Topological Insulator State in HgTe

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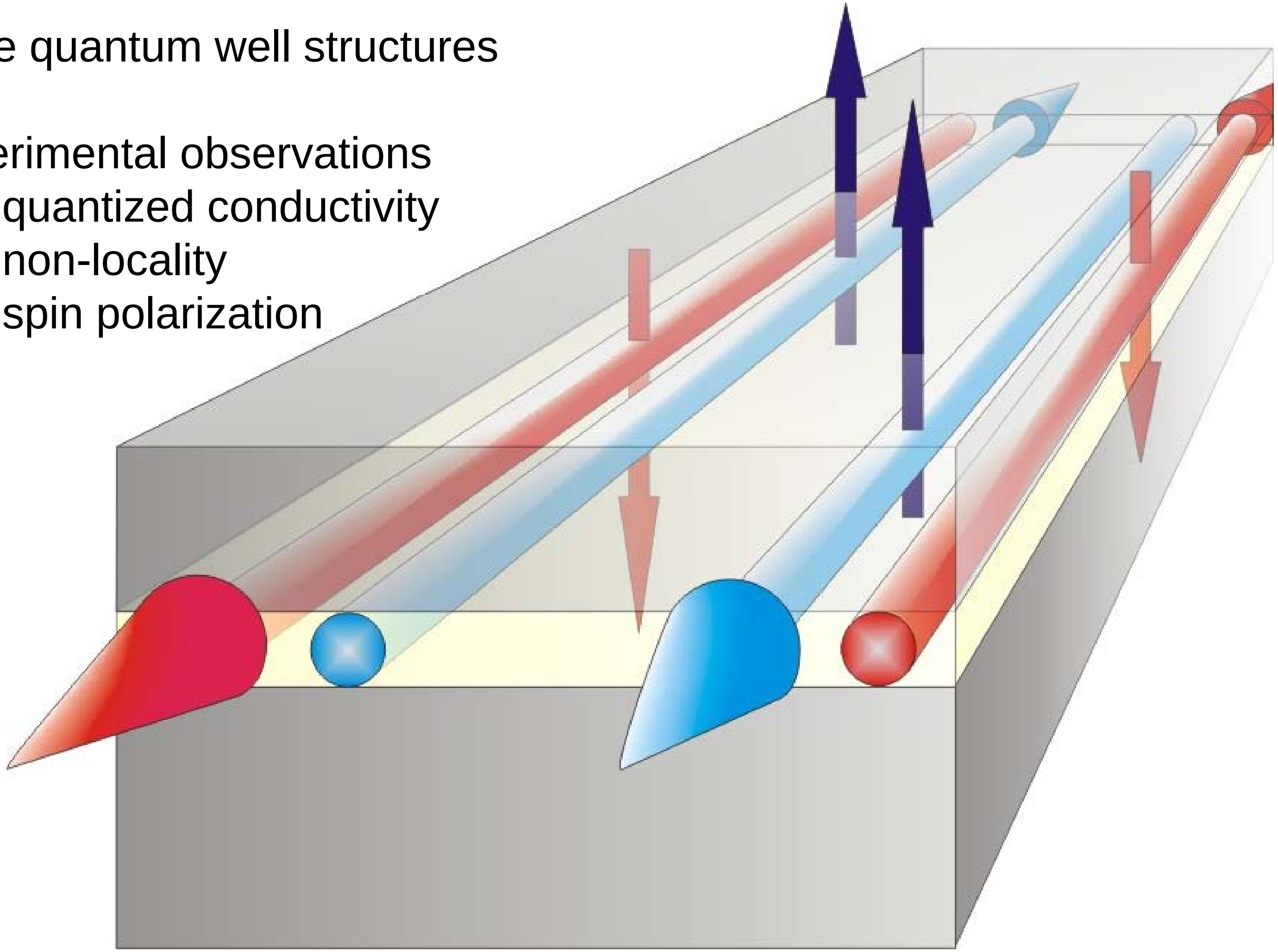
Outline

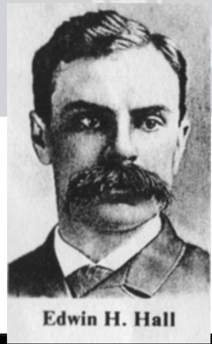
- Hall effects and topological insulators
- HgTe quantum well structures
- experimental observations
    - quantized conductivity
    - non-locality
    - spin polarization

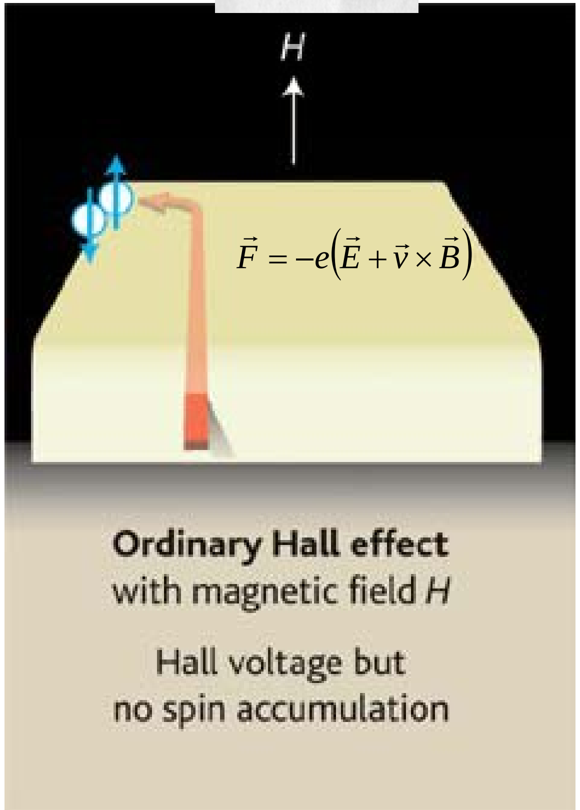


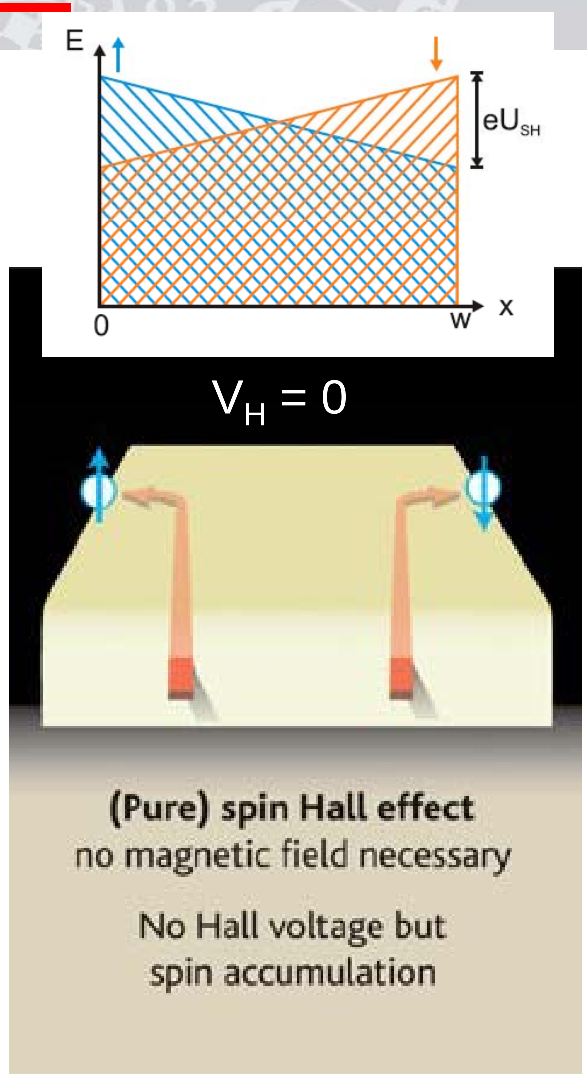
Hall Effects

H. Buhmann

1879







$$\rho_{xy} = E_y / j_x$$

$$\sigma_{sH} \equiv -\frac{j_{sy}}{E_x}$$

(dissipationless spin current)

Quantum Hall Effect

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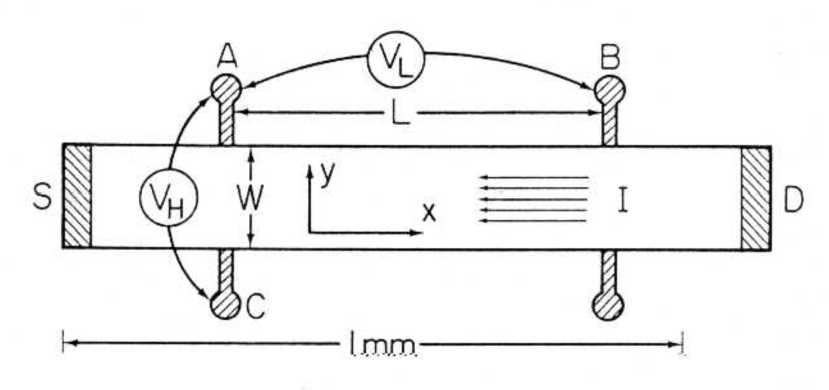
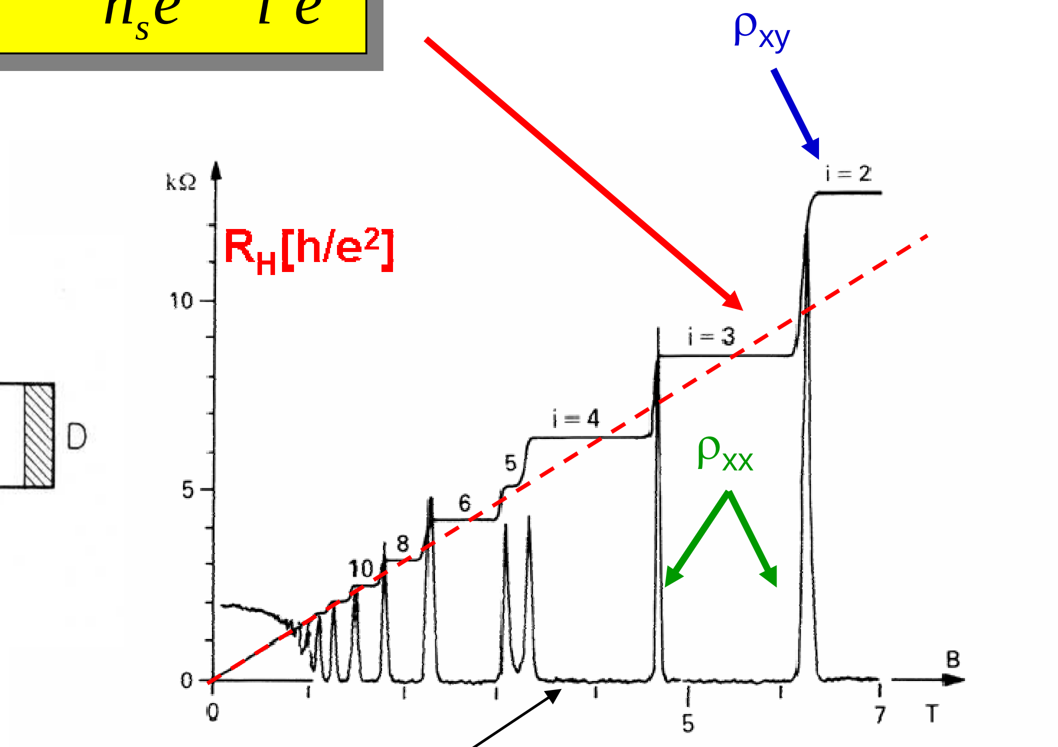
Nobel Prize K. von Klitzing 1985

Hall resistance

$$\rho_{xy} = \frac{B}{n_s e} = \frac{1}{i}\frac{h}{e^2}$$

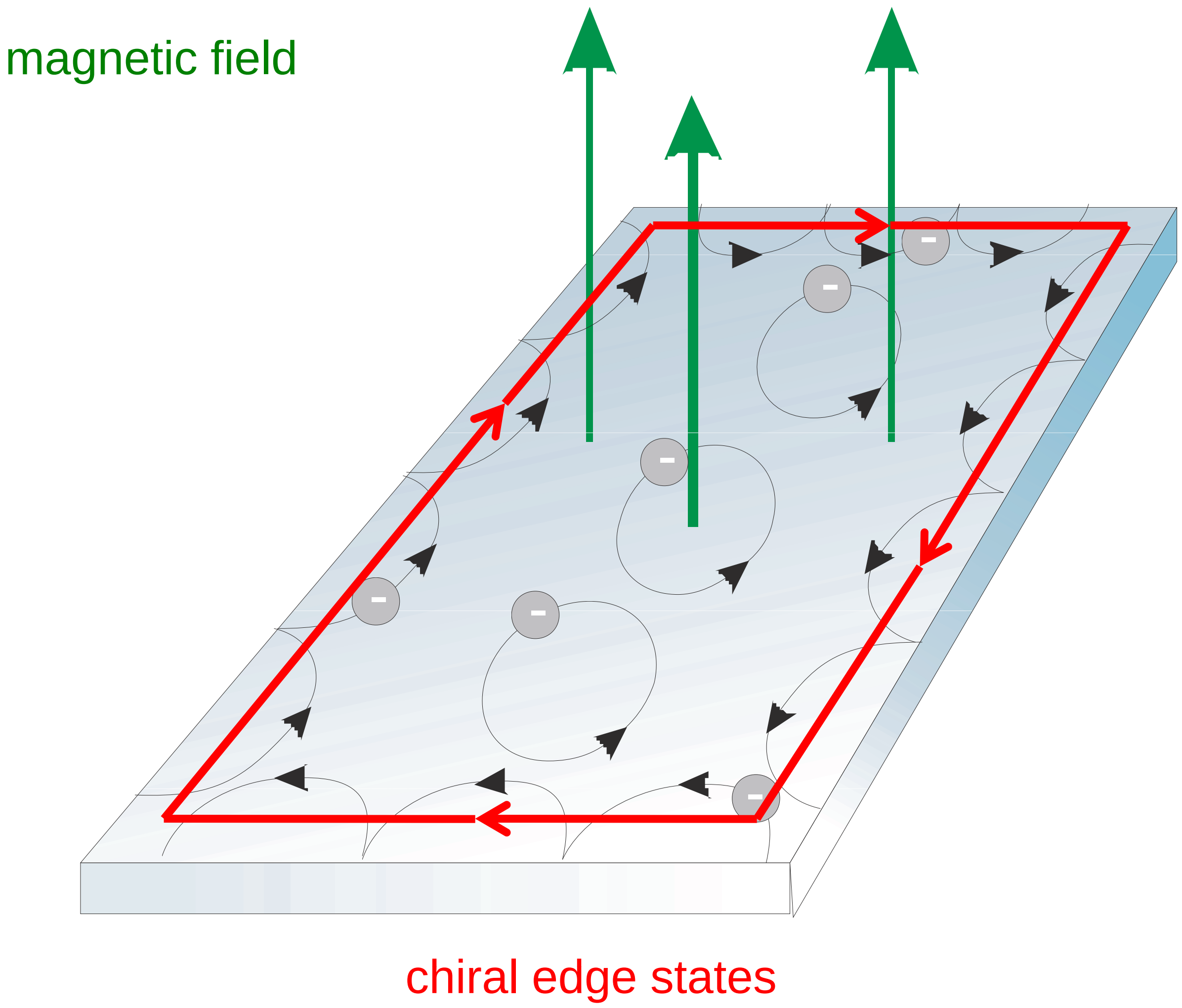
semiconductor 2DEG



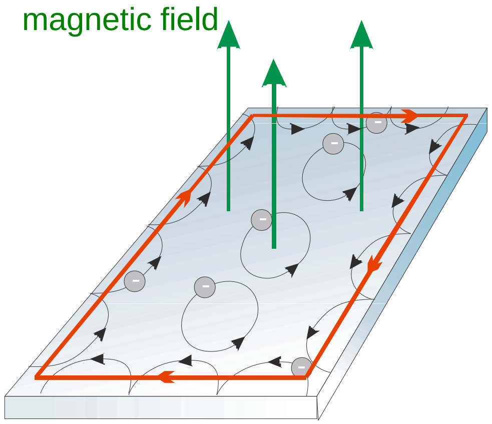


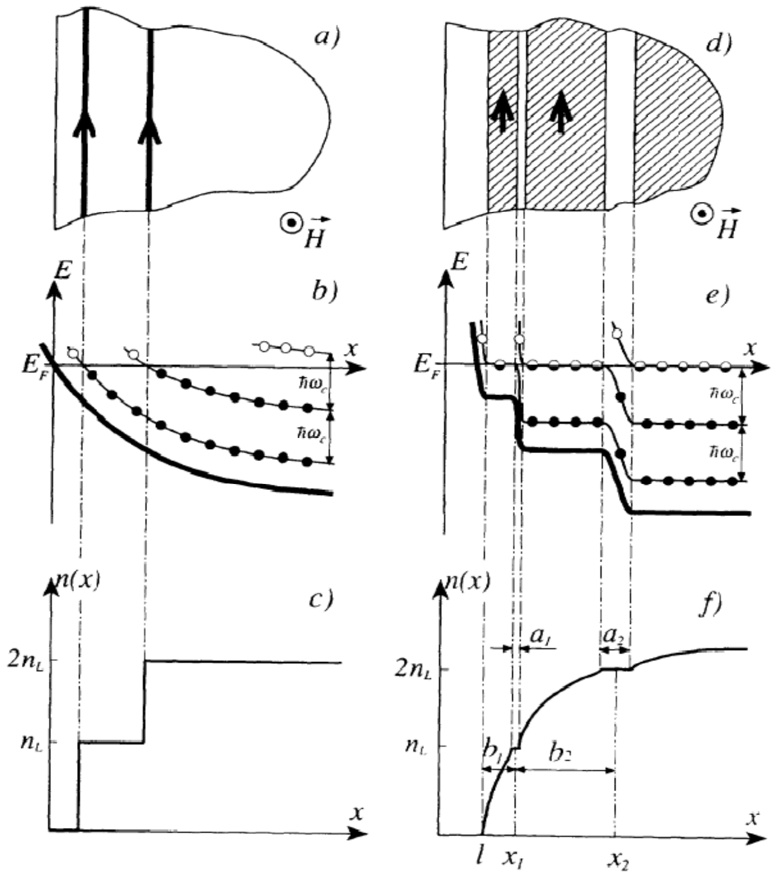
zero longitudinal resistance

2DEG in a Magnetic Field



Edge Channels





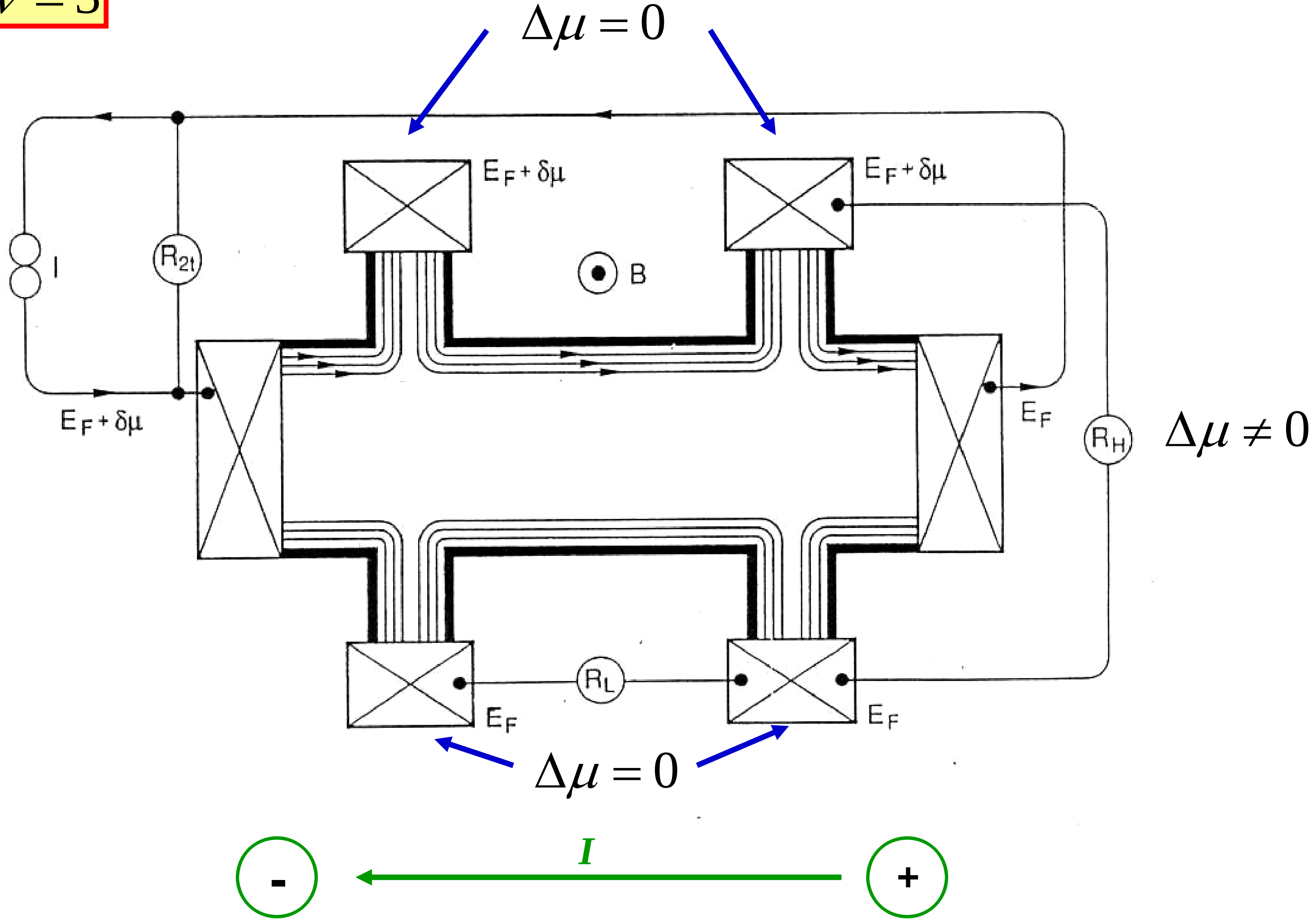
D.B. Chklovskii, B.I. Shklovskii, L.I. Glazman, Phys. Rev. B 46, 4026 (1992)

1d edge channels

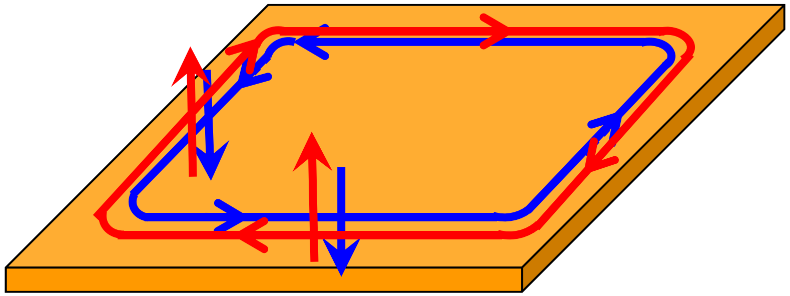
Quantum Hall Effect

Edge Channel Picture

$\nu = 3$



Quantum Spin Hall Effect



two copies of QH states,
one for each spin component, each seeing the opposite magnetic field,

are united in one sample and form

helical edge states.

This new state **does not break the time reversal symmetry**, and can exist without any external magnetic field.

