Topological Insulators: Recent Results and New Directions

Laurens W. Molenkamp

Physikalisches Institut, EP3
Universität Würzburg

Overview

- HgTe/CdTe bandstructure, quantum spin Hall effect
- HgTe as a Dirac system
- Dirac surface states of strained bulk HgTe
- QAHE and Josephson junctions

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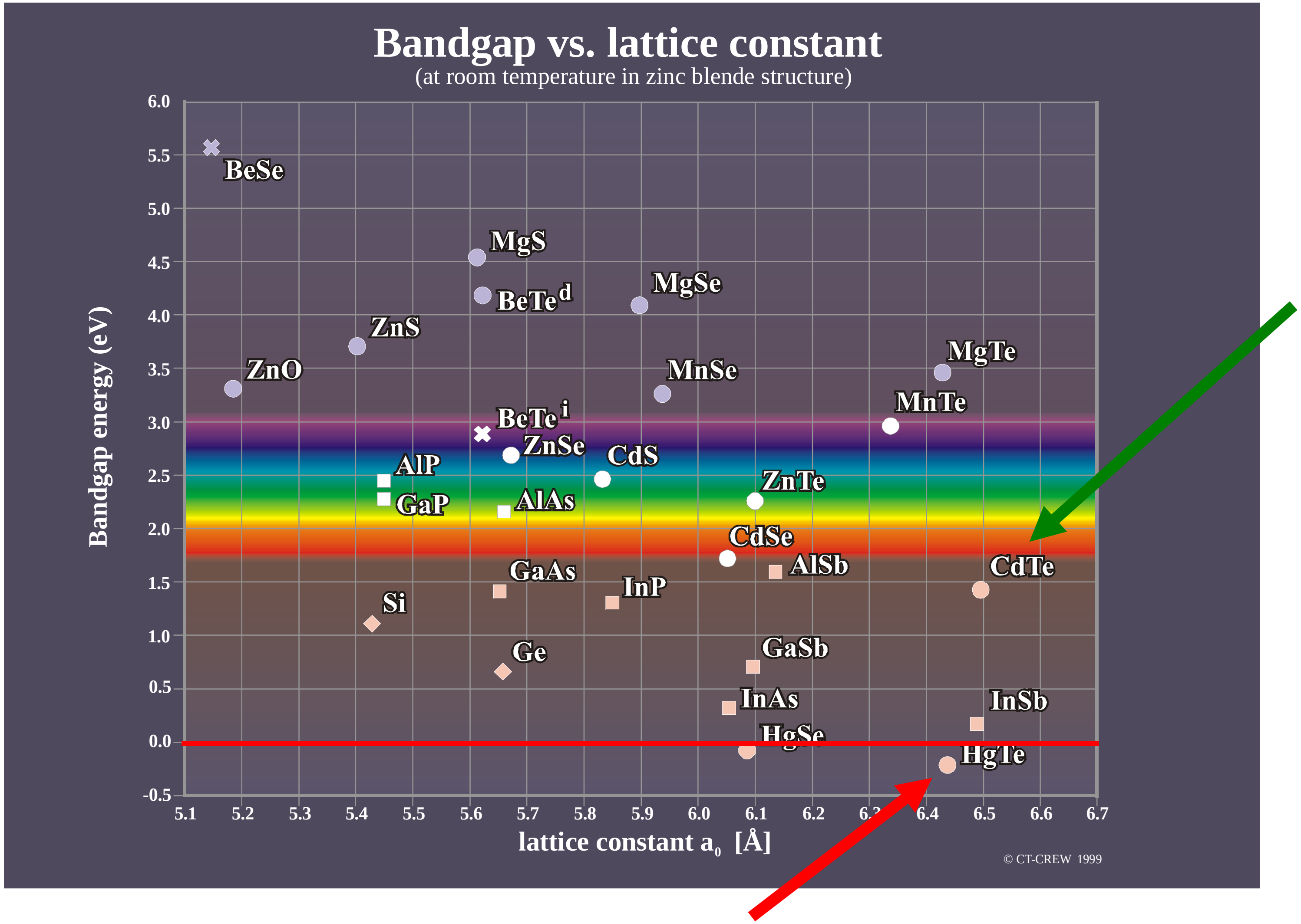
HgTe-Quantum Wells

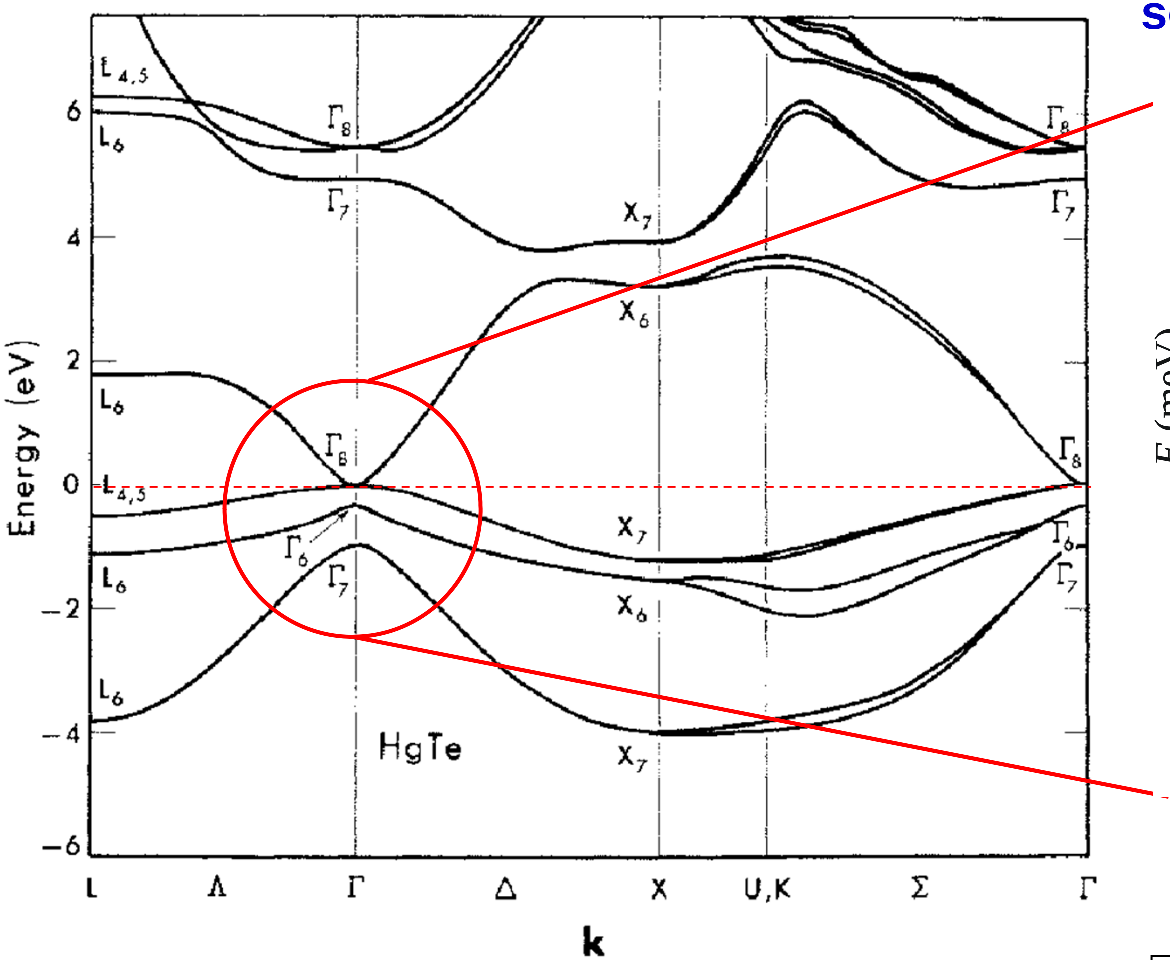
EP 3

MBE-Growth



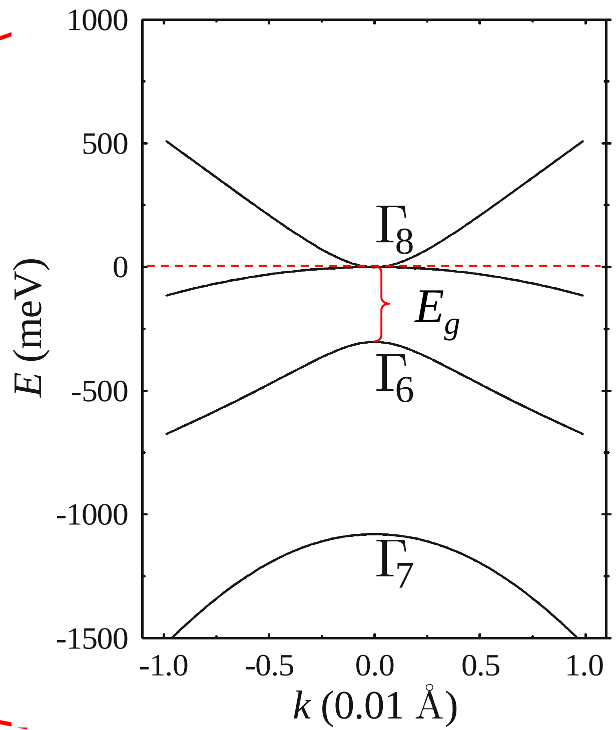
HgTe

band structure



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

semi-metal or semiconductor

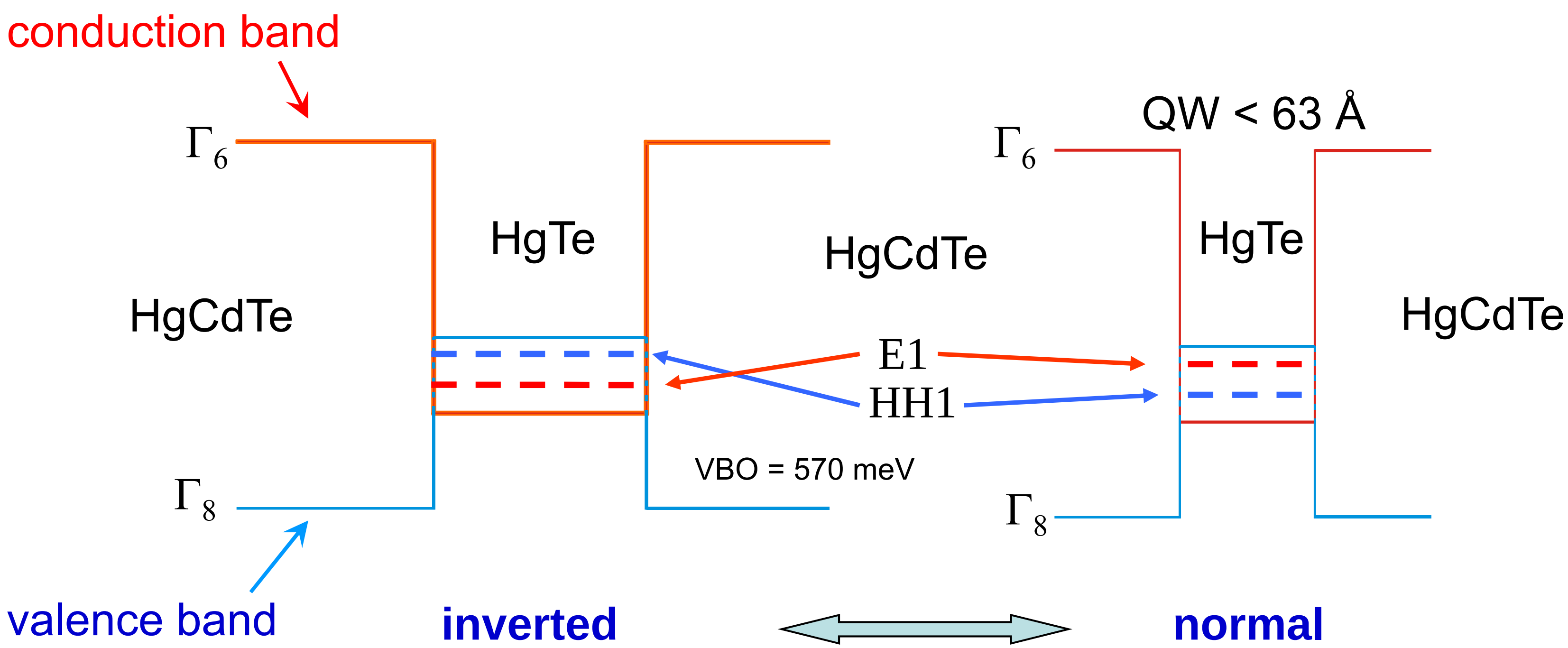


fundamental energy gap

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

HgTe-Quantum Wells

Type-III QW

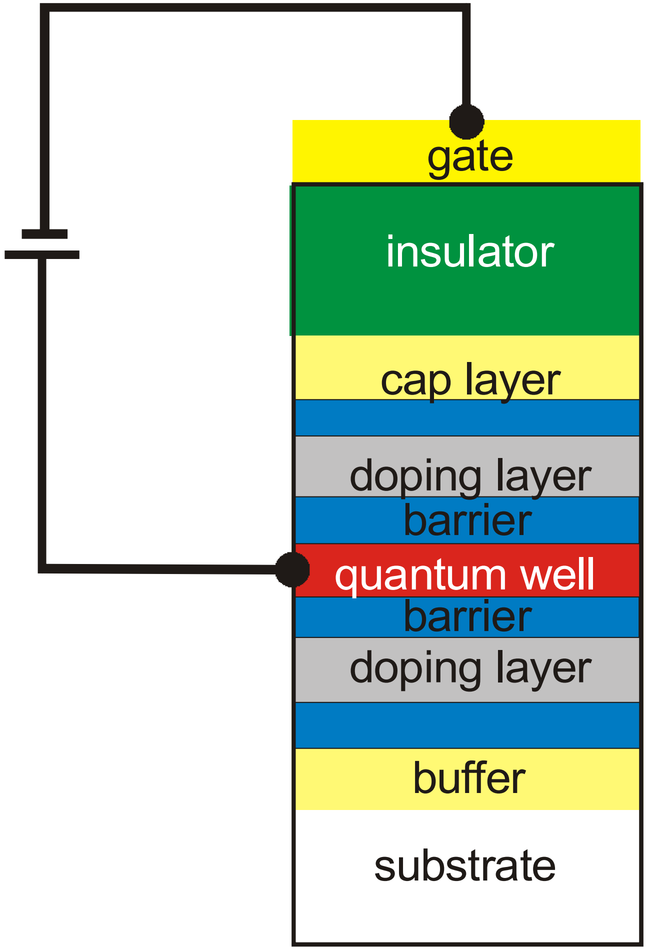


band structure

Layer Structure

Carrier densities: $n_s = 1\text{x}10^{11} \ldots 2\text{x}10^{12}\ \text{cm}^{-2}$

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



Au

100 nm Si_3N_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

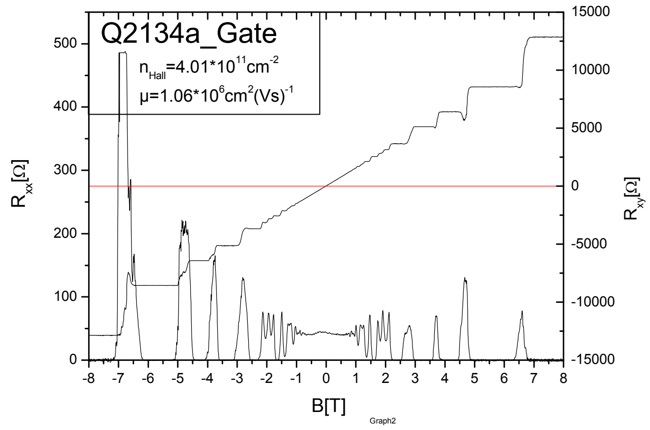
10 nm HgCdTe x = 0.7

9 nm HgCdTe with I

10 nm HgCdTe x = 0.7

25 nm CdTe

CdZnTe(001)



