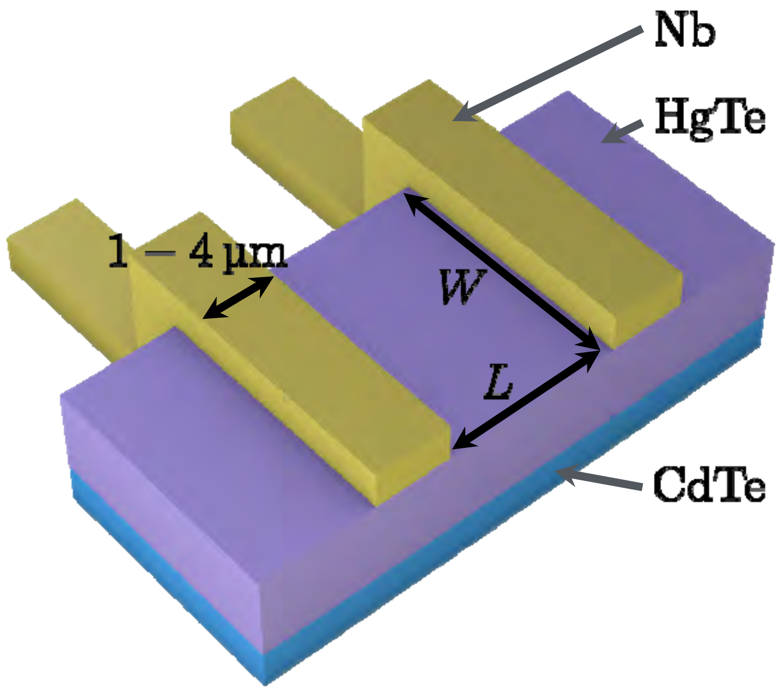
EP 3

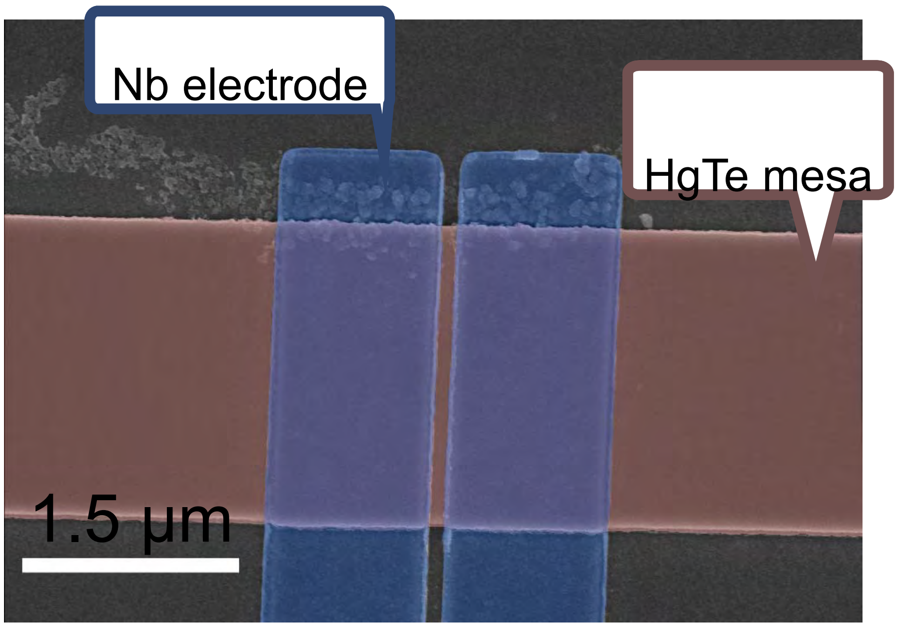


C. Brüne et al., Phys. Rev. X 4, 041045 (2014).

Superconducting Proximity Effects

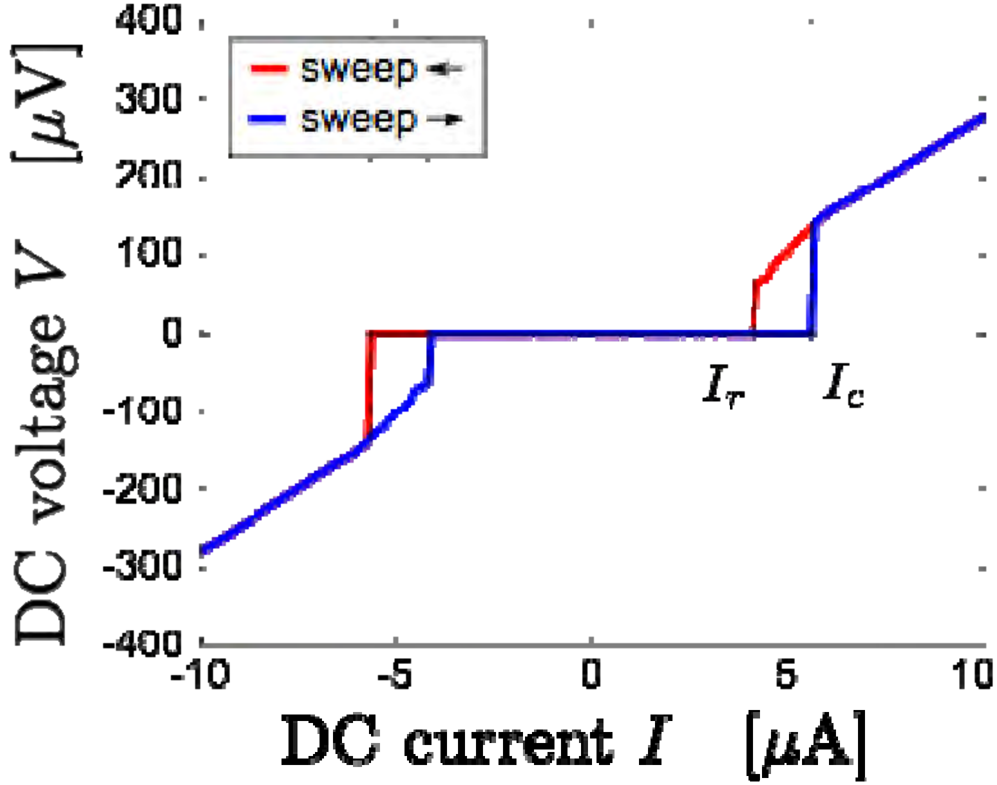
Josephson junction on 3D TI

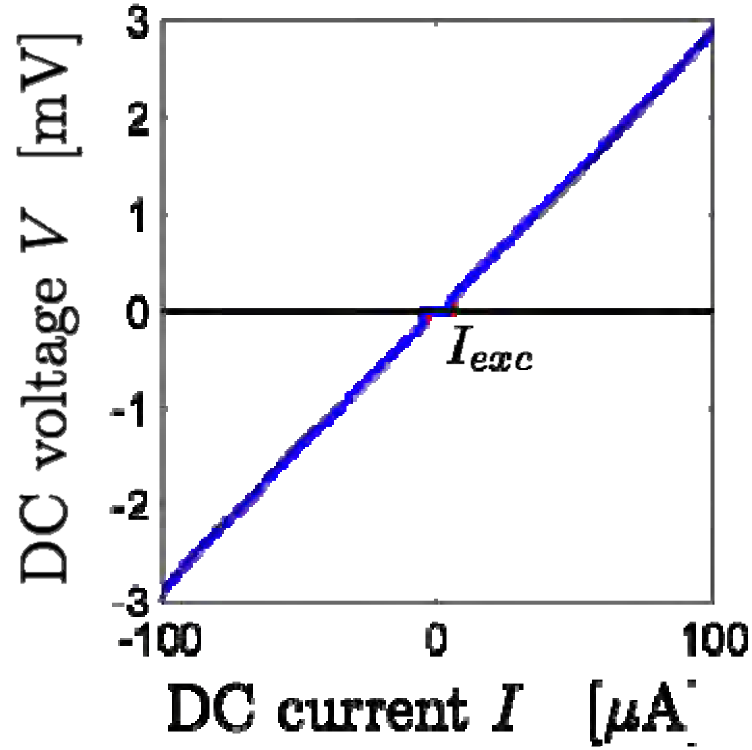




- induced gap $\Delta_i \simeq 0.1 - 0.4\text{meV}$
  - length $L = 150 - 600\,\text{nm}$
  - width $W = 2\,\mu\text{m}$
- ballistic between contacts $L \sim l$
- reproducible