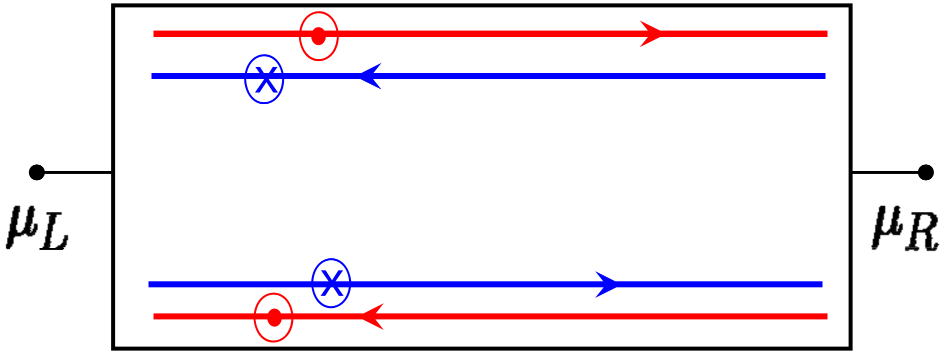
➔Quantum Spin Hall State

consisting of **two** counter propagating spin polarized **edge channels**.
protected by time reversal symmetry (Kramer‘s pair),
and an **insulating bulk**

Quantum Spin Hall Effect

Stability of Helical Edge States: 4 = 2 + 2

backscattering between Kramers' doublets is forbidden $\psi_{k,s+}, \psi_{-k,s-}$

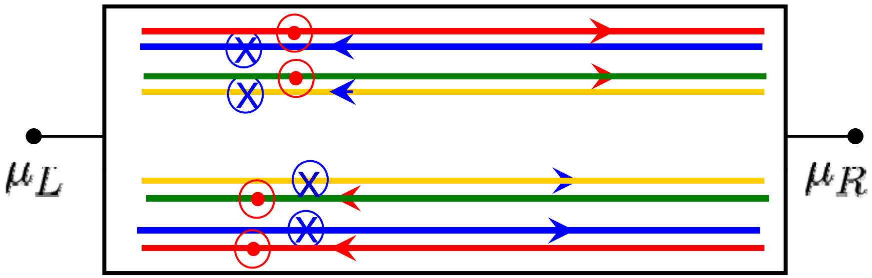


$$G_{QSHE} = \frac{2e^2}{h}$$

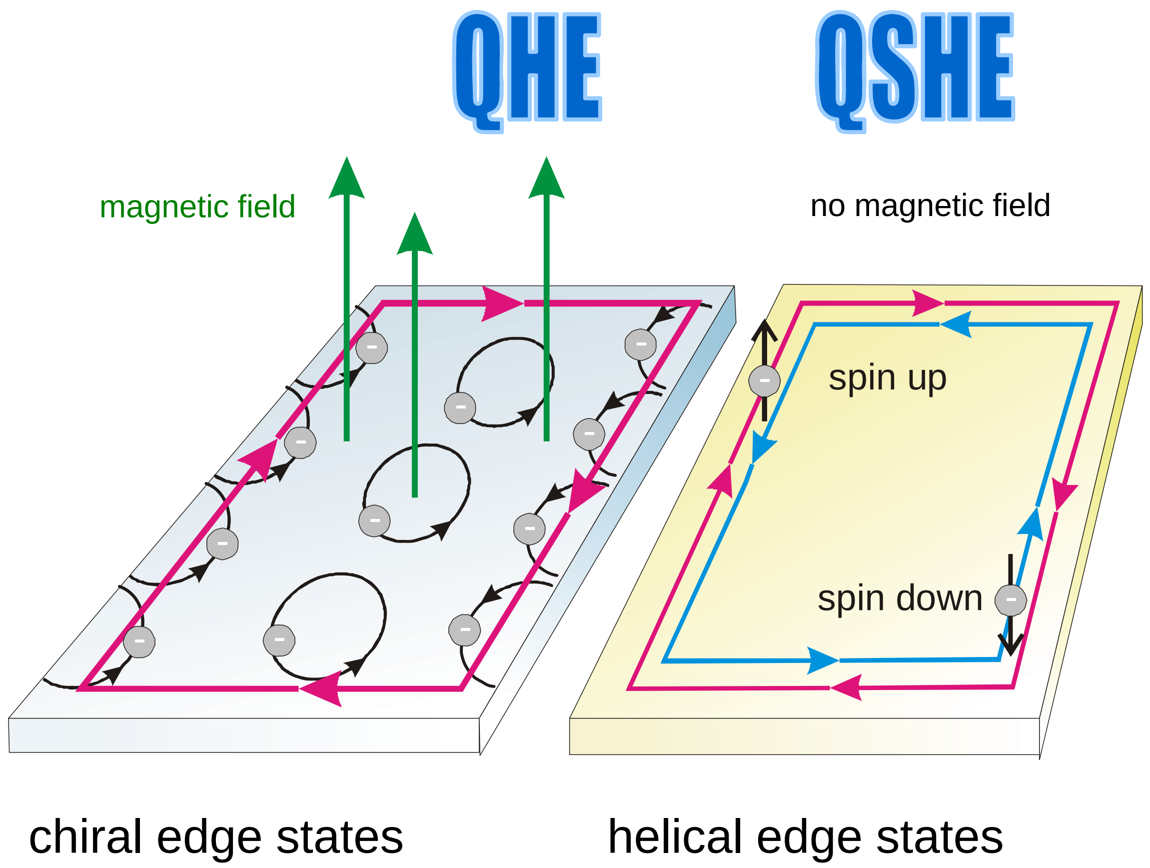
backscattering is only possible by **time reversal symmetry breaking processes** (for example external magnetic fields)

or if **more edge states** exist

$\psi_{k_1,s+}, \psi_{-k_2,s-}$



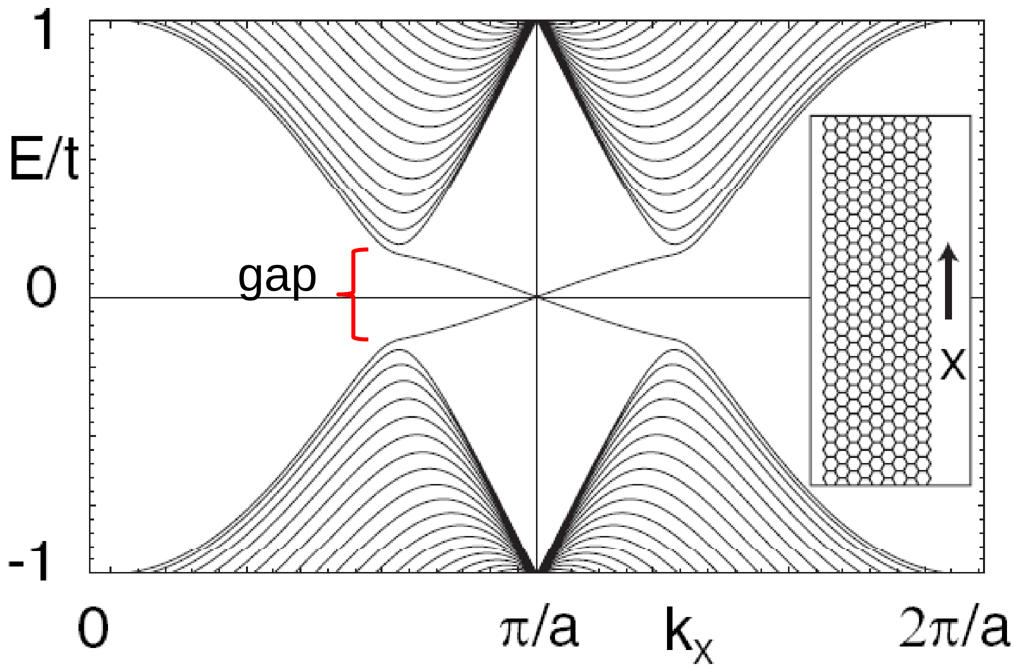
Quantum Spin Hall Effect



In what kind of material does the QSHE exist?

QSHE in Graphene

Graphene edge states



C.L.Kane and E.J.Mele, PRL **95**, 226801 (2005)

- Graphene – spin-orbit coupling strength is too weak ➔ gap only about 10^{-3} meV.
- ➔ **not** accessible in experiments

QSHE in HgTe

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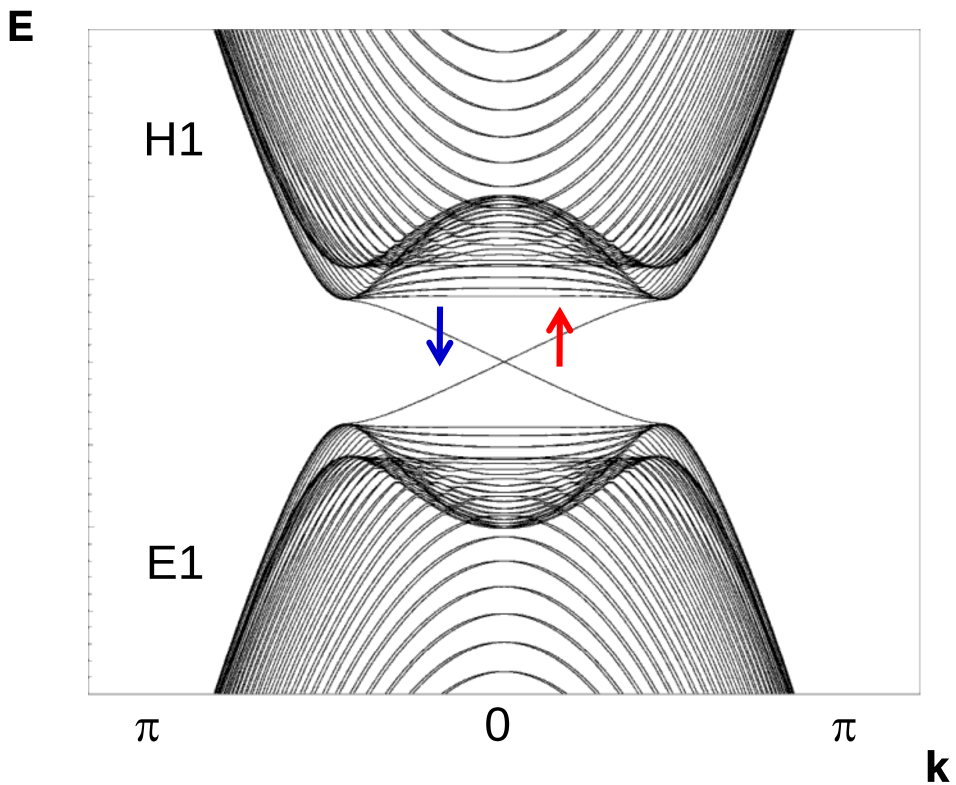
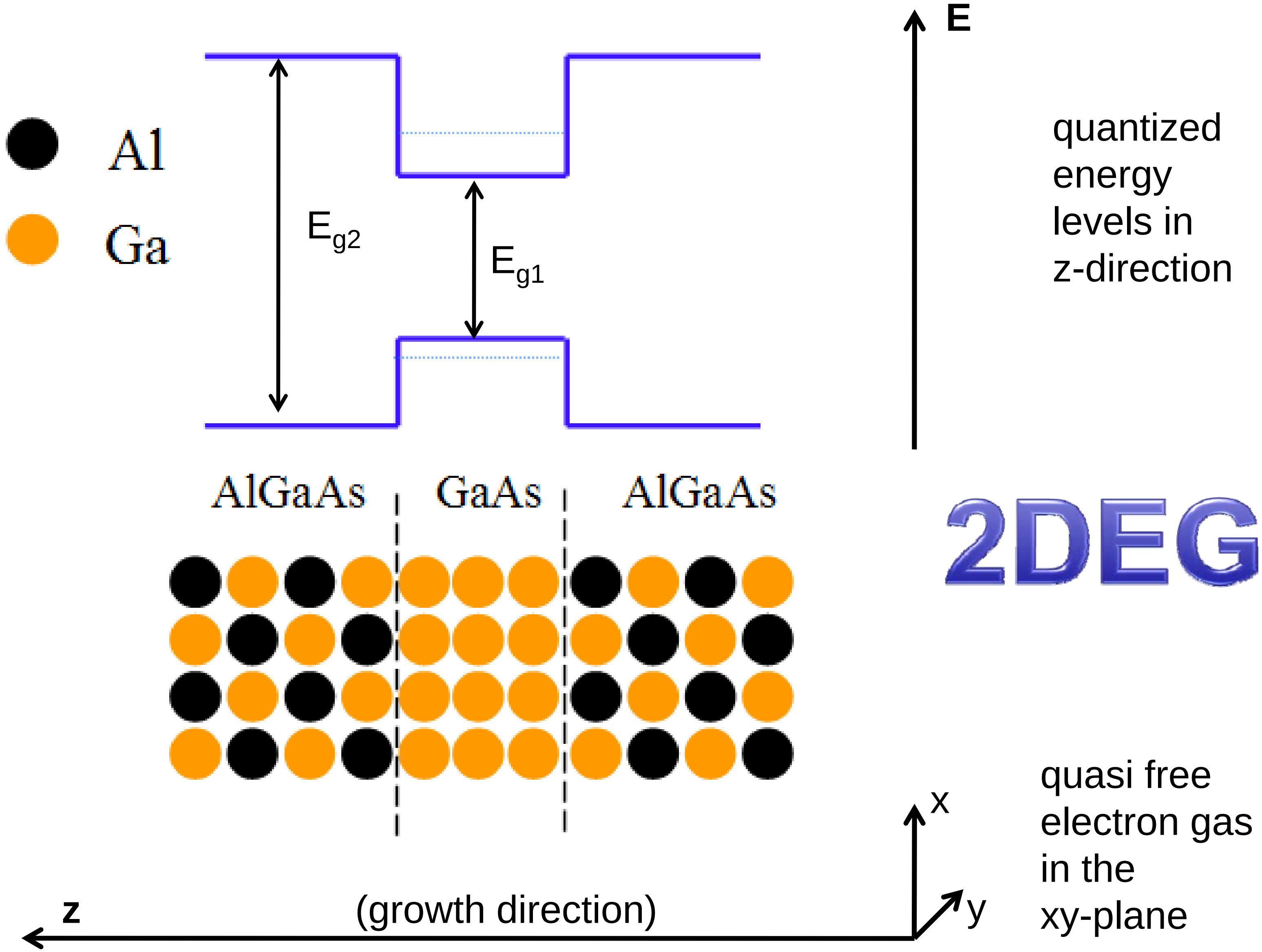
Helical edge states for inverted HgTe QW



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

HgTe-Quantum Well Structures

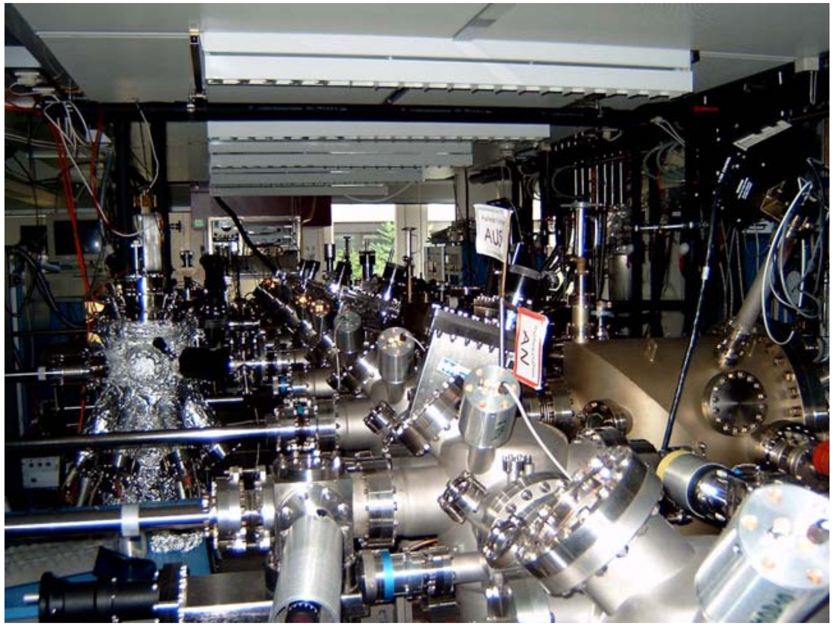
Quantum Well Structures

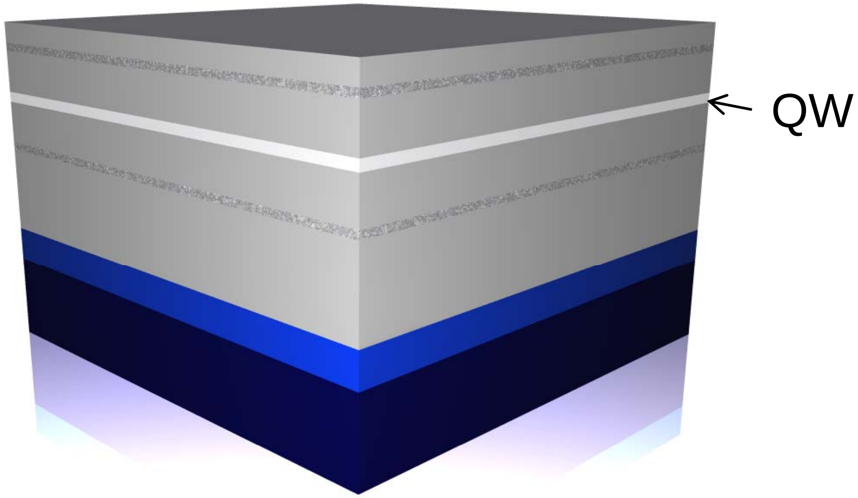


quantized energy levels in z-direction

quasi free electron gas in the xy-plane

Quantum Well Growth
by
Molecular Beam Epitaxy





MBE

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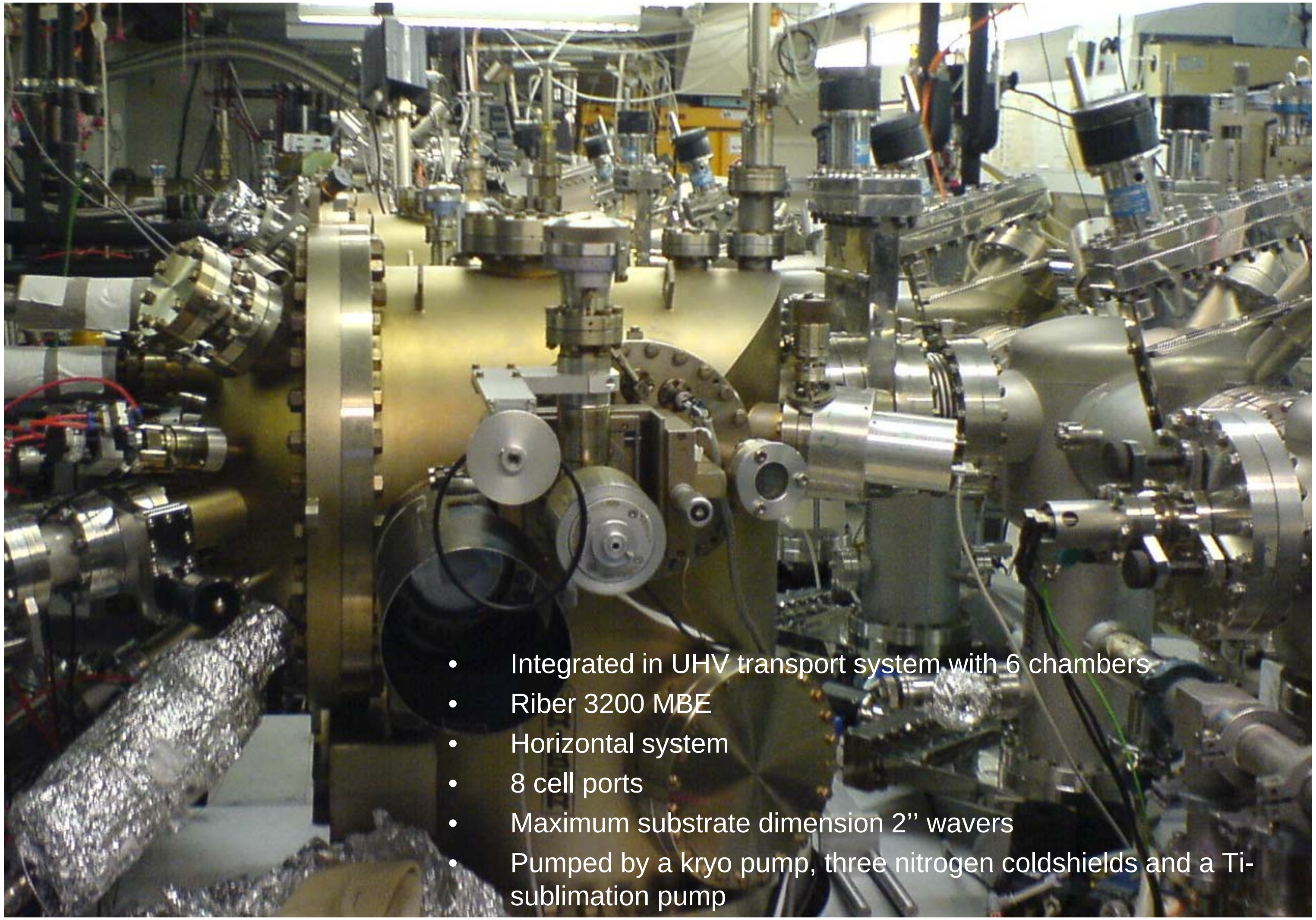
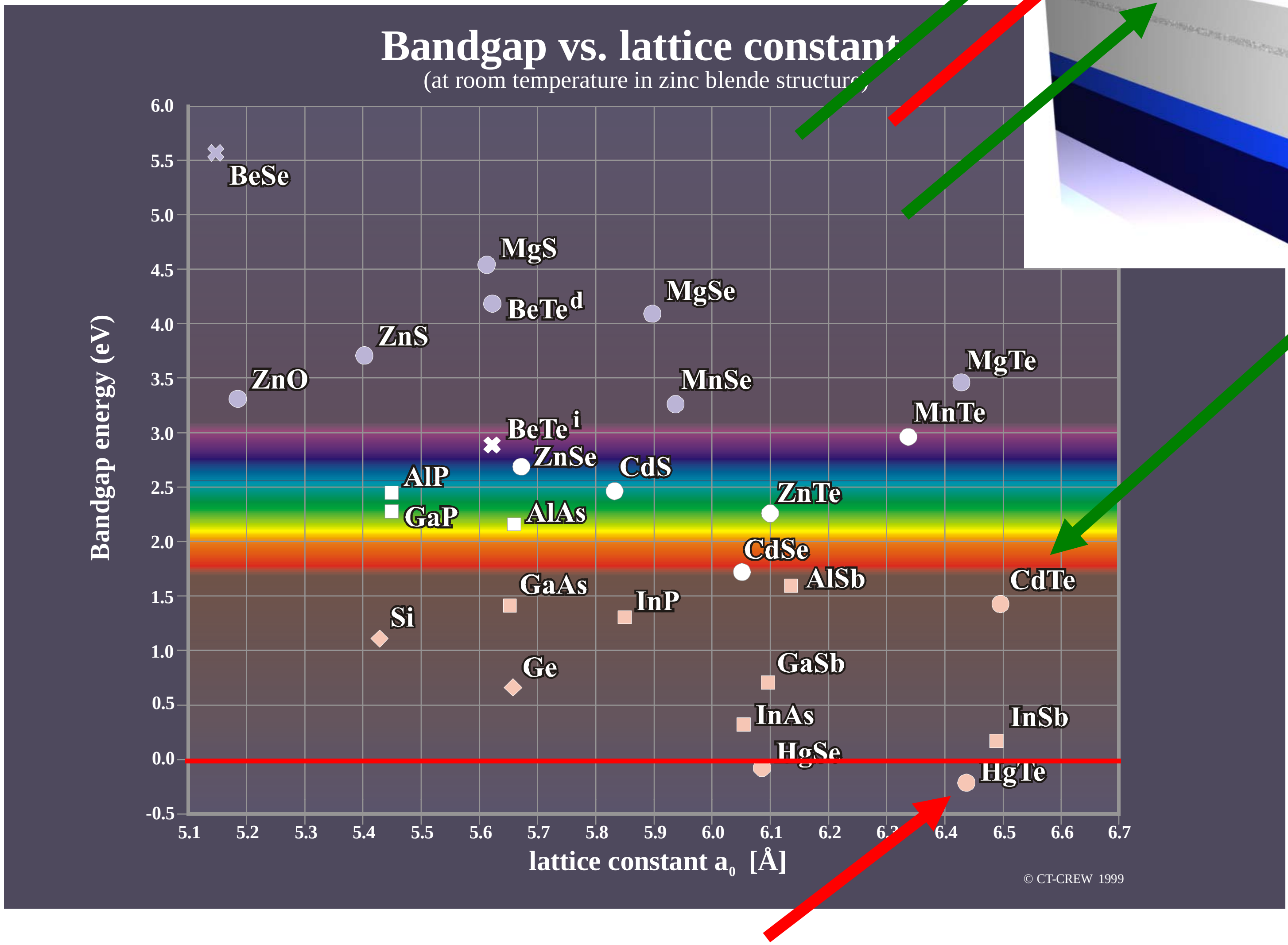
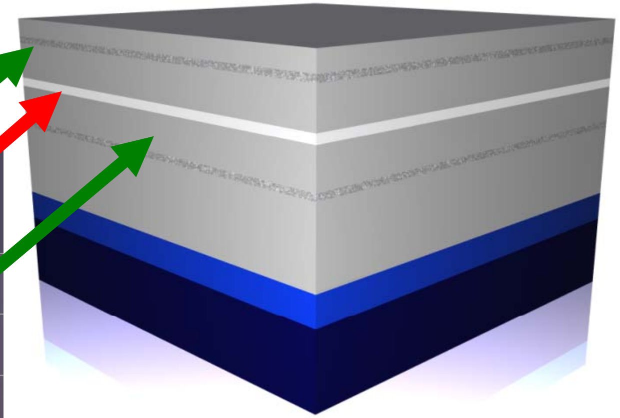