symmetric or asymmetric doping

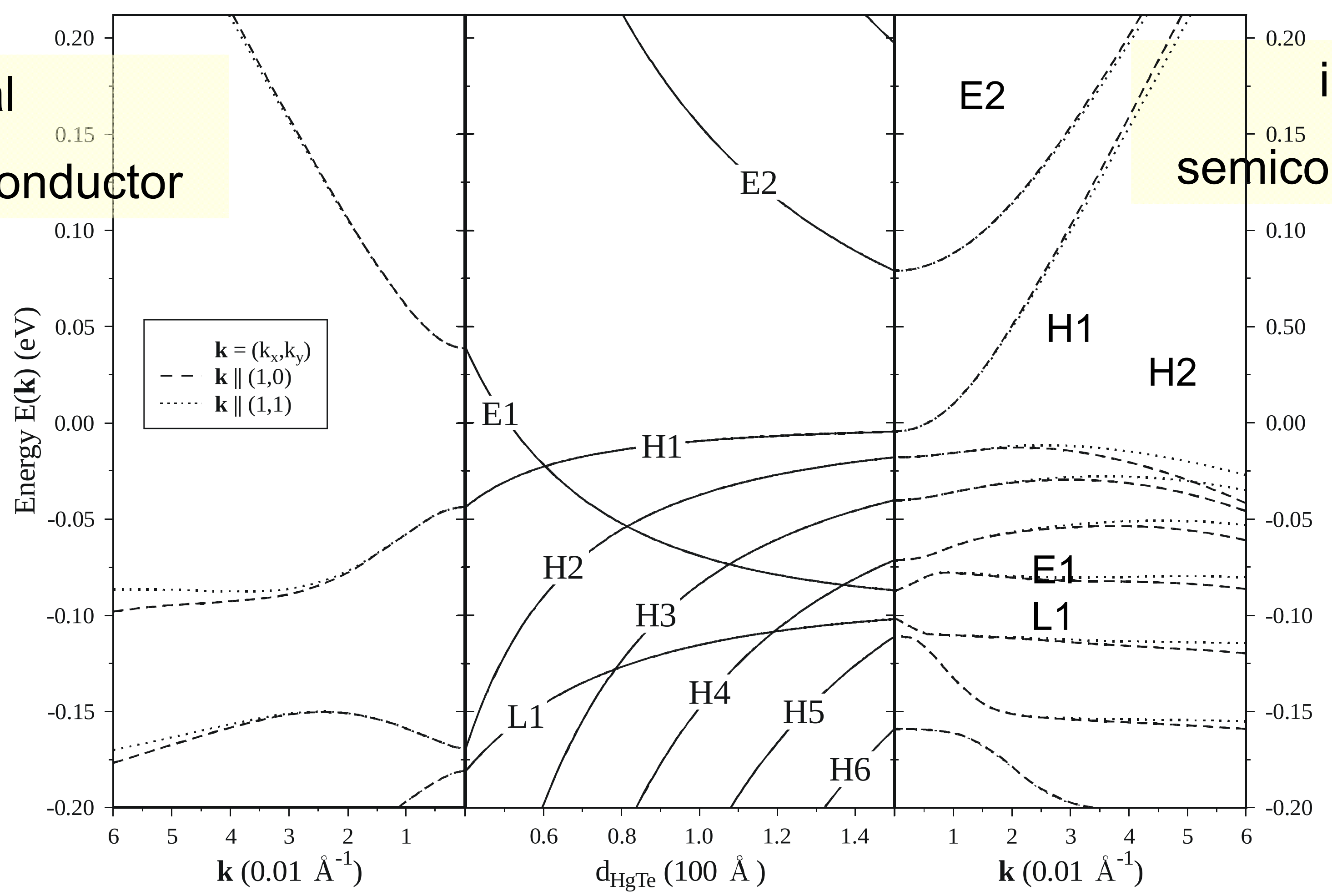
Band Gap Engineering

4 nm QW

15 nm QW

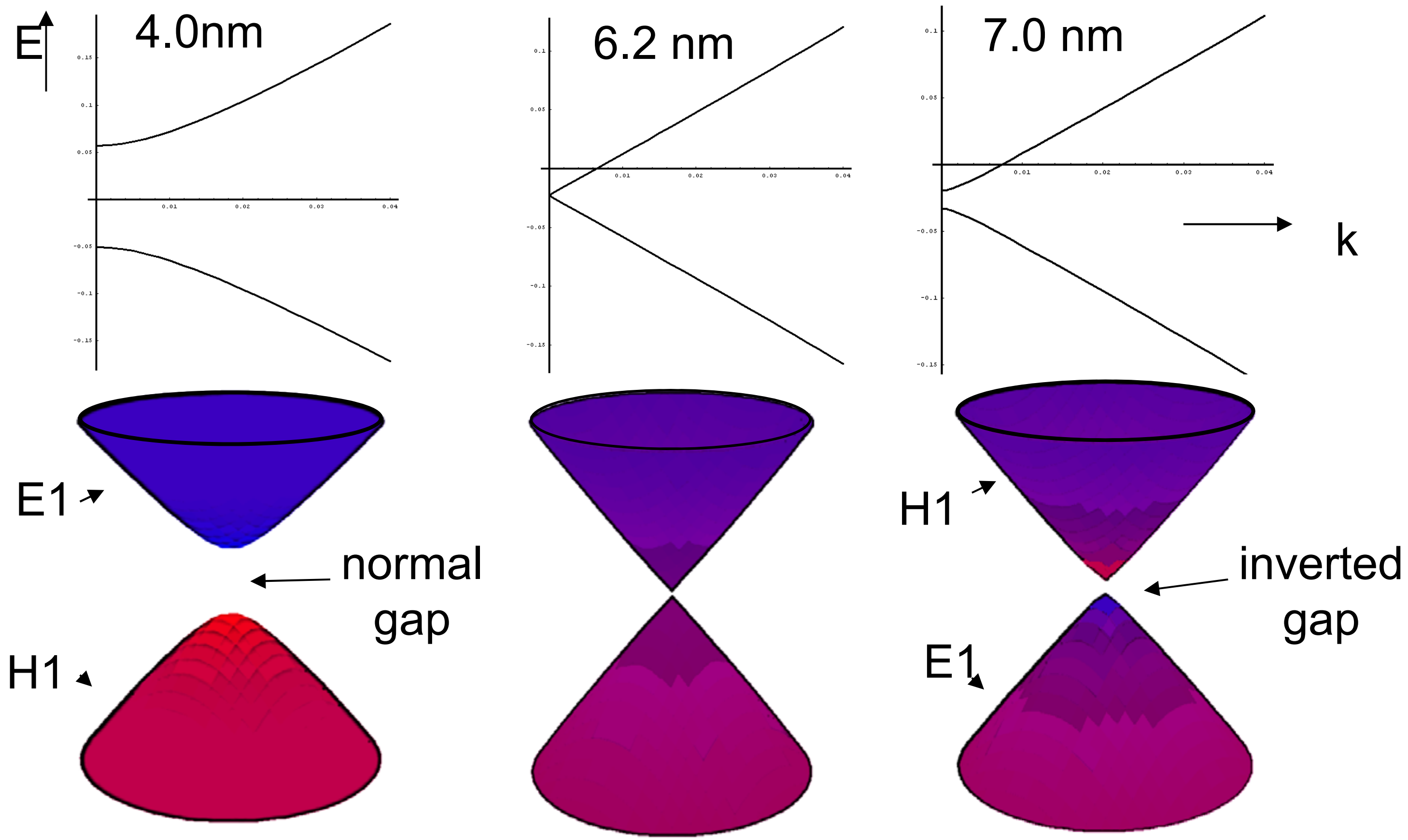
normal semiconductor

inverted semiconductor



Bandstructure HgTe

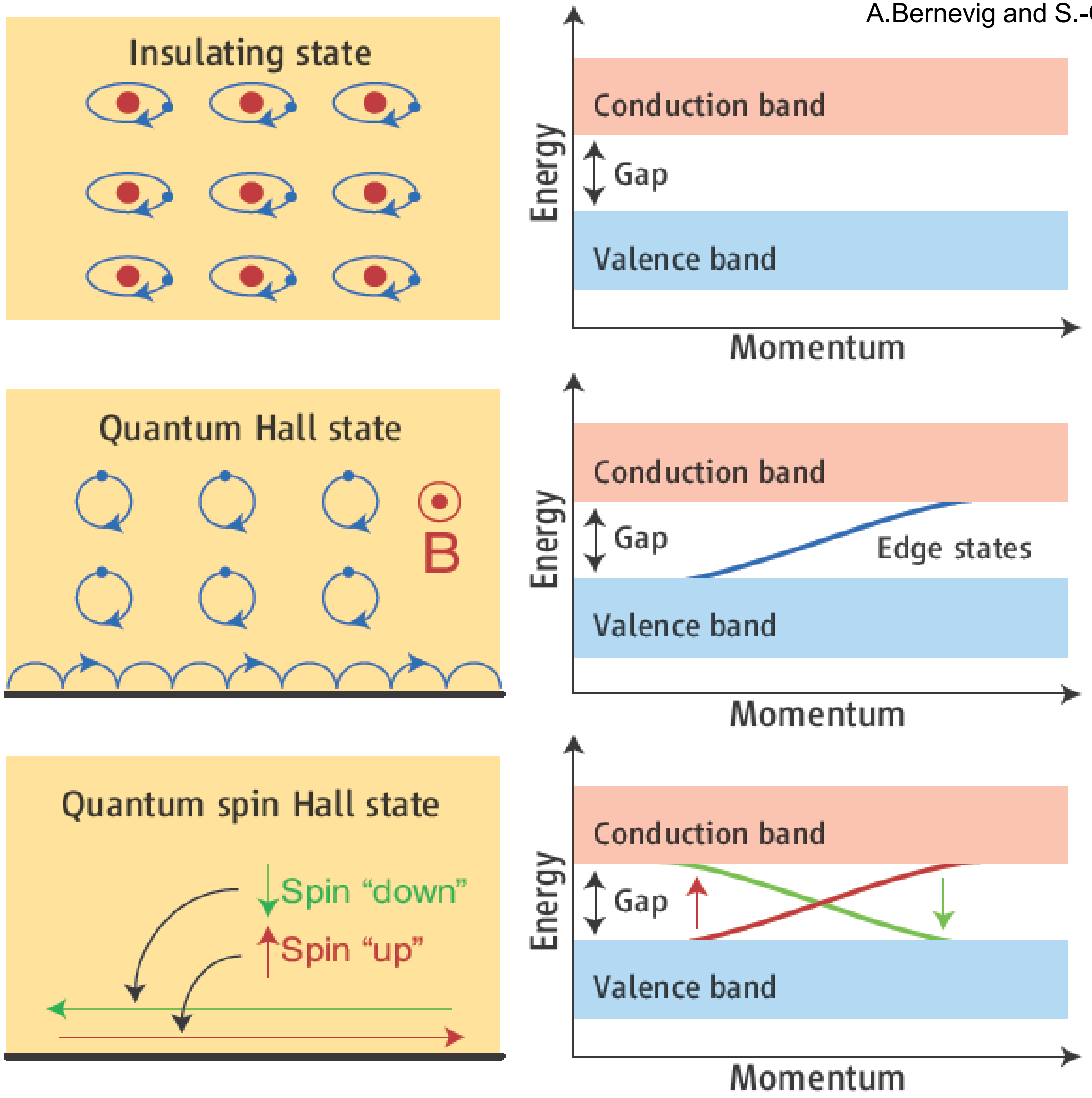
B.A Bernevig, T.L. Hughes, S.C. Zhang, Science **314**, 1757 (2006)



Quantum Spin Hall Effect

Topological Quantization

C.L.Kane and E.J.Mele, PRL **95**, 146802 (2005)
C.L.Kane and E.J.Mele, PRL **95**, 226801 (2005)
A.Bernevig and S.-C. Zhang, PRL **96**, 106802 (2006)

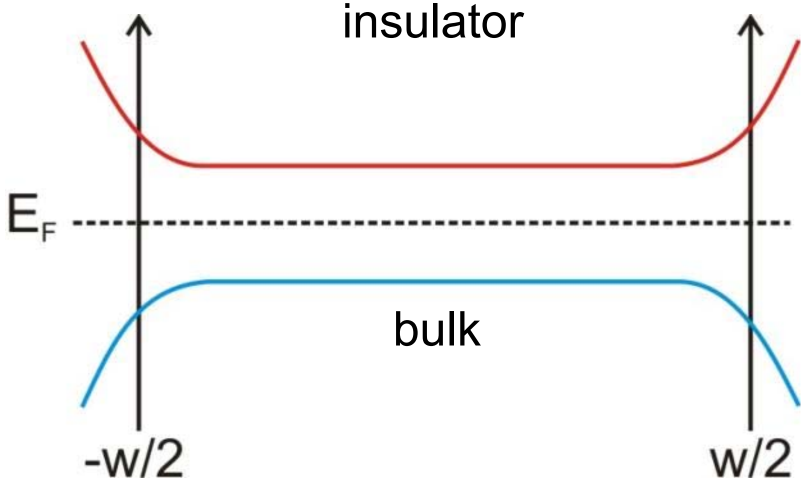


C.L.Kane and E.J. Mele, Science **314,** 1692 (2006)