I-V curves



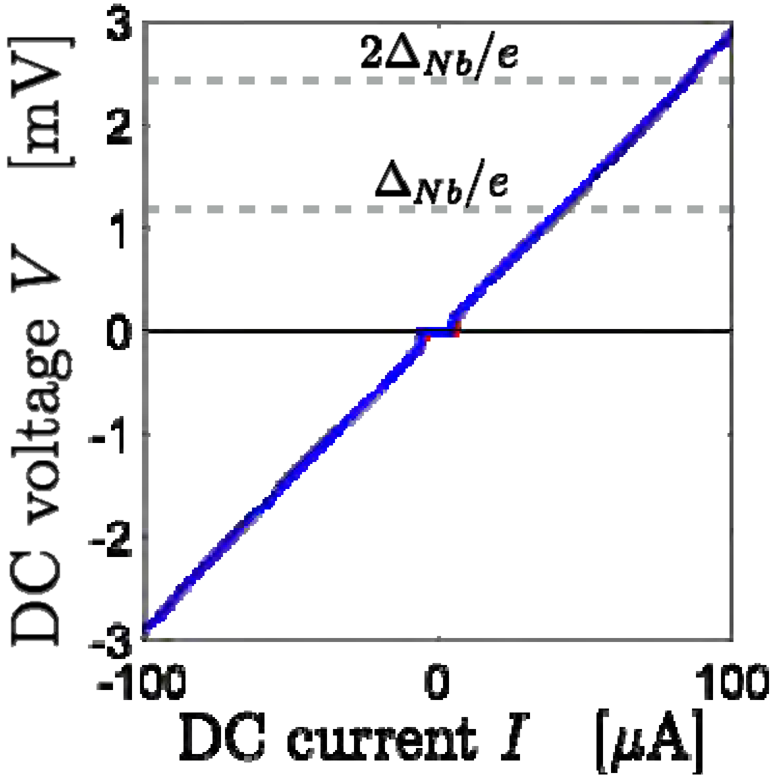


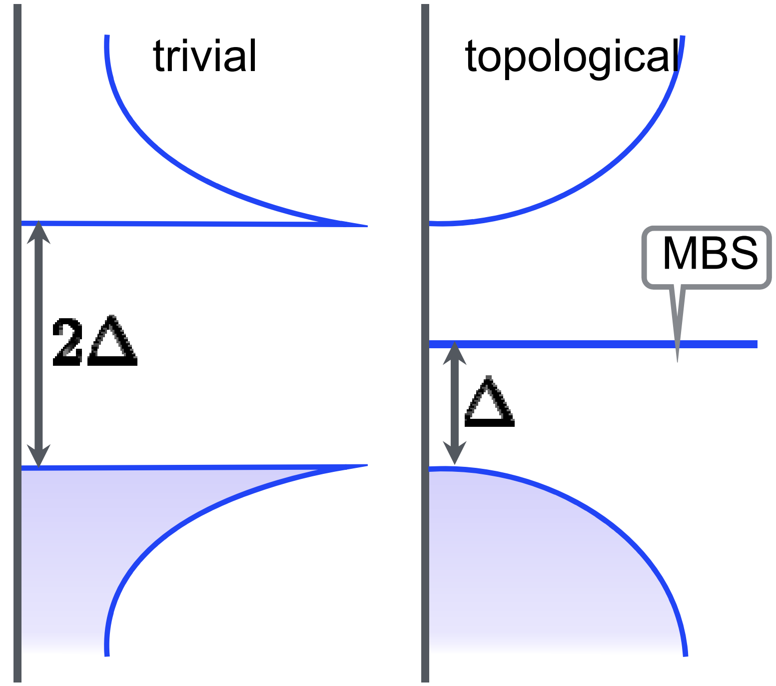
I-V curves

- hysteresis $I_r \neq I_c \Rightarrow$ self-heating?
- excess current $I_{exc} \Rightarrow$ Andreev reflection at S-TI interfaces

Courtois *et al.*, PRL **101** 067002 (2008)
Blonder *et al.*, PRB **25**, 4515 (1982)

Excess current





Excess current

- high biases : 2 S/N interfaces
  - sign of Andreev reflection

Blonder *et al.*, PRB **25**, 4515 (1982)
Klapwijk *et al.*, Physica B+C 109, 1657 (1982)

Sign of midgap states?

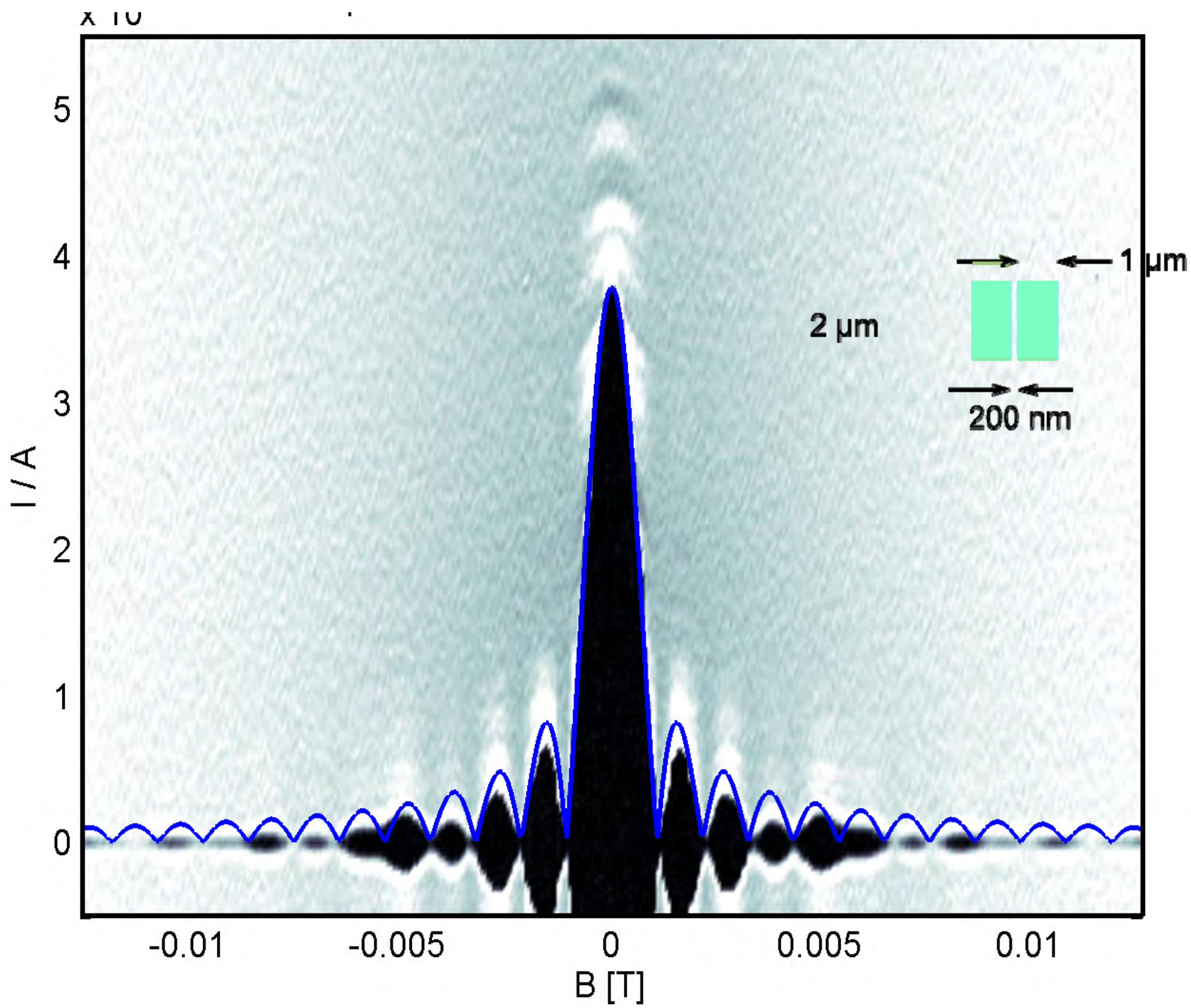
- halved onset
- role of induced DOS ?

Badiane *et al.*, PRL **107**, 177002 (2011)
San Jose *et al.*, NJP 15, 075019 (2013)

Sample with two contacts shows somewhat irregular ‚Fraunhofer' pattern.

Could of course just be inhomogeneous current injection.