- Integrated in UHV transport system with 6 chambers
- Riber 3200 MBE
- Horizontal system
- 8 cell ports
- Maximum substrate dimension 2’’ wavers
- Pumped by a kryo pump, three nitrogen coldshields and a Ti-sublimation pump

HgTe Quantum Wells

MBE-Growth





HgTe Quantum Wells

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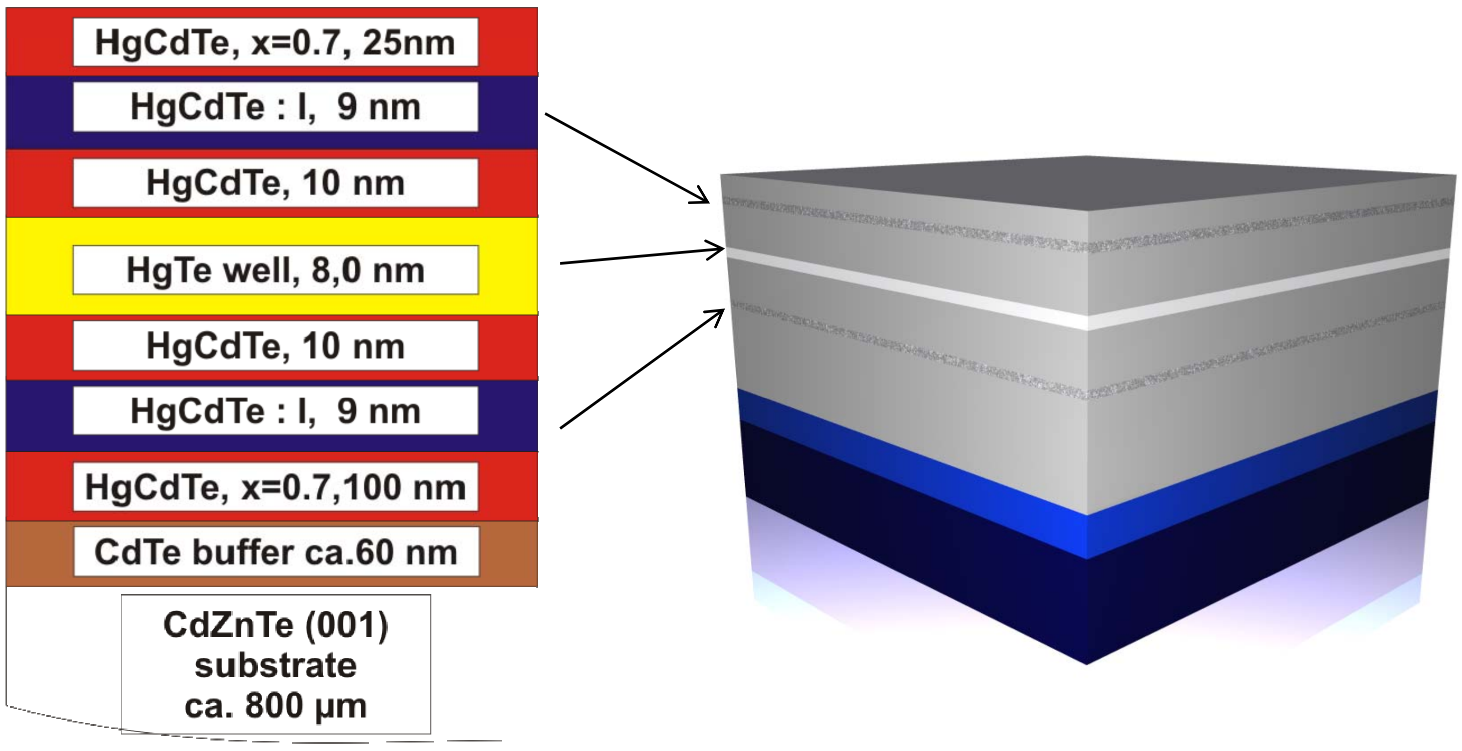
Q2220

free electron gas in the QW

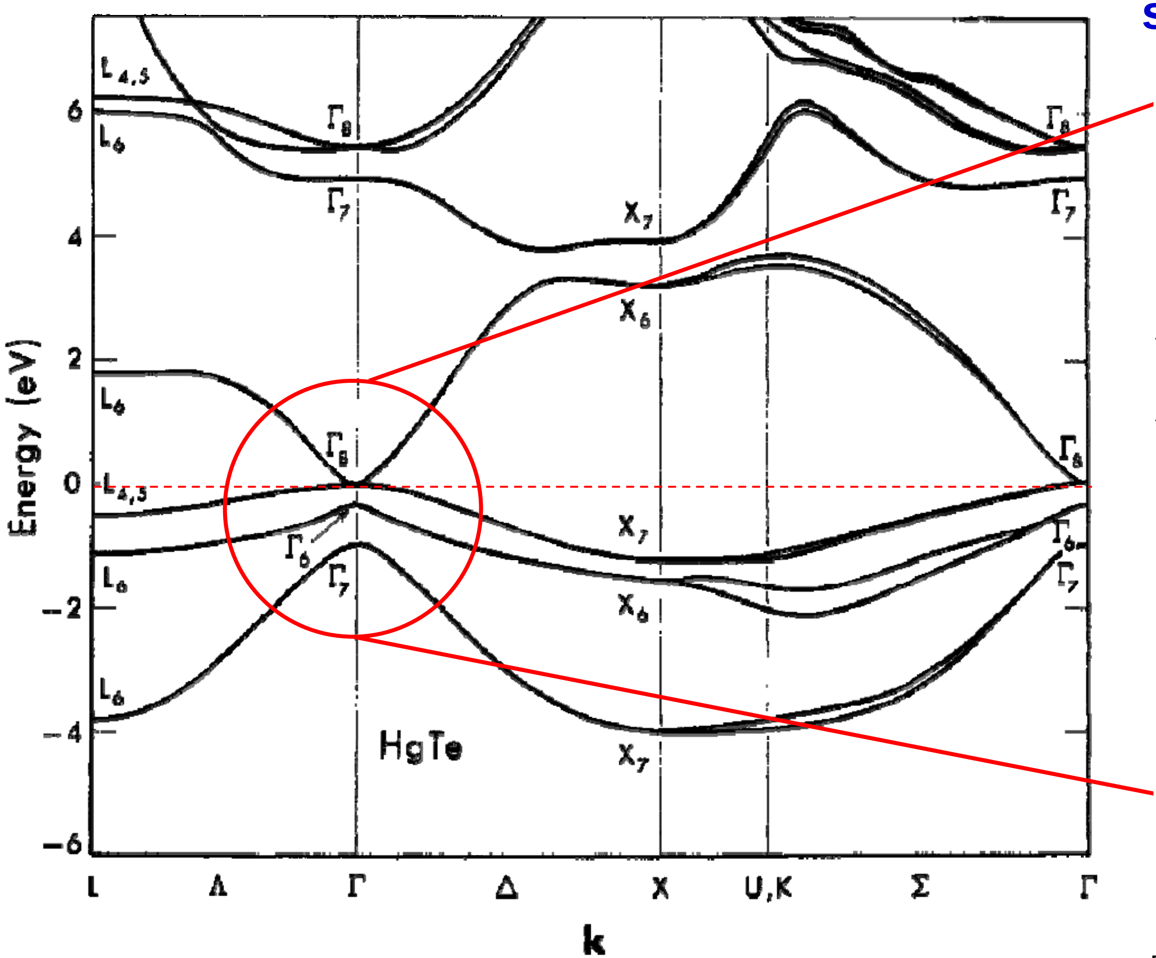
by donor doping of the barriers



HgTe
Band Structure

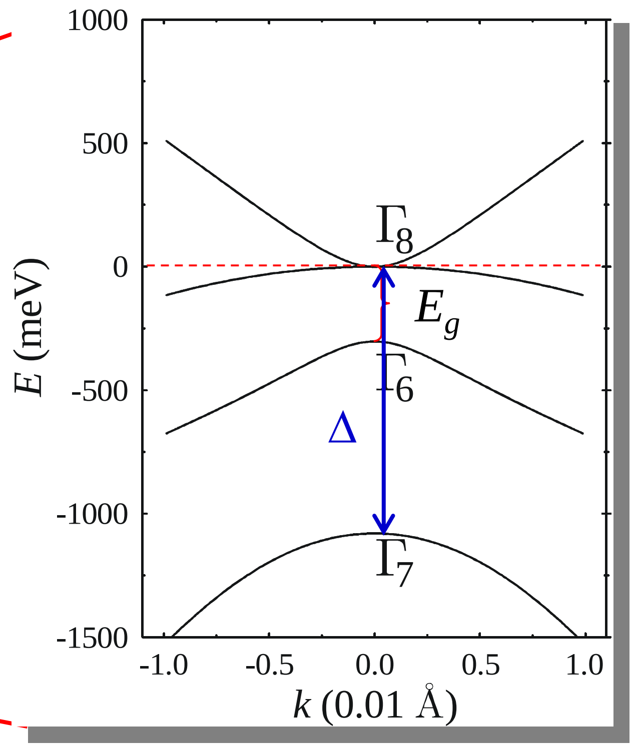
HgTe

band structure



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

semi-metal or semiconductor

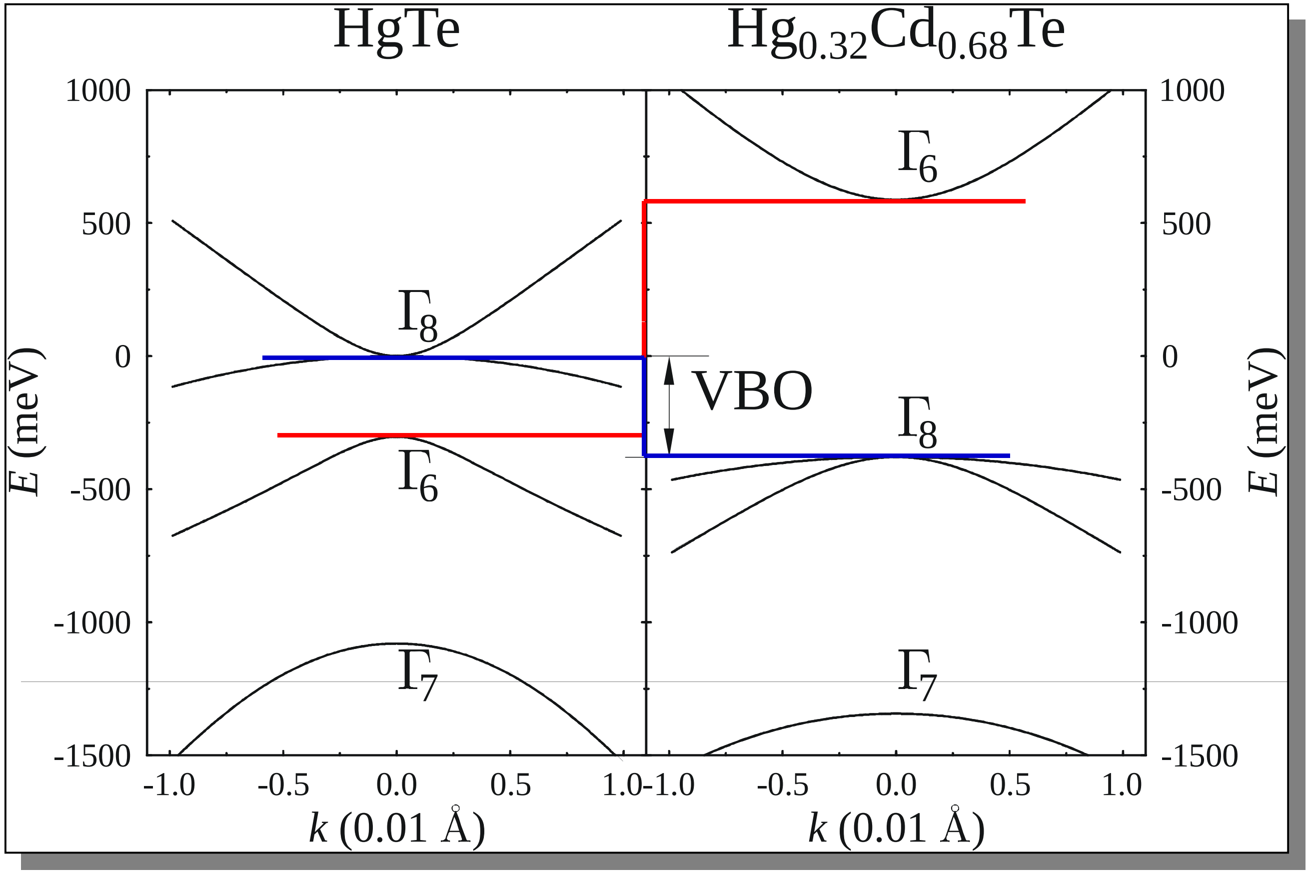


fundamental energy gap

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

HgTe-Quantum Wells

QW | Barrier



VBO = 570 meV

HgTe-Quantum Wells

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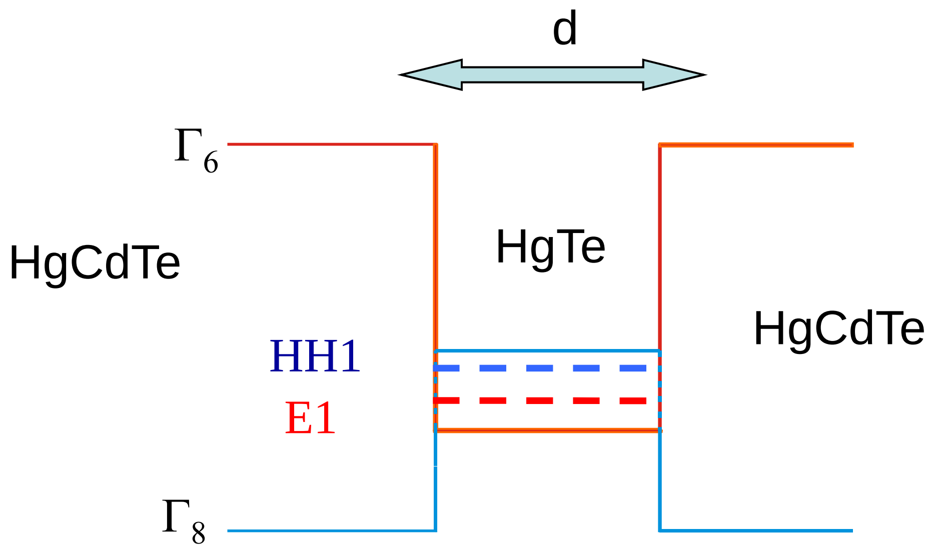
Typ-III QW



normal
inverted

band structure

Band Gap Engineering

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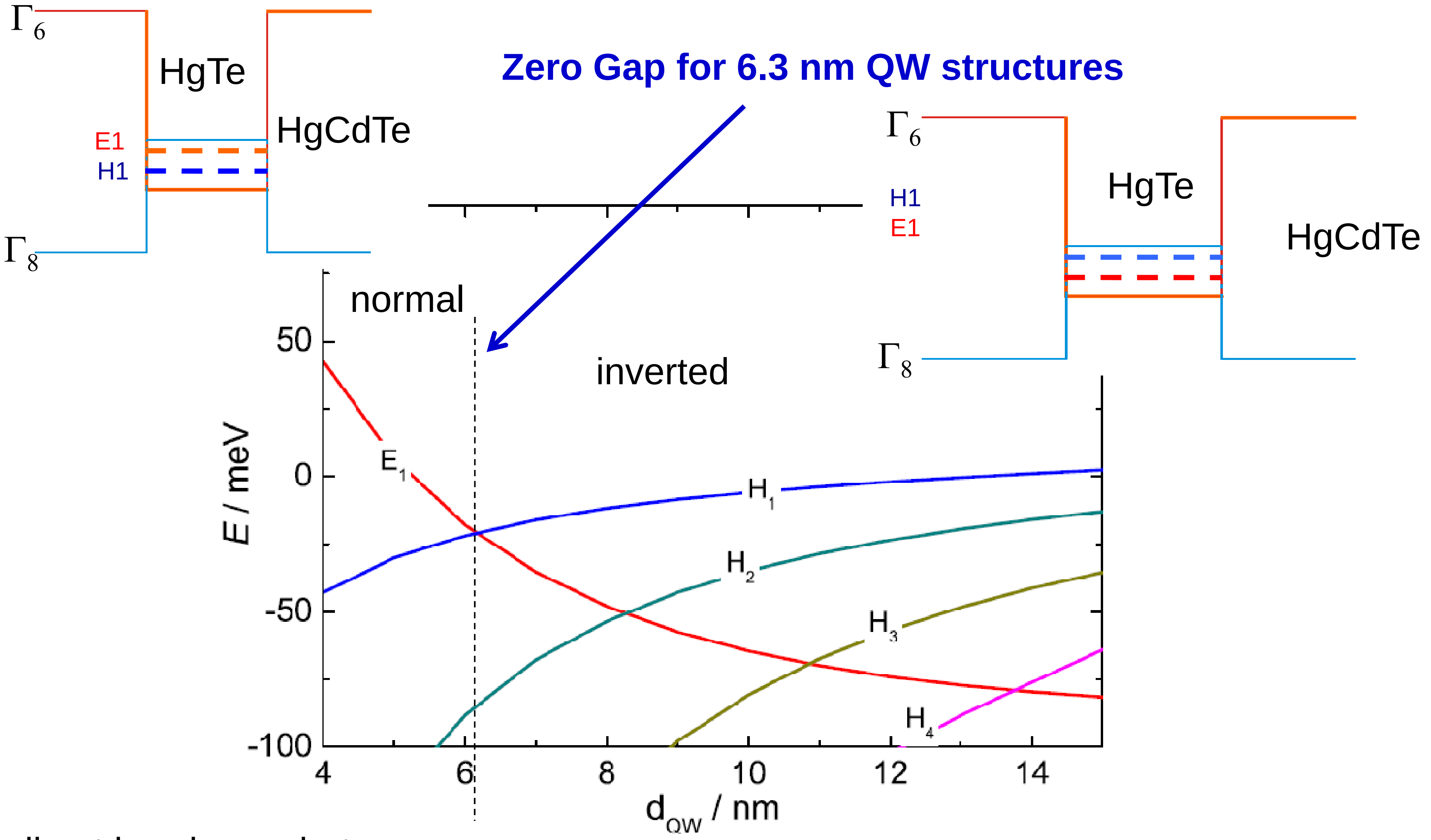
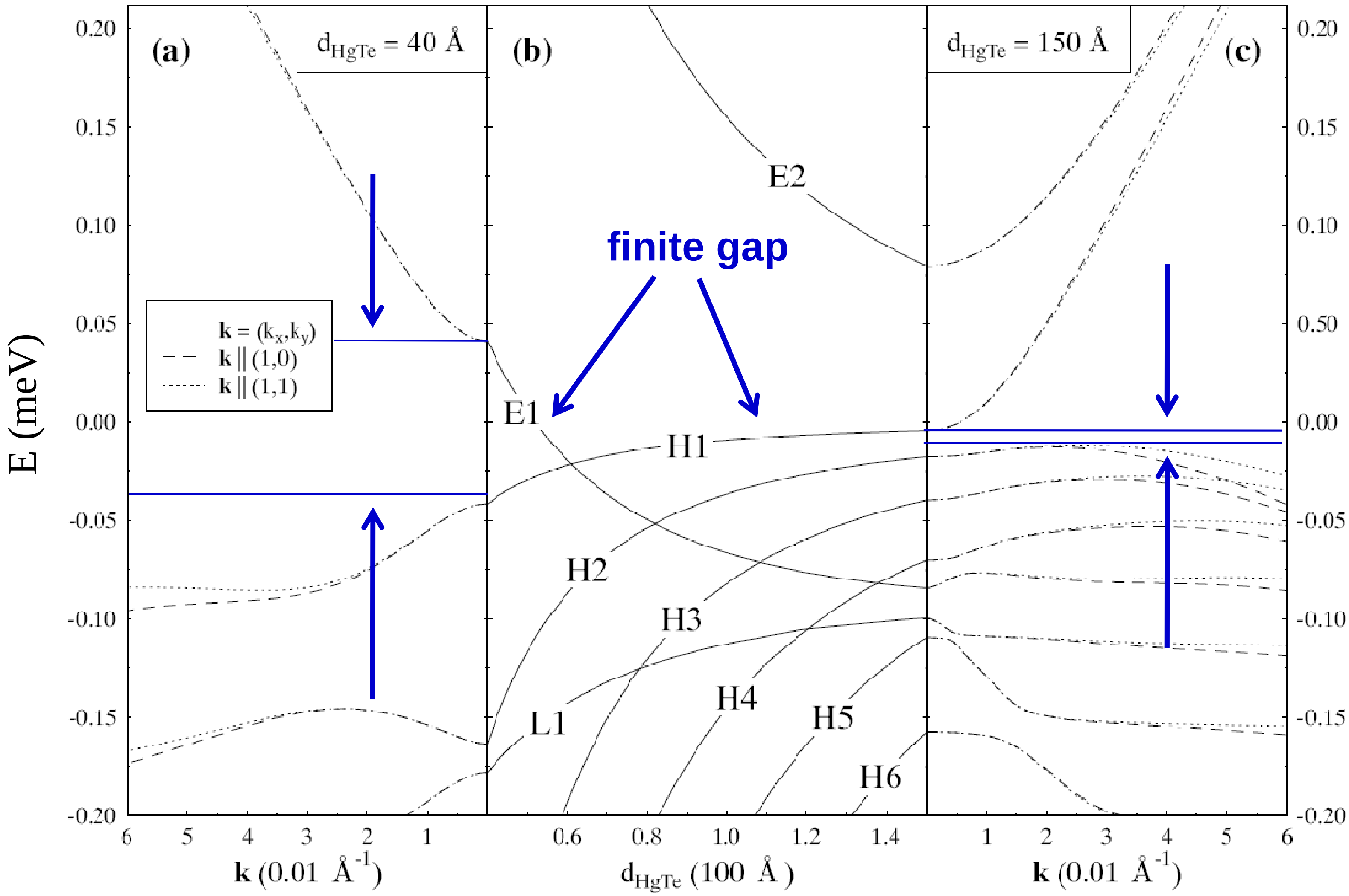


