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EP3

Experiments on the Quantum Spin Hall Effect in HgTe Quantum Wells

Laurens W. Molenkamp

Physikalisches Institut, EP3
Universität Würzburg

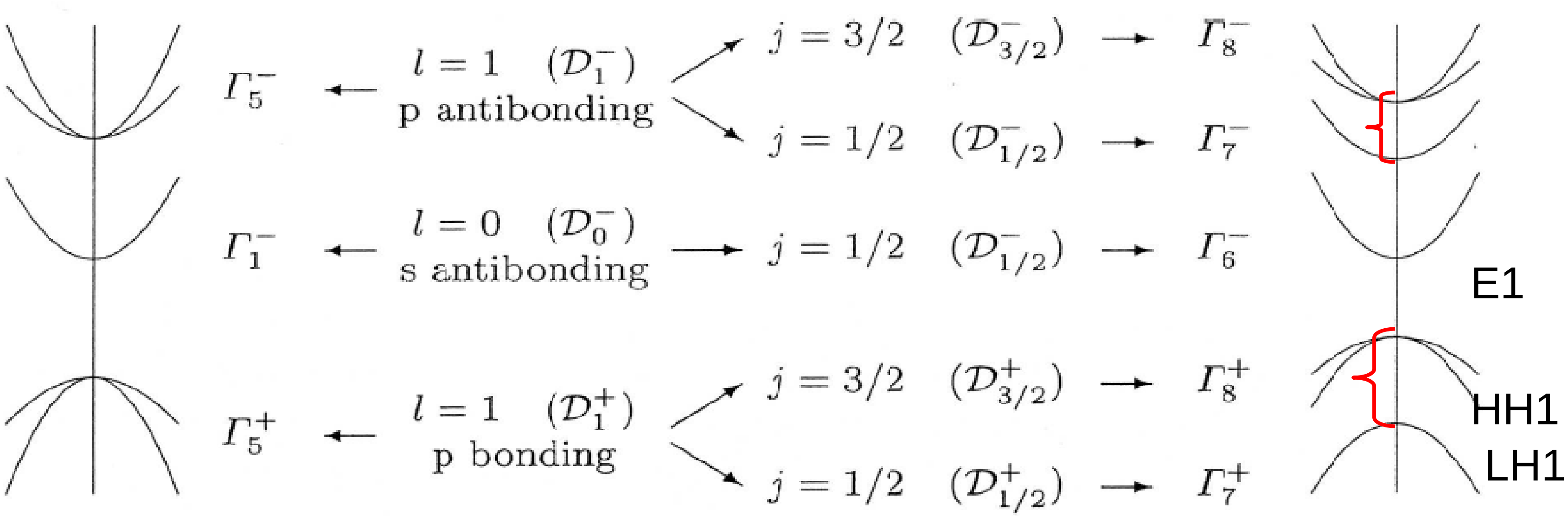
Overview

- Spin-orbit effects in zincblende semiconductors
- HgTe Bandstructure
- QSHI
- edge channels and non-local transport
- intrinsic SHE

Spin-Orbit Interaction

Atomic spin-orbit in zincblende symmetry:

➔ Cannot be controlled experimentally!



Zero-order: only s-o splitting for l>0

Spin-orbit interaction in a solid

(one of the few echoes of relativistic physics in the solid state)

Ingredients: - Electric field → Either from impurity: or Inversion Asymmetry

$$\vec{E} = -\left(\frac{1}{e}\right)\nabla V(r)$$

- Electron motion → In the rest frame of an electron the electric field generates an effective magnetic field

$$\vec{B}_{eff} = -\left(\frac{\hbar\vec{k}}{cm}\right)\times\vec{E}$$

This gives an effective interaction with the electron's magnetic moment

$$H_{SO} = -\mu\cdot Beff = -\left(\frac{e\vec{S}}{mc}\right)\cdot\left[\frac{\hbar\vec{k}}{mc}\times\vec{r}\left(\frac{1}{er}\frac{dV(r)}{dr}\right)\right] = \alpha\vec{S}\cdot\vec{L}$$

FIRST CONSEQUENCE

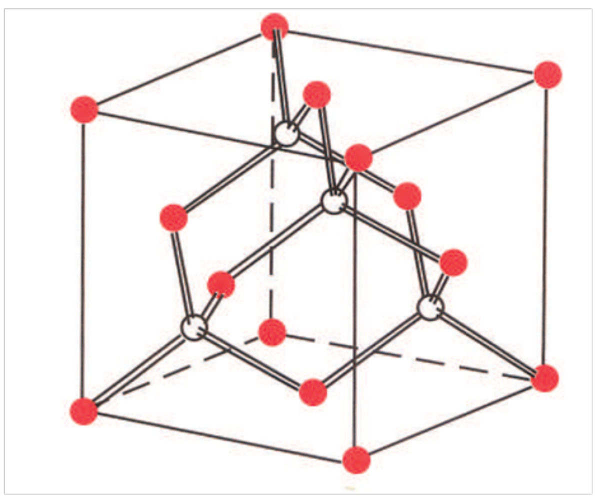
•Quantization axis of spin now depends on electron momentum!!