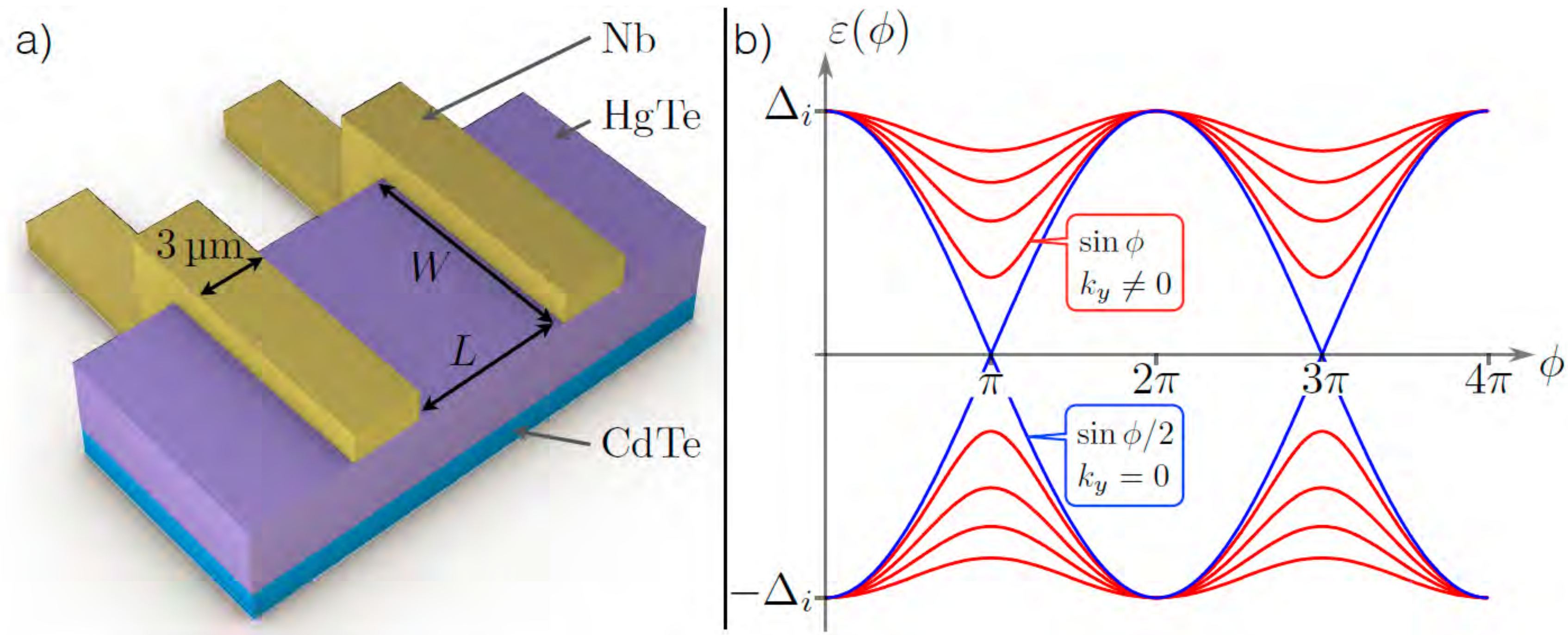
Need other experiments to identify exotic superconductivity.



T ~ 25 mK
Just DC

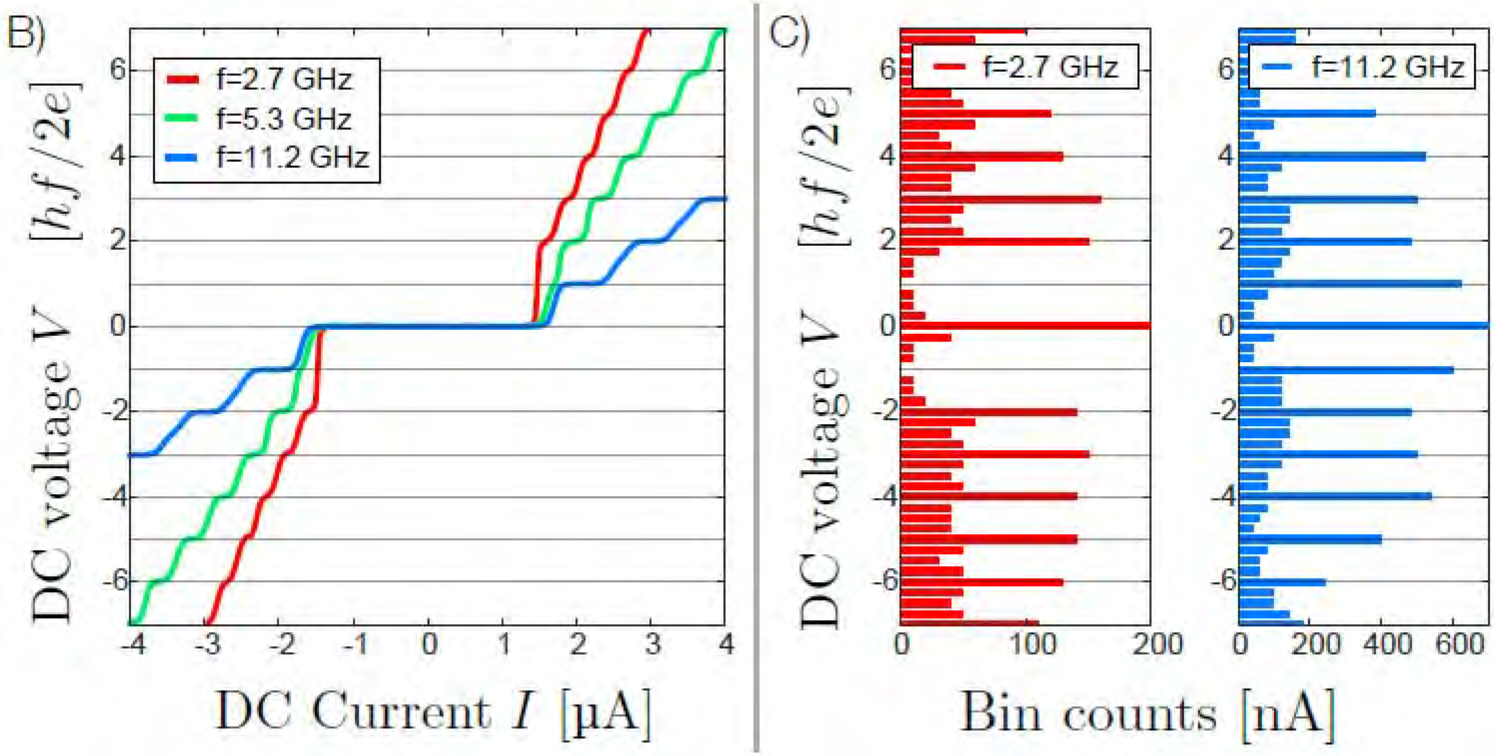
J. Oostinga et al.,
Phys. Rev. X **3**, 021007 (2013).

Midgap Modes in Josephson Junctions



Midgap mode related to Majorana fermions.
4 pi periodicity leads to fractional Josephson effect,
i.e. missing odd steps in Shapiro response.
(D.M. Badiane, M. Houzet, J.S. Meyer, Phys. Rev. Lett., 107, 177002, (2011),
F. Domínguez, F.Hassler, G.Platero, Phys. Rev. B 86, 140503(R) (2012),
P. San-Jose, E. Prada, R. Aguado, Phys. Rev. Lett. 108, 257001 (2012))

Shapiro Steps in Josephson Junctions



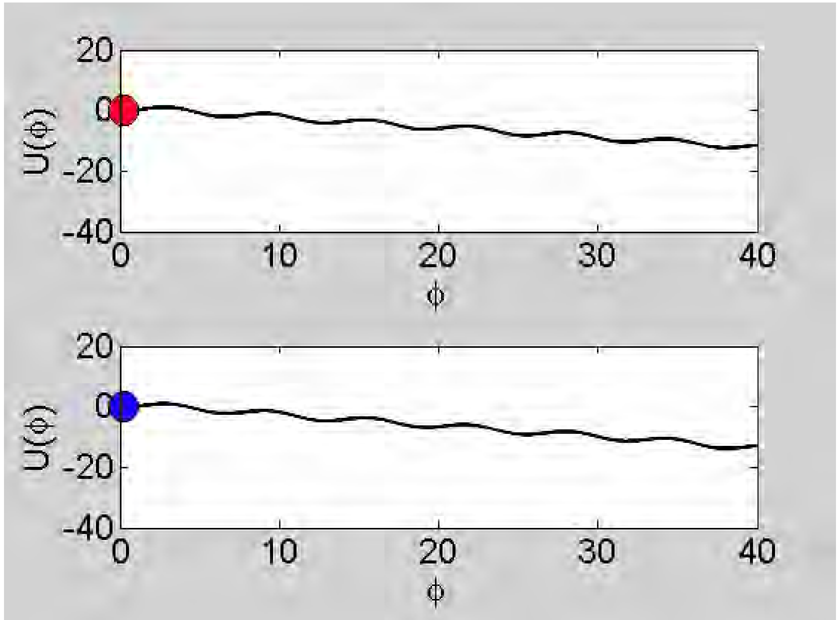
- Measurements: RF irradiation via open coaxial