QSHE, Simplified Picture

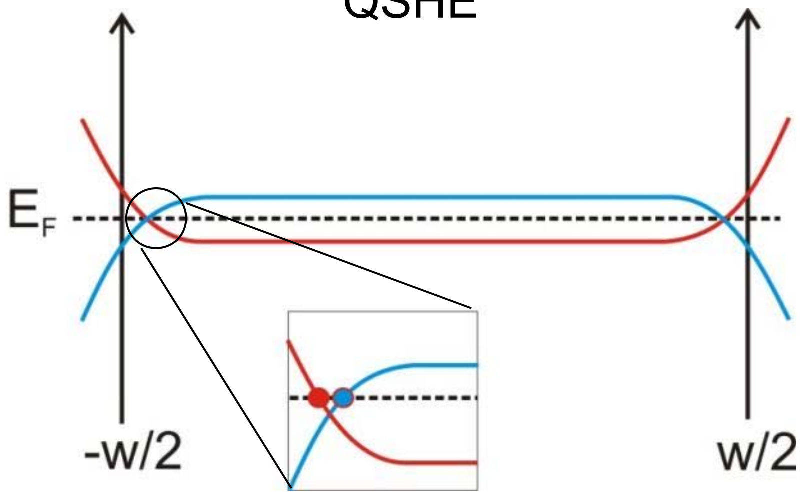
m > 0

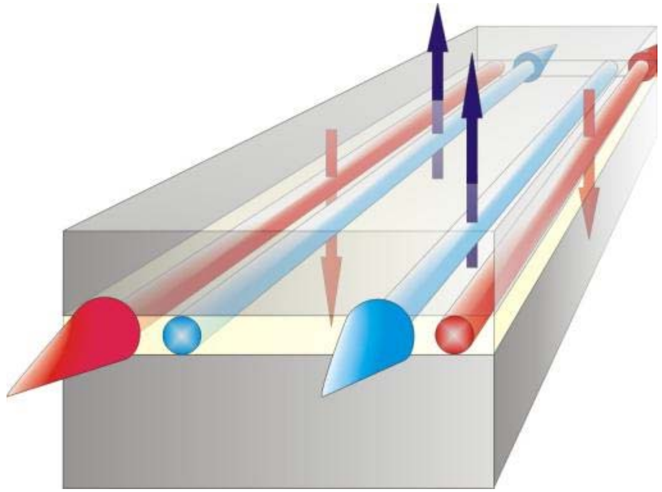
normal
insulator



m < 0

QSHE

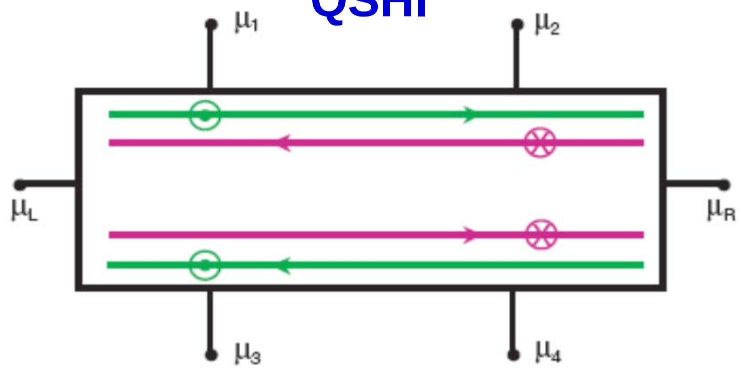


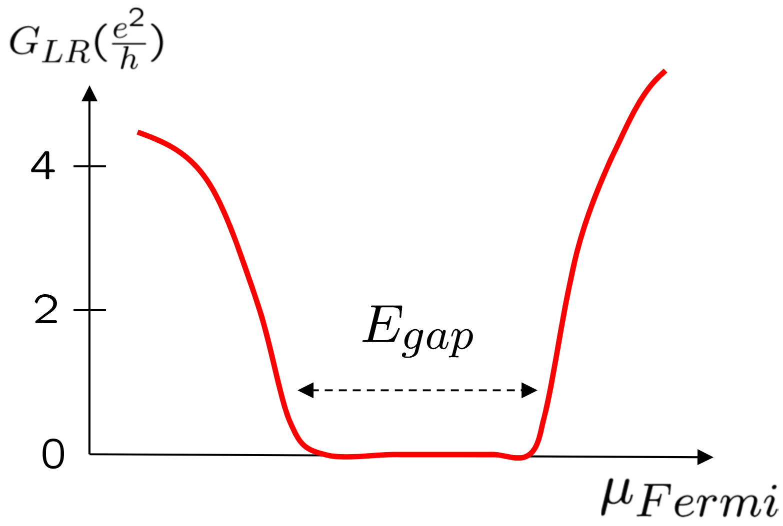


Experimental Signature

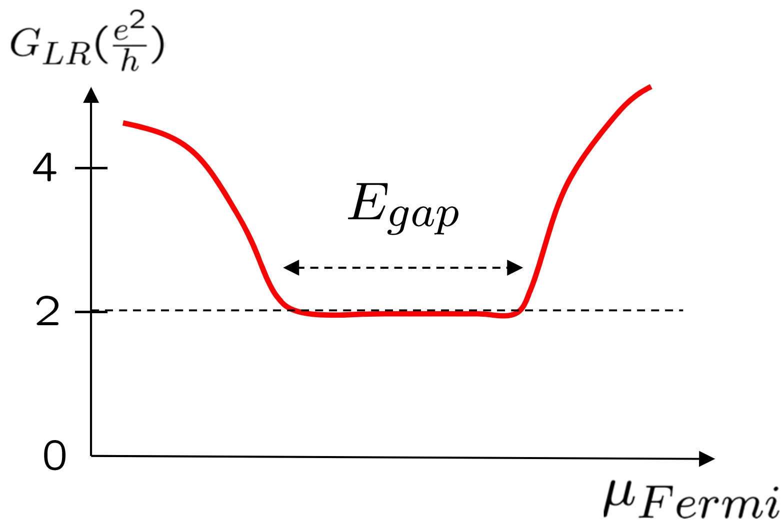
normal insulator state

QSHI



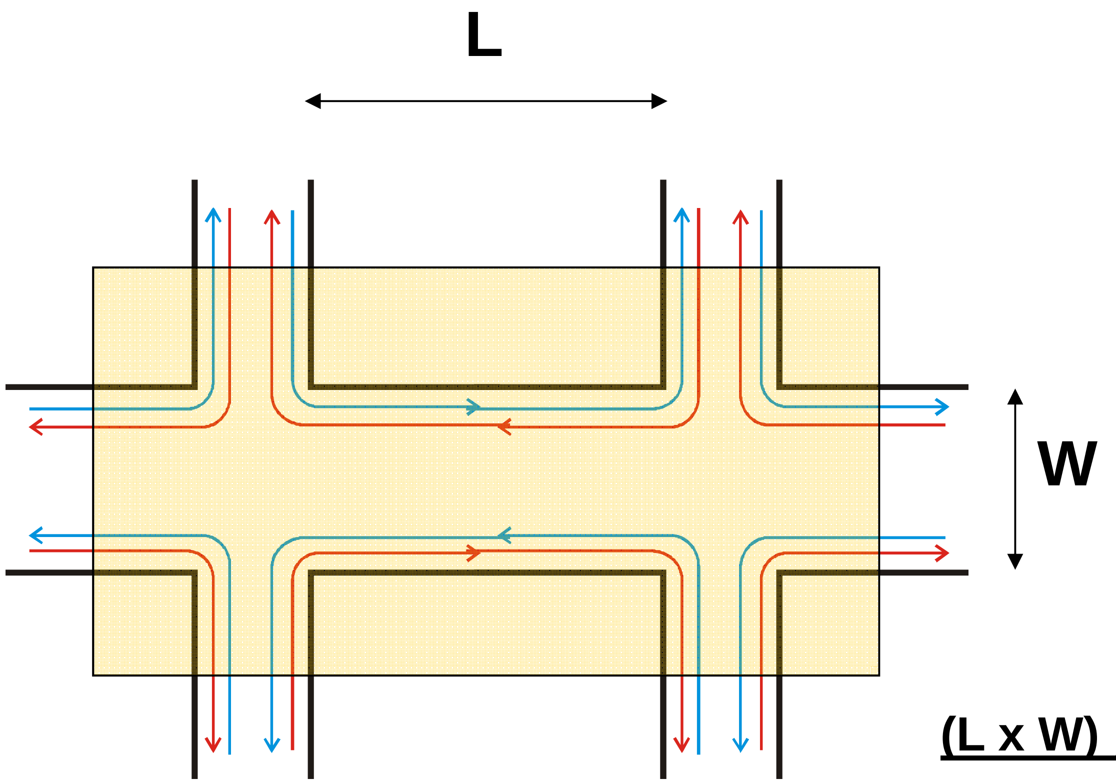


$d < d_c$, normal regime



$d > d_c$, inverted regime

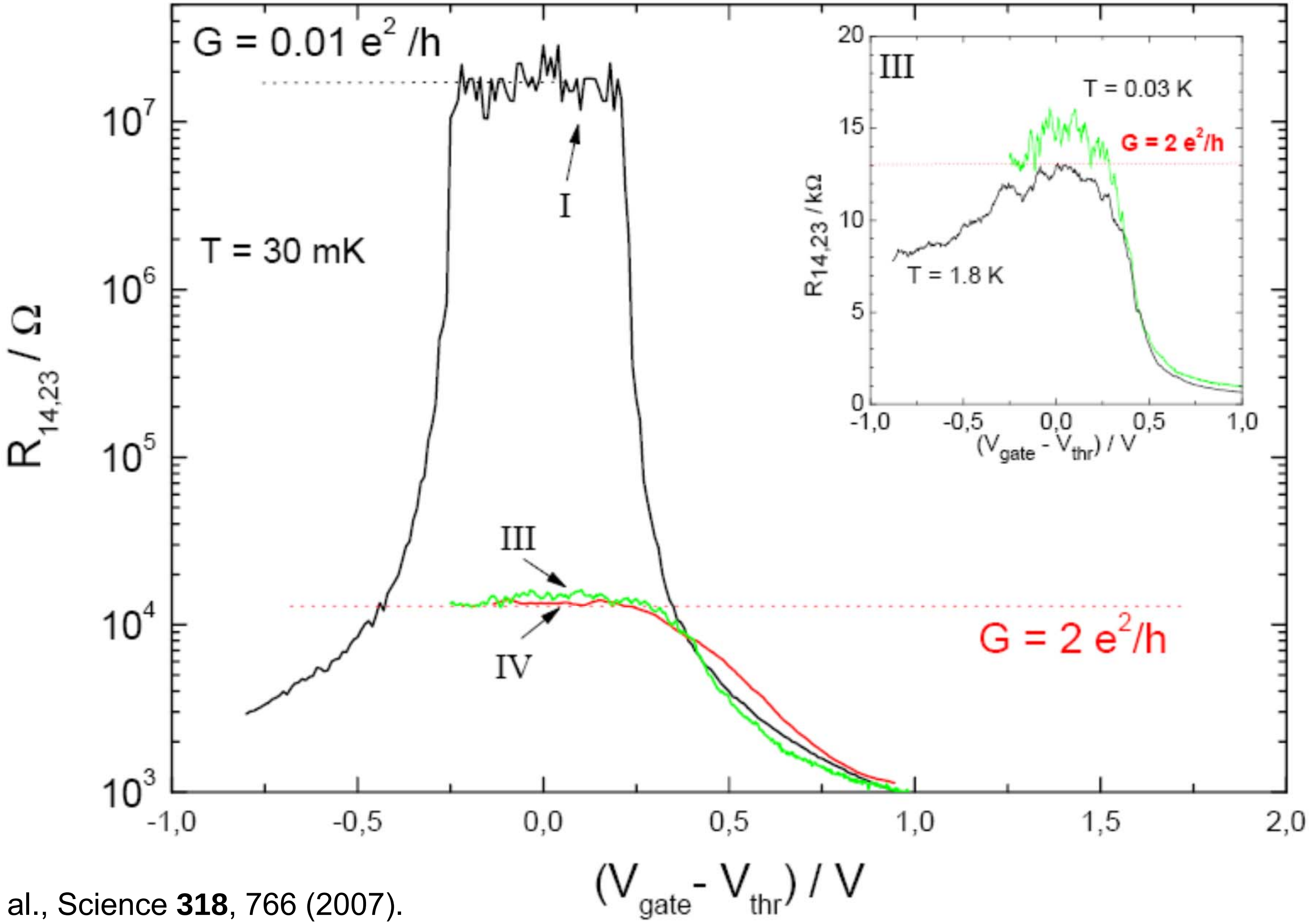
Need small Samples



(L x W) μm

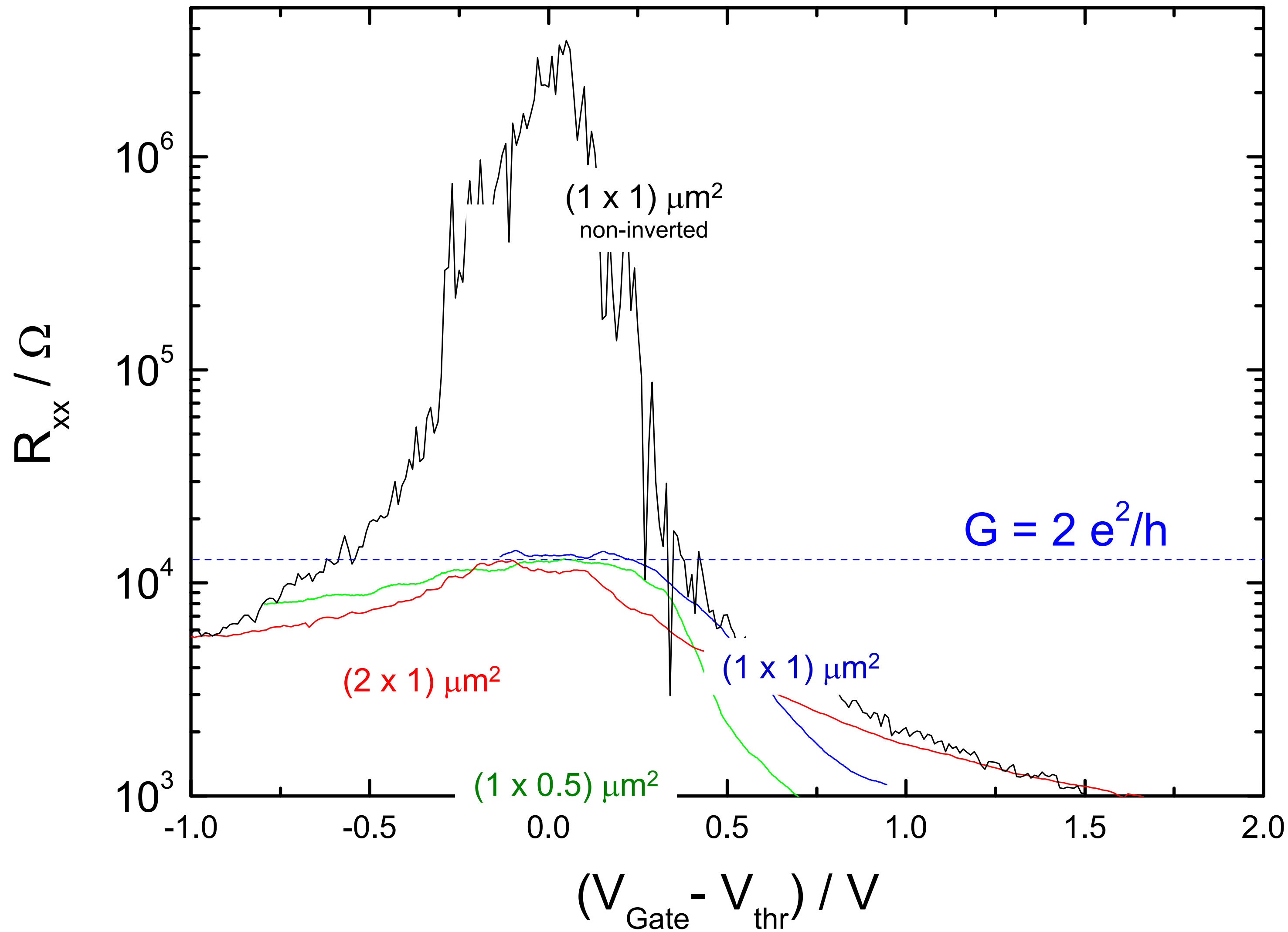
2.0 x 1.0 μm
1.0 x 1.0 μm
1.0 x 0.5 μm

Observation of QSHI state

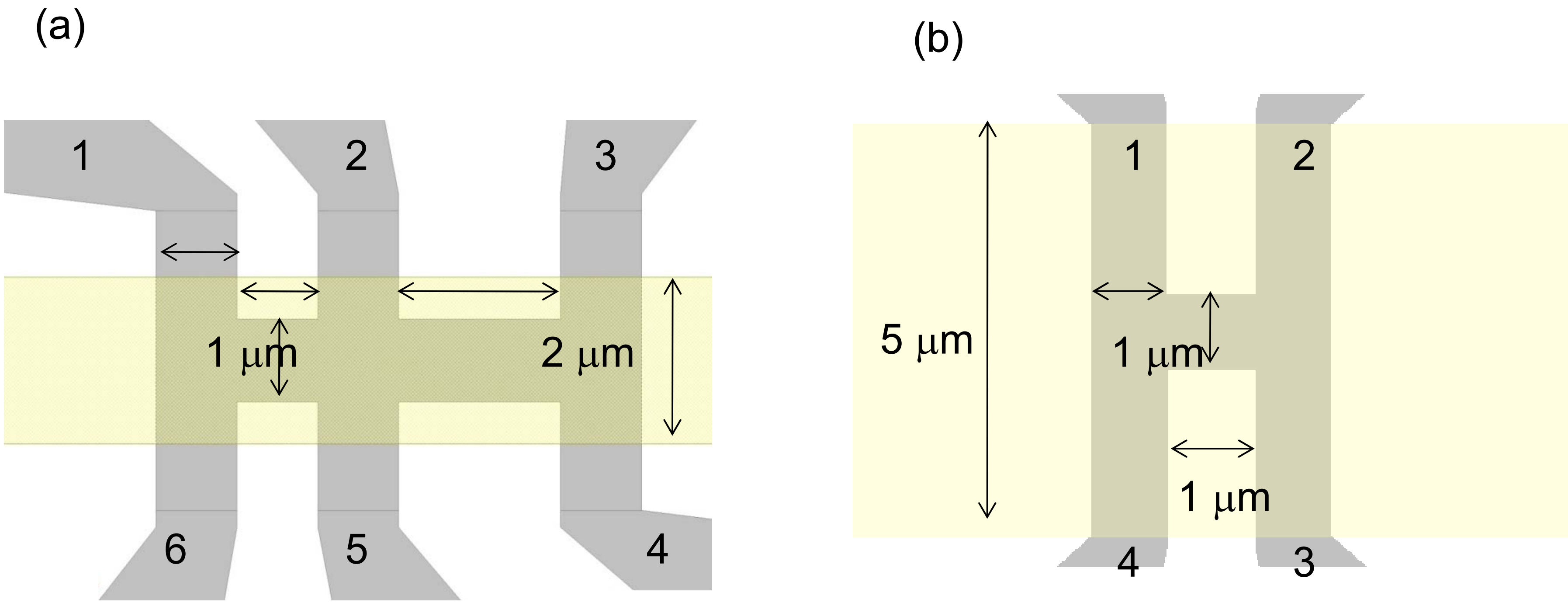


M. König et al., Science **318**, 766 (2007).

Observation of QSH Effect



Verify helical edge state transport

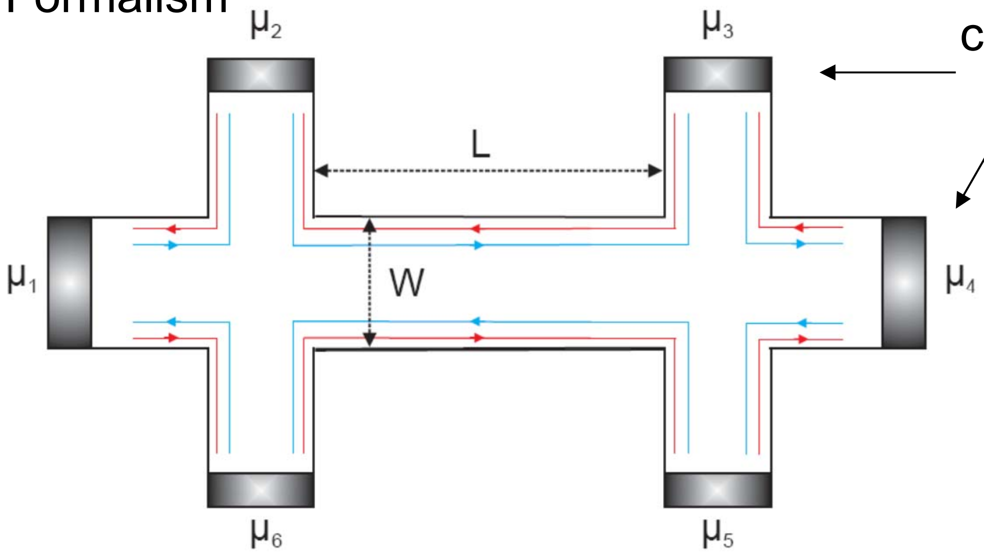


Multiterminal /Non-local transport samples

Multi-Terminal Probe

Landauer-Büttiker Formalism

normal conducting contacts
→ no QSHE



$$T = \begin{pmatrix} -2 & 1 & 0 & 0 & 0 & 1 \\ 1 & -2 & 1 & 0 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 & 0 \\ 0 & 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 1 & -2 & 1 \\ 1 & 0 & 0 & 0 & 1 & -2 \end{pmatrix} \Rightarrow \begin{cases} G_{2t} = \dfrac{I_{14}}{\mu_4 - \mu_1} = \dfrac{2}{3}\dfrac{e^2}{h} \\ G_{4t} = \dfrac{I_{14}}{\mu_3 - \mu_2} = \dfrac{2e^2}{h} \end{cases}$$

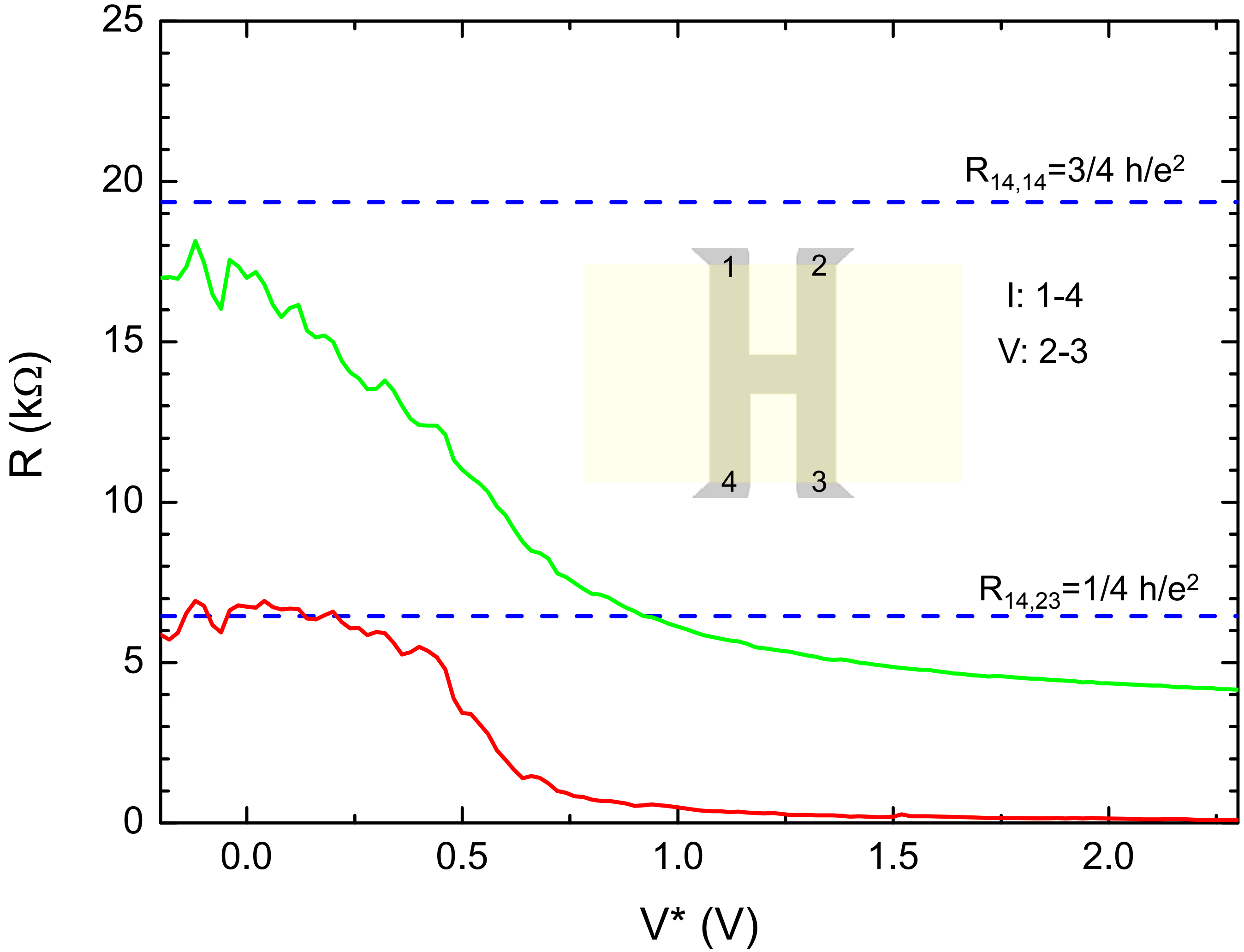
generally

$$R_{2t} = \frac{(n+1)h}{2e^2}$$

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

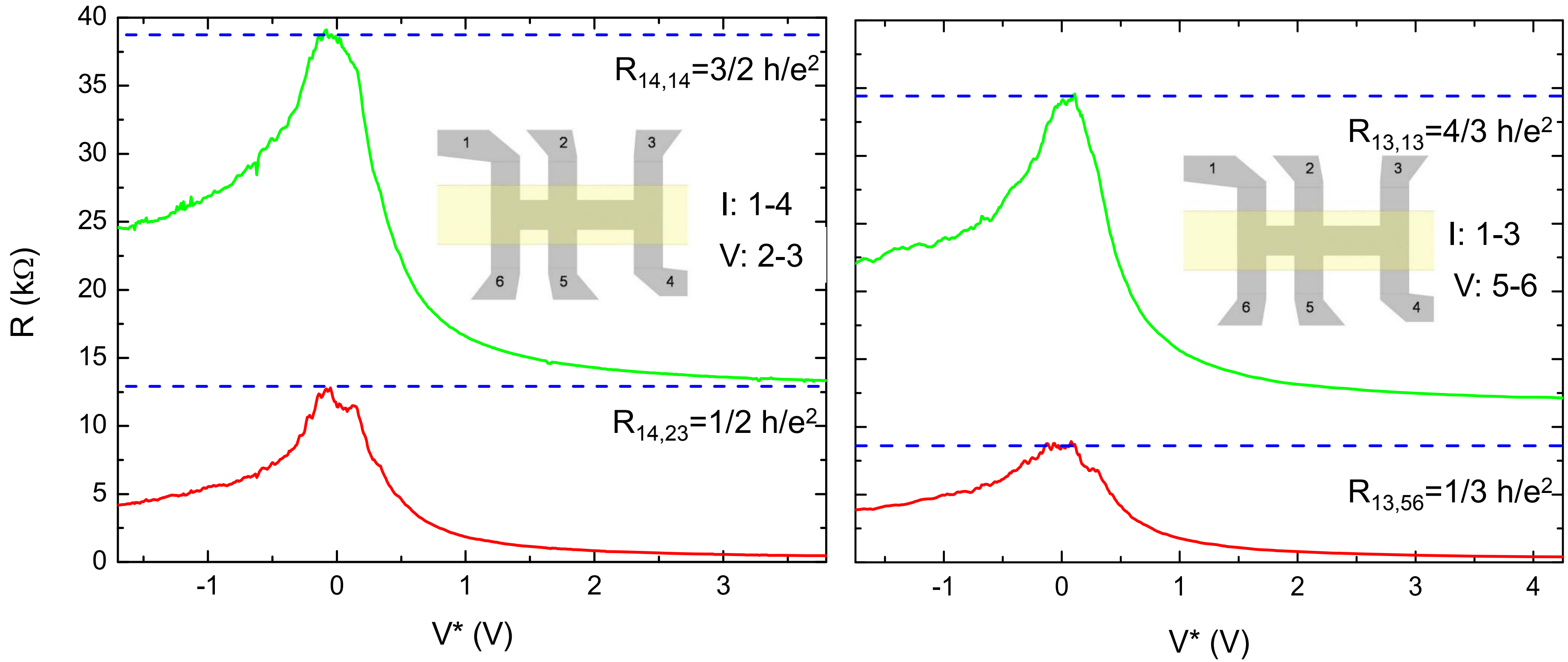
$$\left.\frac{R_{2t}}{R_{4t}}\right|_{\exp} \approx 3$$