Lifting of conduction-band spin-degeneracy at $B = 0$

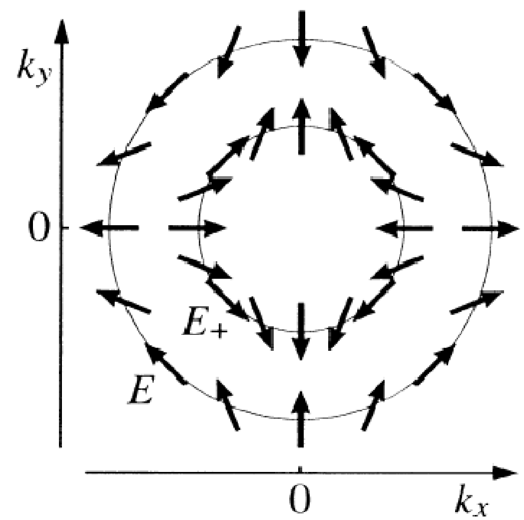
bulk inversion asymmetry (BIA)

Dresselhaus-term: $H_D = \alpha_D(\sigma_x k_x - \sigma_y k_y)$

G. Dresselhaus, Phys. Rev. **100**, 580 (1955)



Zincblende structure

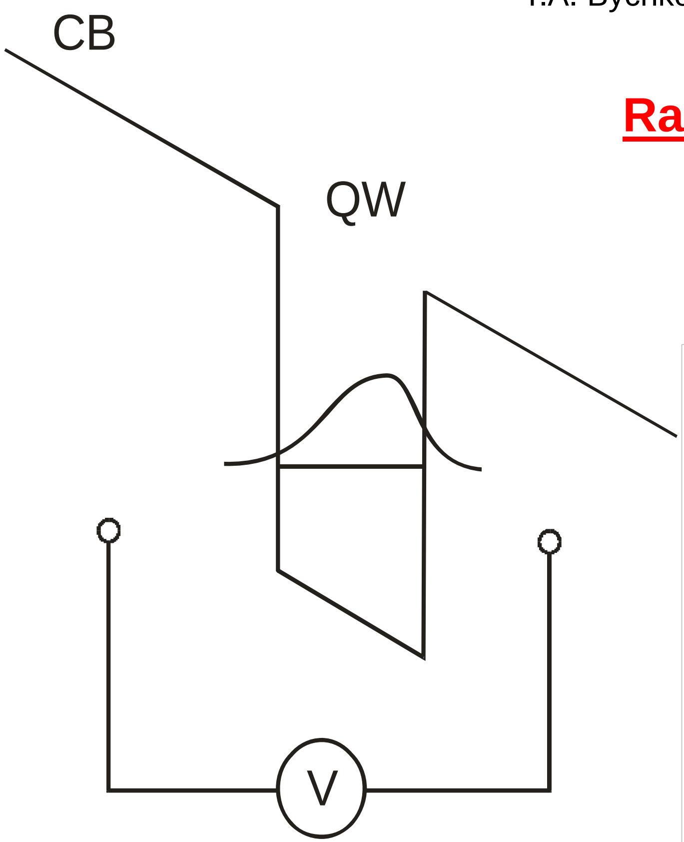


➔ Can not be influenced experimentally!

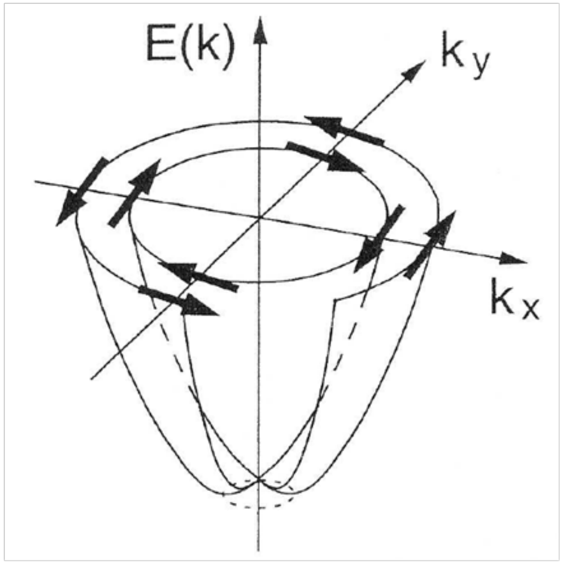
Lifting of conduction-band spin-degeneracy at $B = 0$

structural inversion asymmetry (SIA)