direct band gaps between

80 ... 0 and 0 ... - 30 meV

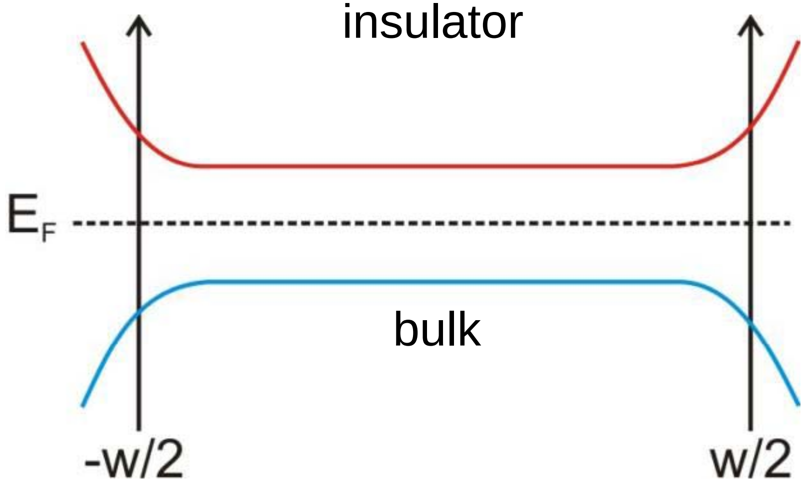
8 band k·p calculation



Simplified Picture

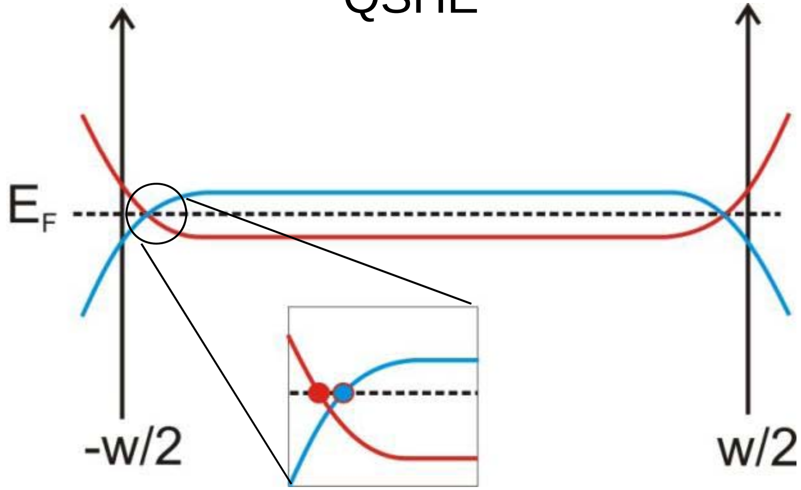
m > 0

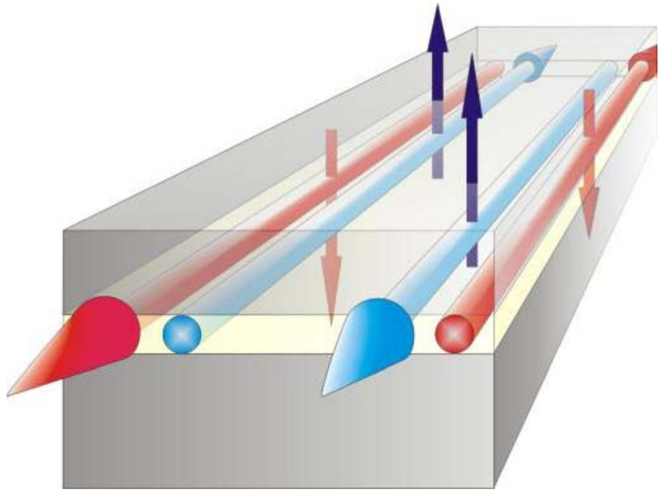
normal insulator



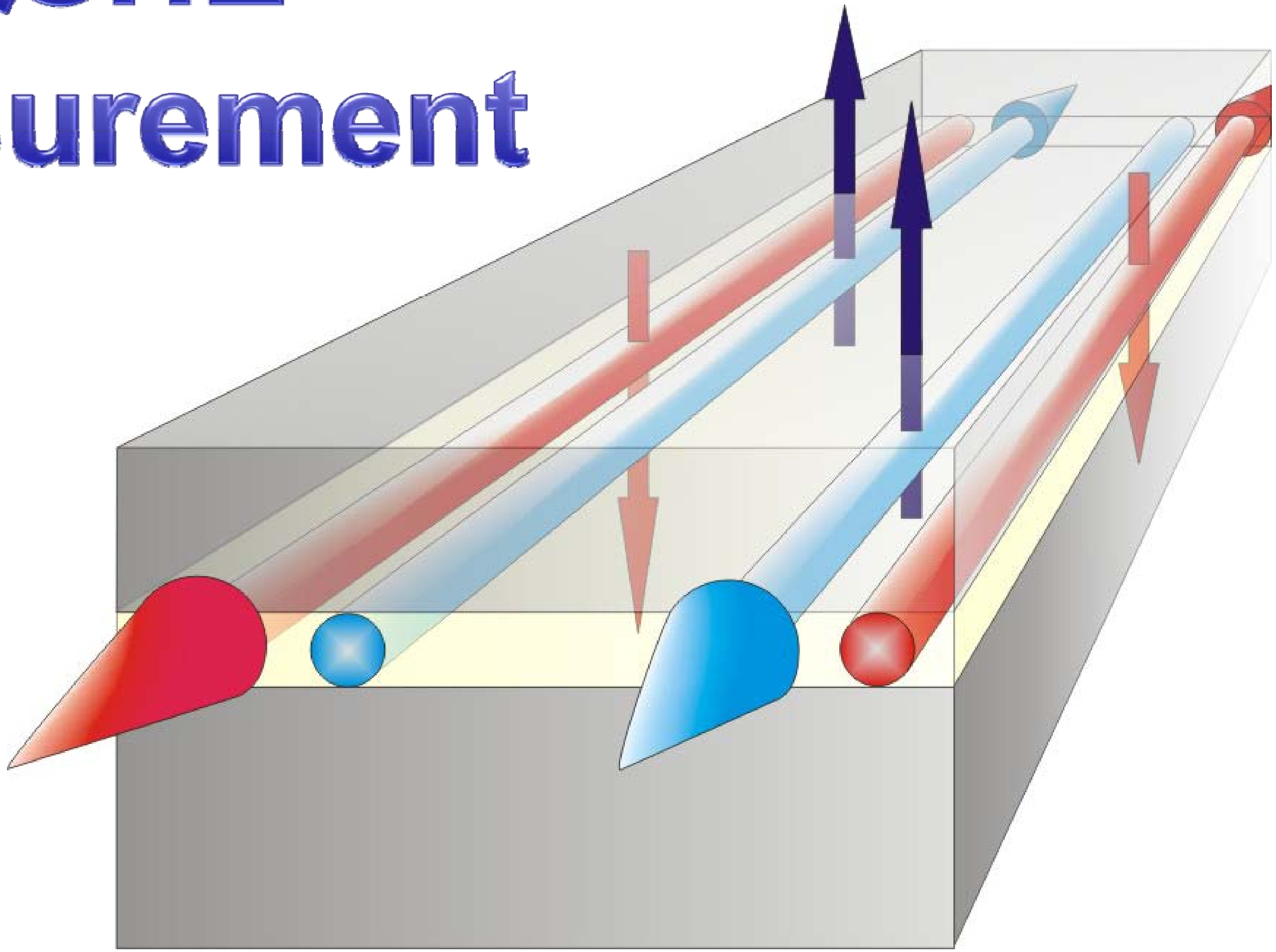
m < 0

QSHE



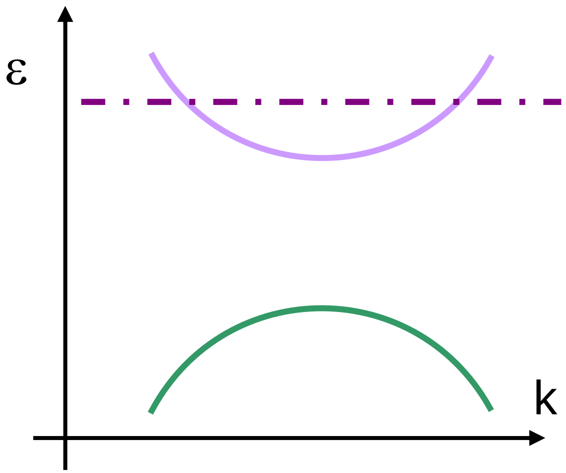


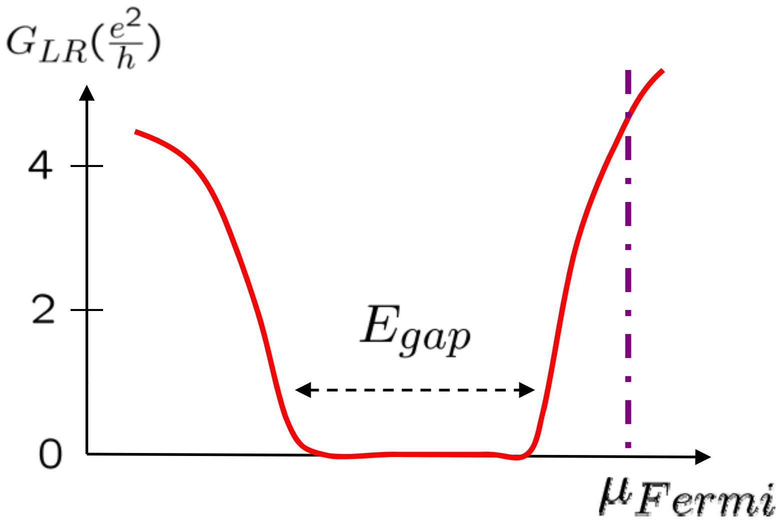
QSHE Measurement



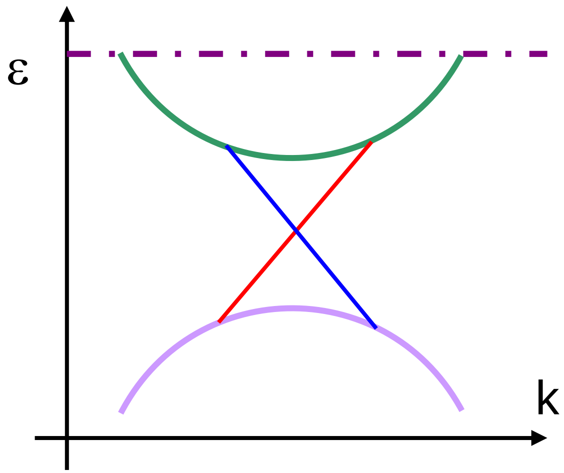
Experiment

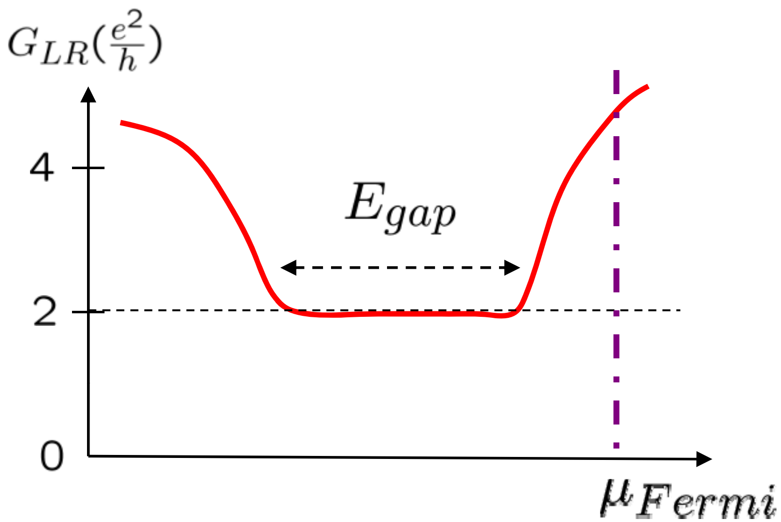
$d < d_c$, normal regime



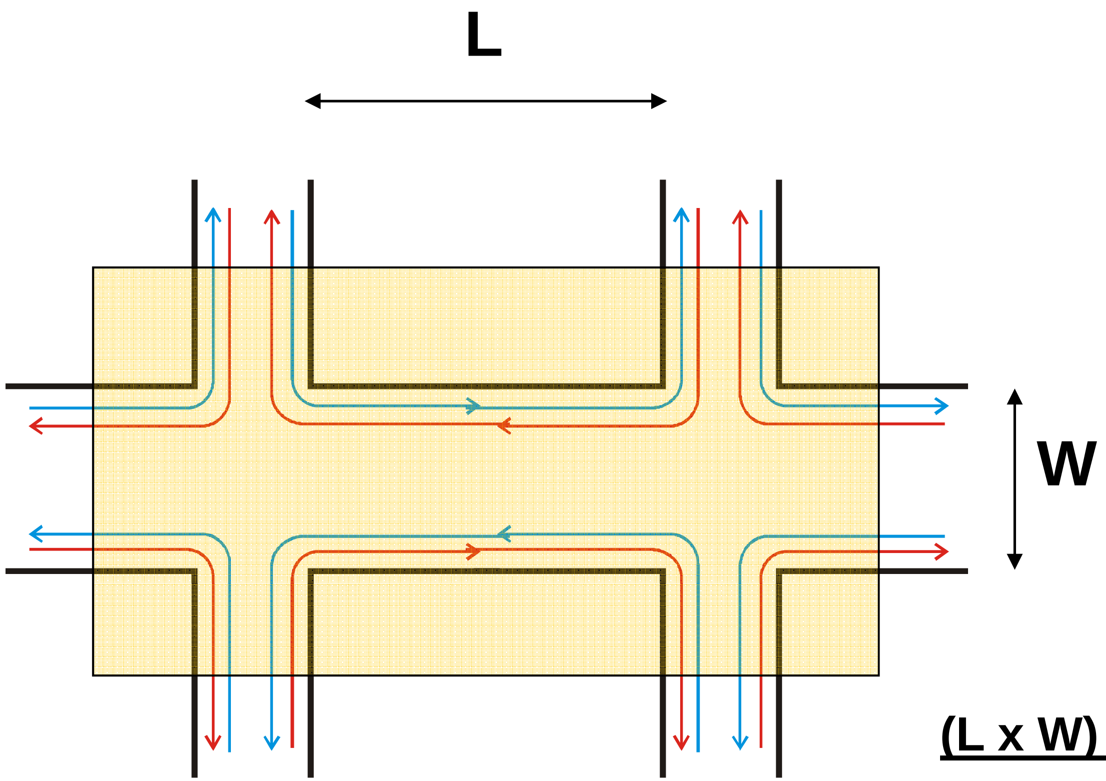


$d > d_c$, inverted regime





Smaller Samples



(L x W) μm

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

QSHE Size Dependence

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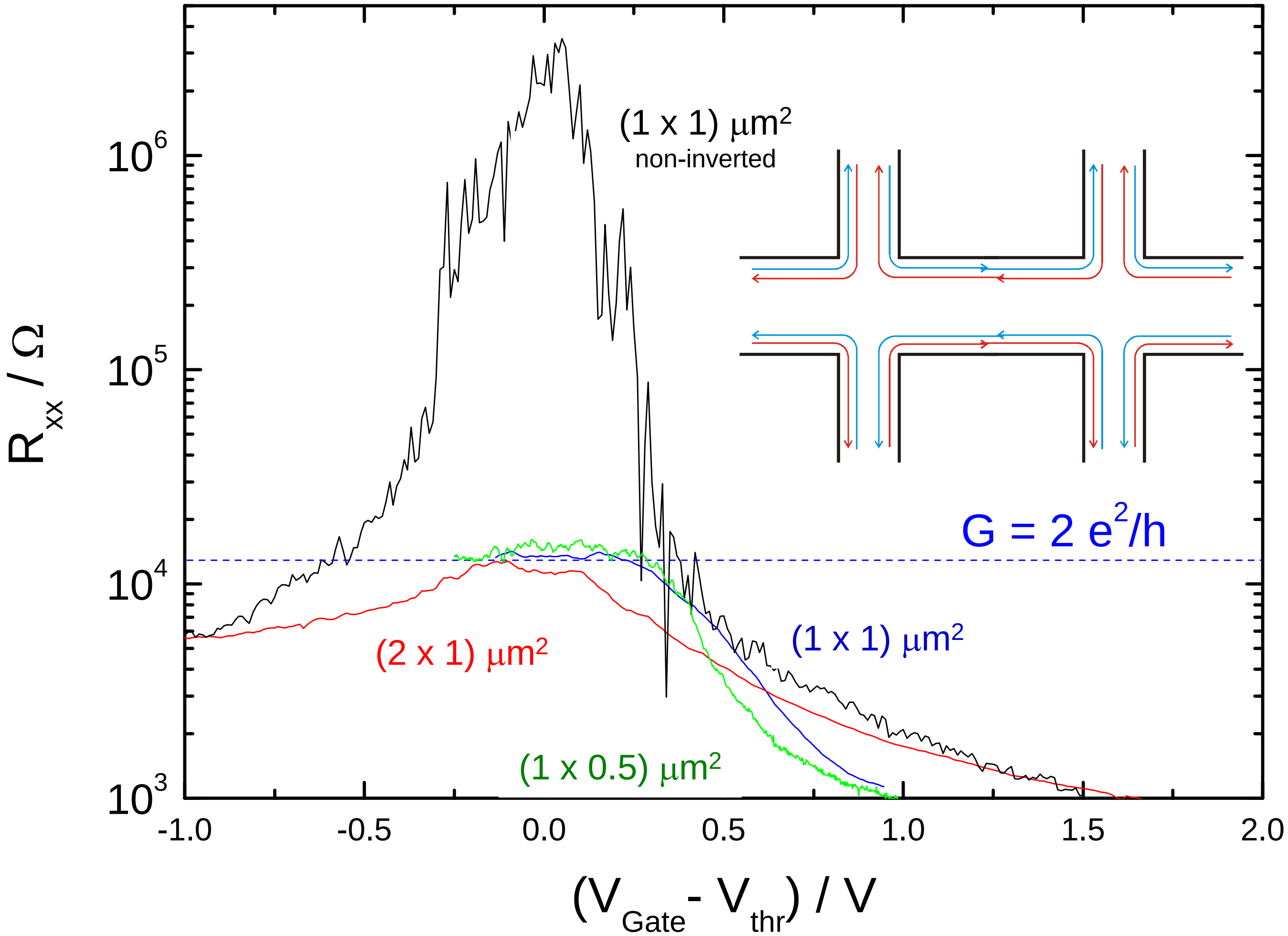
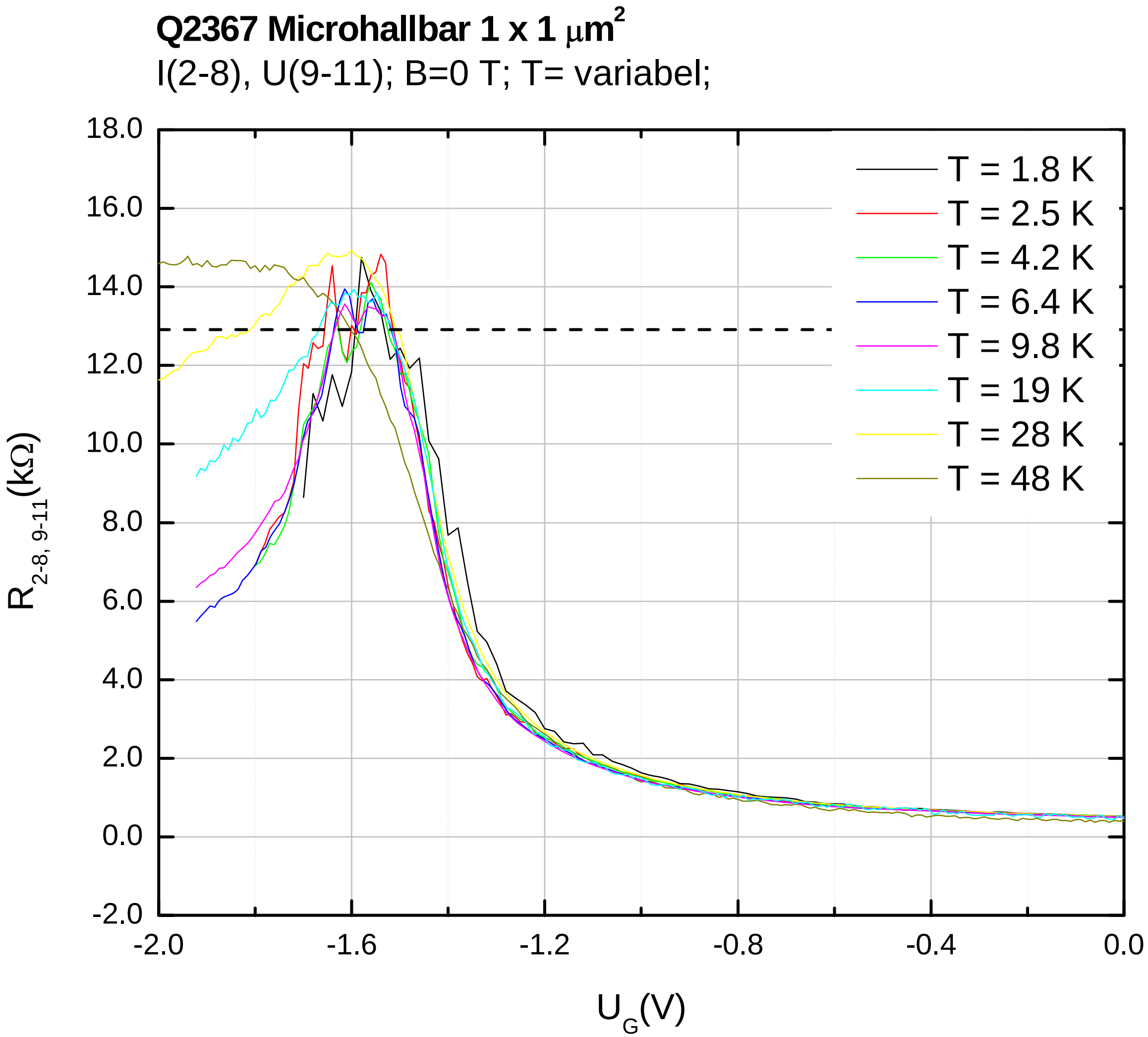


König *et al.*, Science **318**, 766 (2007)

QSHE Temperature Dependence

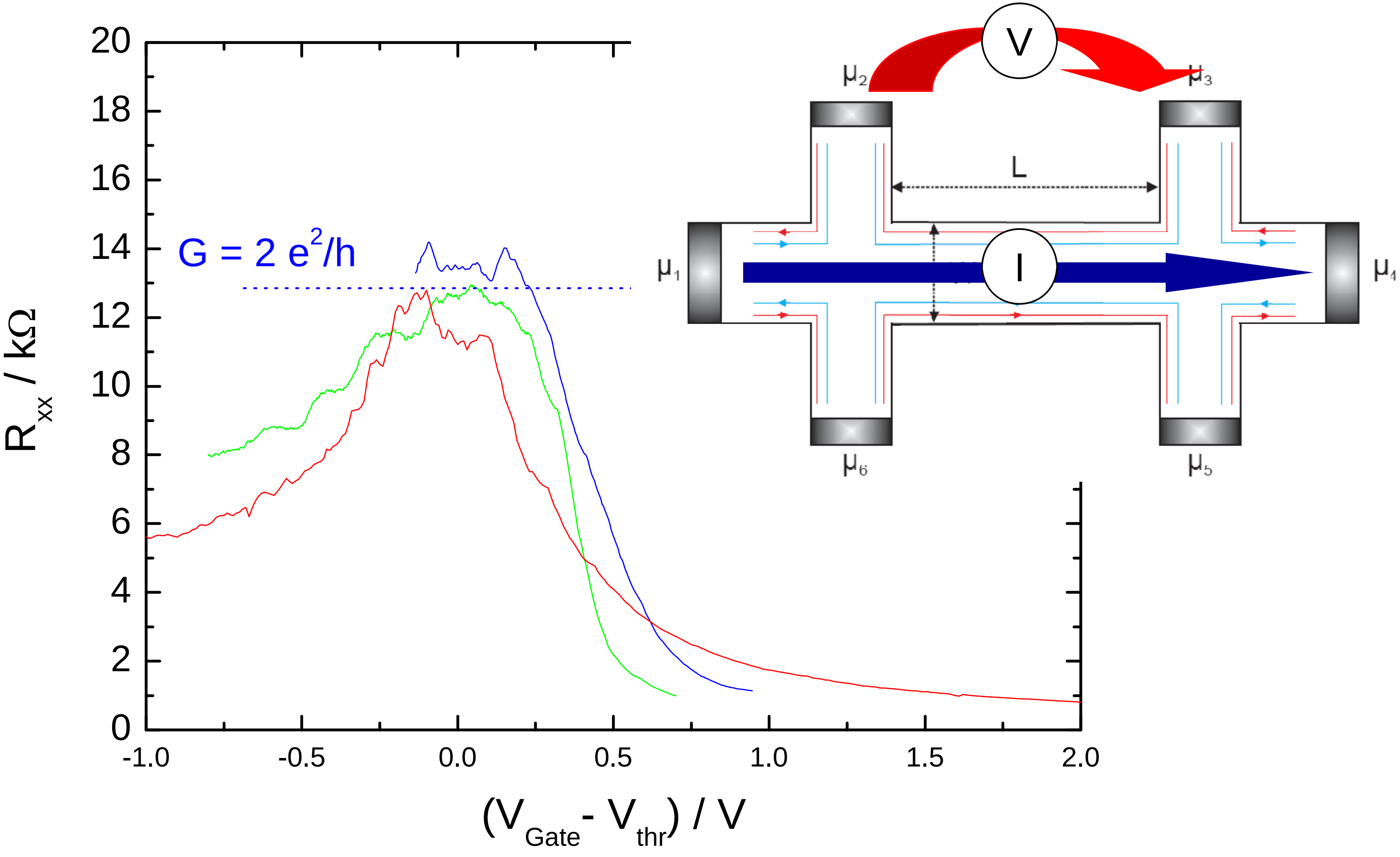


Conductance Quantization

Conductance Quantization

EP3 H. Buhmann

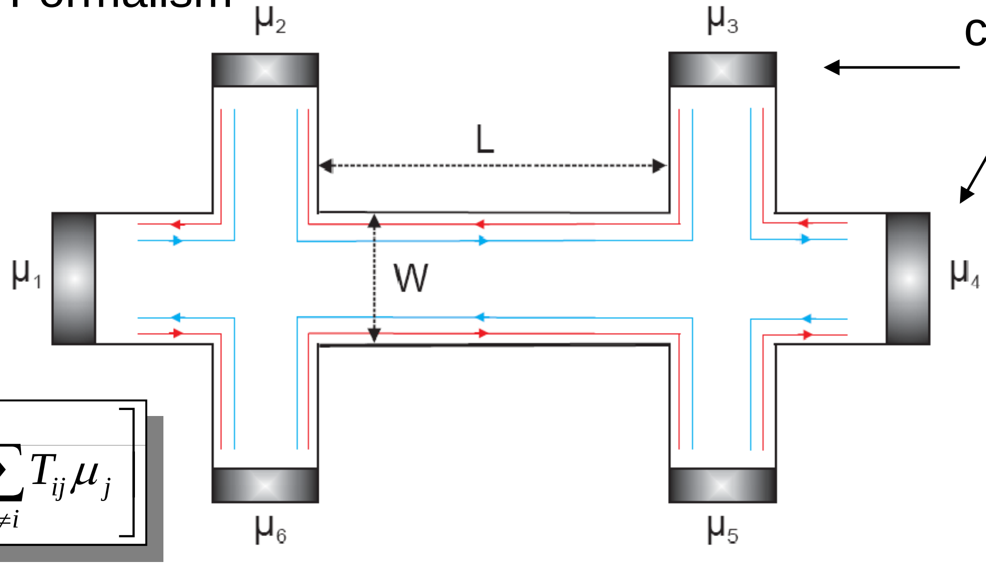
in 4-terminal geometry!?