Non-Local data on H-bar



A. Roth et al., Science **325**, 294 (2009).

Multi-Terminal Measurements



Configurations would be equivalent in quantum adiabatic regime

A. Roth et al., Science **325**, 294 (2009).

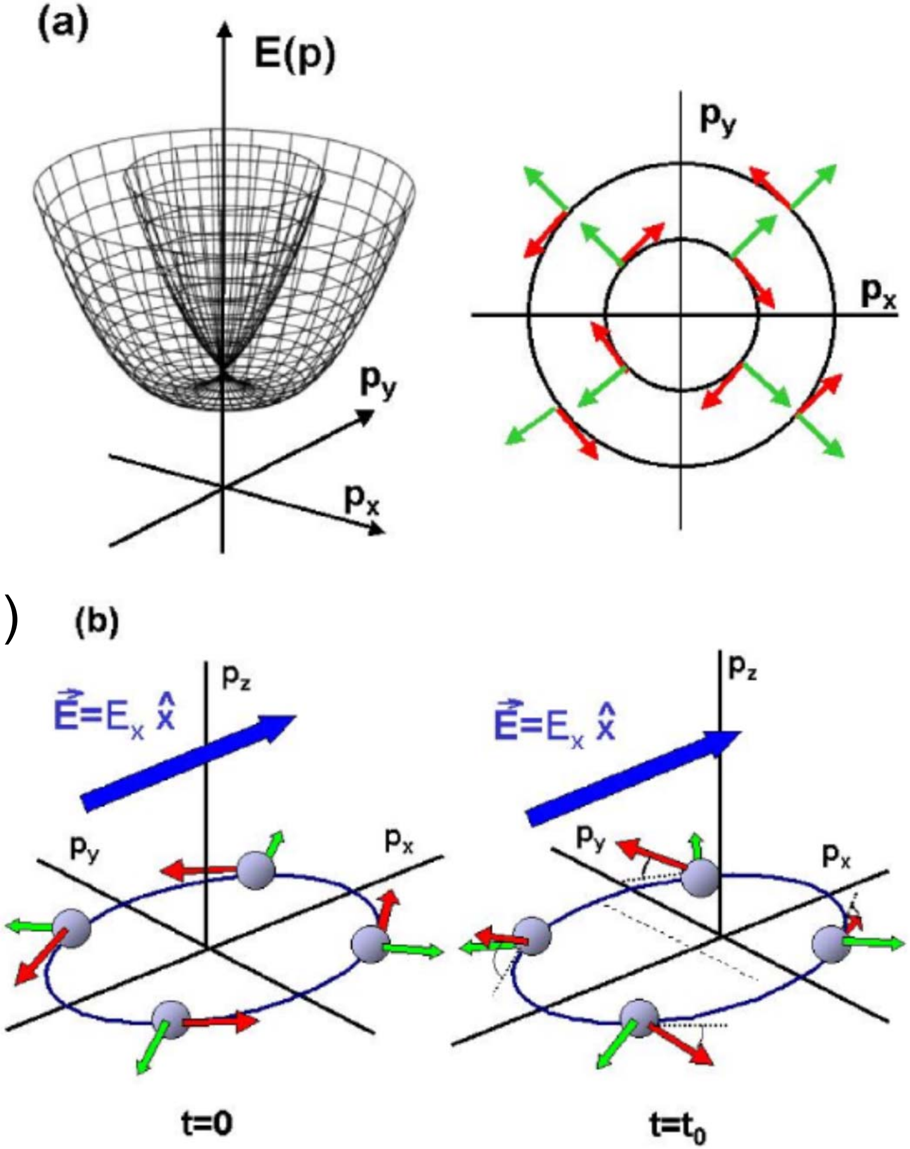
Intrinsic SHE in metallic wells as spin detector

Spin-Hall Effect

Intrinsic SHE

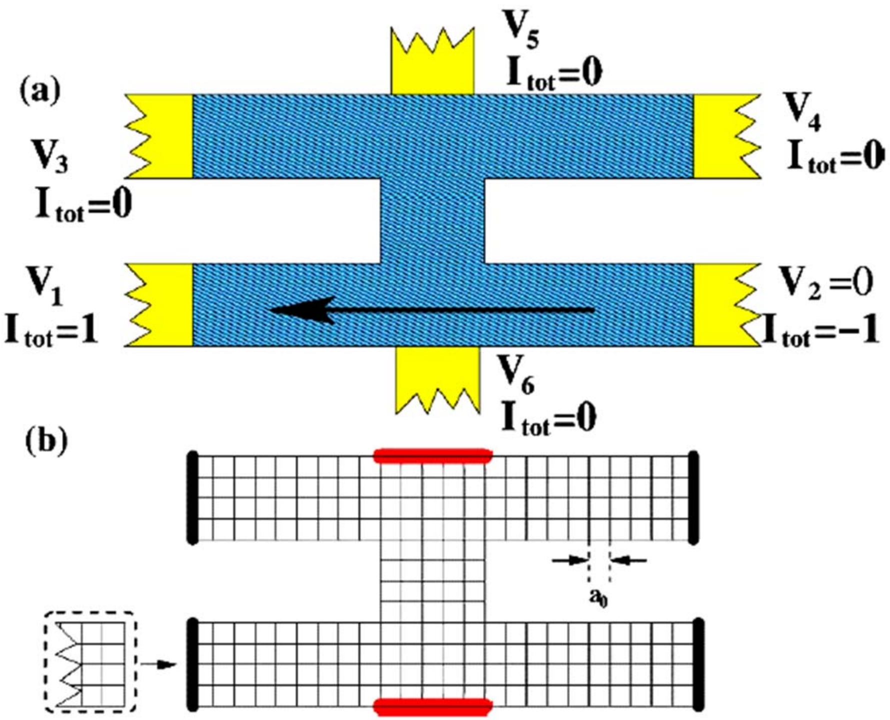
Rashba effect

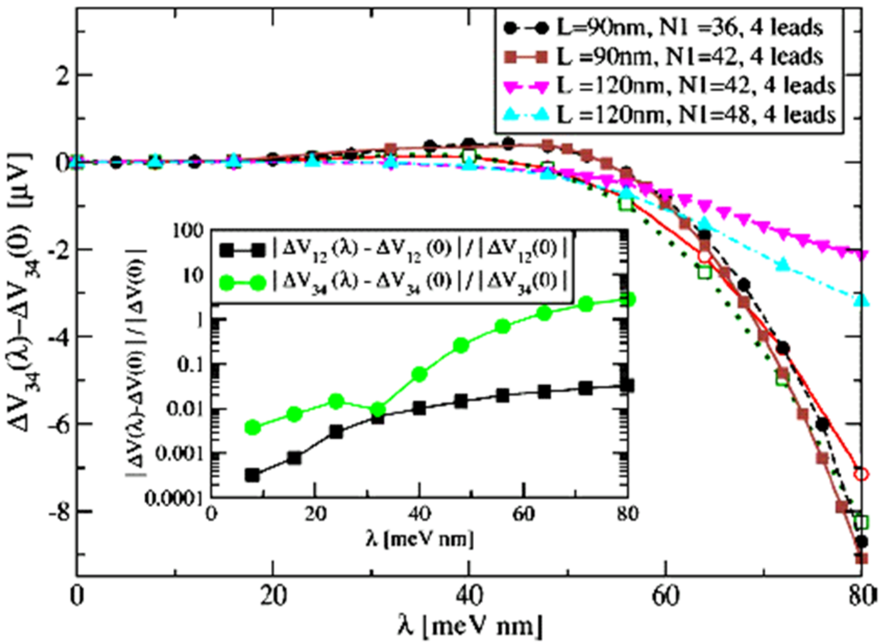
J.Sinova et al.,
Phys. Rev. Lett. **92**, 126603 (2004)



H-bar for detection of Spin-Hall-Effect

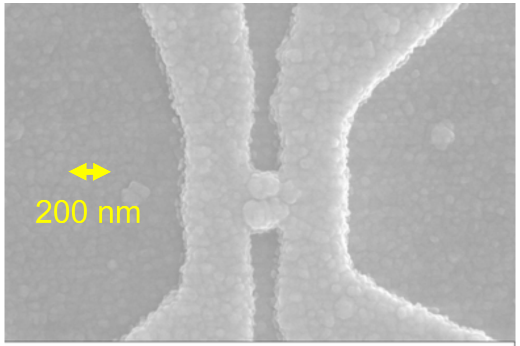
(electrical detection through inverse SHE)

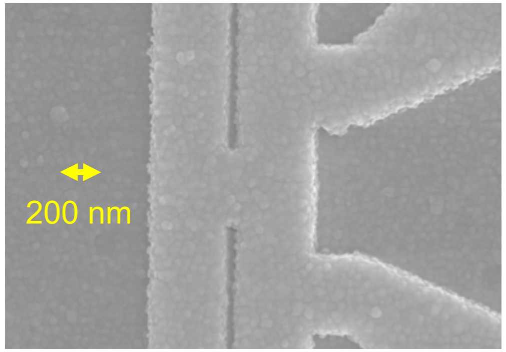


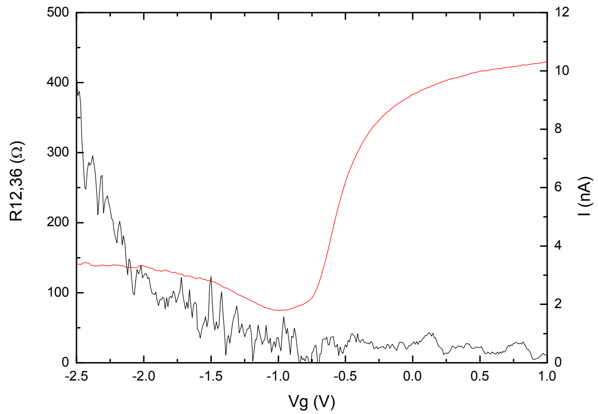


E.M. Hankiewicz et al ., PRB **70**, R241301 (2004)

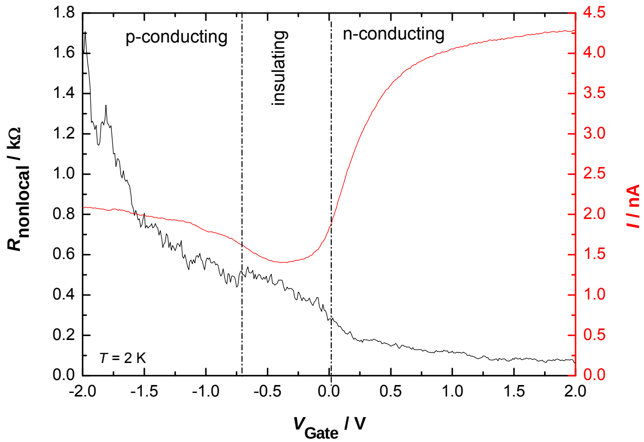
H-bar experiments







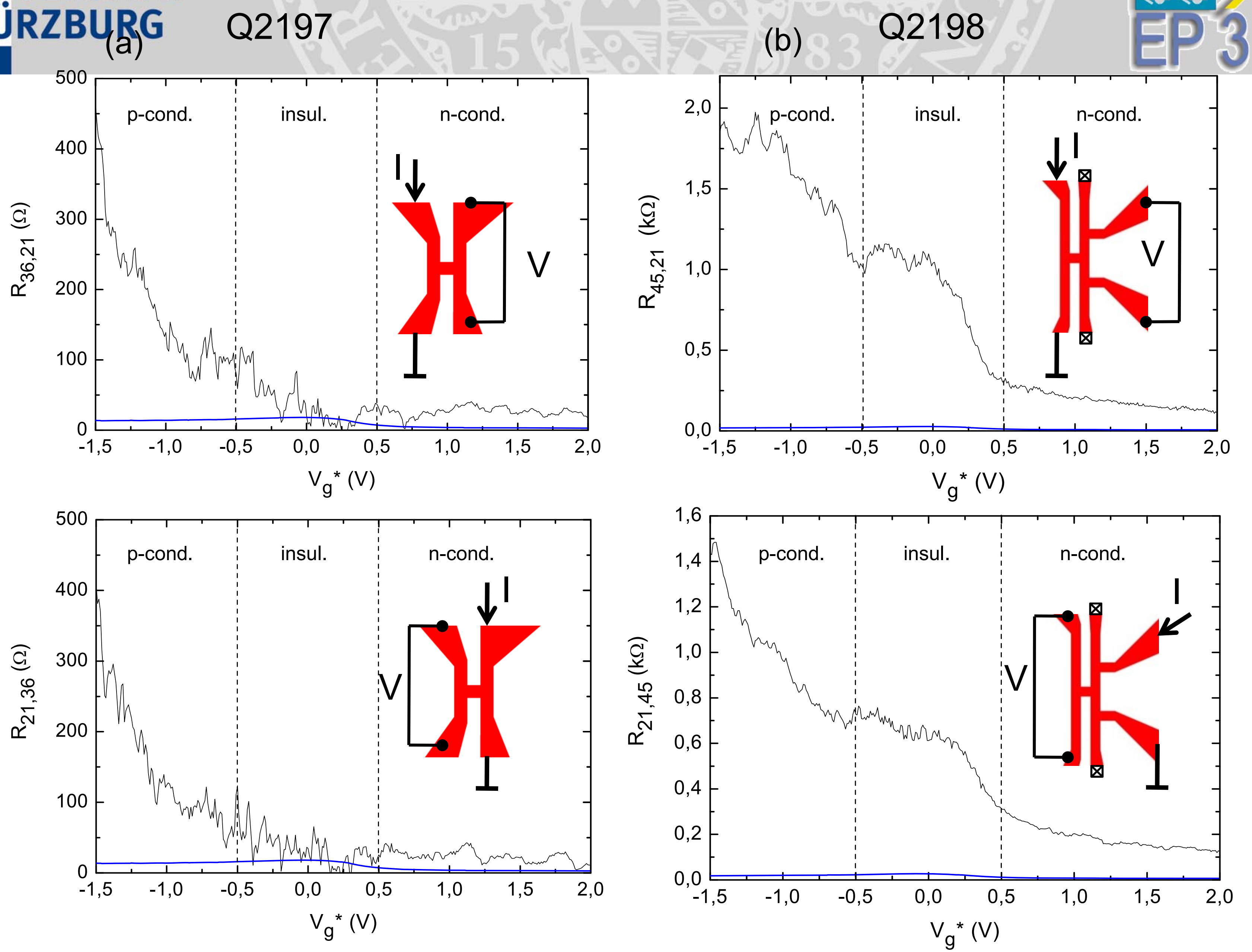
C. Brüne et al., Nature Physics **6**, 448 (2010).



– Suppress non-local QSHE using long leads or narrow wires

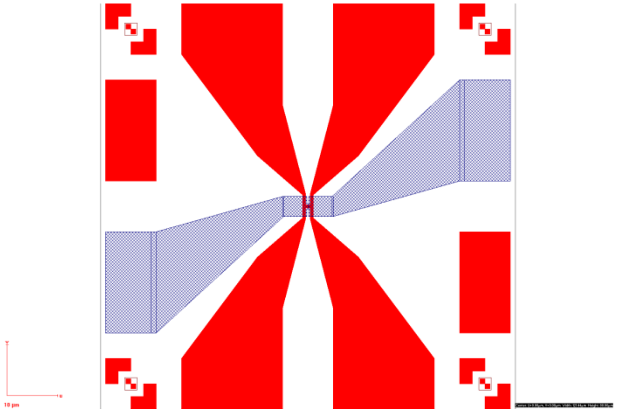
– Intrinsic metallic SHE only shows up for holes: larger spin-orbit

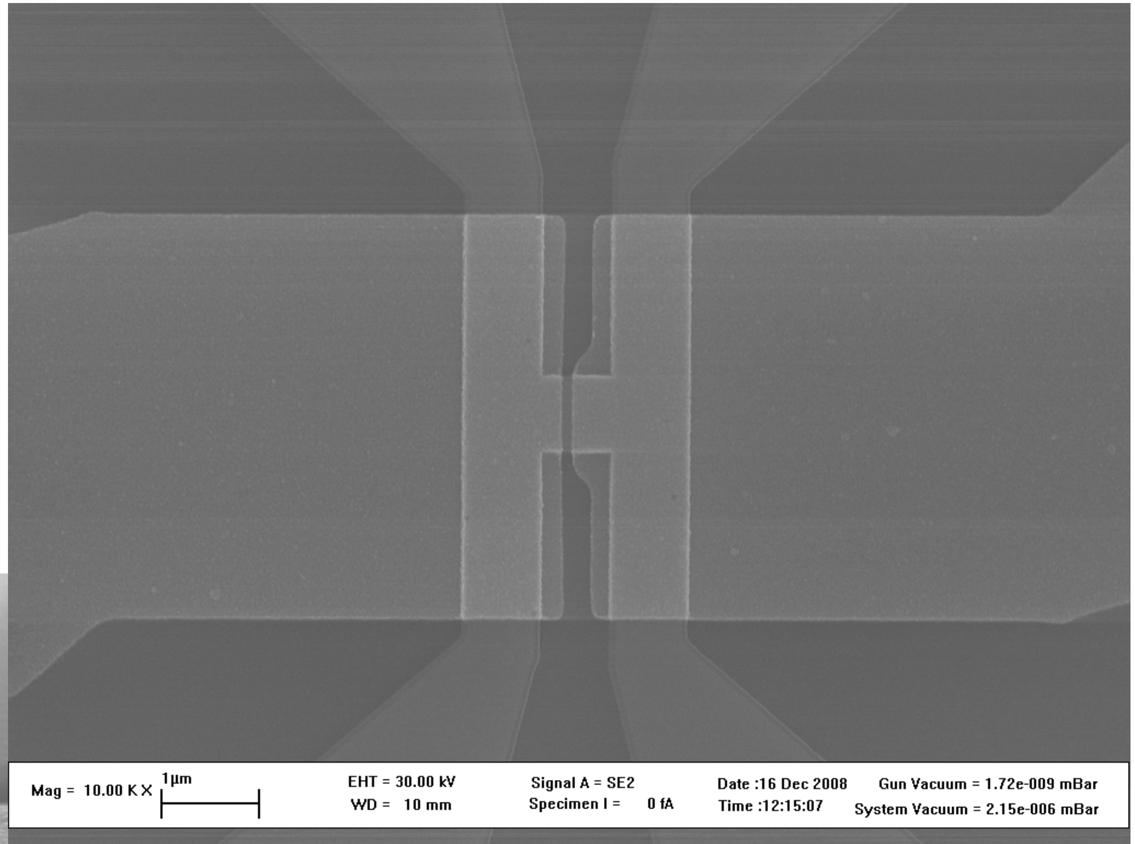
– Amplitude in agreement with modeling (E. Hankiewicz, J. Sinova)