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



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



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

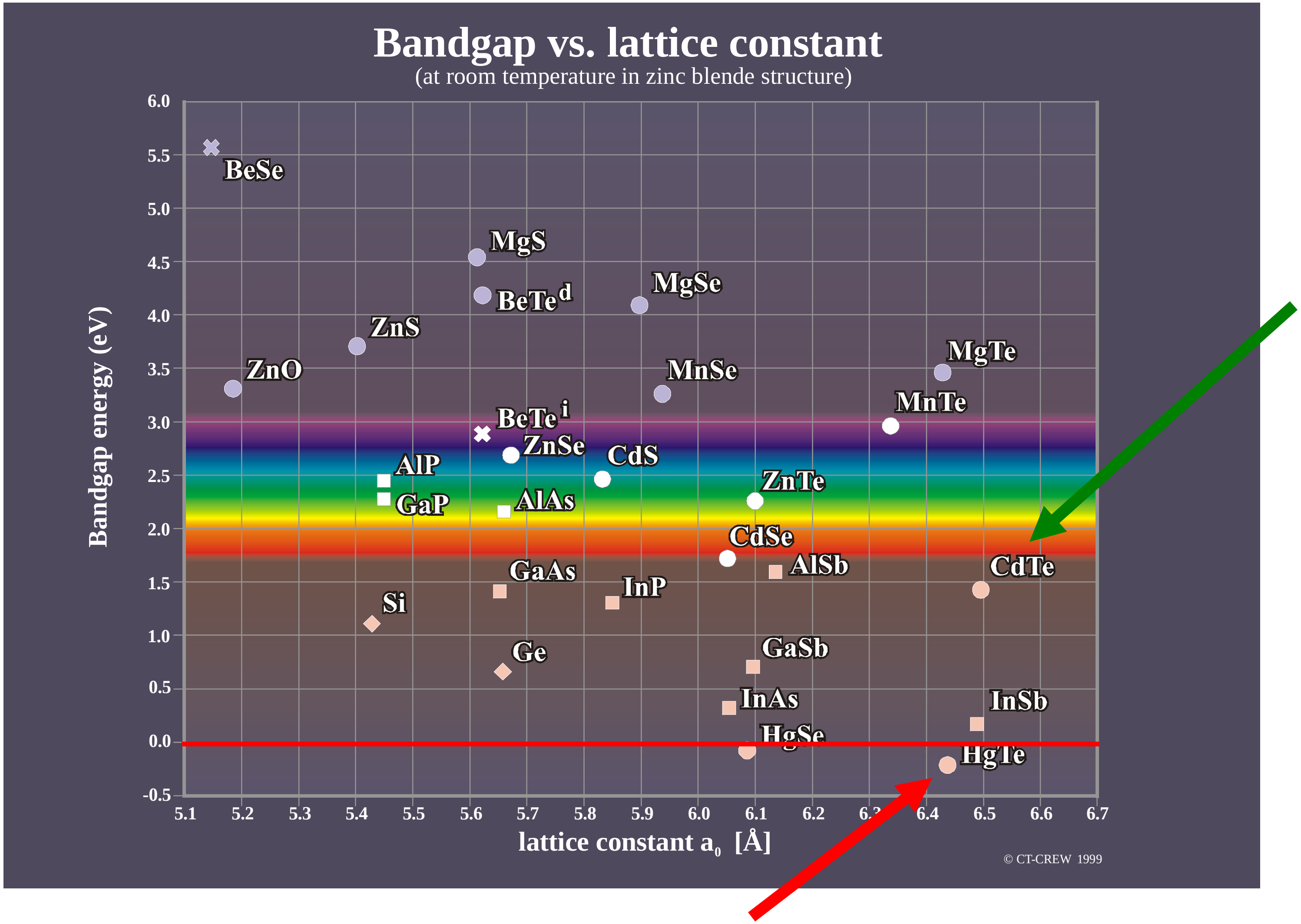
(for elektrons and light holes)

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

(for heavy holes)