J. Wiedenmann et al., Nat.Comm. **7**, 10303 (2016).

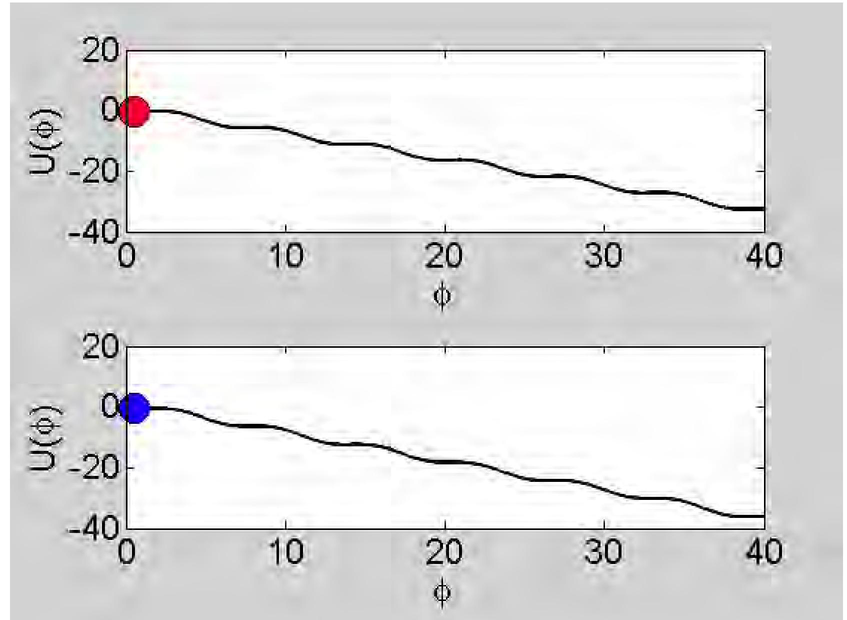
- Shapiro steps clearly visible: normalized by hf/2e (conventional 2π)

- Bin diagrams allow easy comparison

Modeling



Low RF frequency

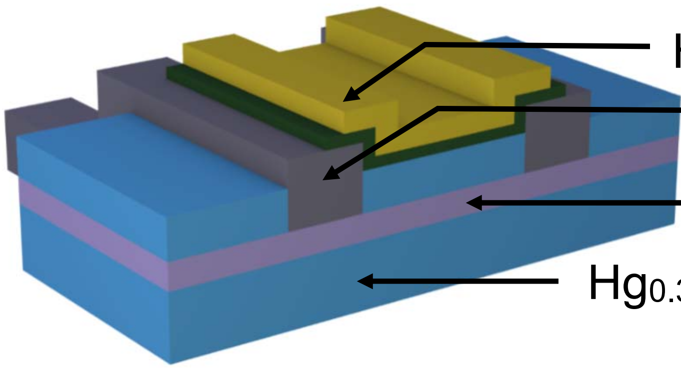


High RF frequency

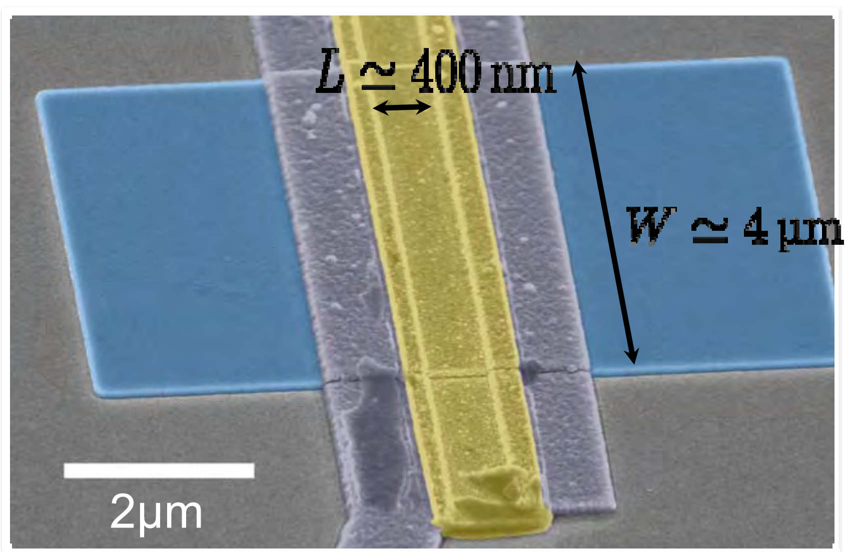
Simulations (similar to Gonzalez et al.):

- Skew CPR gives extra half plateaus (@ high rf power), need sin $\phi/2$ contribution for suppression of first plateau.
- Frequency dependence of effect disfavors Landau Zener mechanism. LZ would also require improbably large transmission, D>0.996 .
- 4π contribution to supercurrent about 150 nA – compared with 60 nA/mode
- Zero energy Andreev mode?

Quantum spin Hall junction

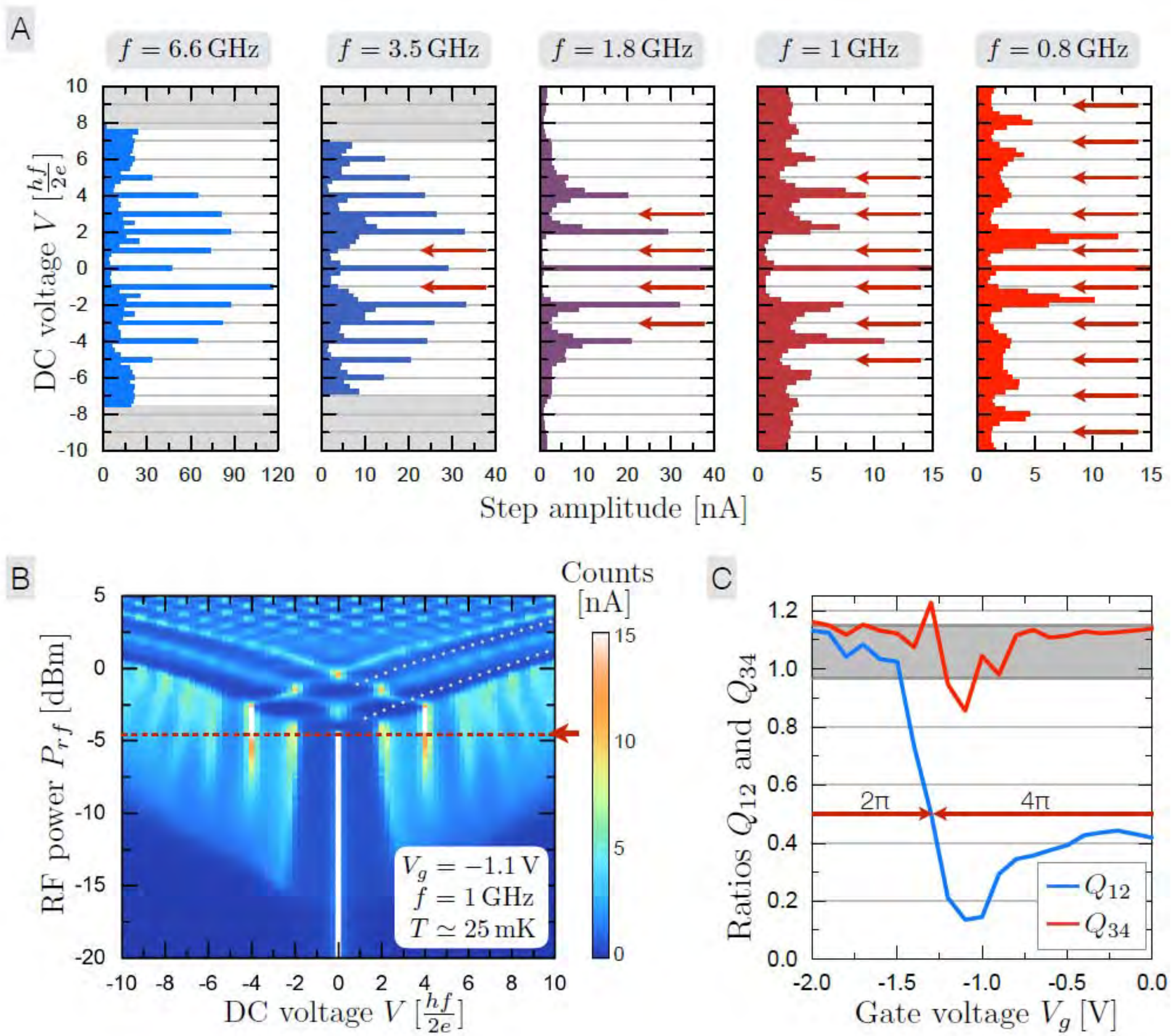


Quantum spin Hall sample
- HgTe quantum well (8 nm)
- Inverted band structure
- High mobility: 2 10^5 $cm^2V^{-1}s^{-1}$