Multi-Terminal Probe

Landauer-Büttiker Formalism

normal conducting contacts
➔ **no QSHE**



$$I_i = \frac{2e}{h}\left[(M_i - R_{ii})\mu_i - \sum_{j\neq i} T_{ij}\mu_j\right]$$

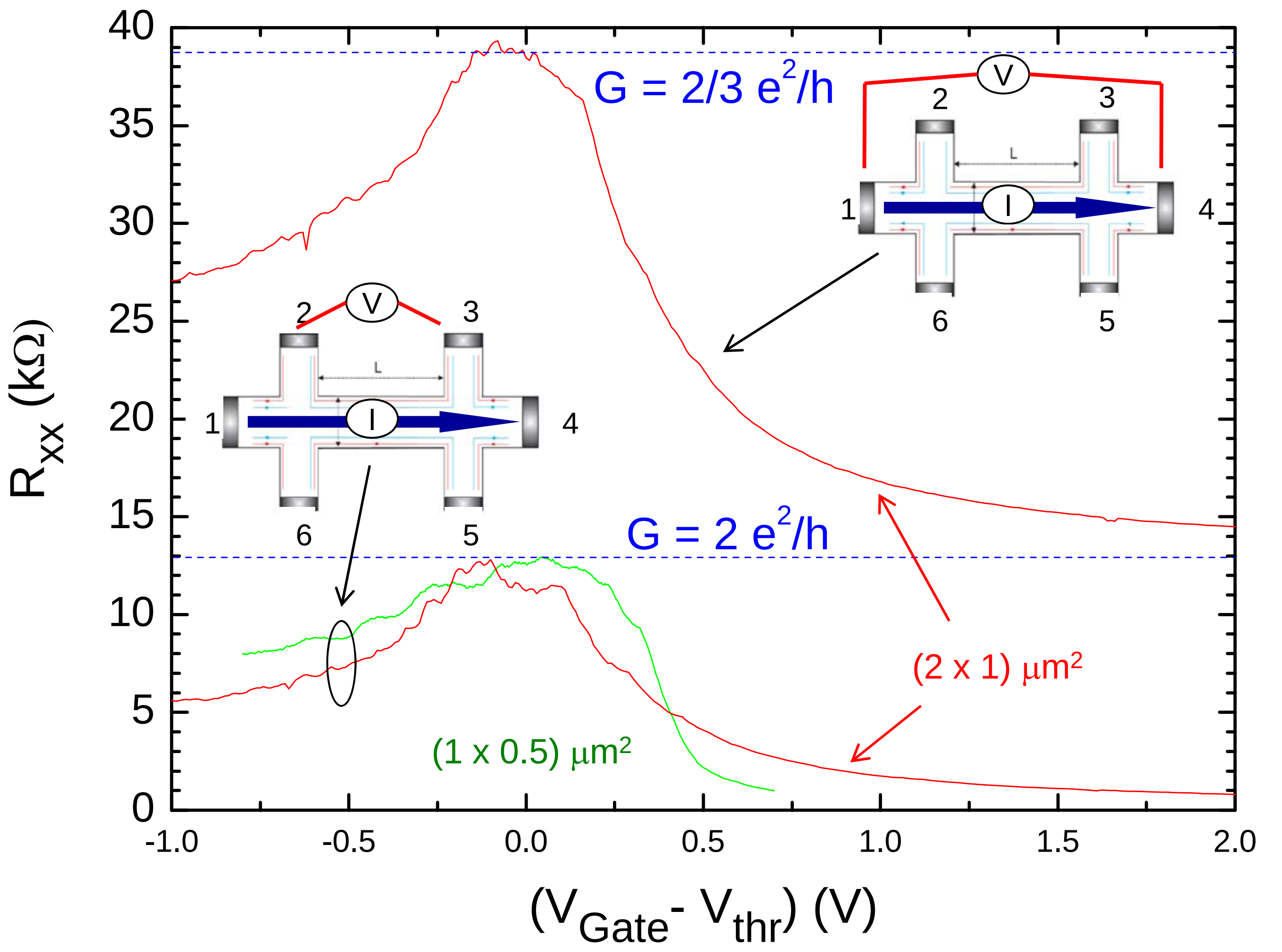
$$T = \begin{pmatrix} -2 & 1 & 0 & 0 & 0 & 1 \\ 1 & -2 & 1 & 0 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 & 0 \\ 0 & 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 1 & -2 & 1 \\ 1 & 0 & 0 & 0 & 1 & -2 \end{pmatrix} \Rightarrow \begin{cases} G_{4t} = \dfrac{I_{14}}{\mu_3 - \mu_2} = \dfrac{2e^2}{h} \\ G_{2t} = \dfrac{I_{14}}{\mu_4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

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

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

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

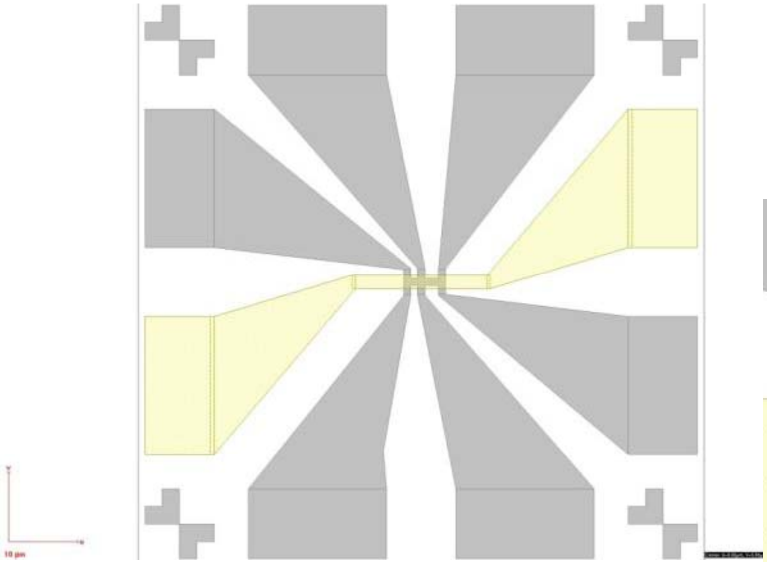
QSHE in inverted HgTe-QWs

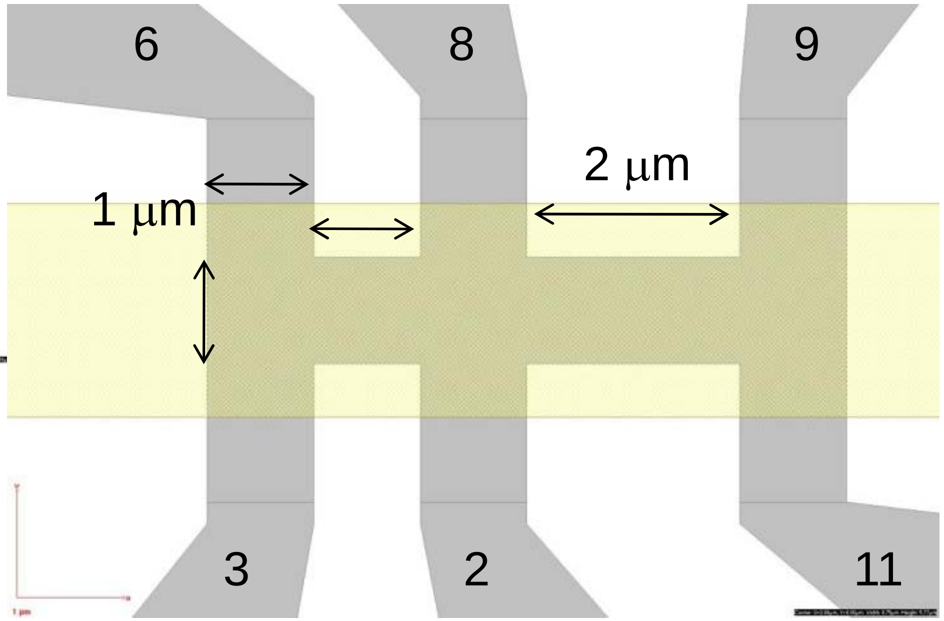


$$\frac{R_{2t}}{R_{4t}} \approx 3$$

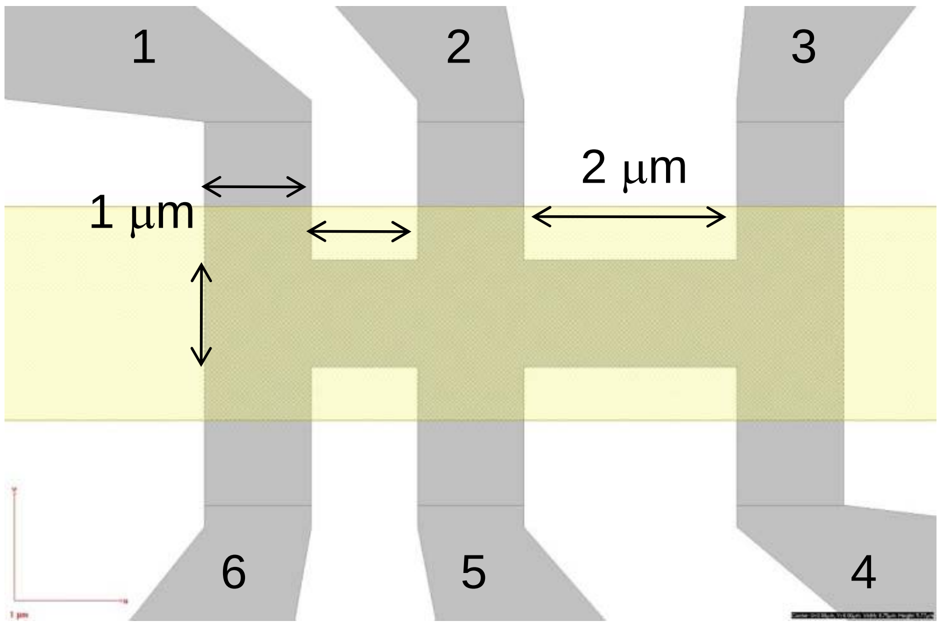
Non-locality

Q2308: 250 | 90: 0.1 | 400 | 90 | 400 | 90: 0.1 | 1000 | n_s= 3.1x10^{11}, μ =143 000





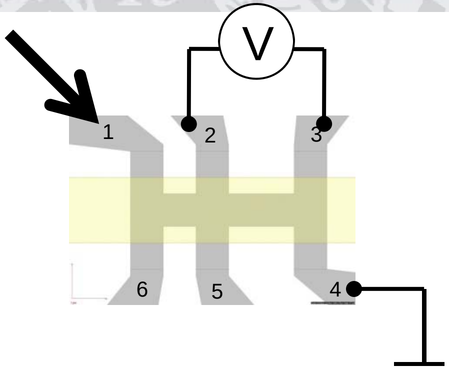
Non-locality



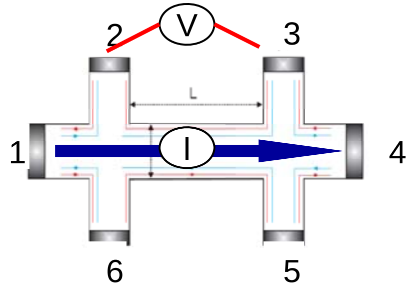
Non-locality

I: 1-4

V_{nl}:2-3

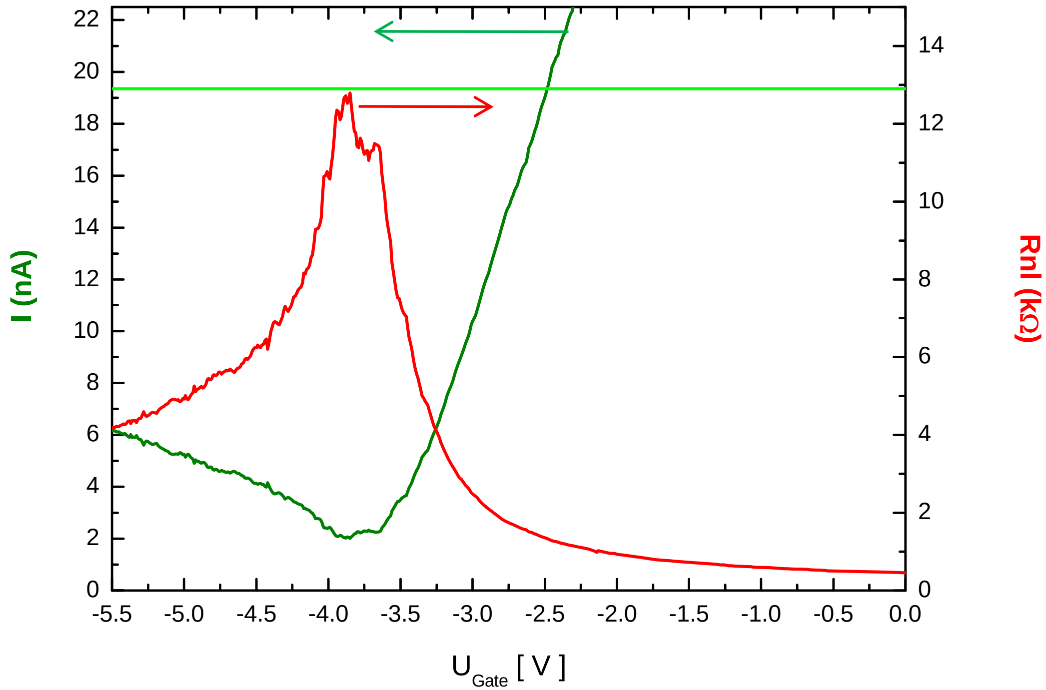


⇔



Q2308-02

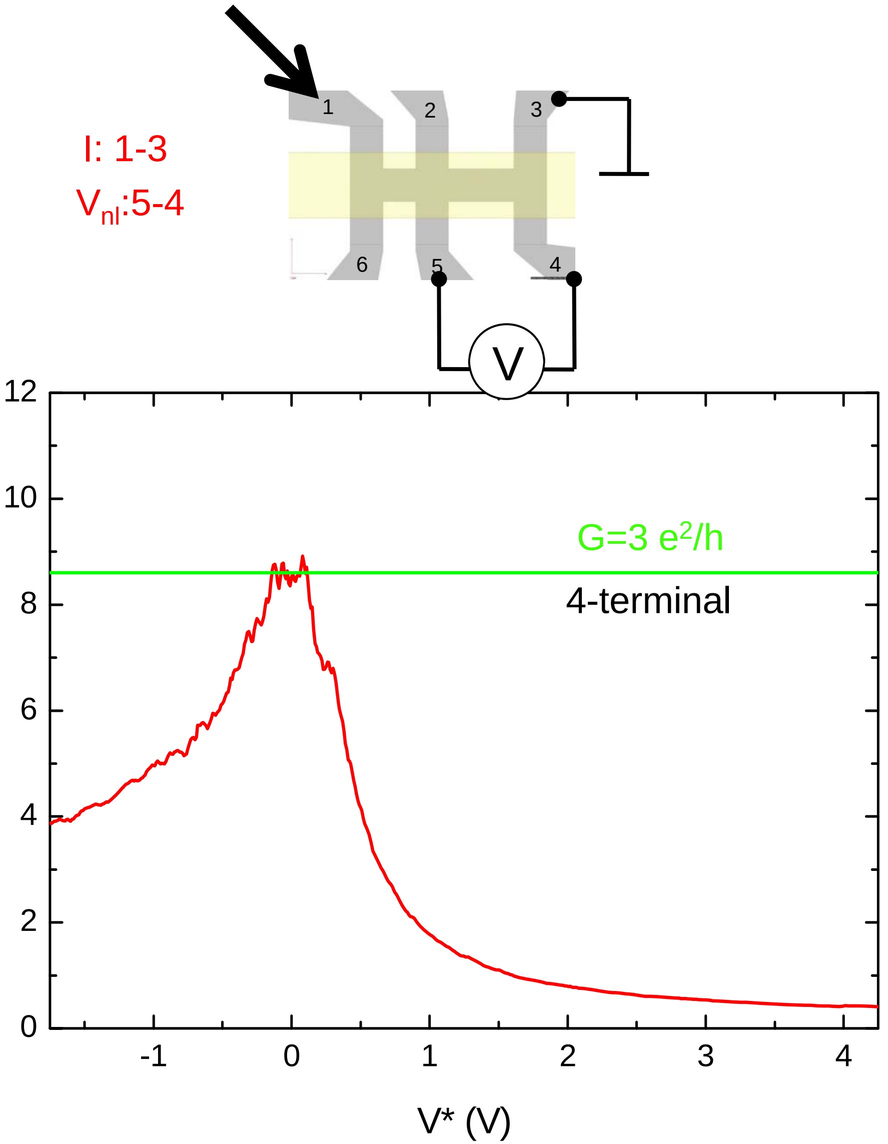
@6 mK



A. Roth, HB et al.,
Science 325,295 (2009)

Non-locality

LB: 8.6 kΩ



A. Roth, HB et al.,
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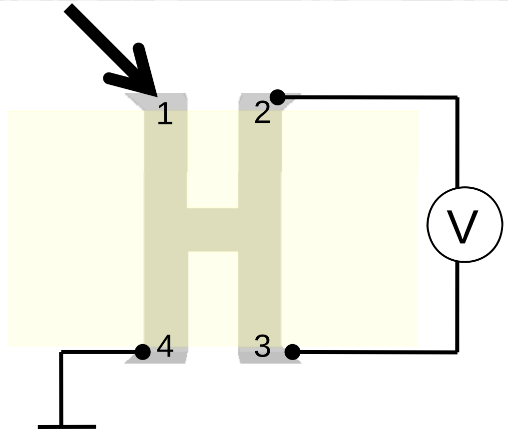
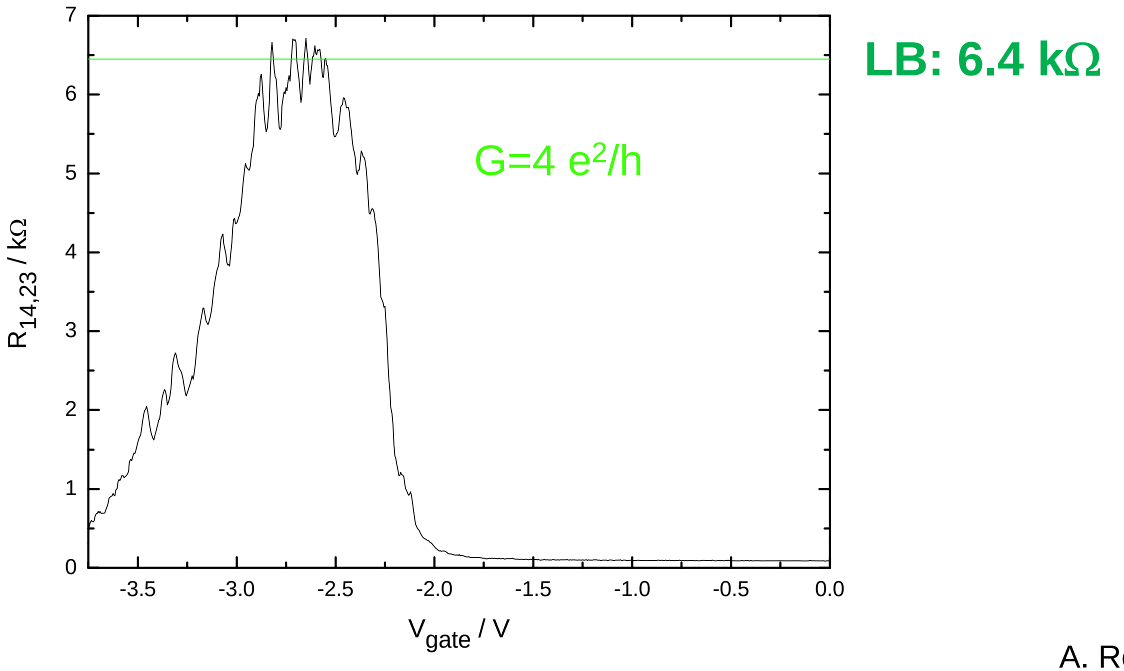
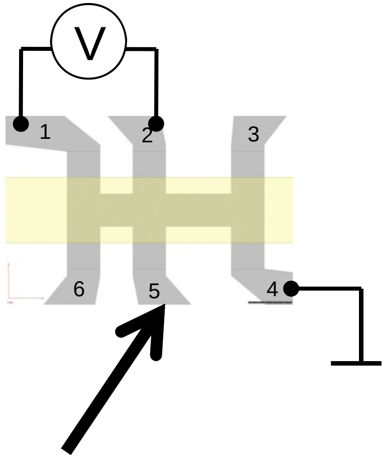