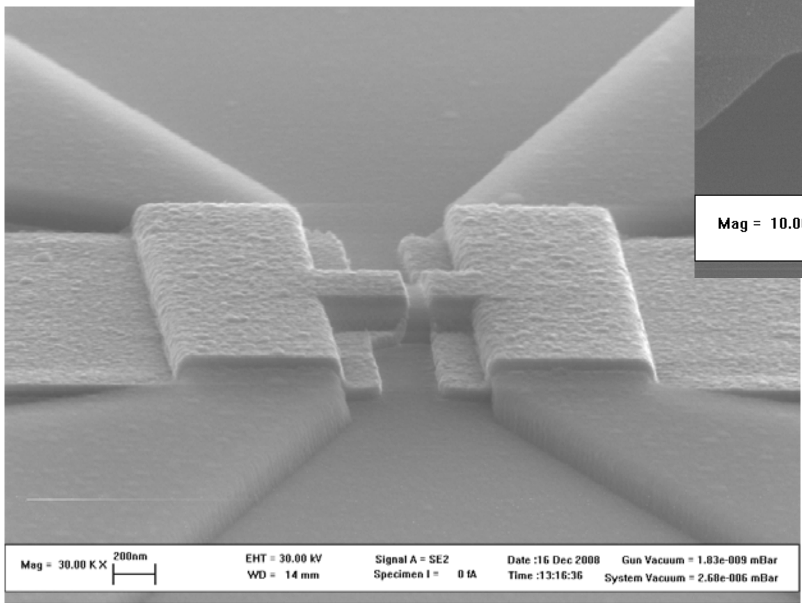


C. Brüne et al., Nature Physics **6**, 448 (2010).

QSHE and iSHE as spin injector and detector

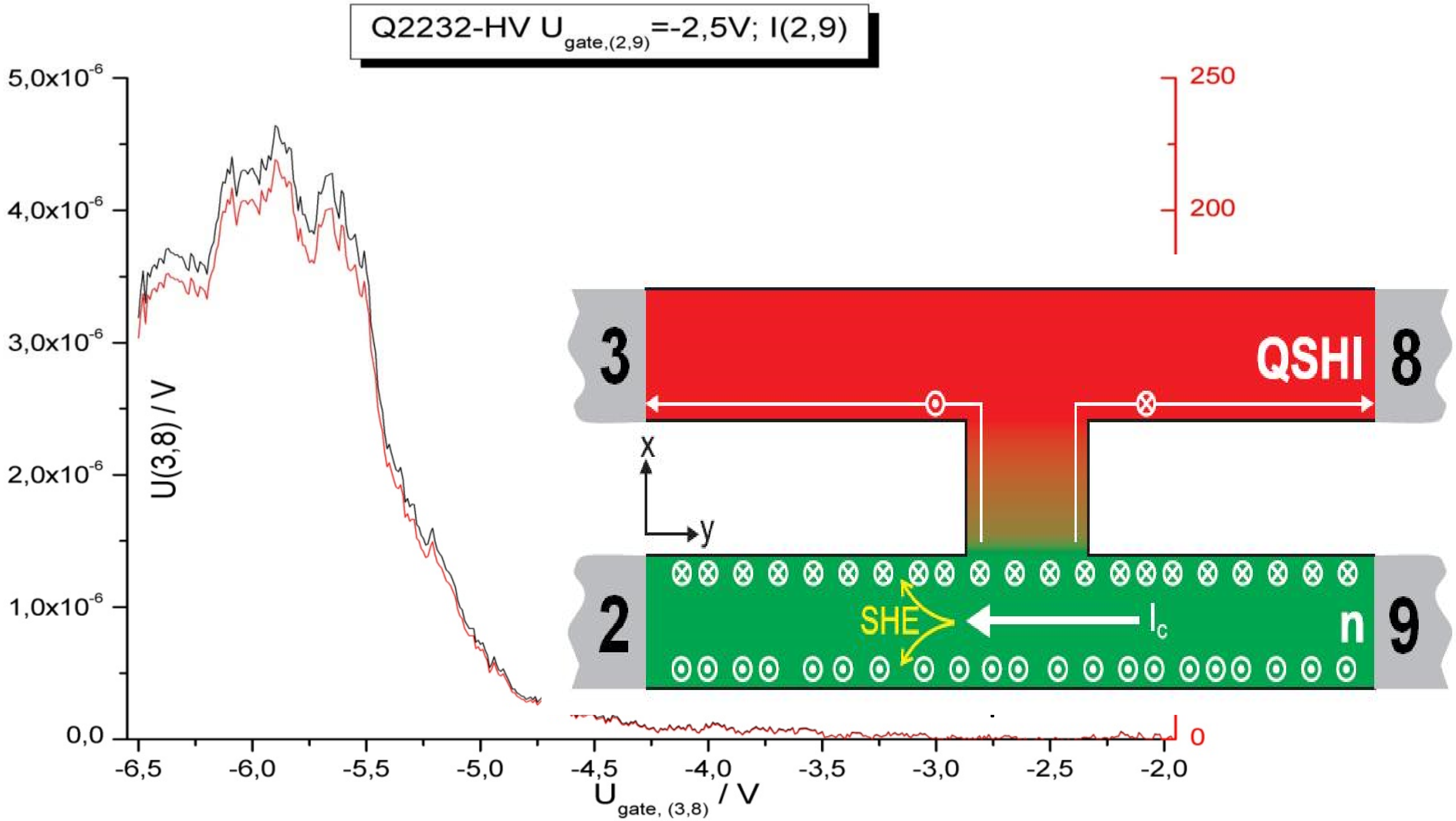






Split-gated H-bar

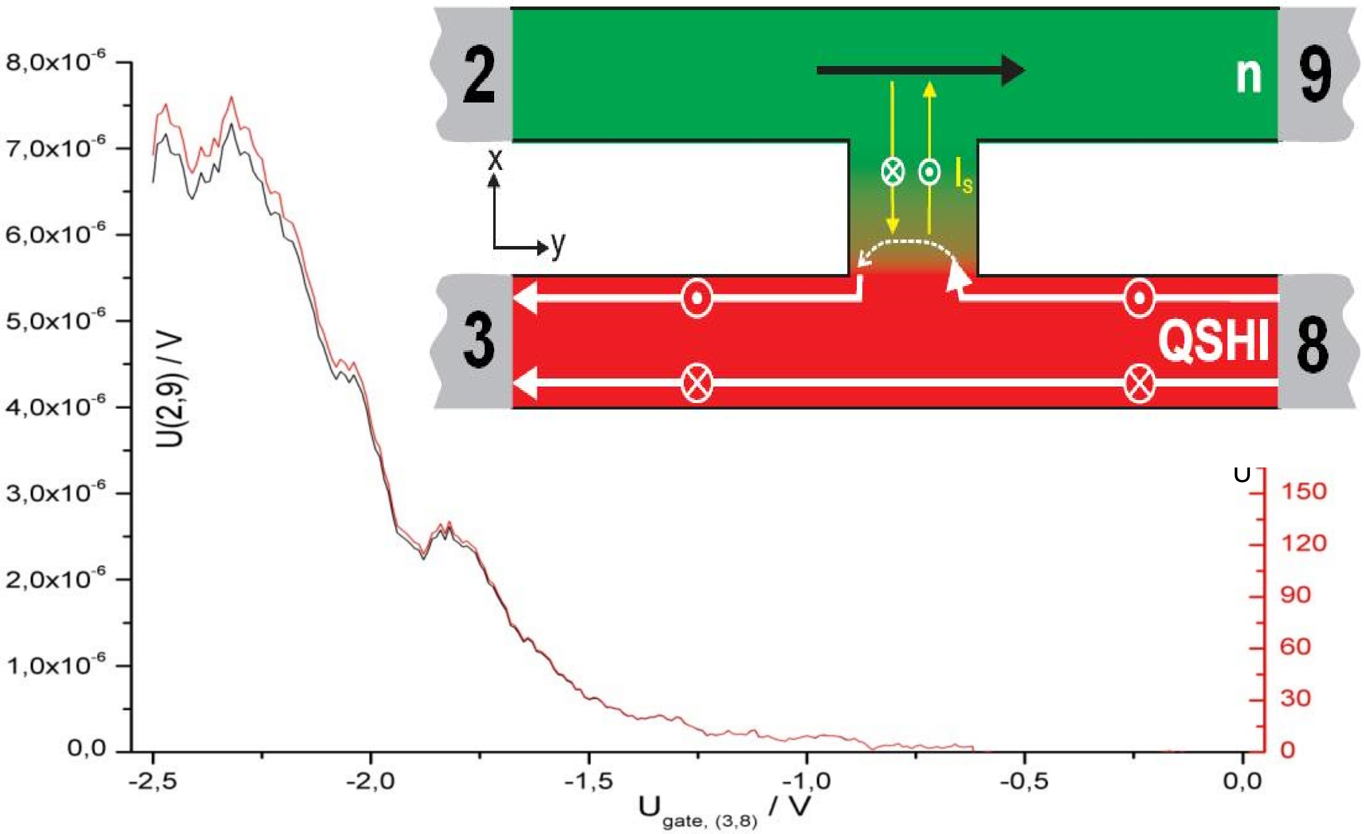
Detect iSHE through QSHI edge channels



Gate in 3-8 leg is scanned, 2-9 leg is n-type metallic, current passed between contacts 2 and 9.

C. Brüne et al.,
Nature Physics **8**, 486–491 (2012)

Detect QSHI through inverse iSHE



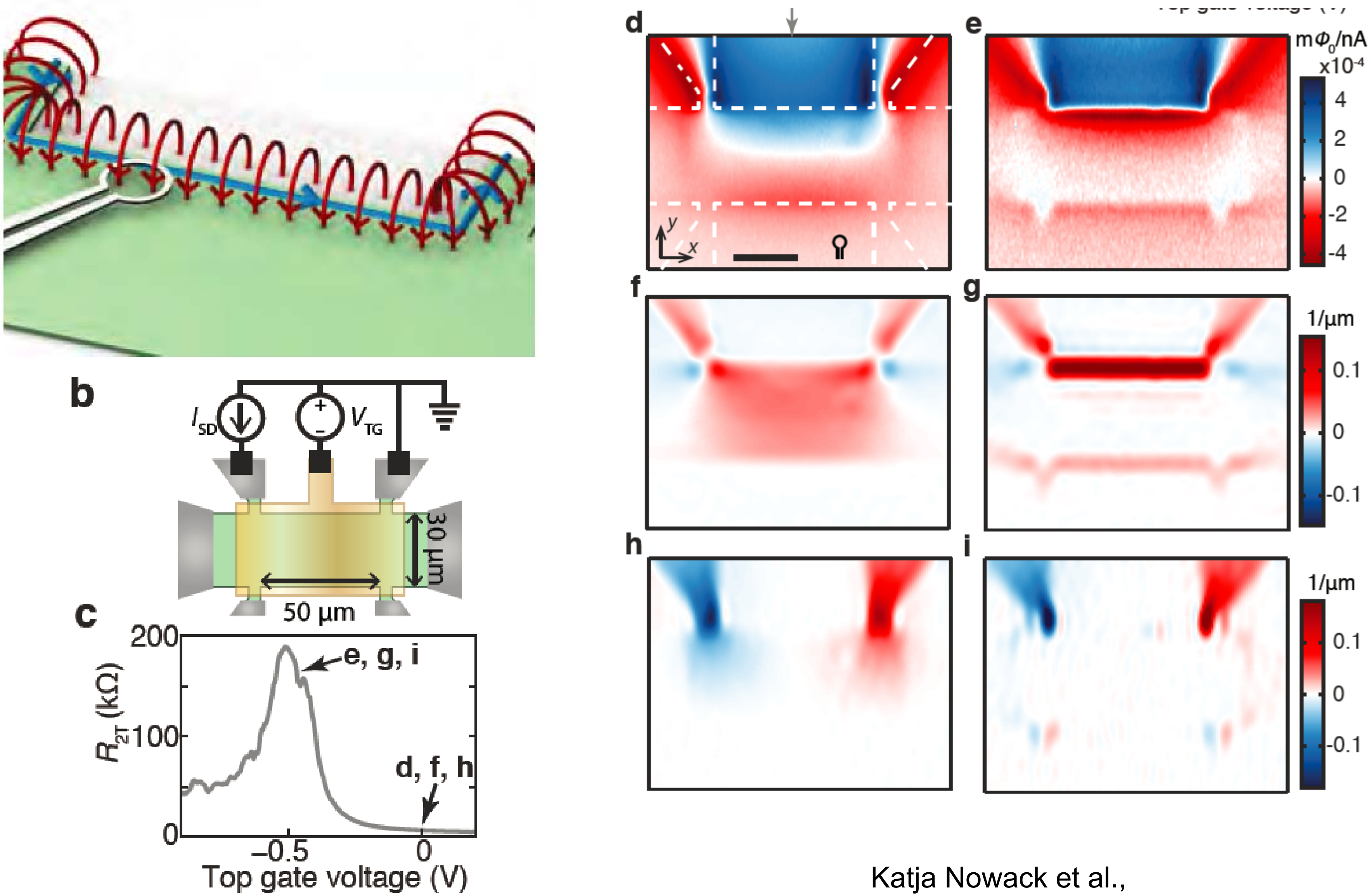
Gate in 3-8 leg is scanned, 2-9 leg is n-type metallic,

current passed between contacts 3 and 8

C. Brüne et al.,
Nature Physics **8**, 486–491 (2012).

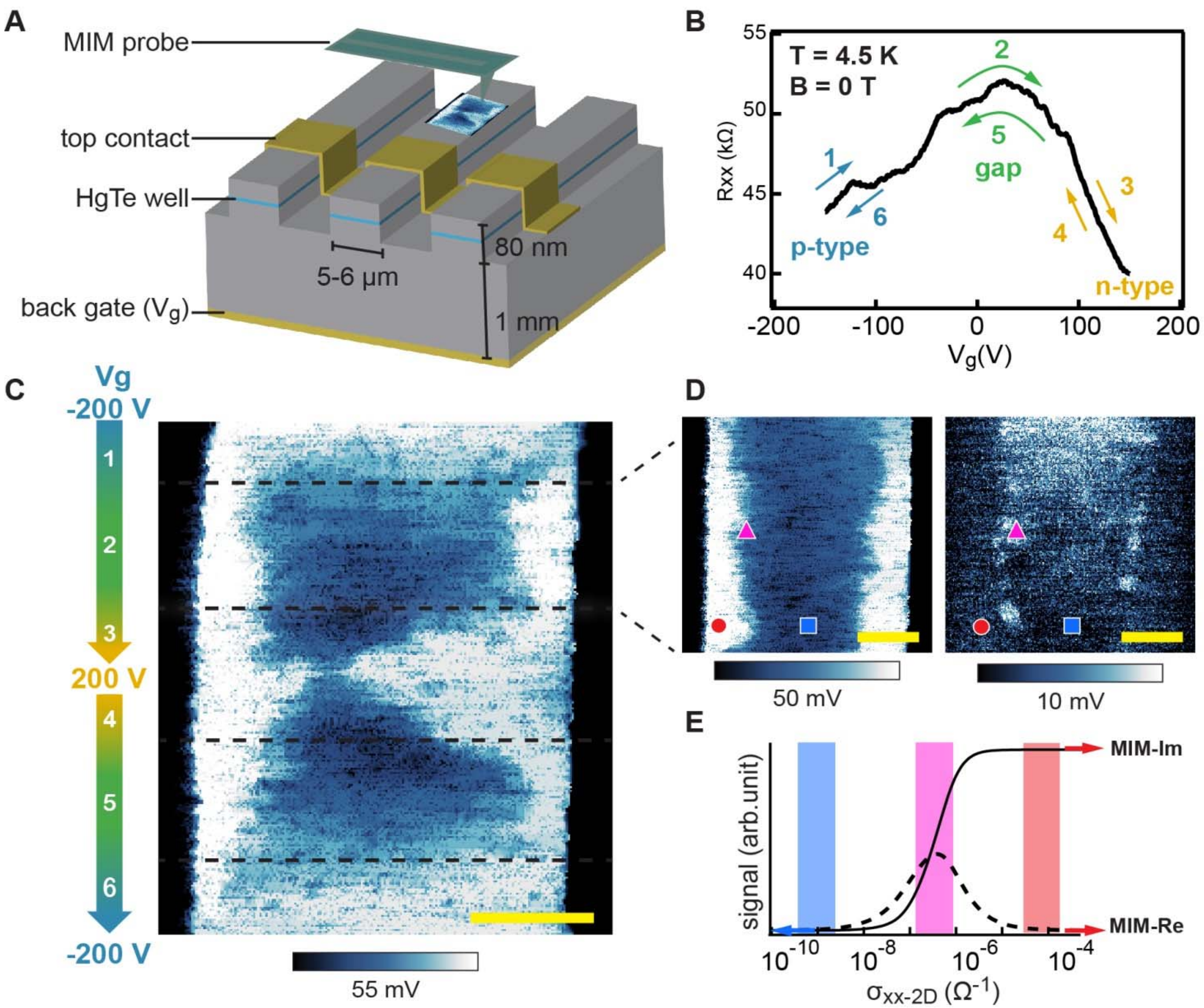
Scanning Probe Visualization

Scanning SQUID



Katja Nowack et al.,
(Kam Moler group, Stanford)

Scanning Microwave Impedance



Yue Ma et al.,
(Z.X. Shen group, Stanford).