Josephson junctions
- Ti/Al contacts/HfO_2 Au gate
- No overlap of edge states
- Ballistic/ intermediate regime
- L~ξ<<l

Shapiro steps in QSH 2D Josephson junctions



So far :

- all previous features visible
- odd steps missing up to n=9

E. Bocquillon et al., Nature Nanotechn. **12**, 137 (2017).

Detecting Josephson Radiation

Voltage biased junction

- Josephson equation

$$\frac{d\phi}{dt} = \frac{2eV}{\hbar}$$

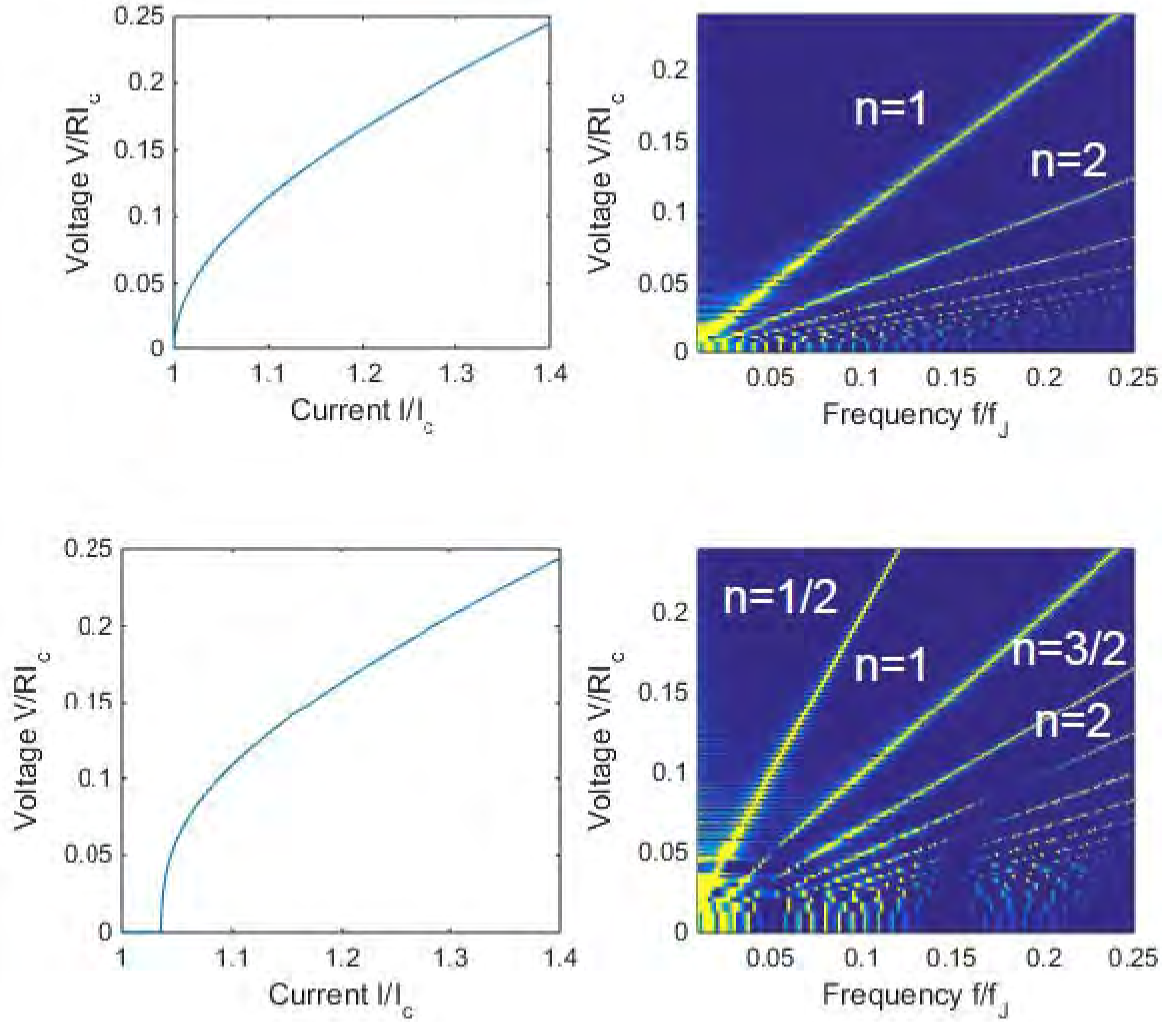
- $I(\phi) = I_c \sin\phi$

  $\Rightarrow$ emission at $f_J = \frac{2eV}{\hbar}$

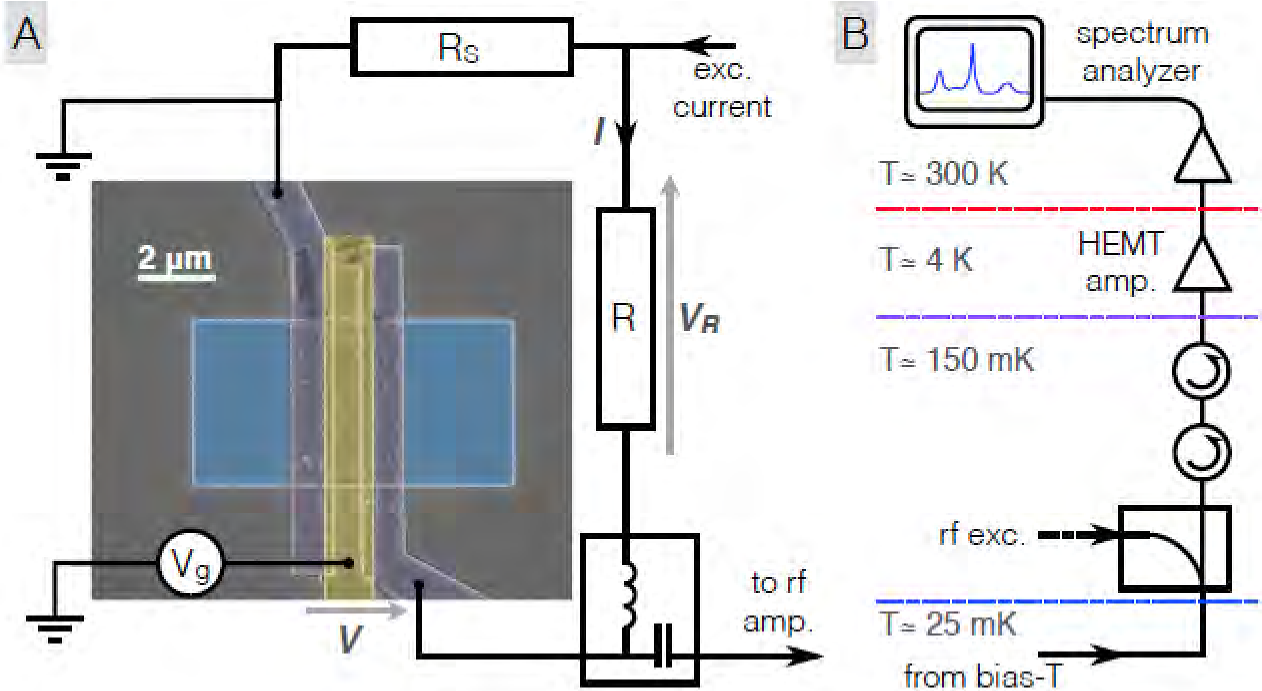
- $\sin\phi/2$ term in CPR

  $\Rightarrow$ emission at $f_J/2$

- unchanged with current bias



Setup



Sensitivity ≈ 0.1 fW
Measurement Range 2-10 GHz

DC setup

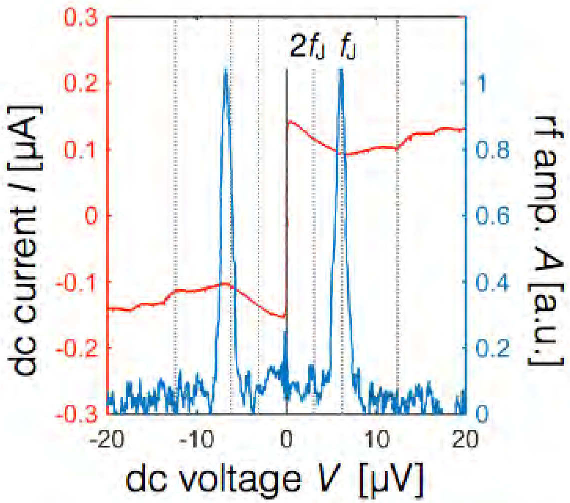
- ≃Voltage bias
  10 Ω for current meas.
  1 Ω shunt
- filtered lines