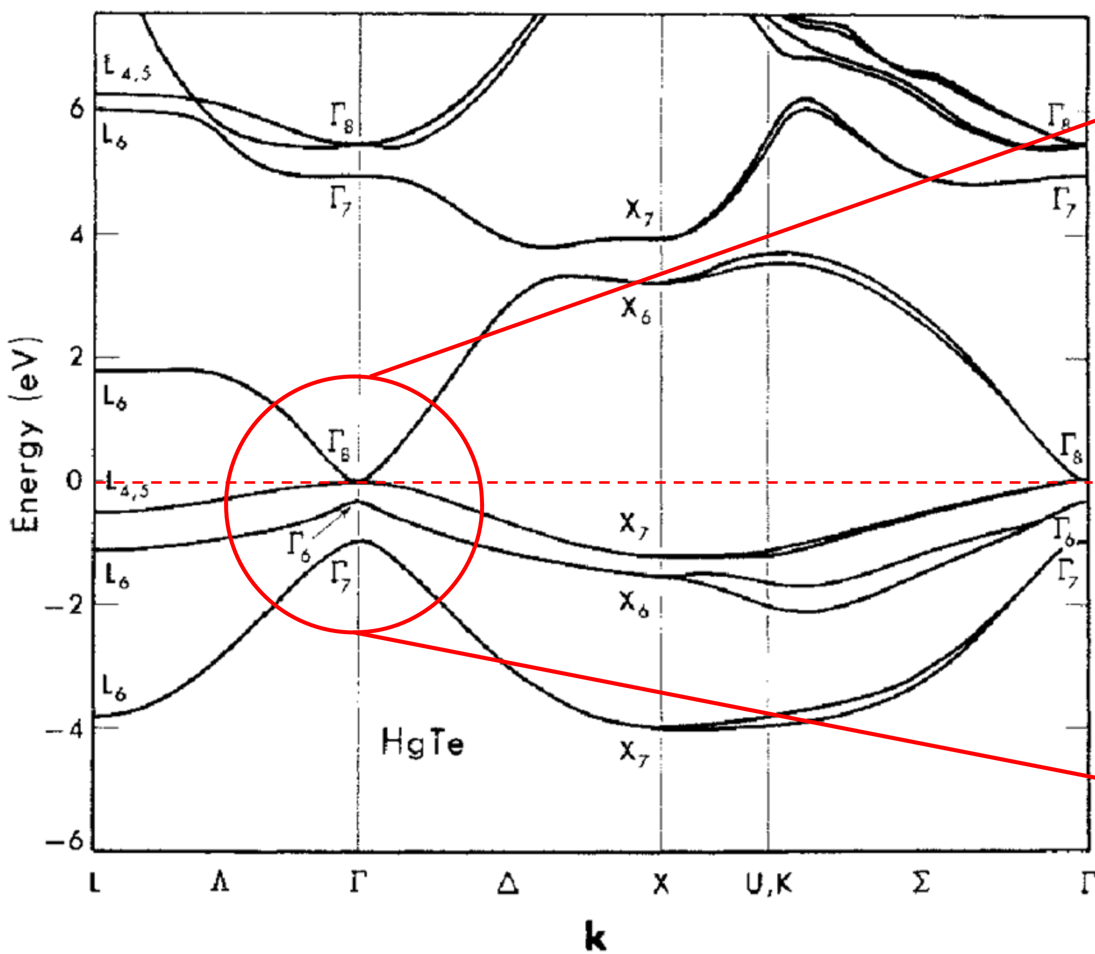
HgTe-Quantum Wells

MBE-Growth



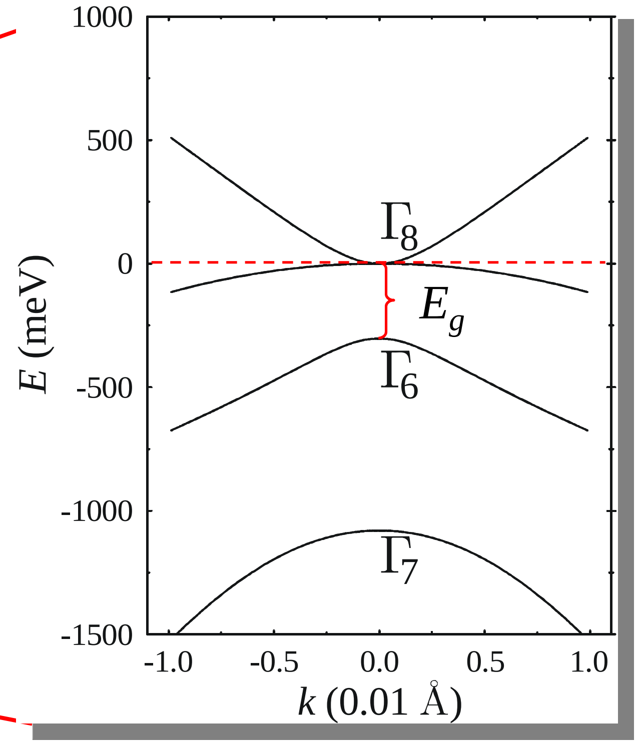
HgTe

band structure



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