Dirac Surface States
on
strained bulk HgTe

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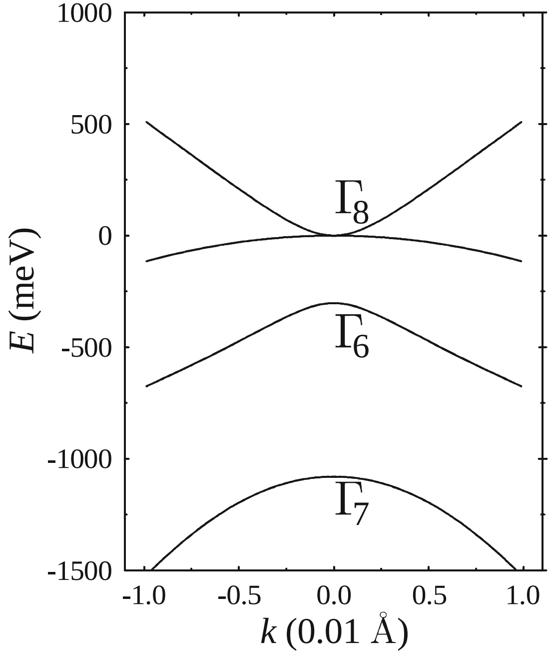
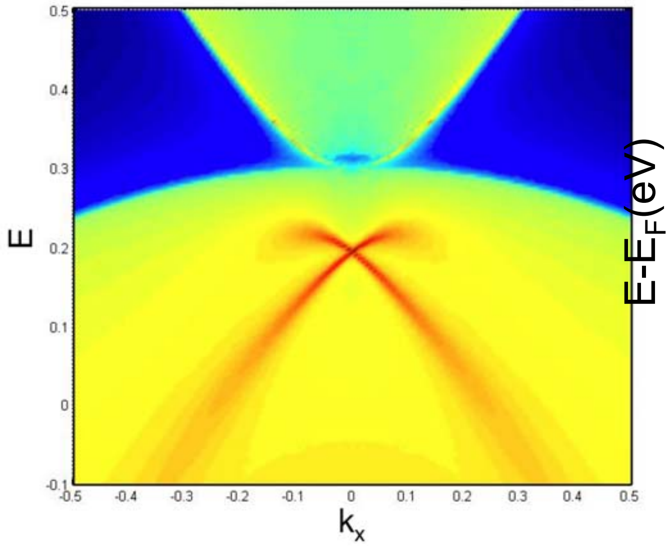
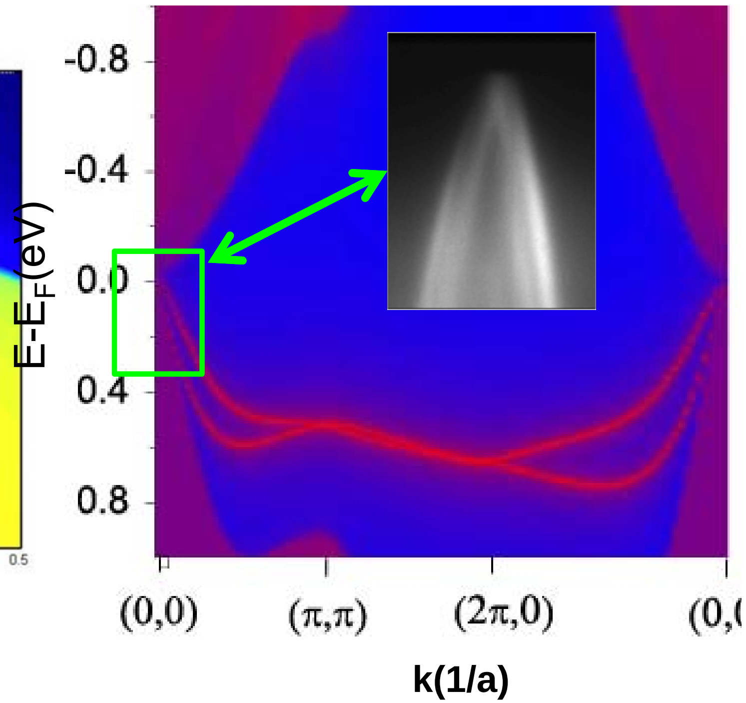
Bulk HgTe as a 3-D Topological ‚Insulator‘

EP 3







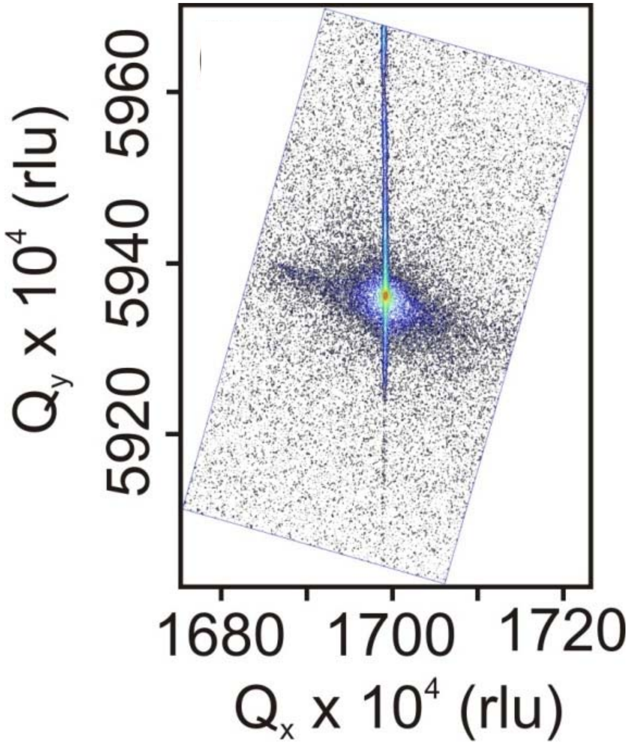
Bulk HgTe is semimetal,

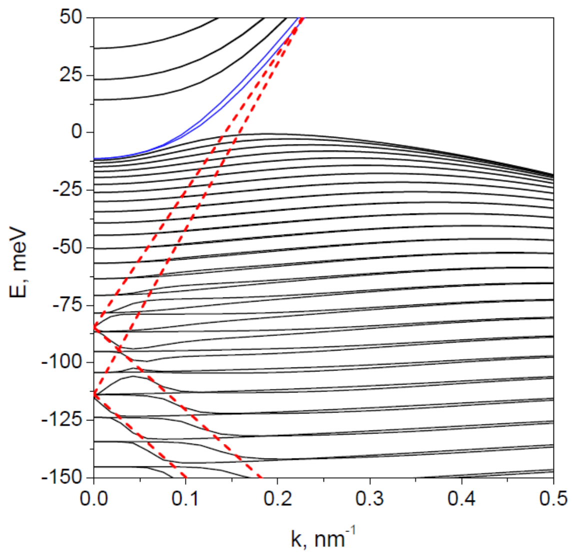
topological surface state overlaps w/ valenceband.

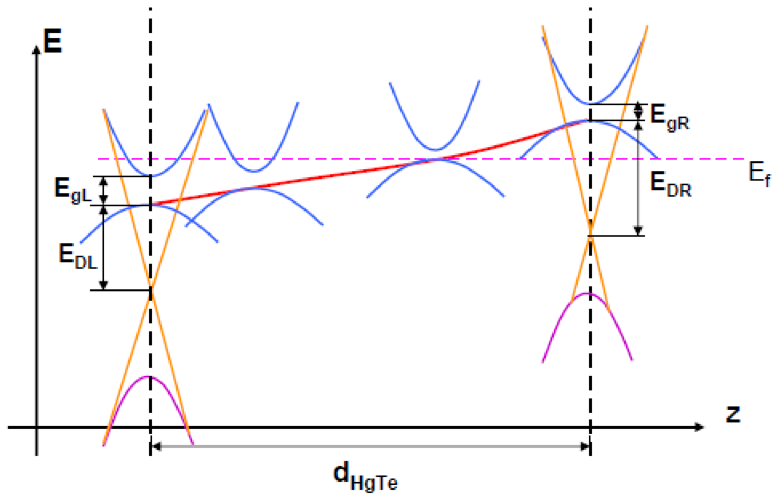
C. Brüne et al., Phys. Rev. Lett. **106**, 126803 (2011).

ARPES:
Yulin Chen, ZX Shen,
Stanford

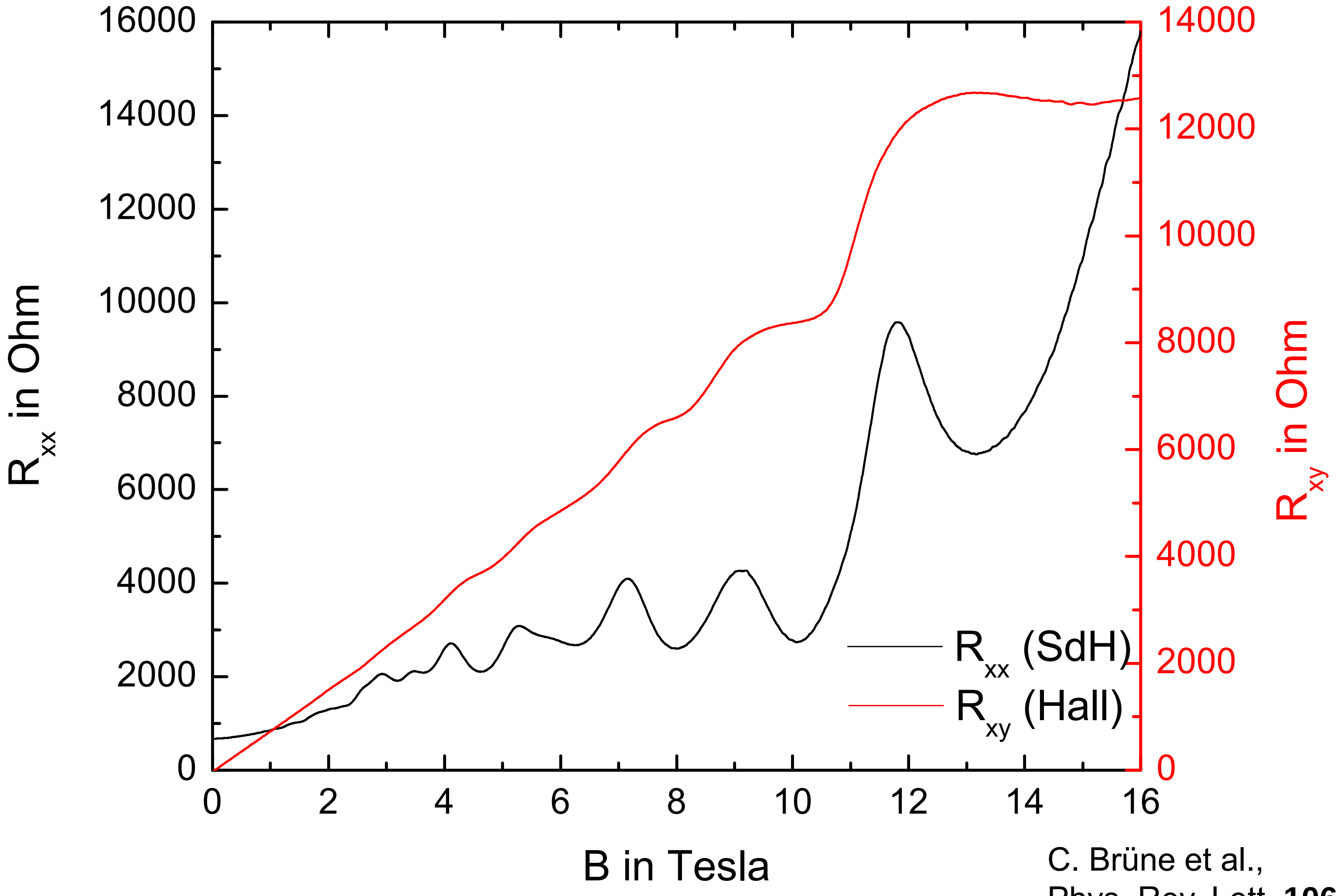
70 nm layer on CdTe substrate: coherent strain opens gap







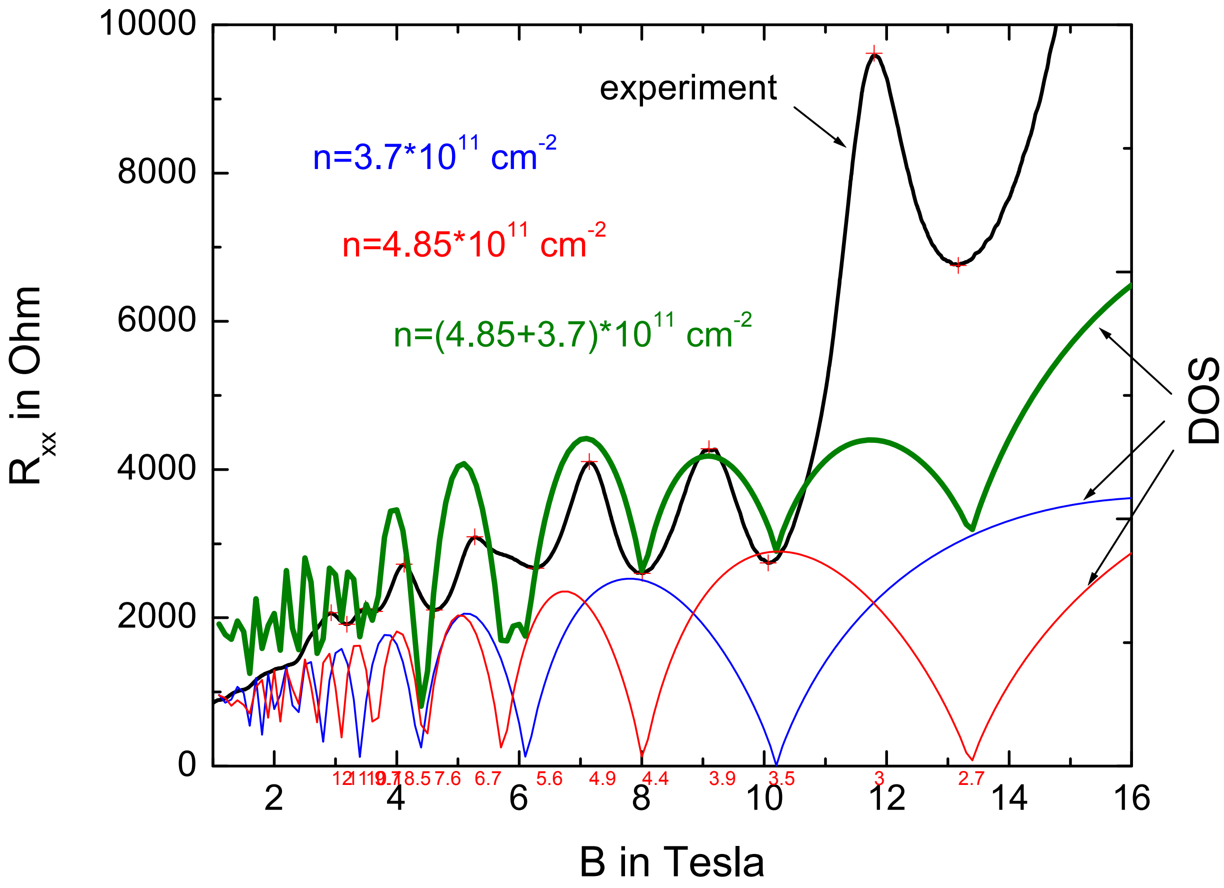
Bulk HgTe as a 3-D Topological ‚Insulator‘