RF setup

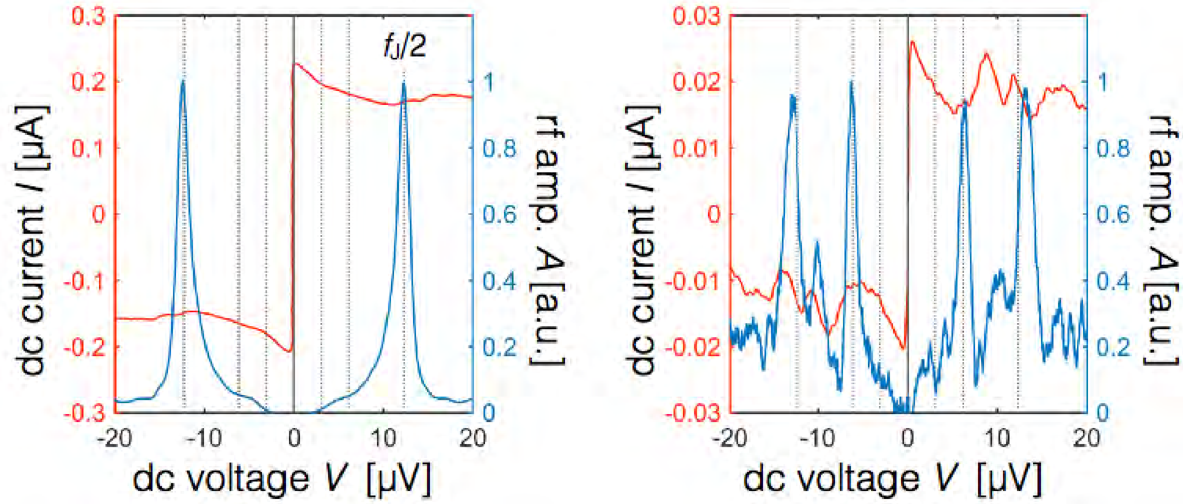
- pick-up via bias-tee
- HEMT cryo. amp.
- RF excitation
  via directional coupler

Emission spectra

Trivial QW



Topological QW

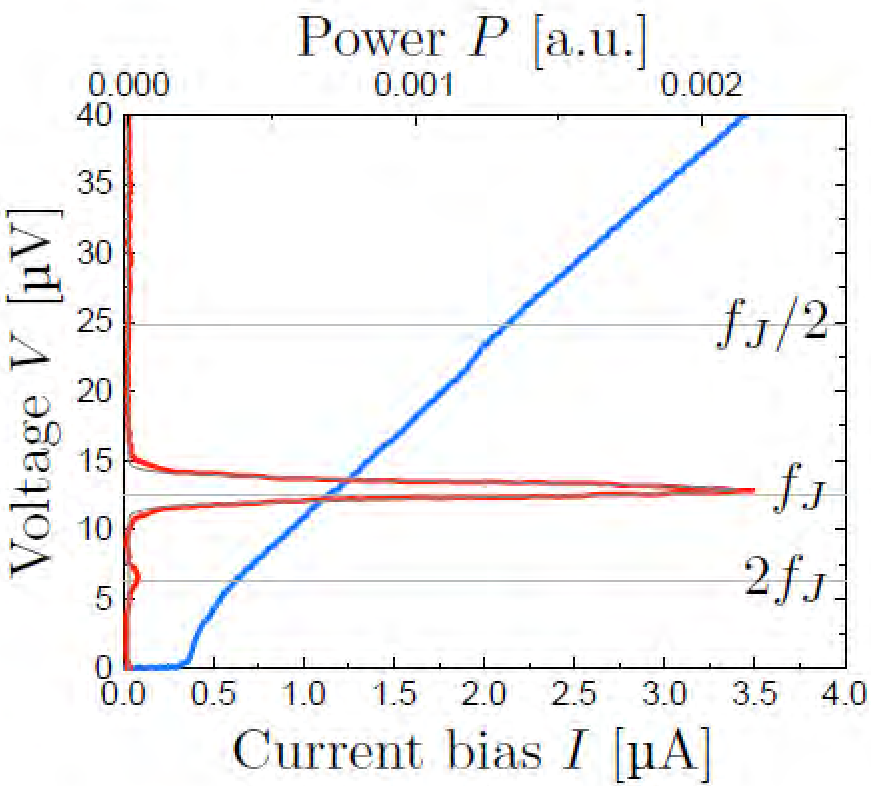


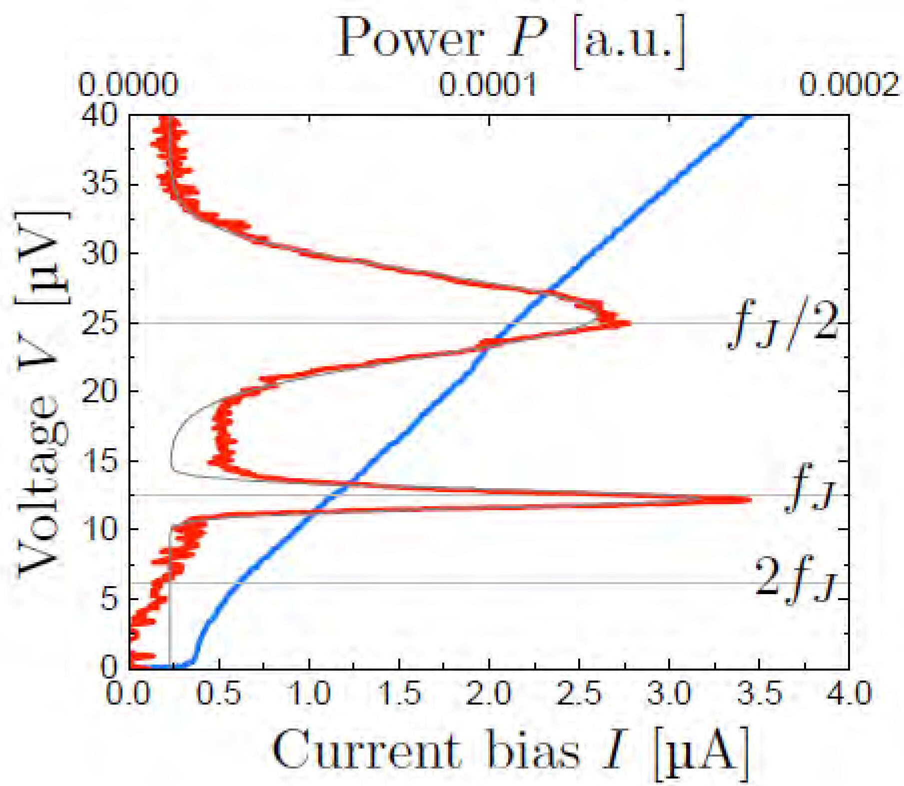
- voltage *V* swept
- integrated power at f_d=3 GHz (in 8 MHz bandwidth)