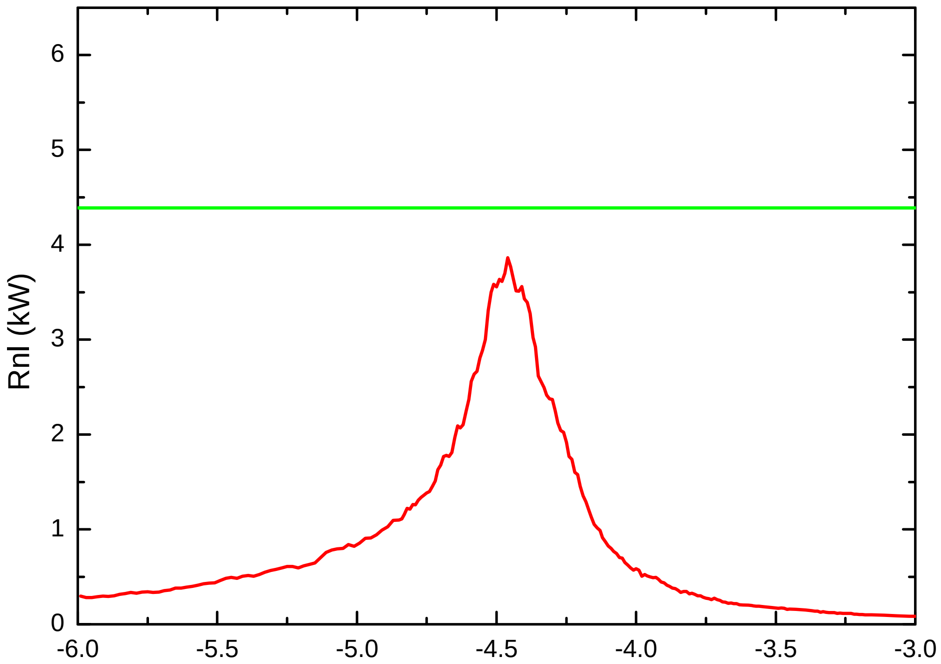


A. Roth, HB et al., Science 325,295 (2009)

Non-locality



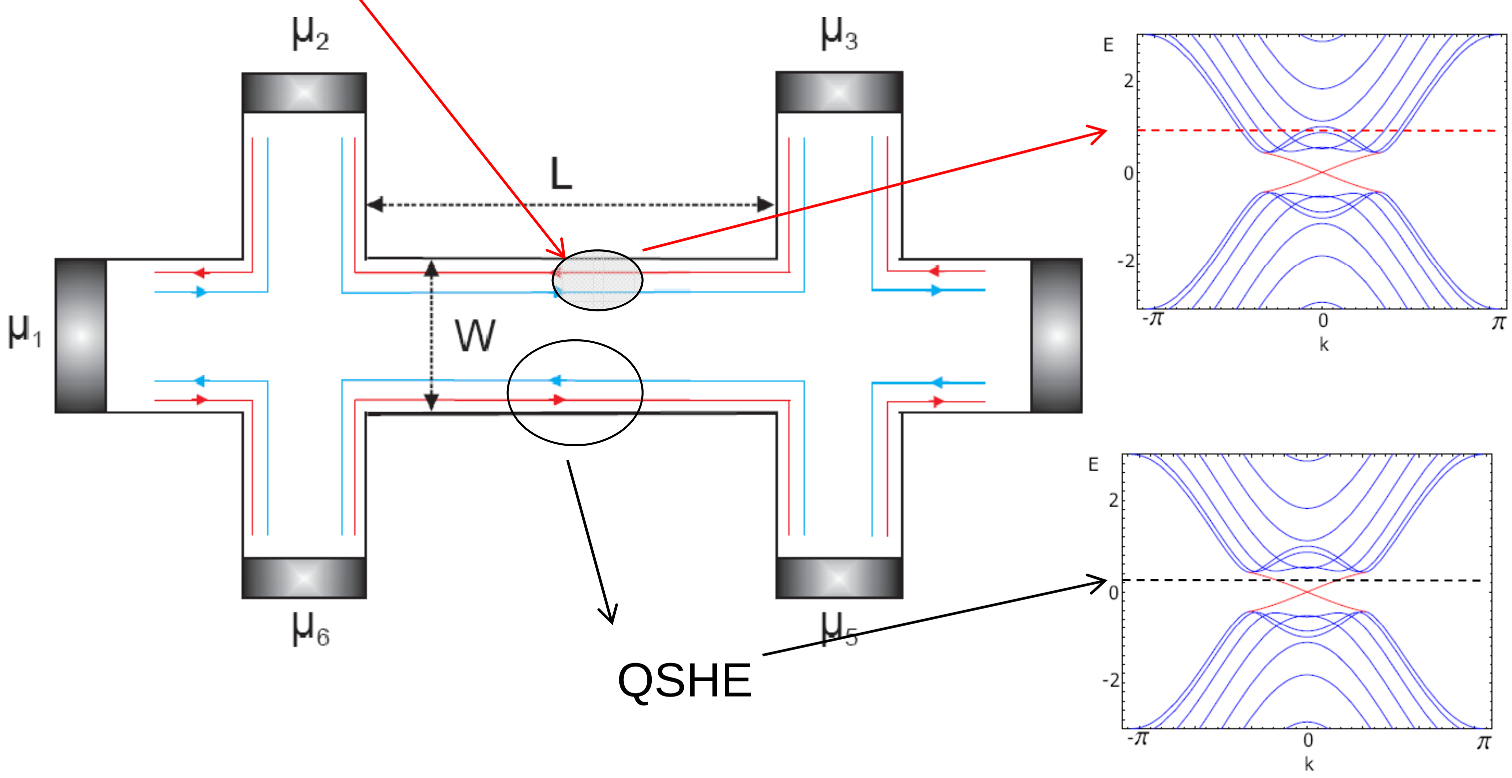
LB: 4.3 kΩ



A. Roth, HB et al.,
Science 325,295 (2009)

Back Scattering

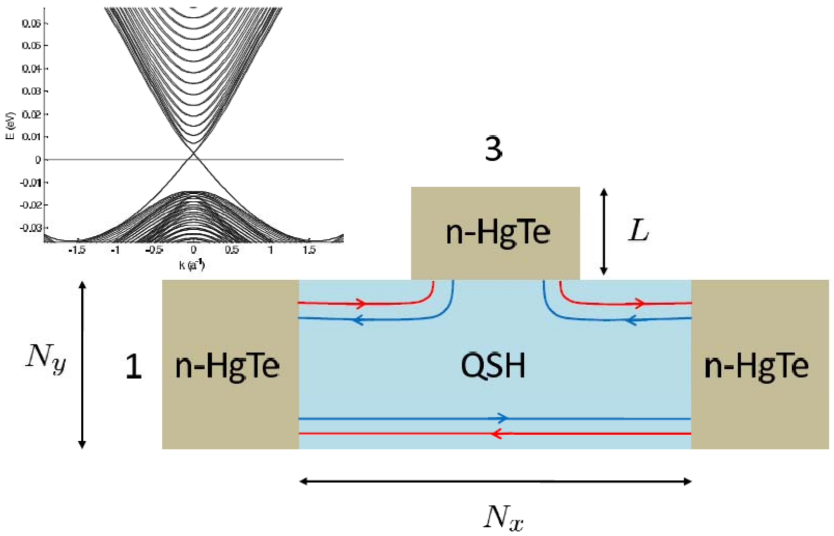
potential fluctuations introduce areas of normal metallic (n- or p-) conductance in which back scattering becomes possible

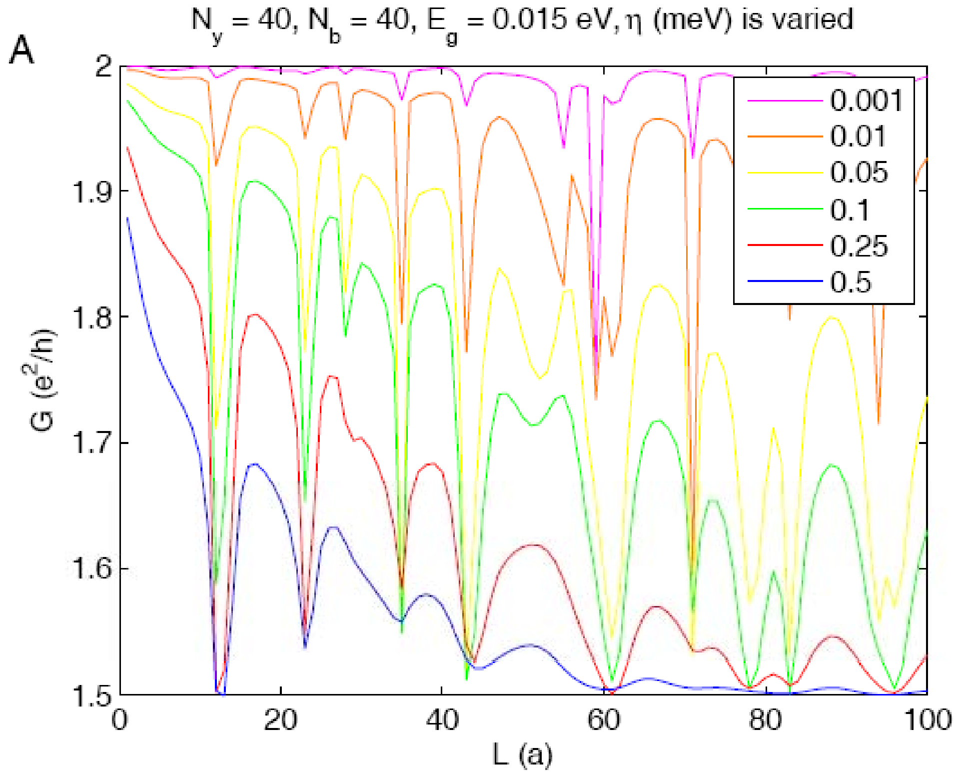


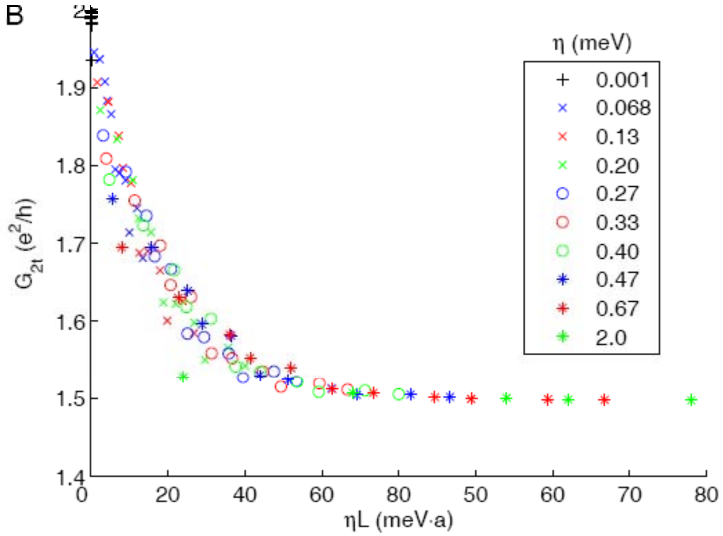
The potential landscape is modified by gate (density) sweeps!

Additional Scattering Potential

Transition from **2 e^2/h** to **3/2 e^2/h**







A. Roth, HB et al.,
Science 325,295 (2009)

Potential Fluctuations

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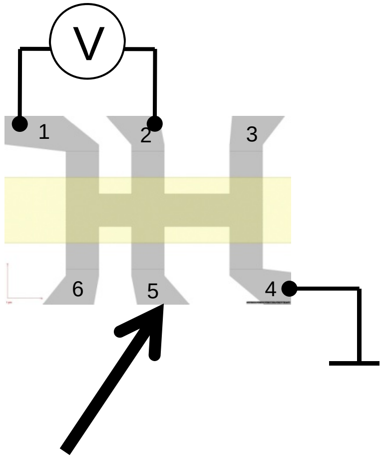
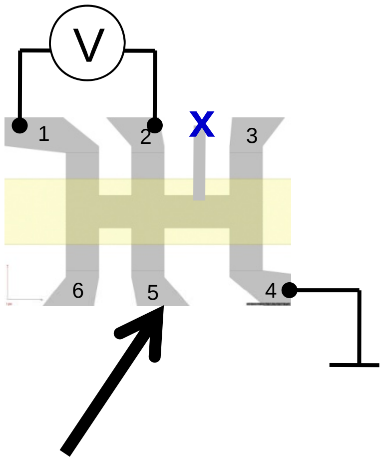
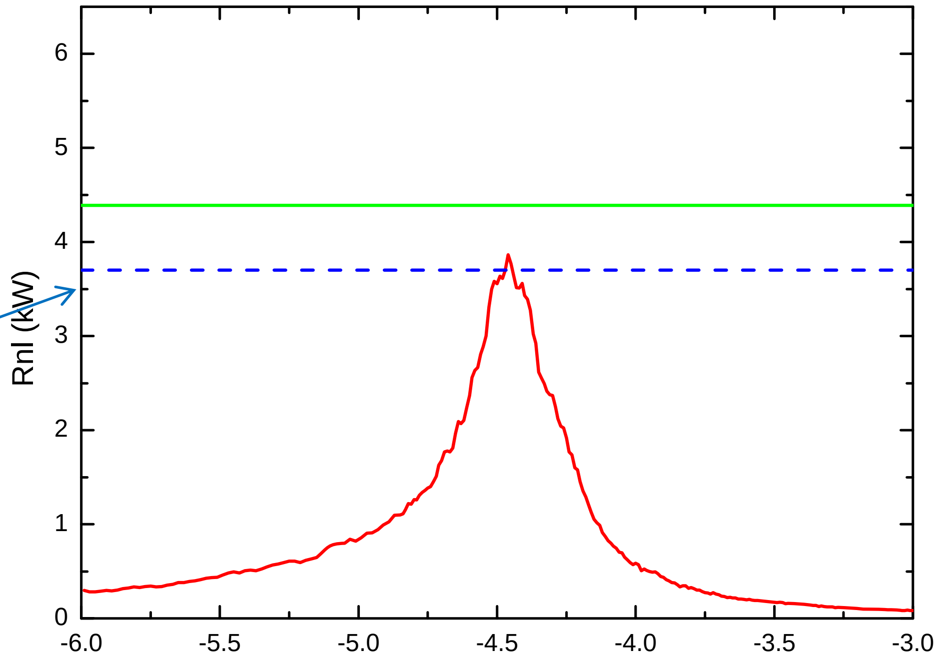


LB: 4.3 kΩ

one additional contact:
• between 2 and 3
➔ **3.7 kΩ**

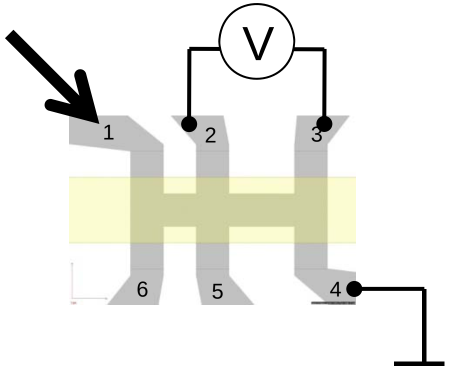




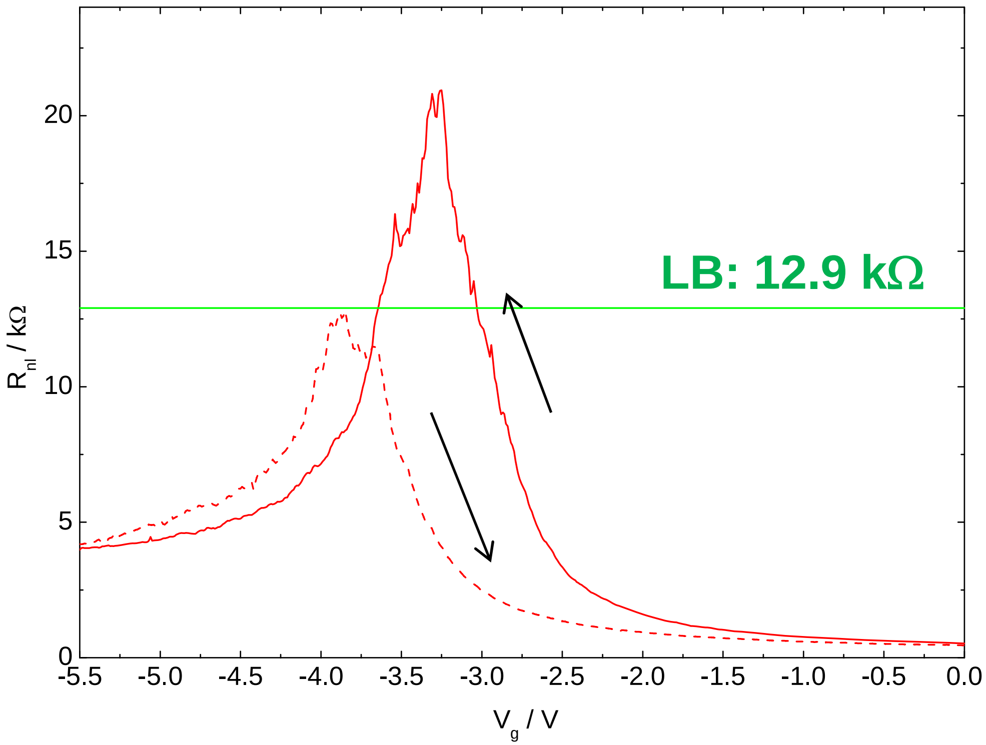
A. Roth, HB et al.,
Science 325,295 (2009)

Potential Fluctuations

different gate sweep direction



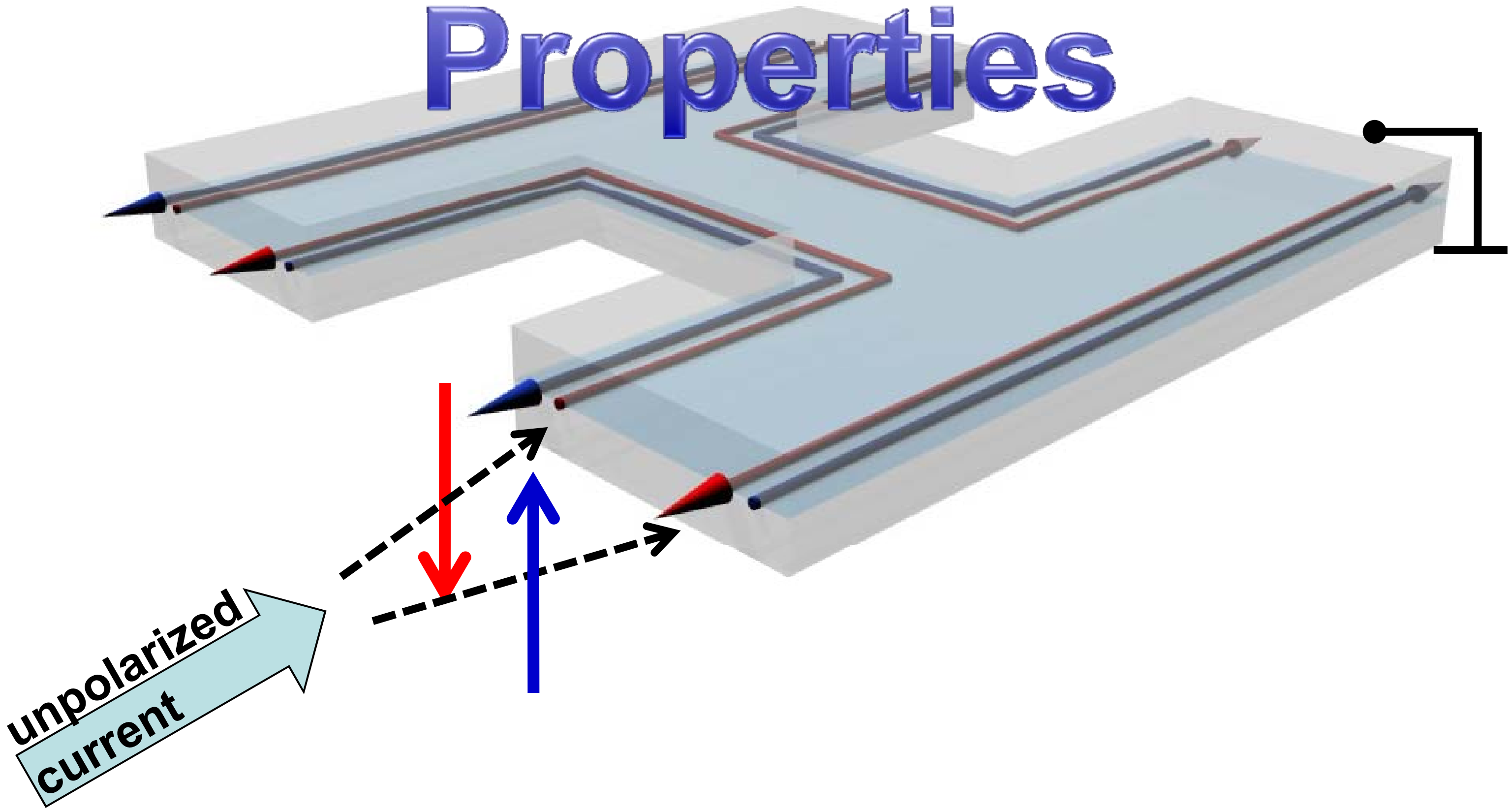
control of backscattering



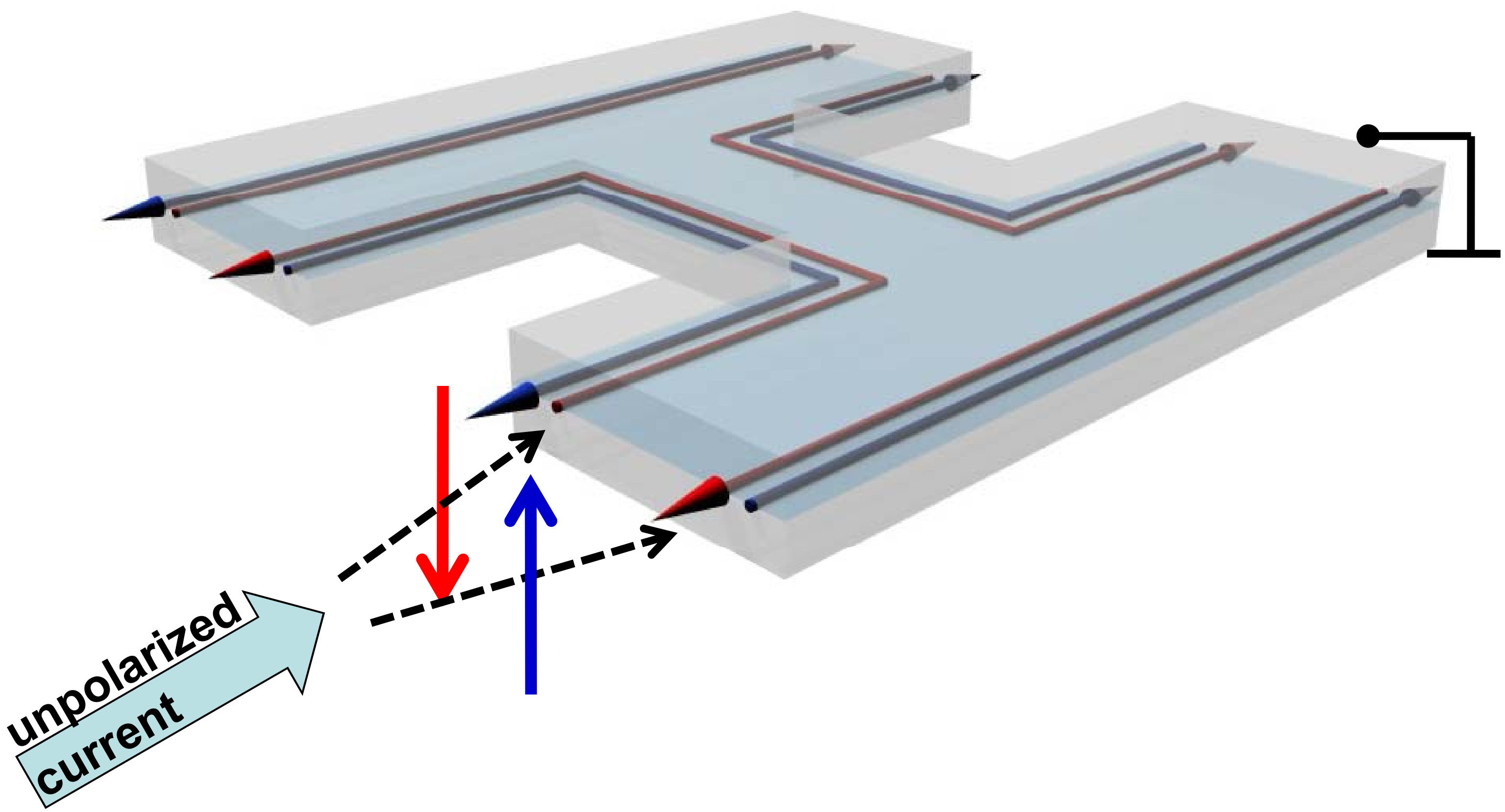
- Hysteresis effects due to charging of trap states at the SC-insulator interface