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

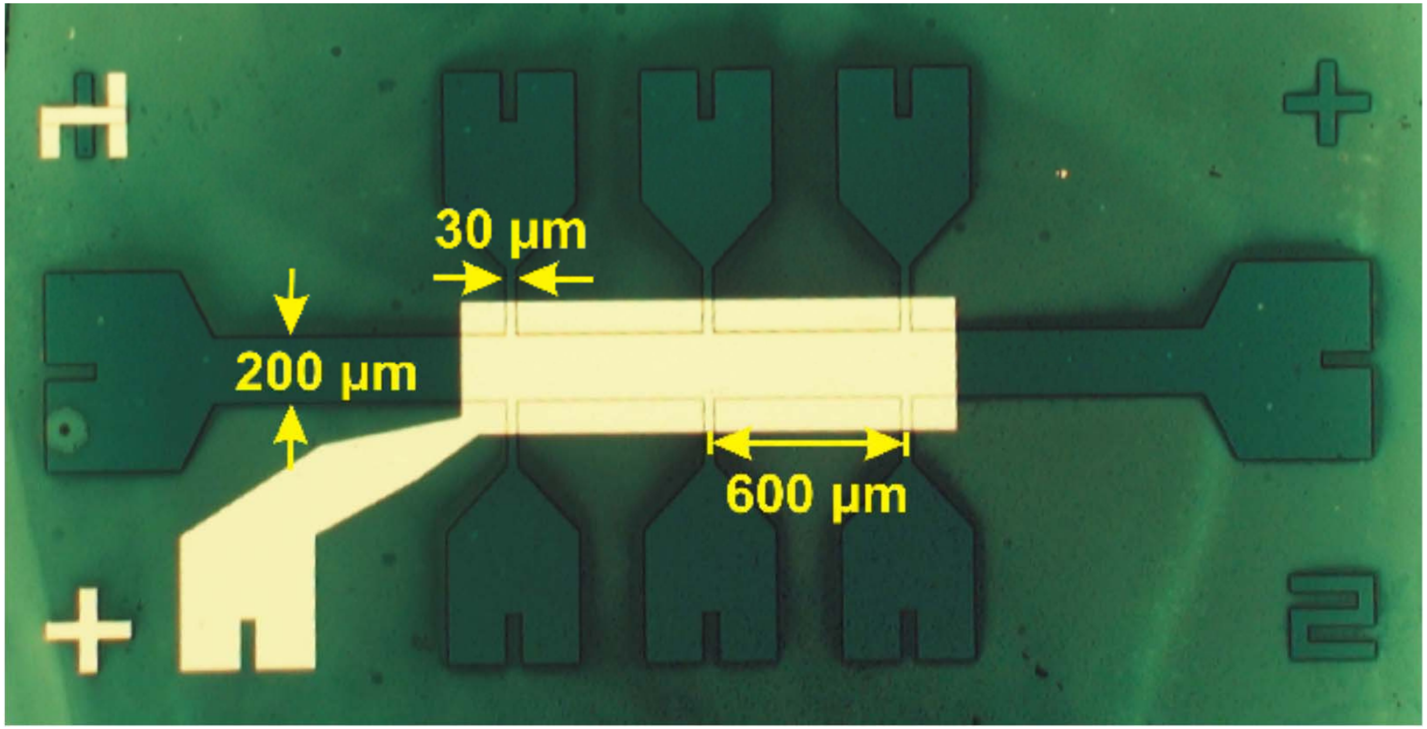
3D HgTe-calculations



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

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

Experiments on a gated Hallbar



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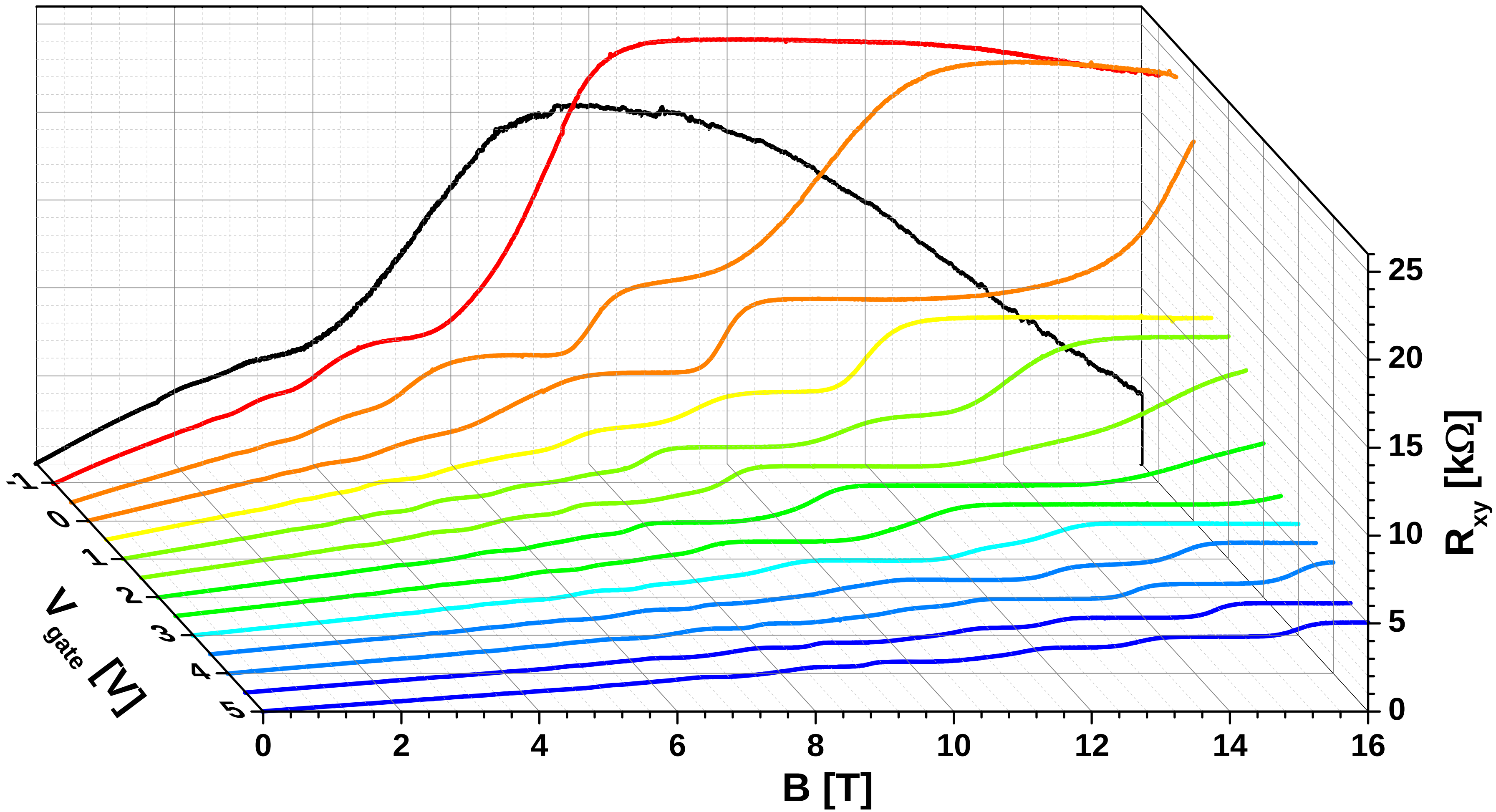
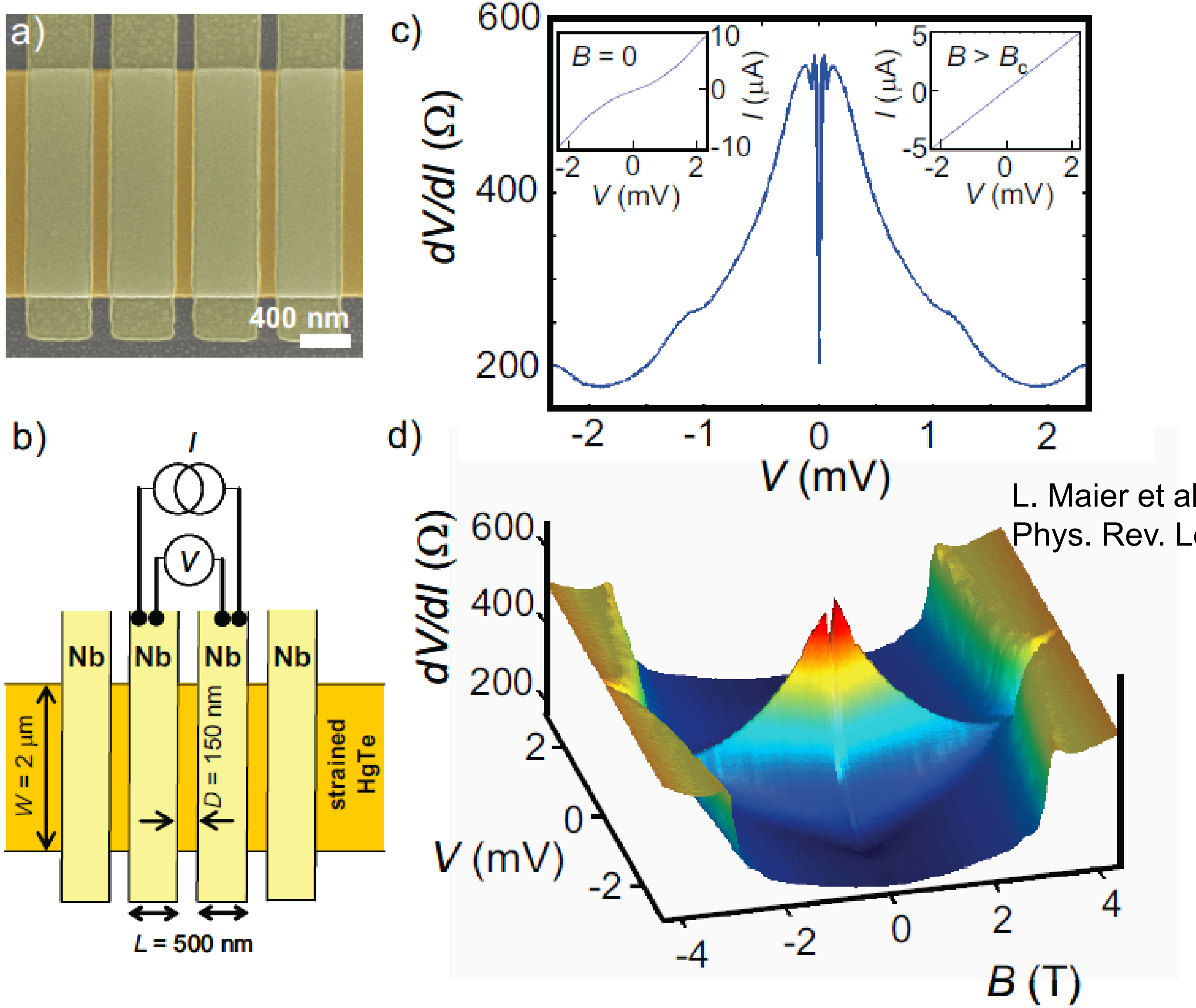
Rxy from -1.5V to 5V

EP 3



Superconducting Proximity Effects

Superconducting contacts on strained HgTe



L. Maier et al.,
Phys. Rev. Lett. **109**, 186806 (2012).

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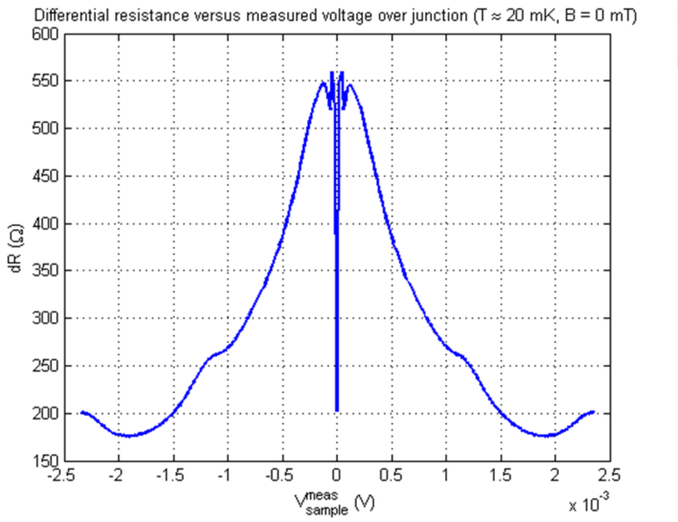
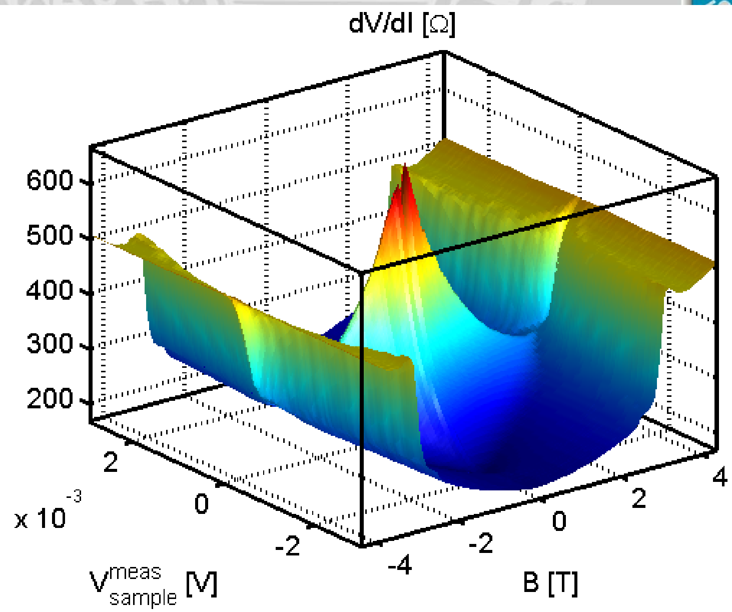
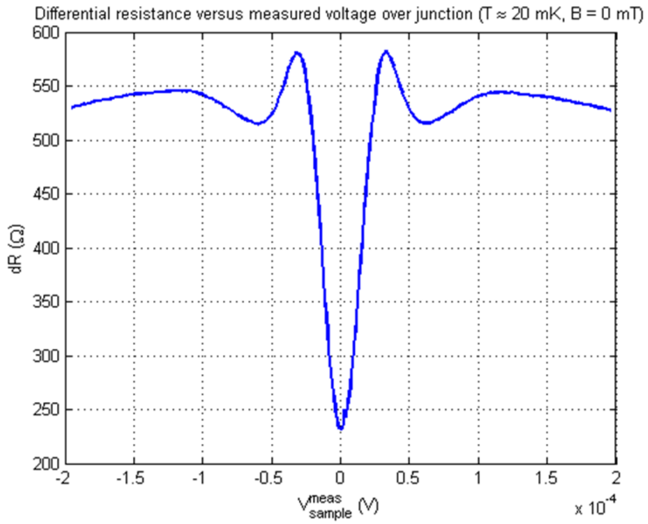
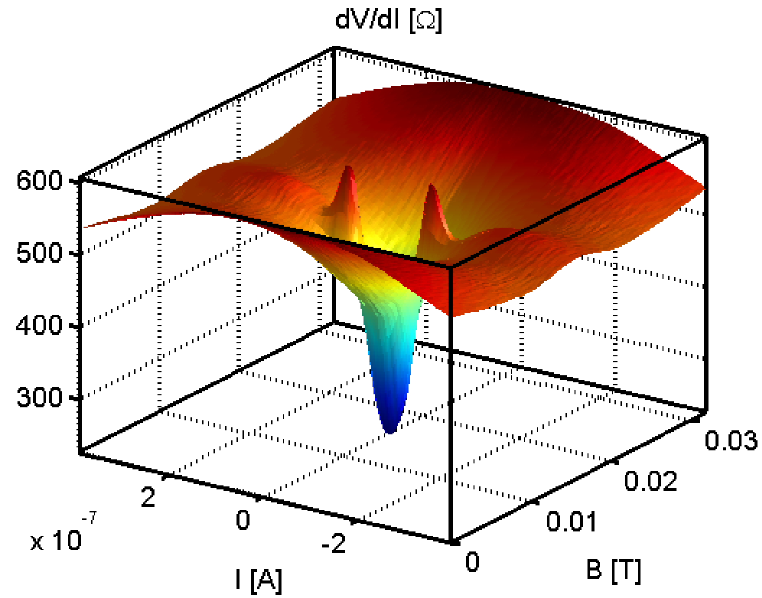
dV/dI (V_{bias}, B) at 20 mK

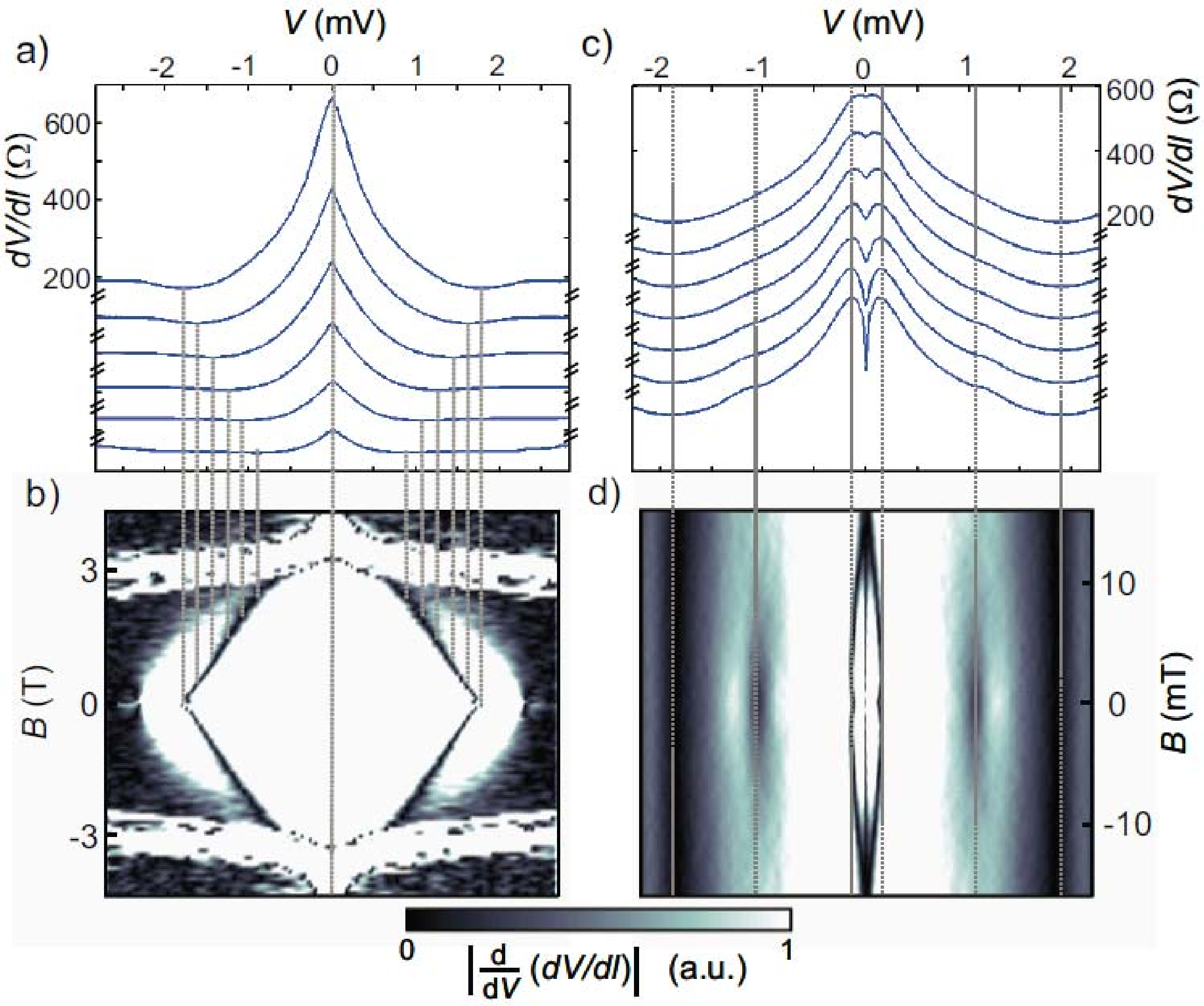




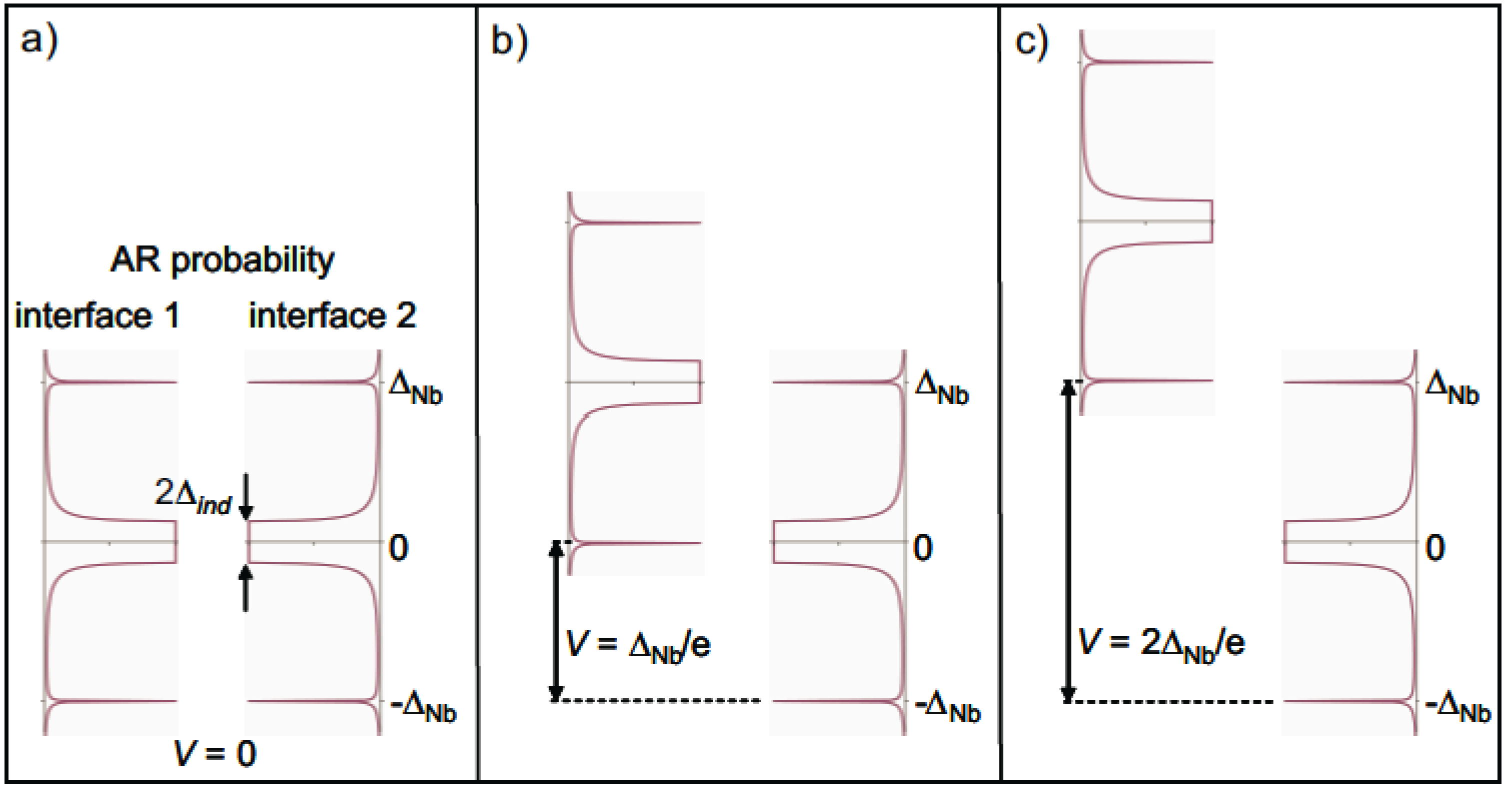
dV/dI (I_{bias}, B) at 20 mK







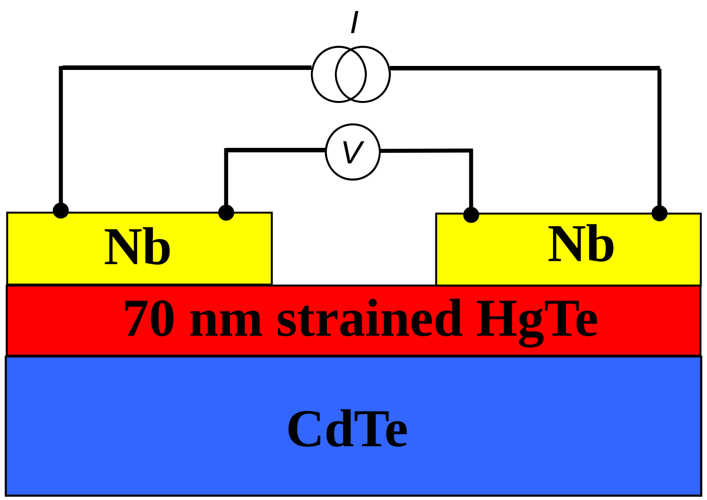
L. Maier et al., Phys. Rev. Lett. **109**, 186806 (2012).