- trivial QW : signal at $f_d=f_J$
- topological QW : at $f_d=f_J$ and $f_J/2$

R. Deacon *et al.*, Phys. Rev. **X** 7, 021011 (2017)

Josephson Radiation from 2D TI



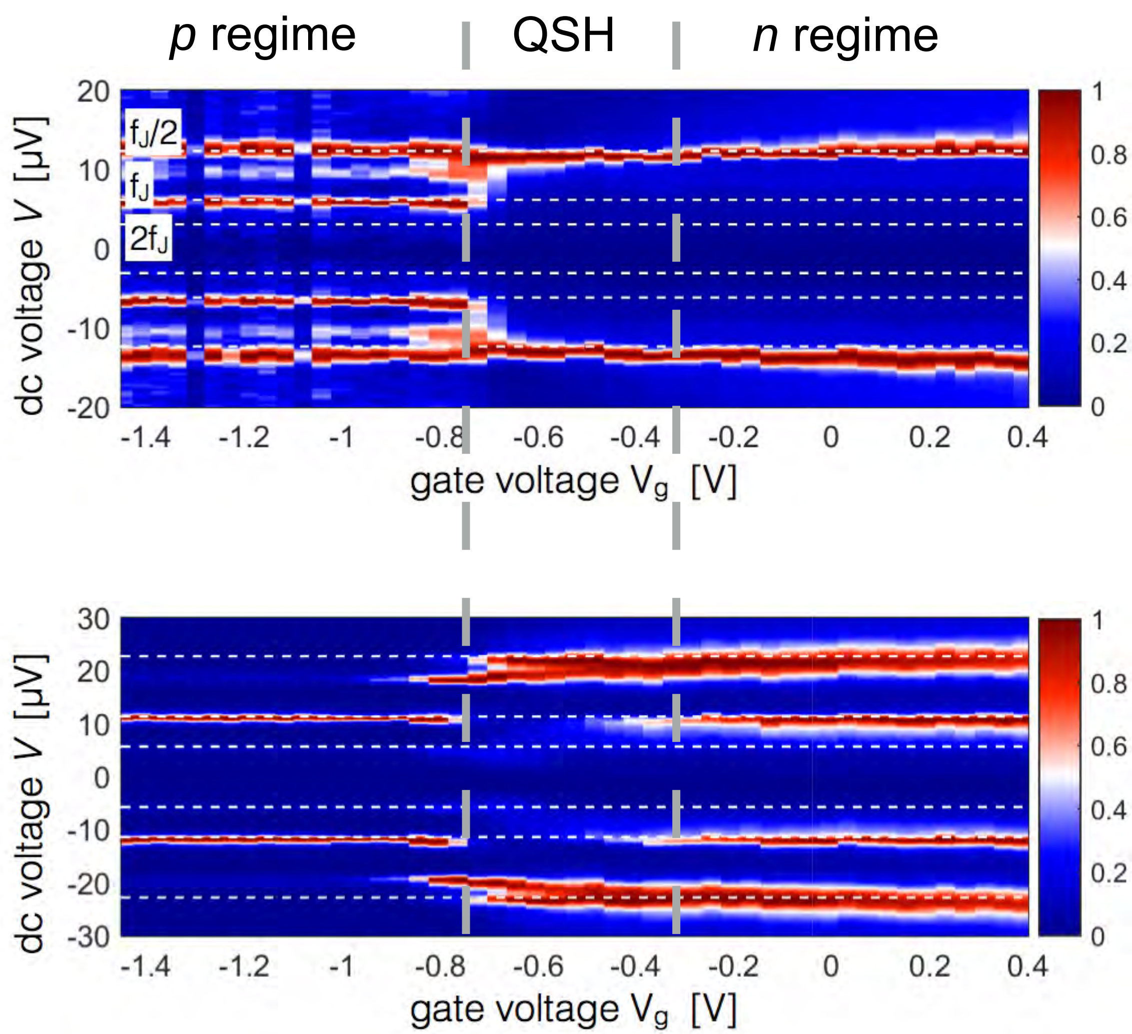


Trivial:
conventional line f_J
over the whole gate range

Topological:

- f_J in valence and conduction band
- $f_J/2$ in the gap and conduction band
- Linewidth $f_J/2 > f_J$
- (coherence time $\tau_{2\pi}$=3- 4 ns / $\tau_{'4\pi}$=0.3- 4 ns)