J. Hinz, HB *et al*., Semicond. Sci. Technol. **21 (2006) 501–506**

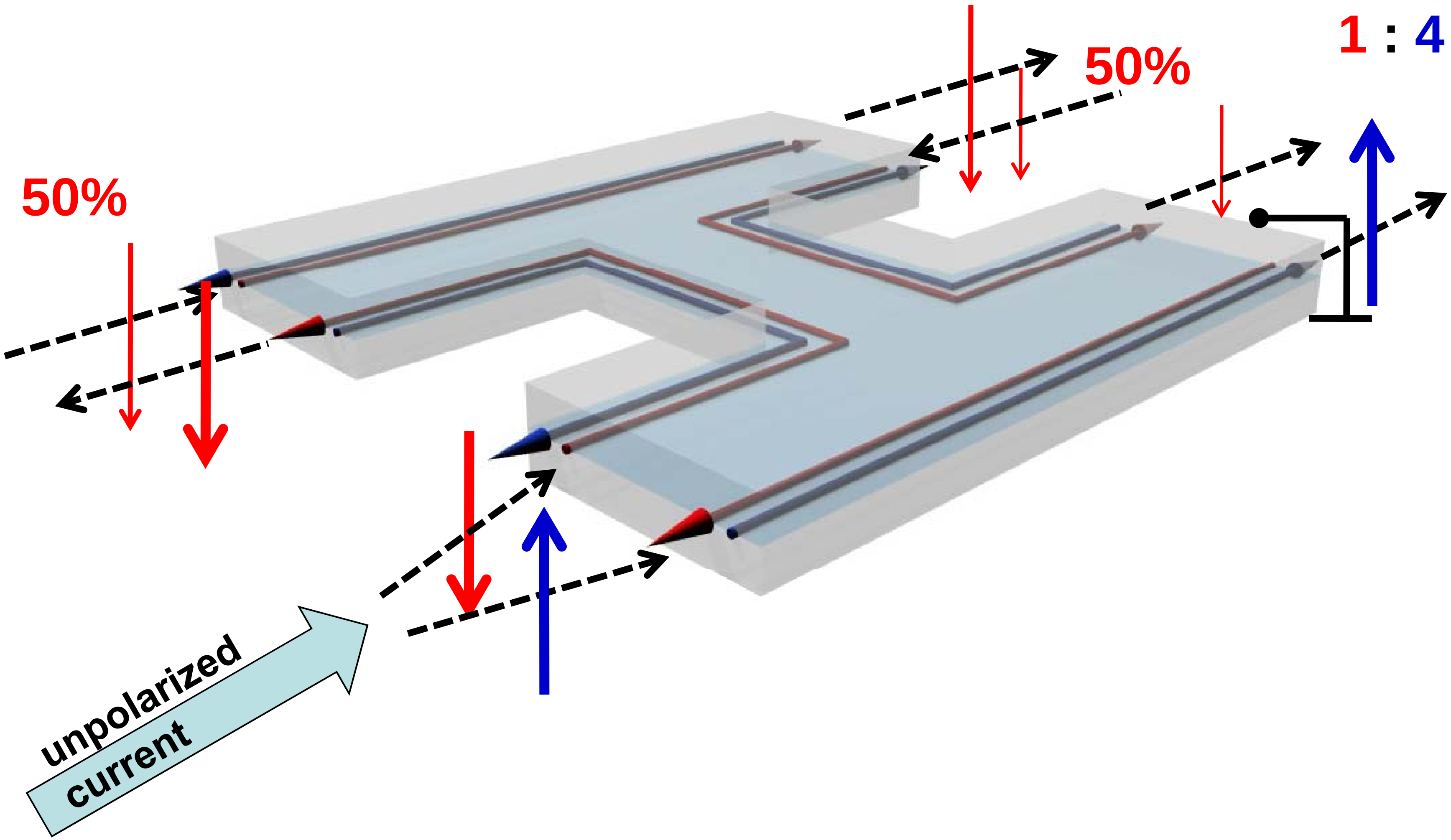
Spin Polarizing Properties



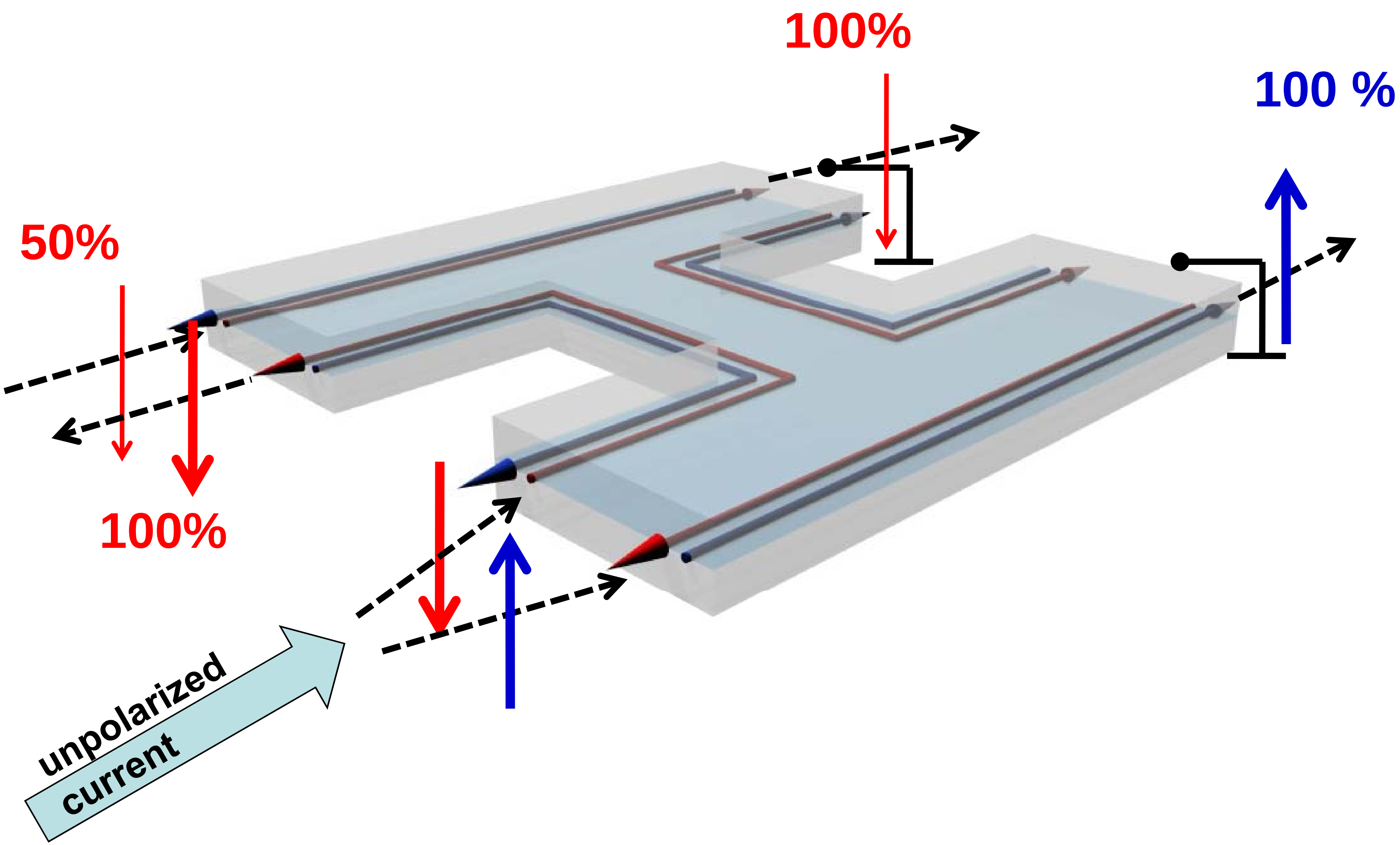
Spin Polarizer



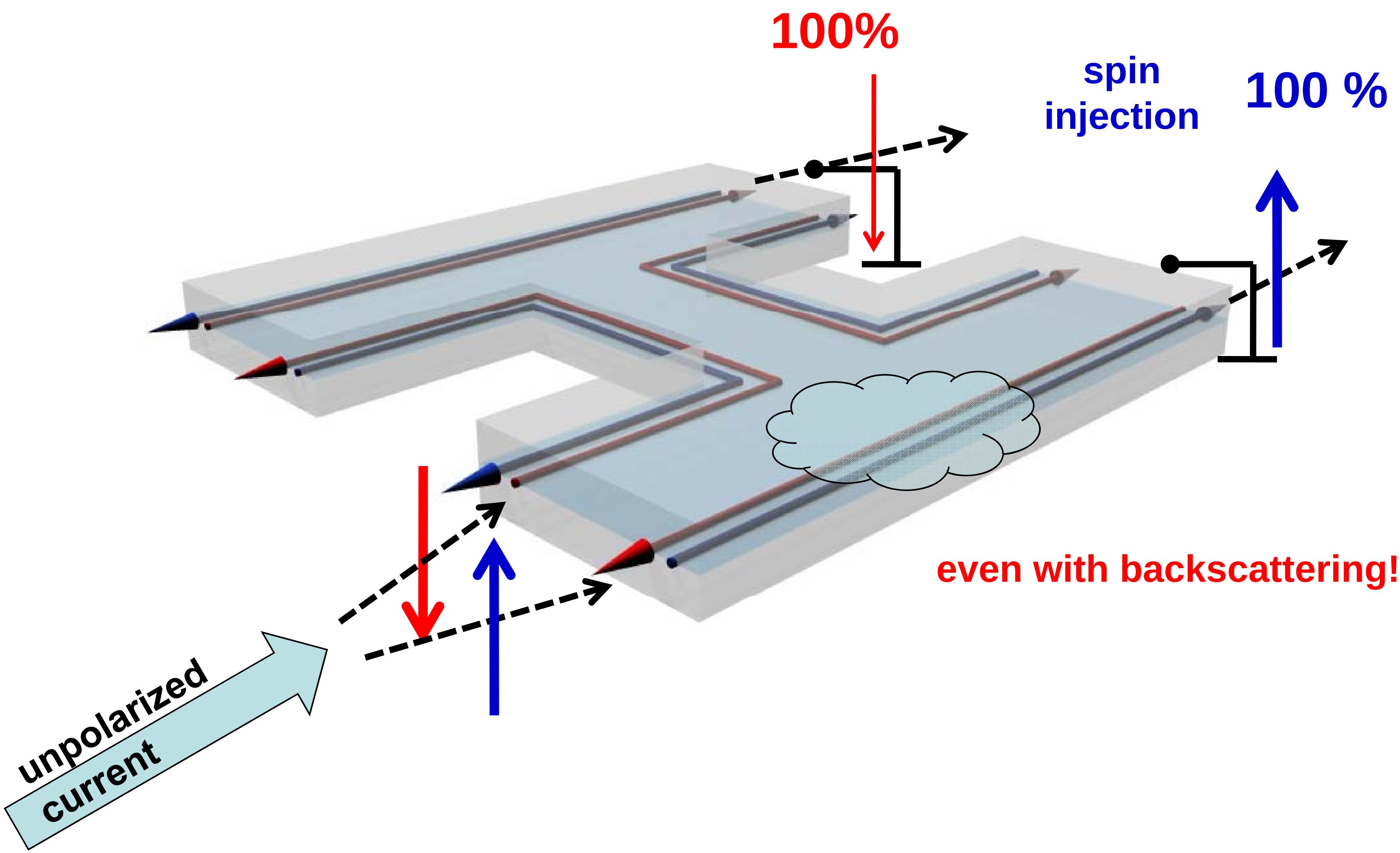
Spin Polarizer



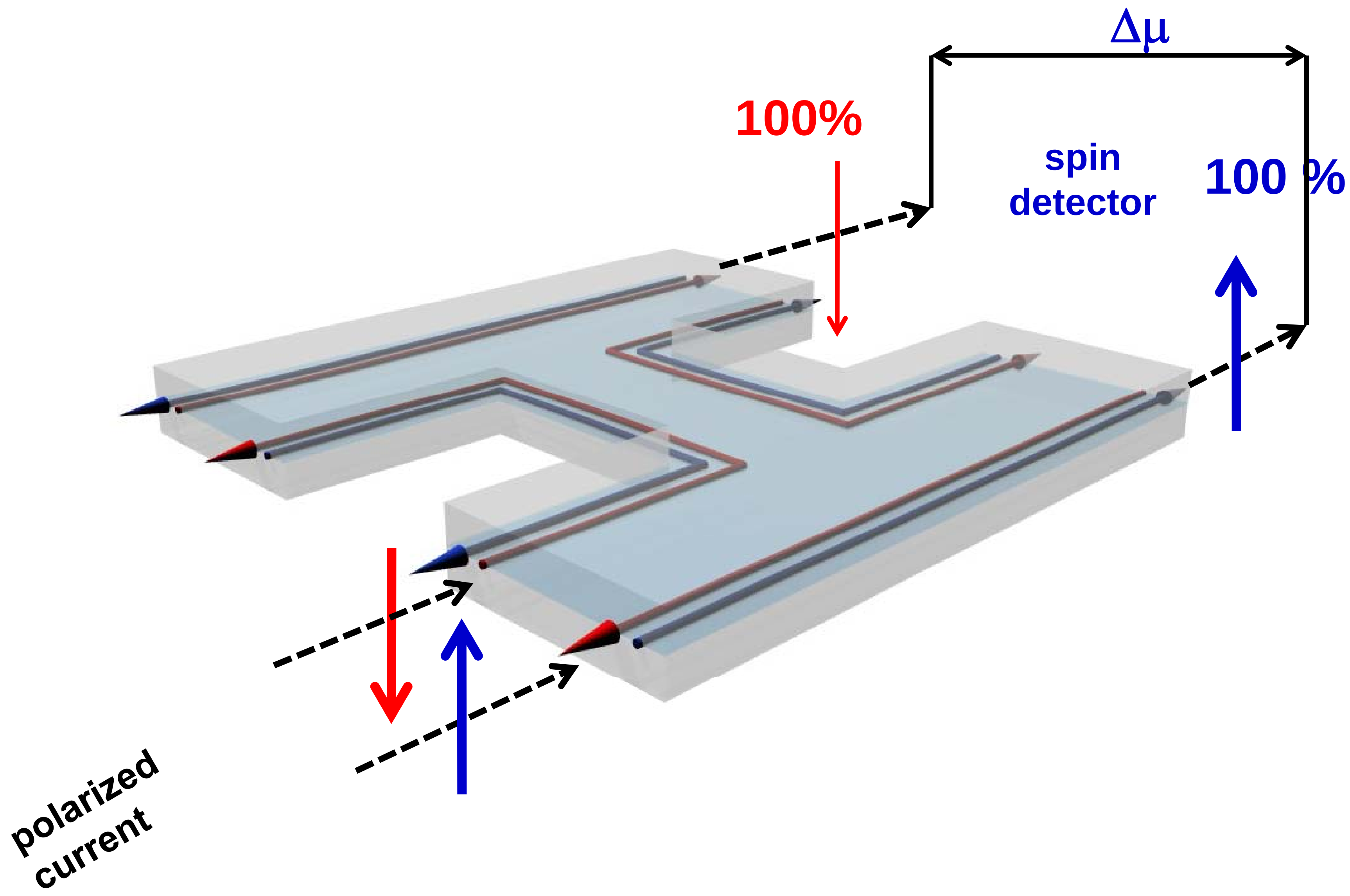
Spin Polarizer



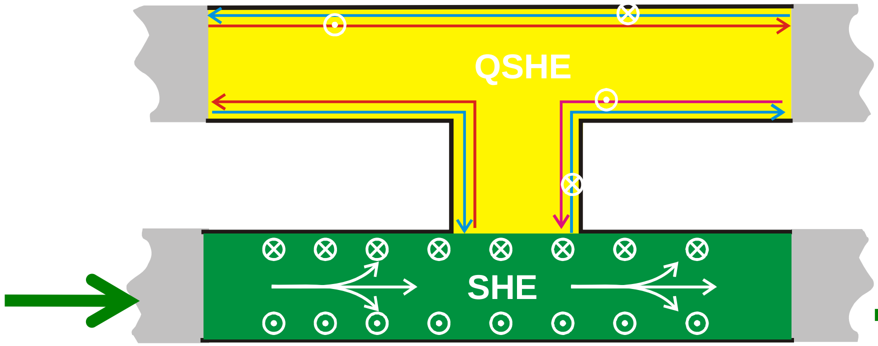
Spin Injector

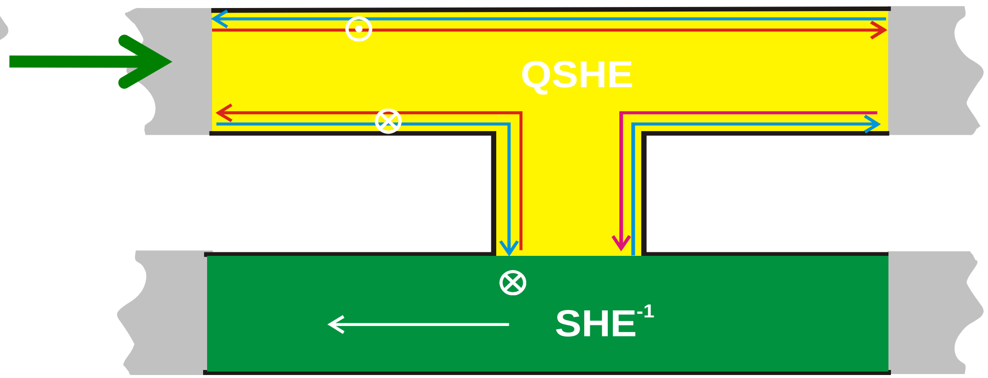


Spin Detection



QSHE as spin detector and injector





Spin Hall Effect
as creator and analyzer of
spin polarized electrons

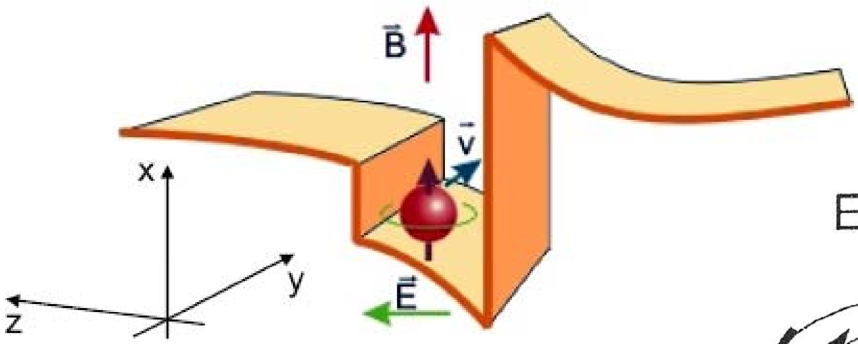
Rashba Effect

H. Buhmann

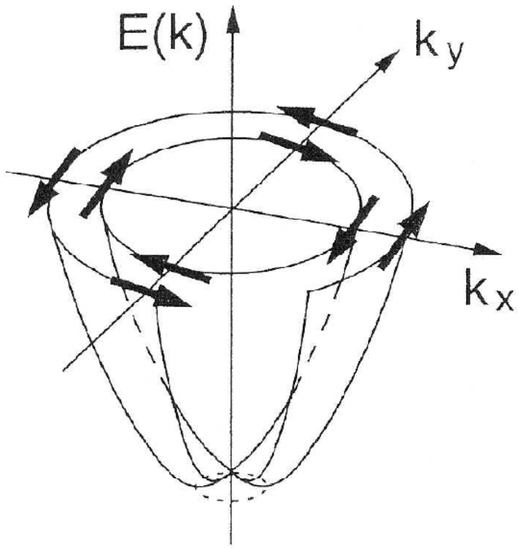
structural inversion asymmetry (SIA)

Y.A. Bychkov and E.I. Rashba, JETP Lett. **39**, 78 (1984); J. Phys. C **17**, 6039 (1984):

Rashba-Term: $$H_R = \alpha_R \left(\sigma_x k_y - \sigma_y k_x \right)$$



$$\boldsymbol{B}_{eff} \propto \boldsymbol{p} \times \boldsymbol{E}$$



$$E^{\pm} = E_i + \frac{\hbar^2 k_{\parallel}^2}{2m^*} \pm \alpha k_{\parallel}$$

(for electrons)

$$E^{\pm} = E_i + \frac{\hbar^2 k_{\parallel}^2}{2m^*} \pm \beta k_{\parallel}^3$$

(for holes)

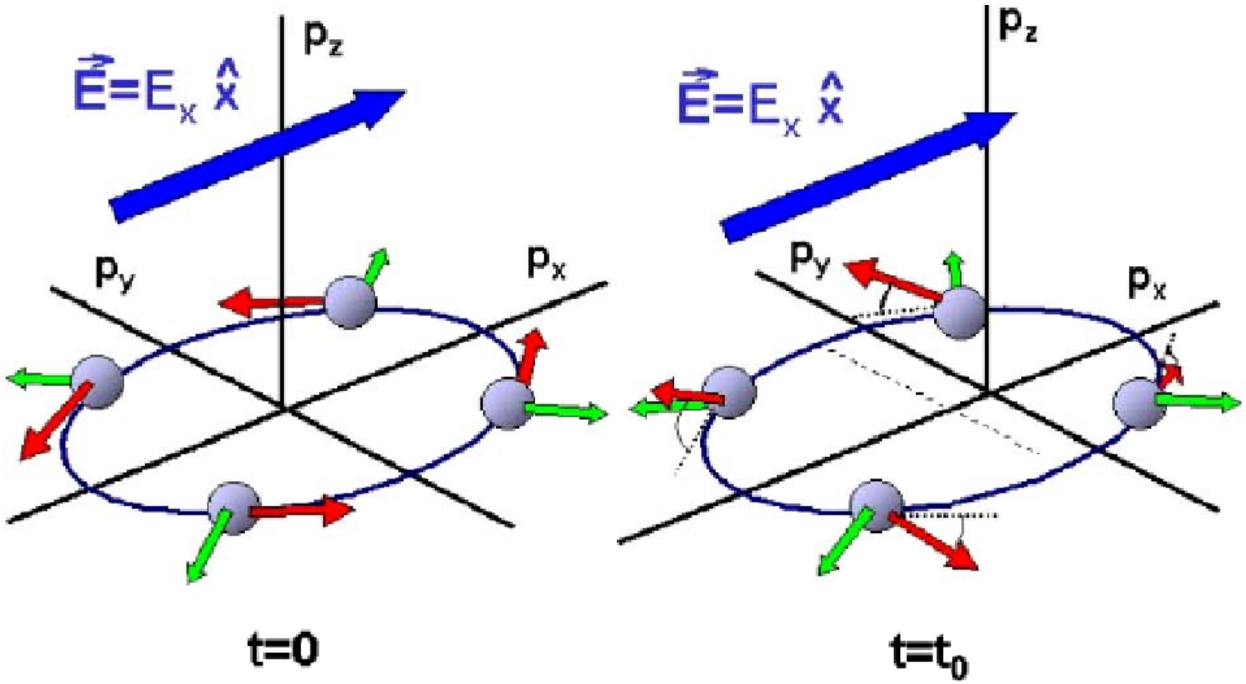
Origin of the Spin-Hall Effect

EP3
H. Buhmann

$$\mathbf{B}_{eff} \propto \mathbf{p} \times \left(\mathbf{E}_z + \mathbf{E}_x\right)$$

intrinsic

2DEG

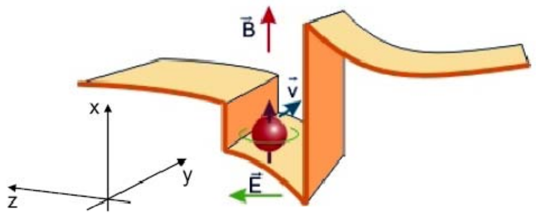


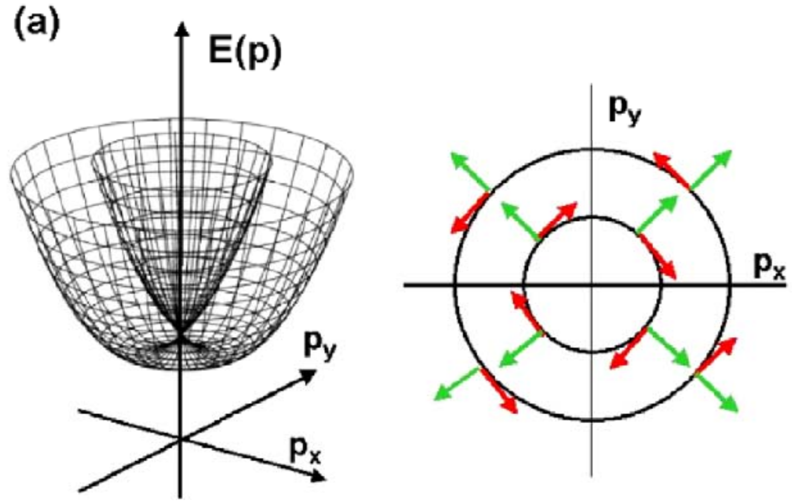
J.Sinova et al.,
Phys. Rev. Lett. **92**, 126603 (2004)