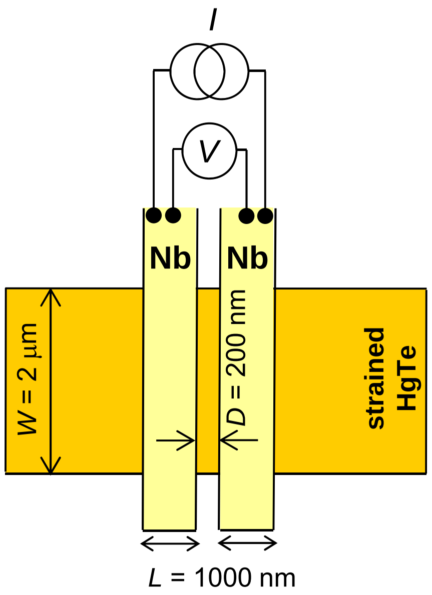


L. Maier et al., Phys. Rev. Lett. **109**, 186806 (2012).

Sample "Quad", device A

Device with improved HgTe-Nb interfaces.



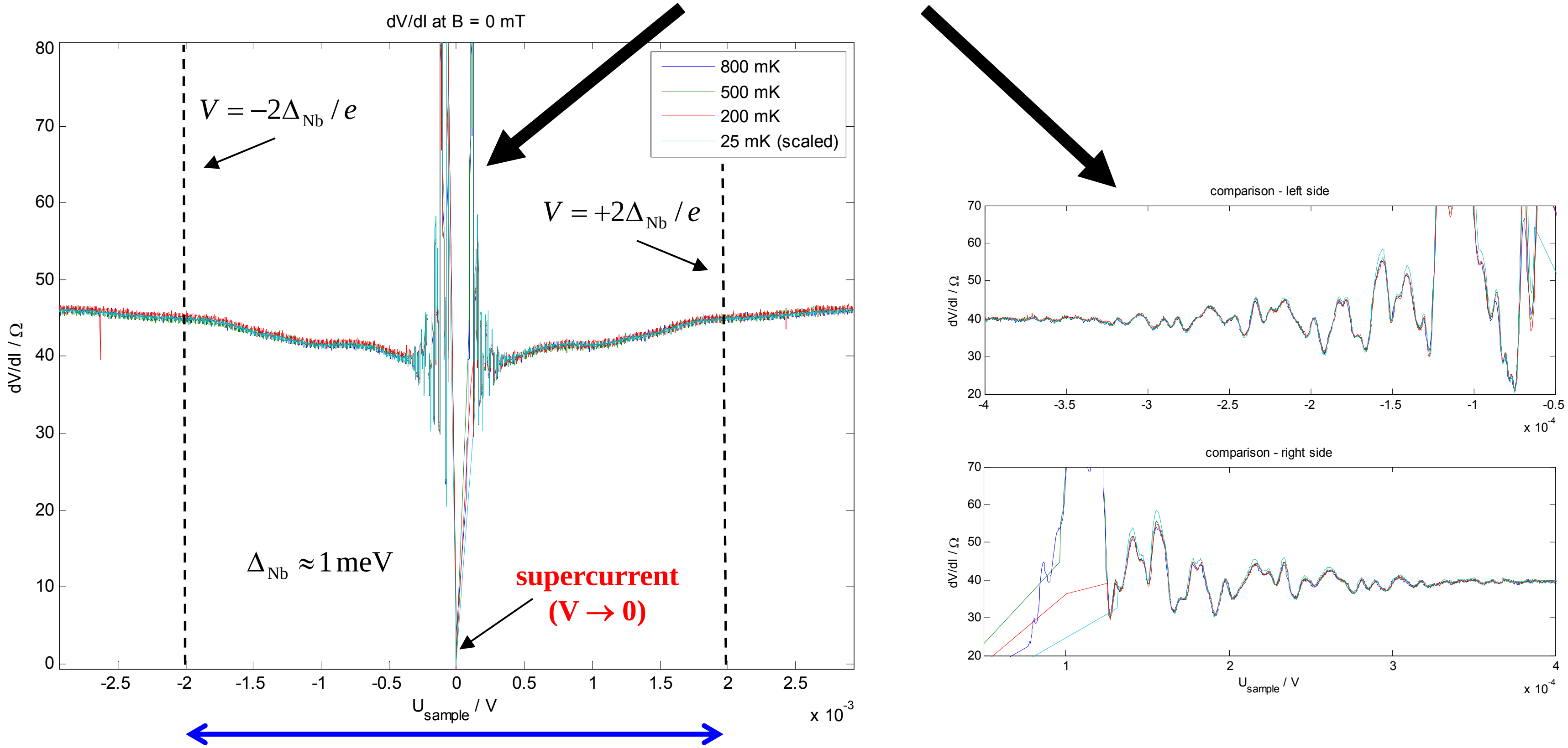


J. Oostinga et al.,
Phys. Rev. X **3**, 021007 (2013).

Subgap regime

At T = 25 mK, 200 mK, 500, 800 mK

Reproducible oscillations

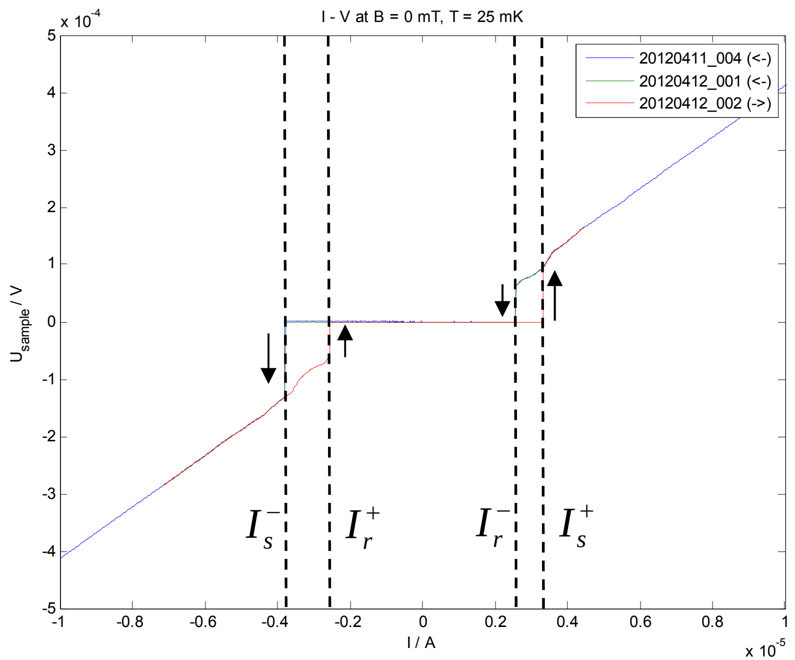


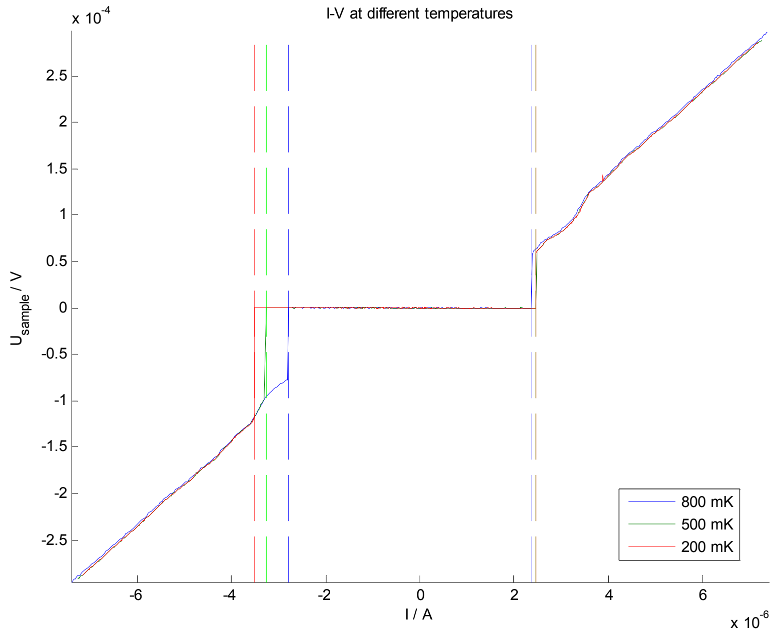
$|eV| < 2\Delta_{Nb}$ **subgap regime:**

Decrease of differential conductance in subgap regime in the range $|eV| < 2\Delta_{Nb}$ is due to strongly enhanced probability of Andreev reflection (corresponding to improved transparency of the HgTe-Nb interfaces).

Supercurrent regime

At T = 25 mK, 200 mK, 500, 800 mK





Switching current depends on sweeping direction (origin unknown): $I_s^- \neq I_s^+$

Retrapping current does not depend on sweeping direction: $I_r^- = I_r^+$

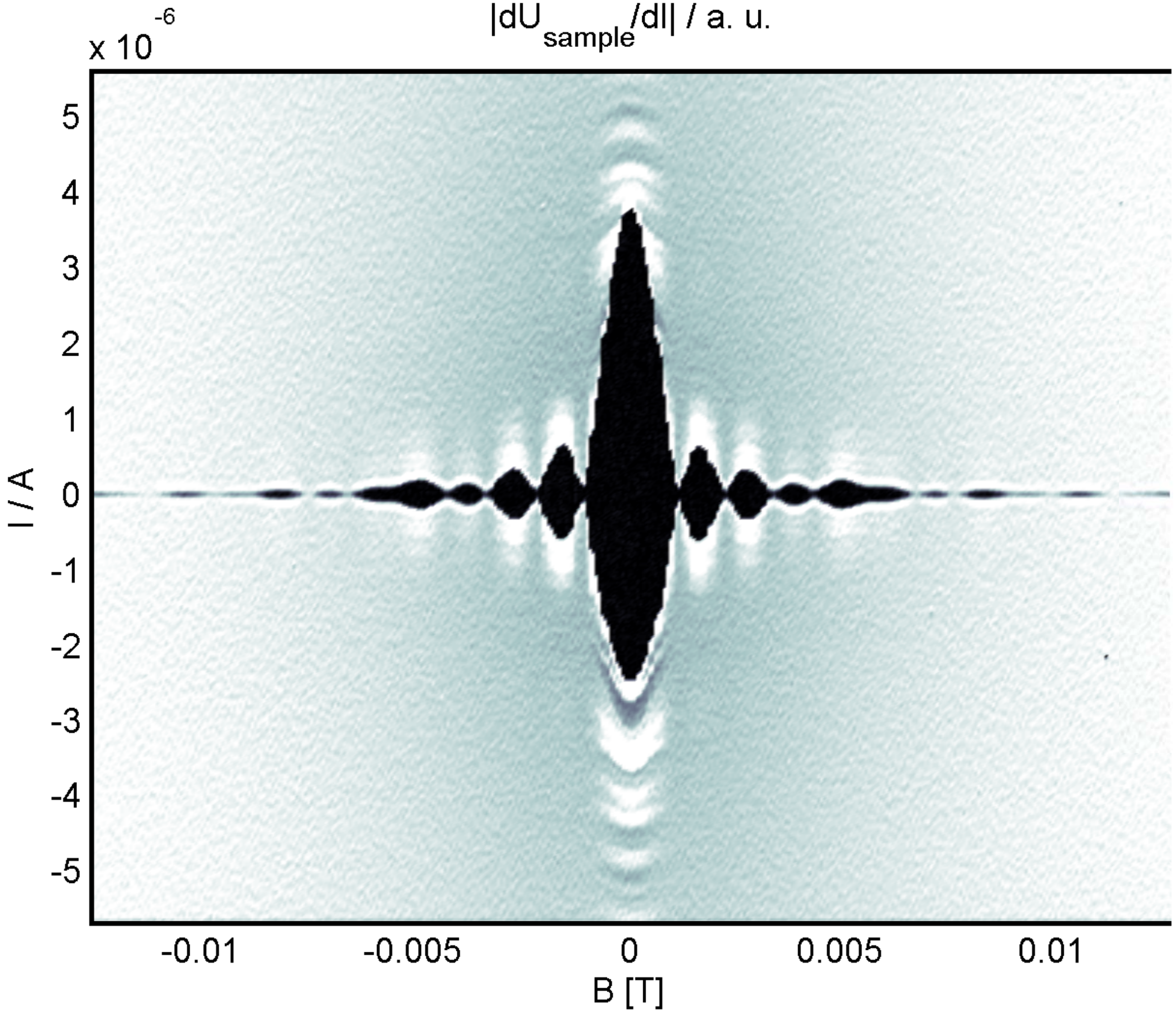
At T = 25 mK:

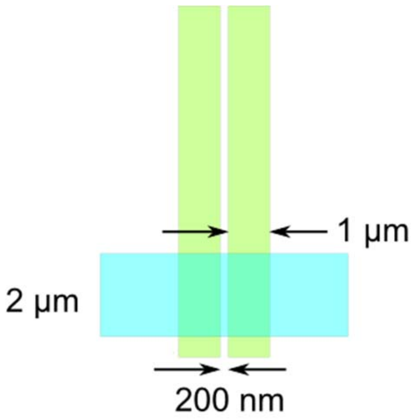
$I_c \approx I_s \approx$ 3-4 μA

$R_N \approx 50\ \Omega$

$I_c R_N \approx$ 0.15-0.2 mV

T ~ 25 mK
Just DC



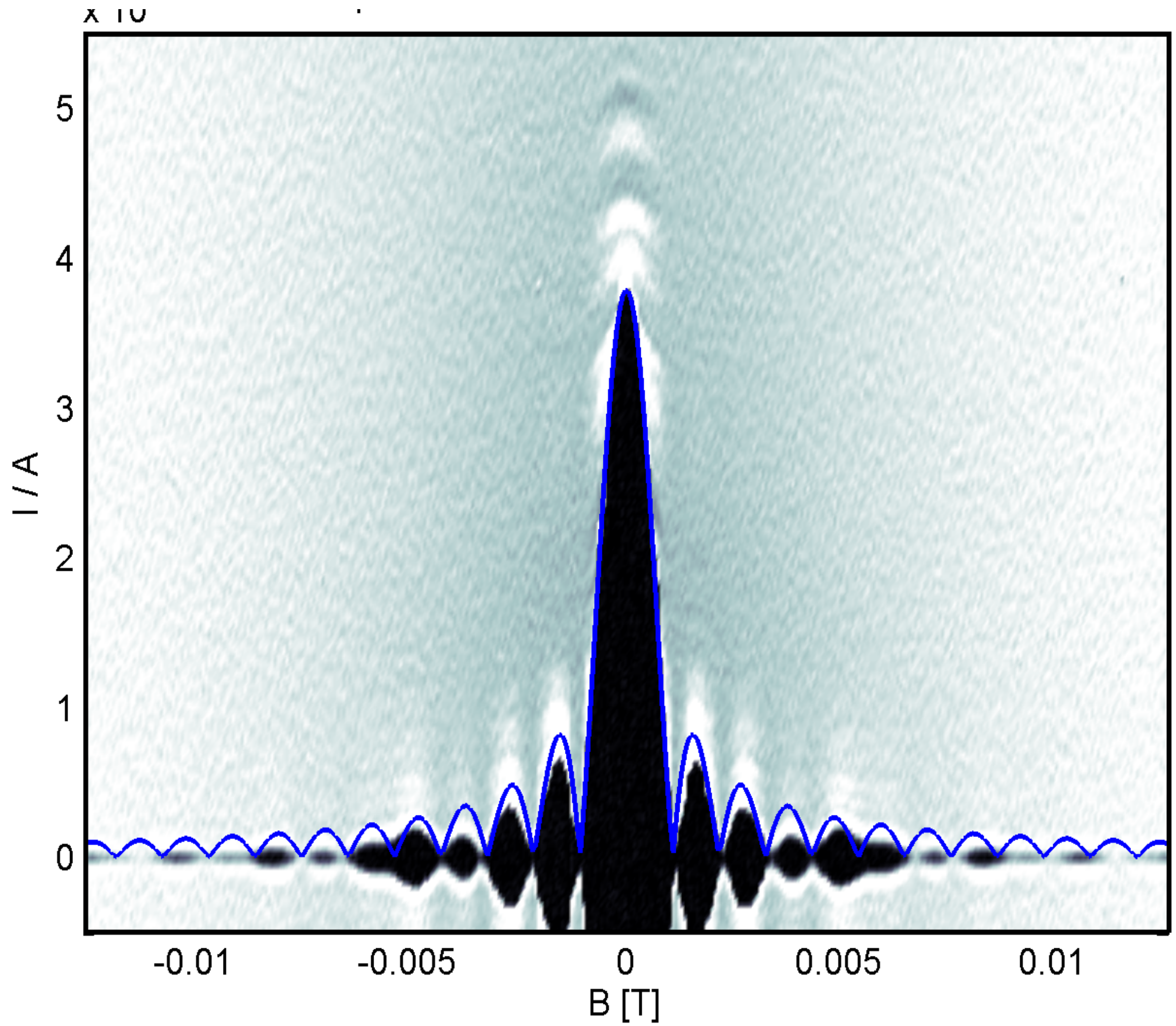


Sample with two contacts also shows somewhat irregular ‚Fraunhofer' pattern.

I_C = 3.78 µA T ~ 25 mK
B_p = 1.09 mT Just DC

Could of course just be inhomogeneous current injection.

Next steps:
- build SQUID
- go for 2D samples



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

Julius-Maximilians-
UNIVERSITÄT
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Conclusions

EP 3

- HgTe quantum wells: normal and inverted gap, linear (Dirac) dispersion
- show Quantum Spin Hall Effect and Quantum Anomalous Hall Effect
- demonstrated helical edge channels and spin polarization
- strained 3D layers show QHE of topological surface states
- In which a supercurrent can be induced

Collaborators:
Bastian Büttner, Christoph Brüne, Hartmut Buhmann, Markus König, Luis Maier, Matthias Mühlbauer, Jeroen Oostinga, Cornelius Thienel

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

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