Gate voltage dependence



QSH regime

- mostly $f_J/2$

n regime

- $f_J/2$ at low f_d
- $f_J/2+f_J$ at high f_d

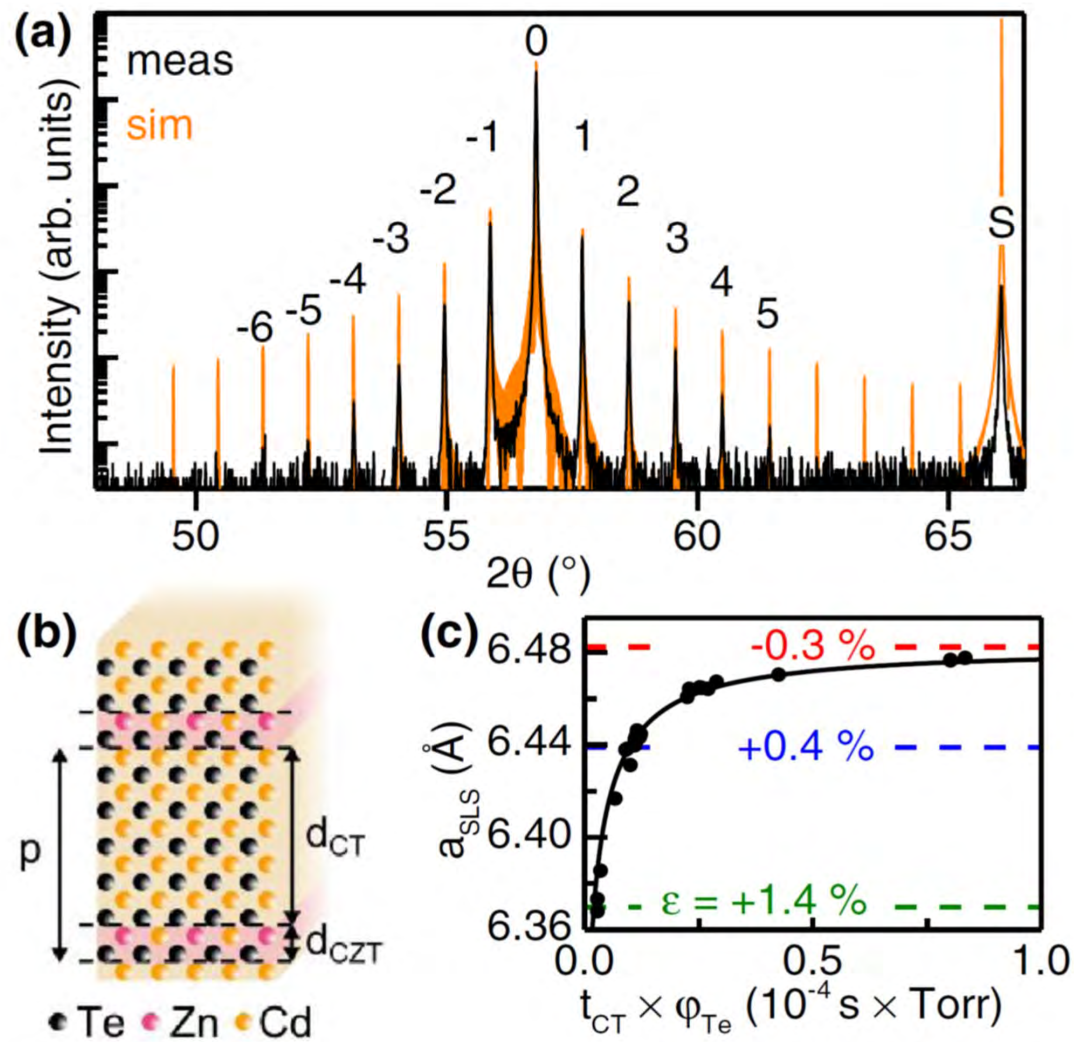
p regime

- $f_J/2+f_J$ at low f_d
- f_J at high f_d

R. Deacon *et al.*, Phys. Rev. X **7**, 021011 (2017)

Strain Engineering: Virtual Substrates

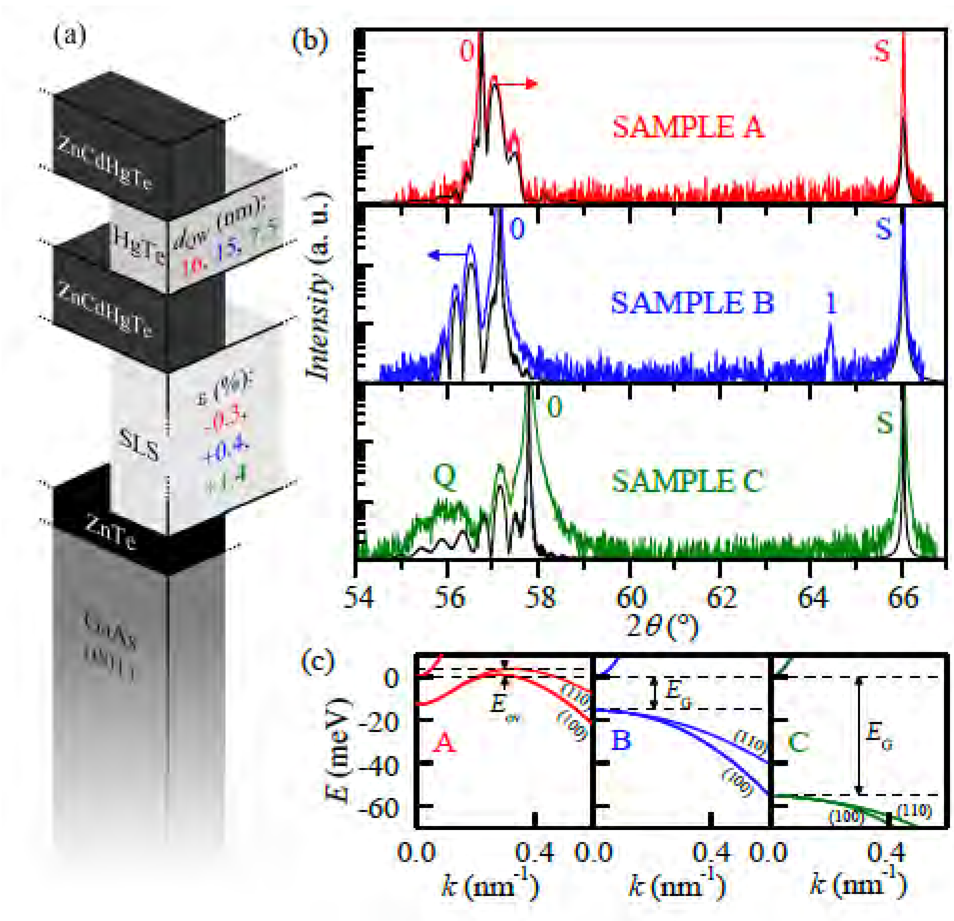
Strained Superlattices

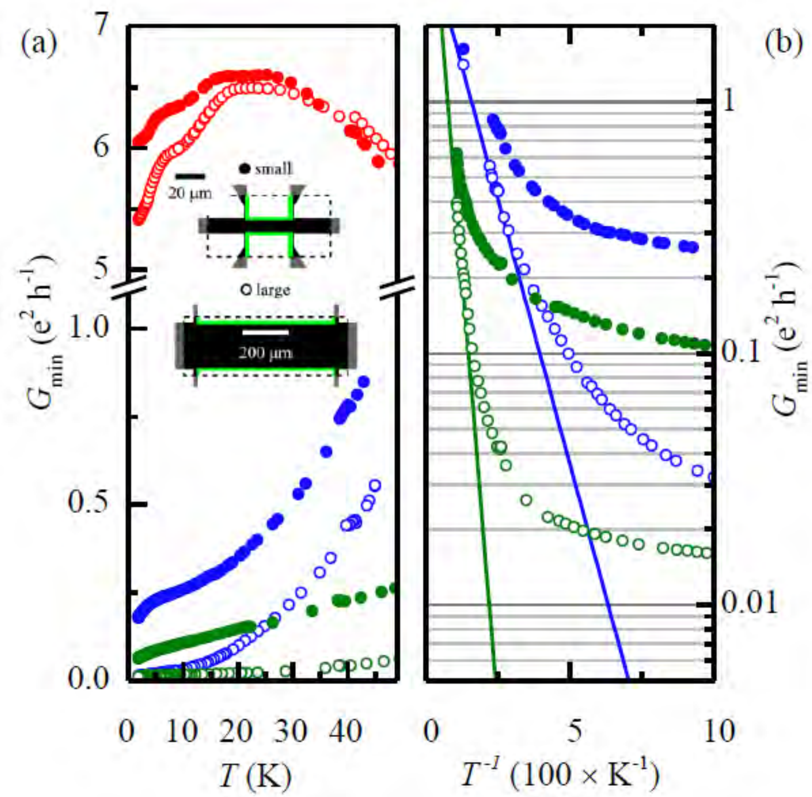


Using CdZnTe/CdTe superlattices on a GaAs substrate:

can adjust strain from tensile to compressive.

Strain Engineering in QWs





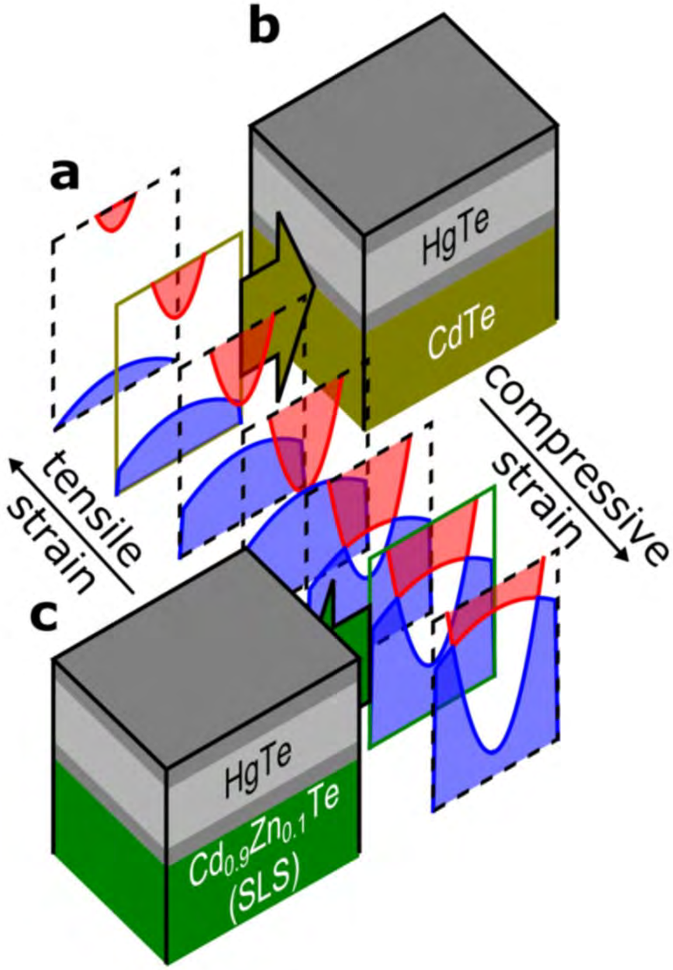
Tensile strain yields semimetal;

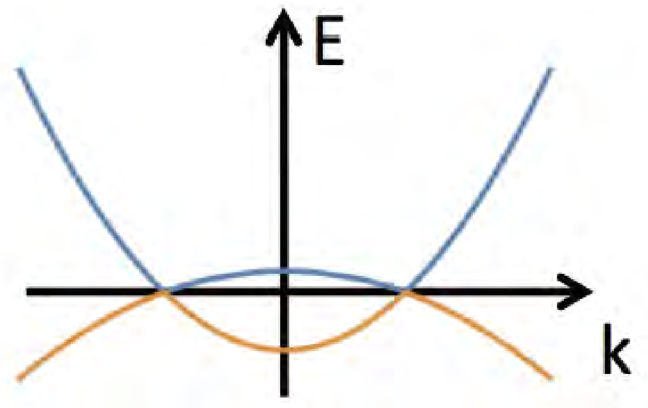
Compressive strain yields gap up to 60 meV.

P. Leubner et al., Phys. Rev. Lett. **117**, 086403 (2016).

Compressive Strain in bulk HgTe

Γ8 band develops Dirac/Weyl points





(a)

Conclusions

- HgTe: can be made into 2D and 3D Topological Insulator
- TI behavior very obvious in transport
- Superconducting proximity in both 2D and 3D
- 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, Martin Stehno, Jonas Wiedenmann (Würzburg); Amir Yacoby (Harvard), Russell Deacon, Koji Ishibashi, Seigo Tarucha (Tokyo); Teun Klapwijk (Delft & Würzburg)

Theory: Ewelina Hankiewicz, Björn Trauzettel (Würzburg)

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