Rashba and Spin-Hall Effect

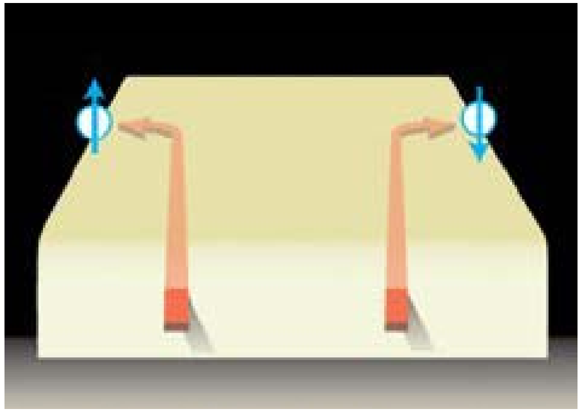
intrinsic SHE

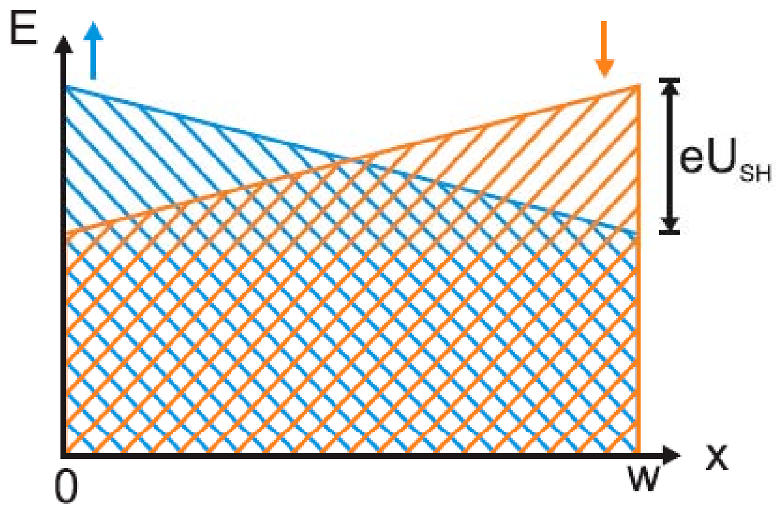
Rashba effect



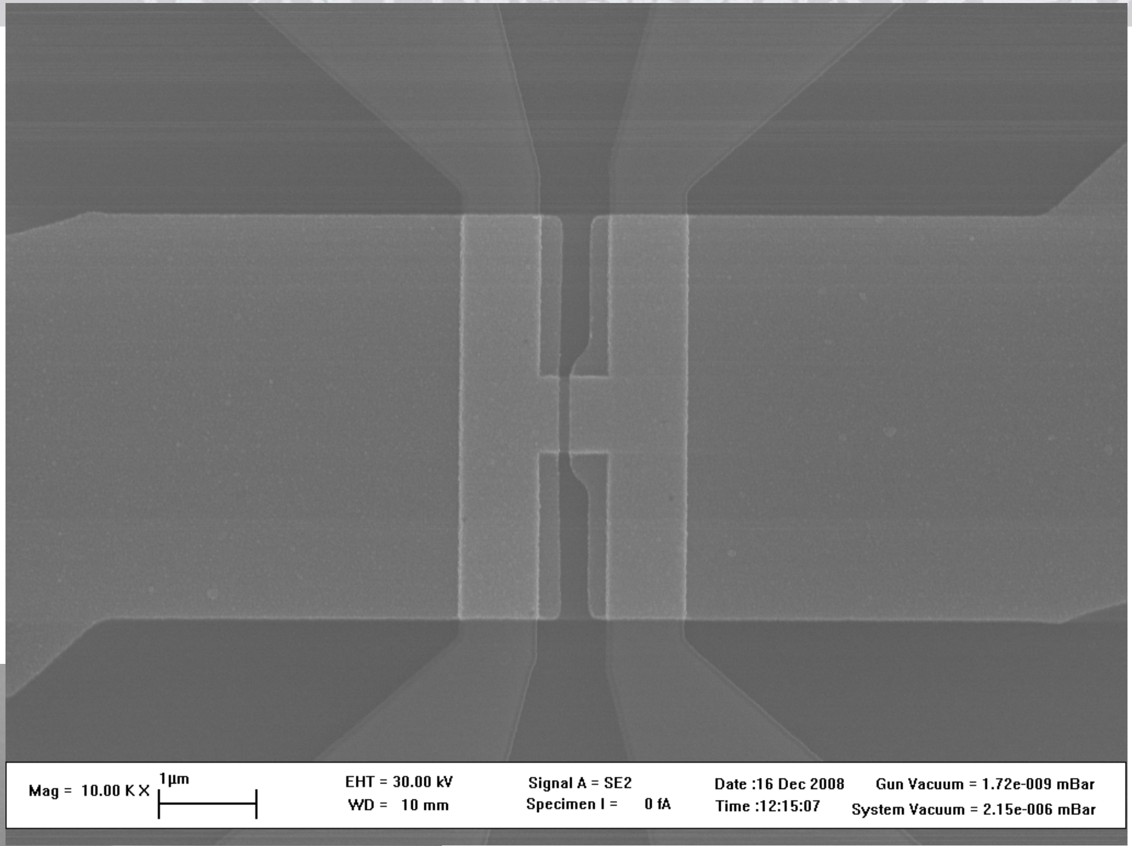


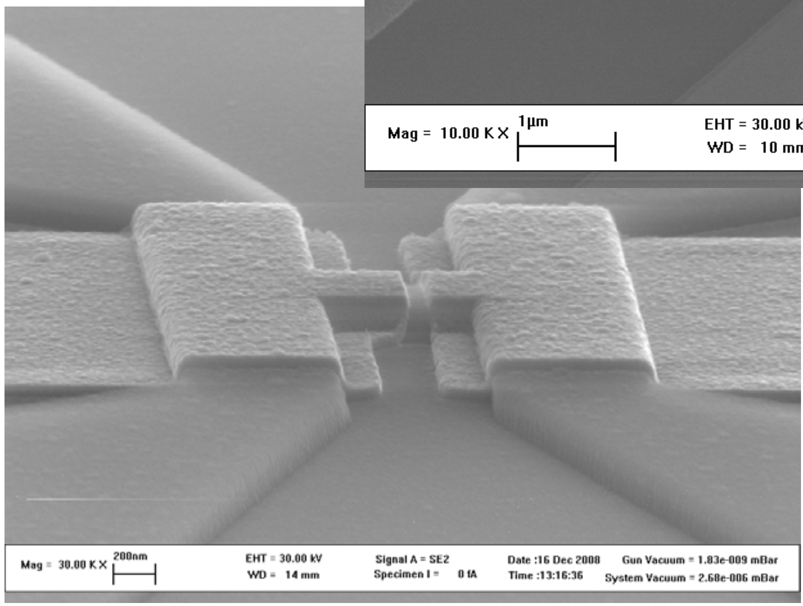
$$B_{eff} \propto p \times E$$



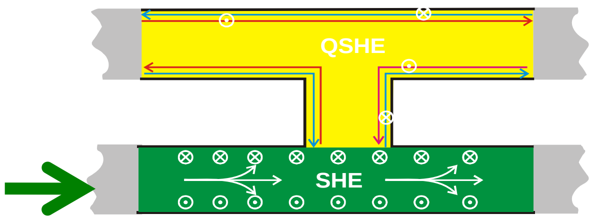


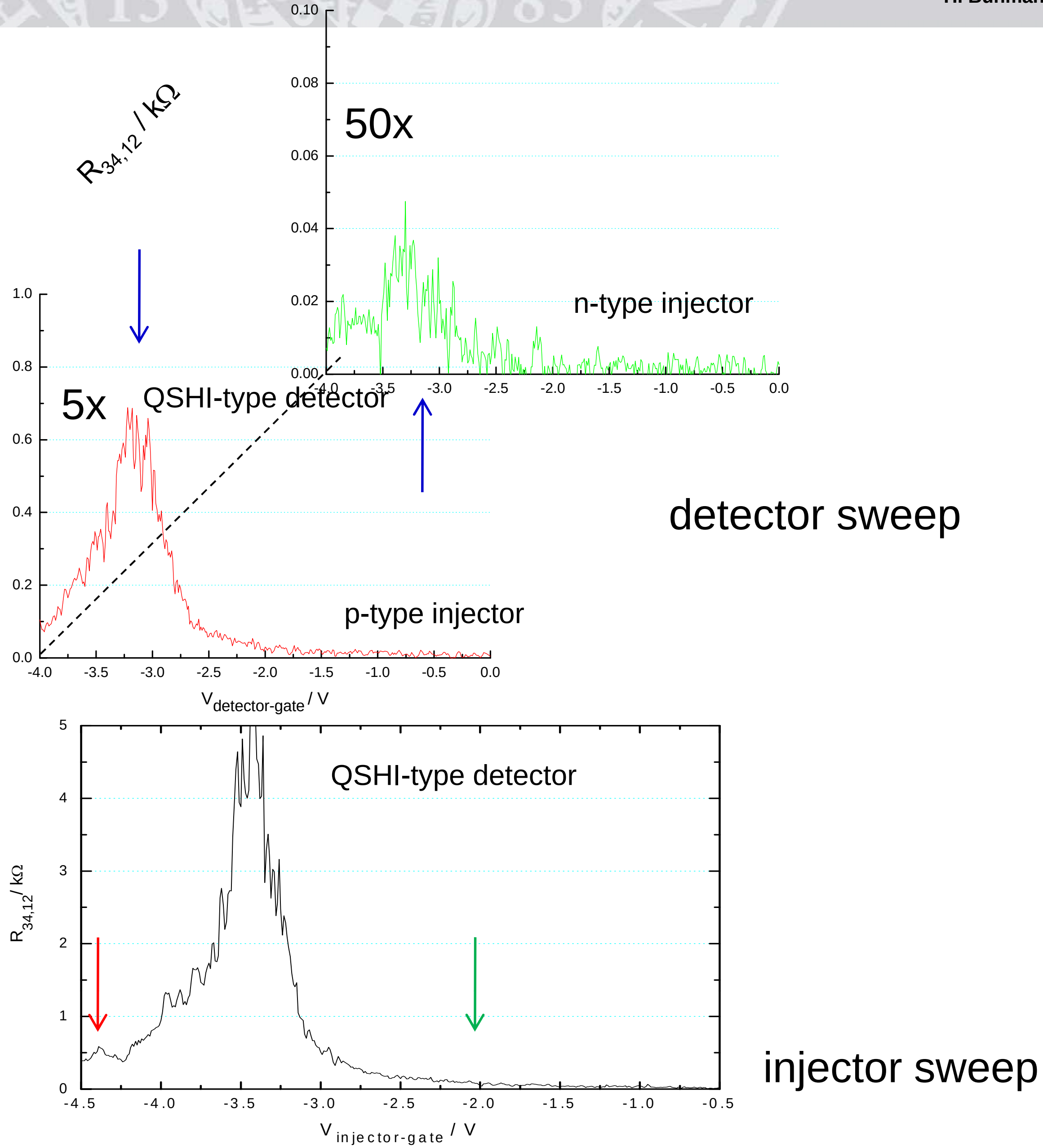
Split Gate H-Bar





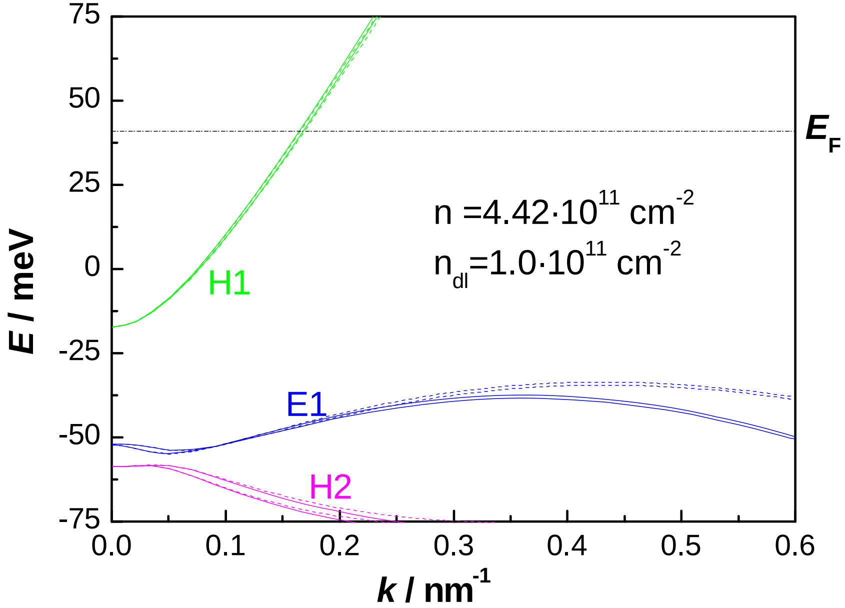
QSHE Spin-Detector



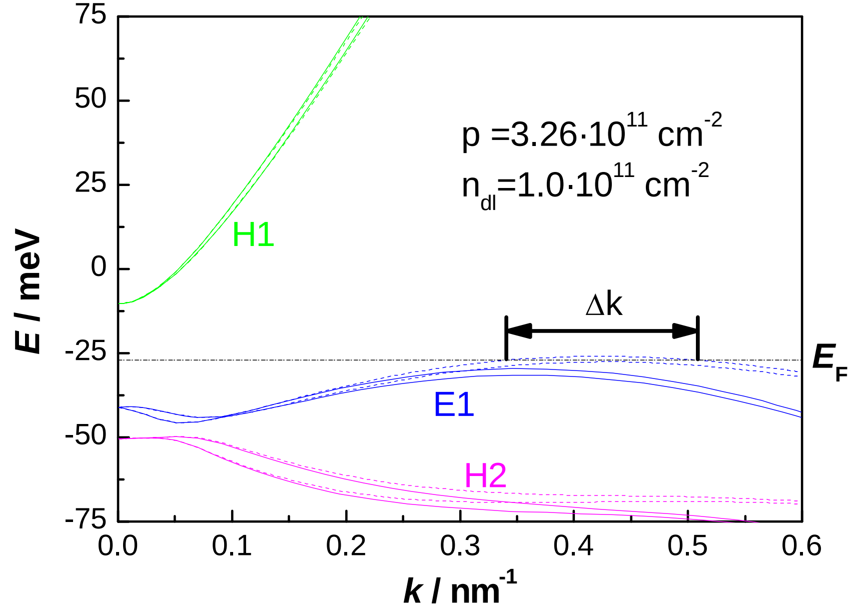


Q2198

n-regime



p-regime



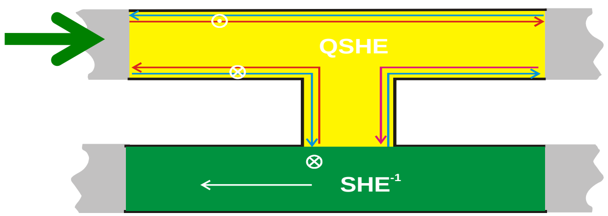
Intrinsic Spin Hall Effekt
Nature Physics
Published online: 02 May 2010
doi:10.1038/nphys1655

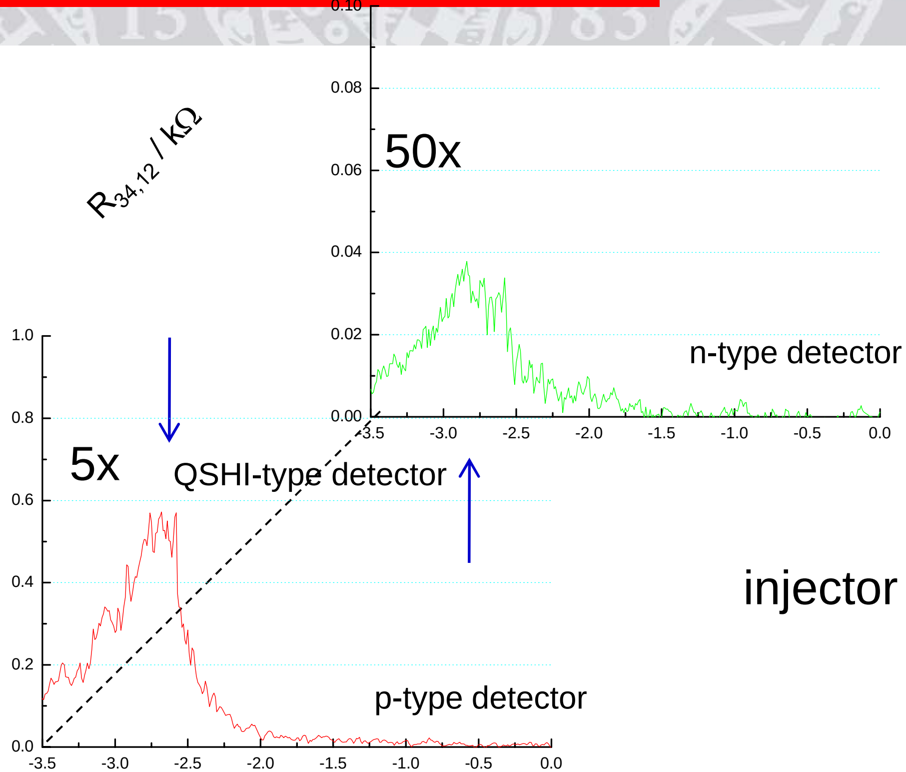
$$j_{s,y} = \frac{-eE_x}{16\pi\lambda m}\left(p_{F+} - p_{F-}\right) \propto \Delta k$$

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

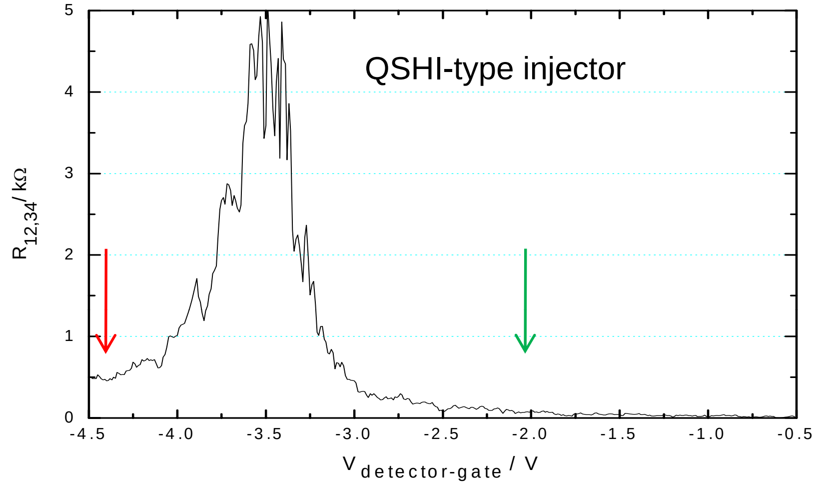
QSHE Spin-Injector

H. Buhmann



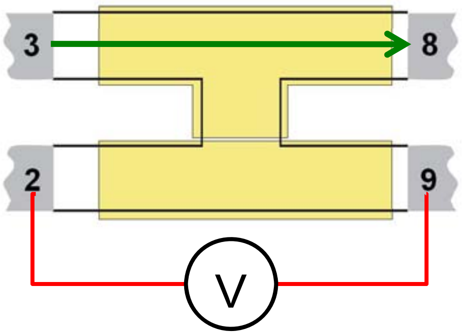


injector sweep

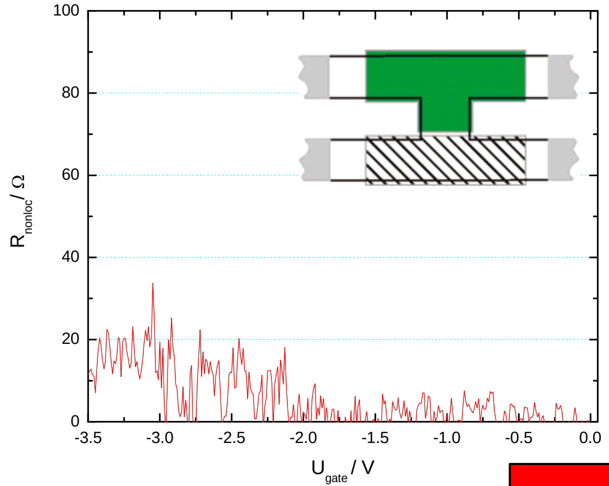


detector sweep

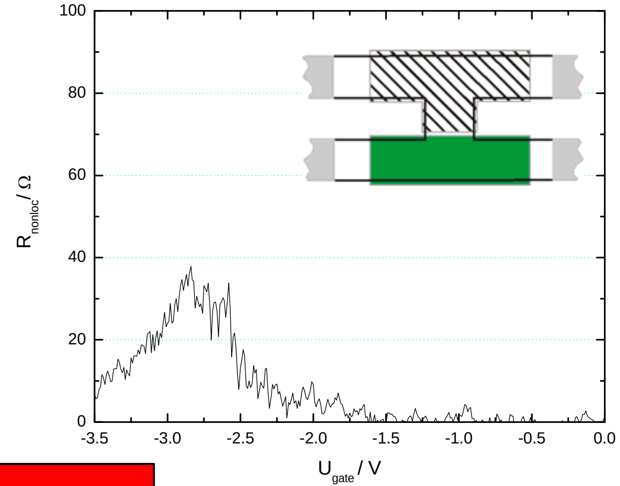
n-type



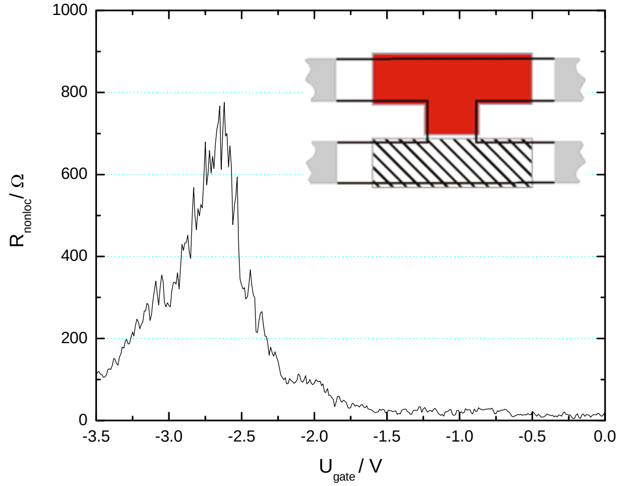
detector sweep

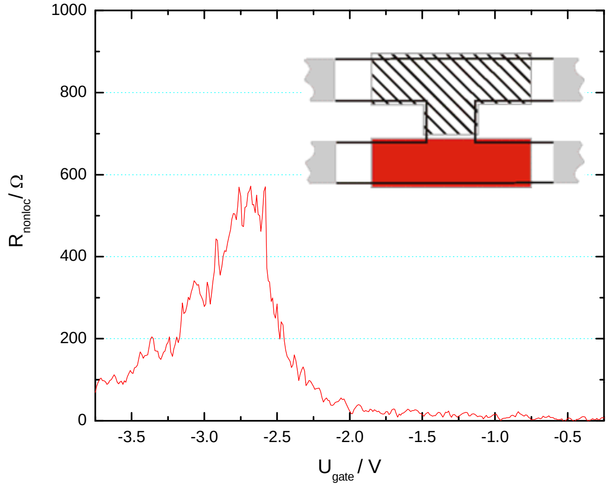


injector sweep



p-type





Summary II: QSH Effect

EP3 H. Buhmann

- the QSH effect which consists of
  - an insulating bulk and
  - two counter propagating **spin polarized** edge channels (Kramers doublet)

- the QSH effect can be used as an effective
  - spin injector and
  - spin detector

  with 100 % spin polarization properties

- the Rashba Effect in HgTe QW structures can be used for spin manipulation

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		M. Mühlbauer	H. Thierschmann	

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Inst. f. Theoretische Physik
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Texas A&M University
J. Sinova

Weizmann Institute
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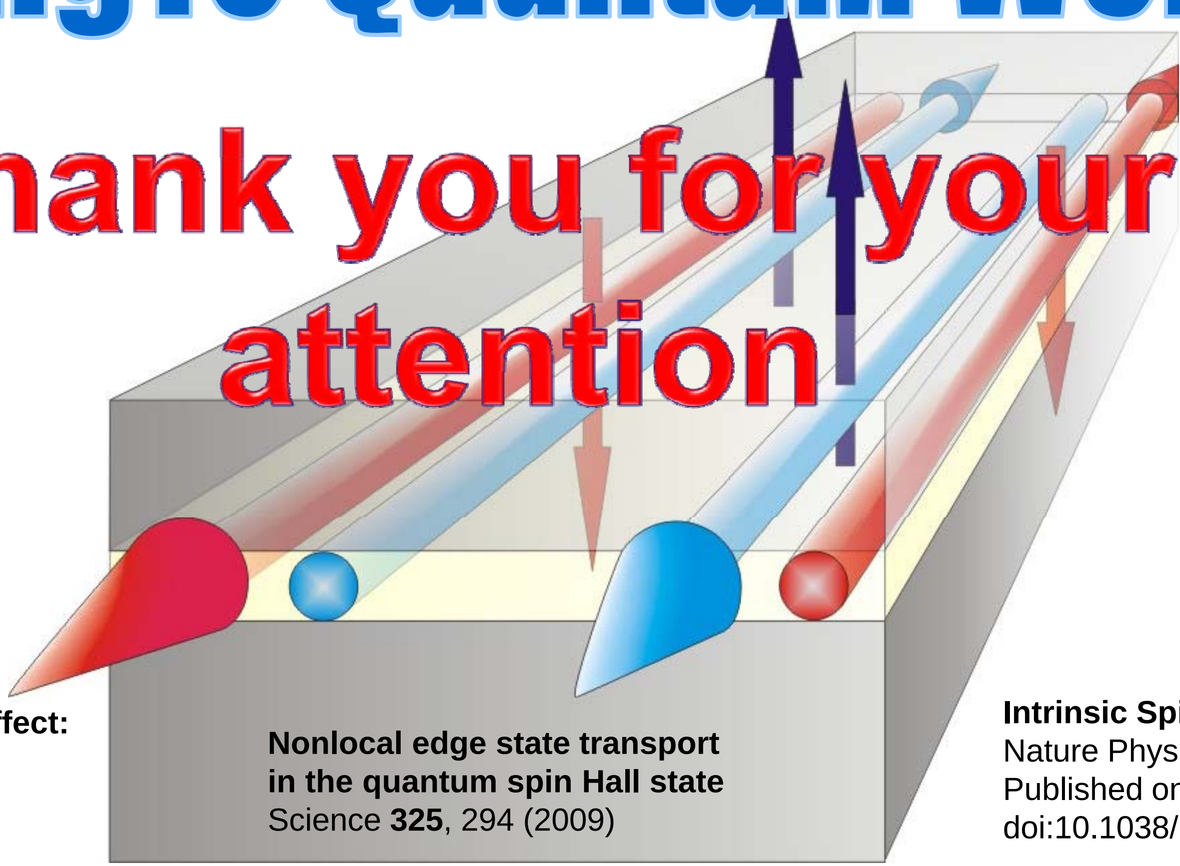
Institute Néel, CNRS
C. Bäuerle
L. Saminaydar

Quantum Spin Hall Effect in HgTe Quantum Wells



Thank you for your attention

Quantum Spin Hall Effekt
Science 318, 766 (2007)

The Quantum Spin Hall Effect: Theory and Experiment
J. Phys. Soc. Jap.
Vol. 77, 31007 (2008)

Nonlocal edge state transport in the quantum spin Hall state
Science **325**, 294 (2009)

Intrinsic Spin Hall Effekt
Nature Physics
Published online: 02 May 2010
doi:10.1038/nphys1655