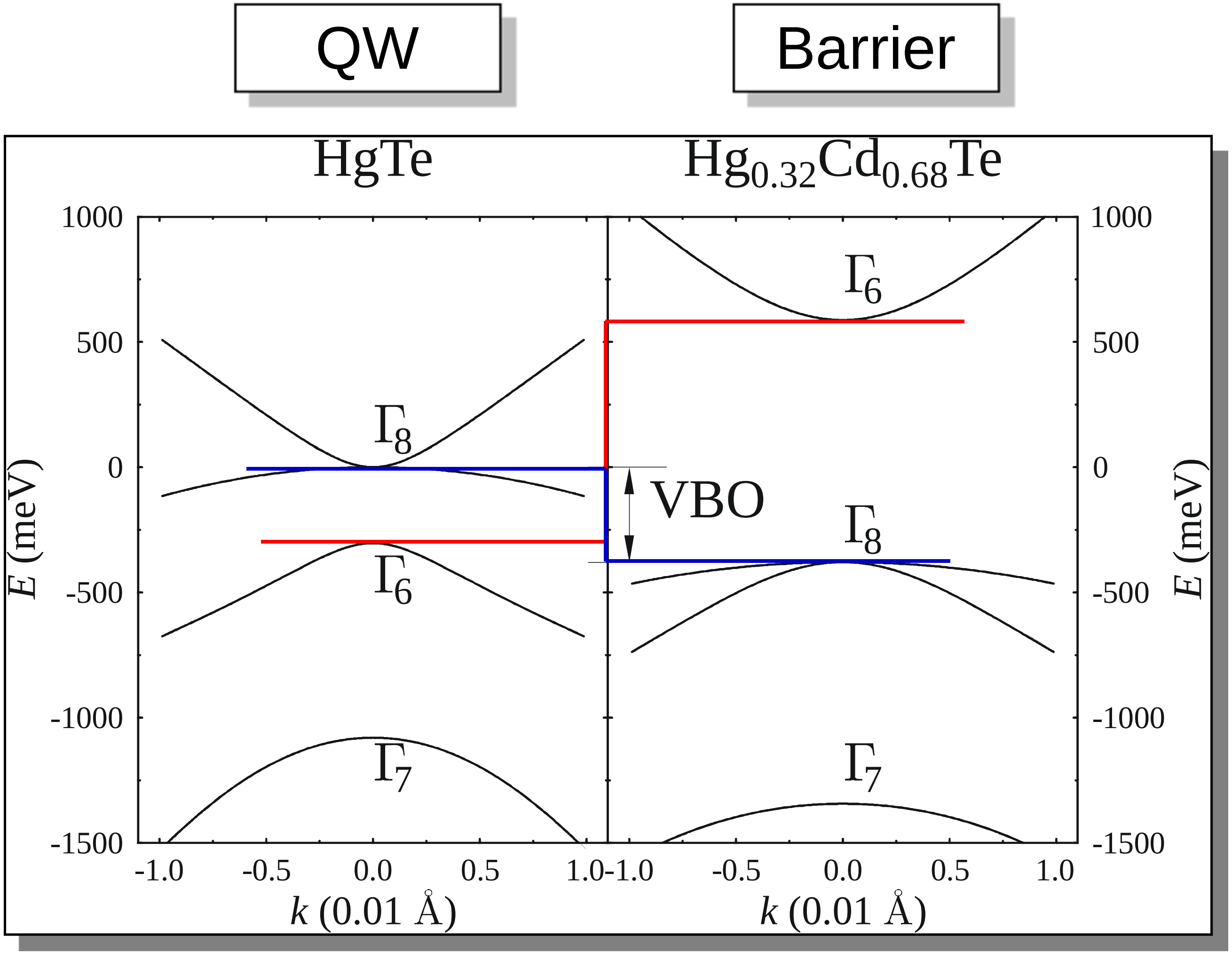
semi-metal or semiconductor



fundamental energy gap

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

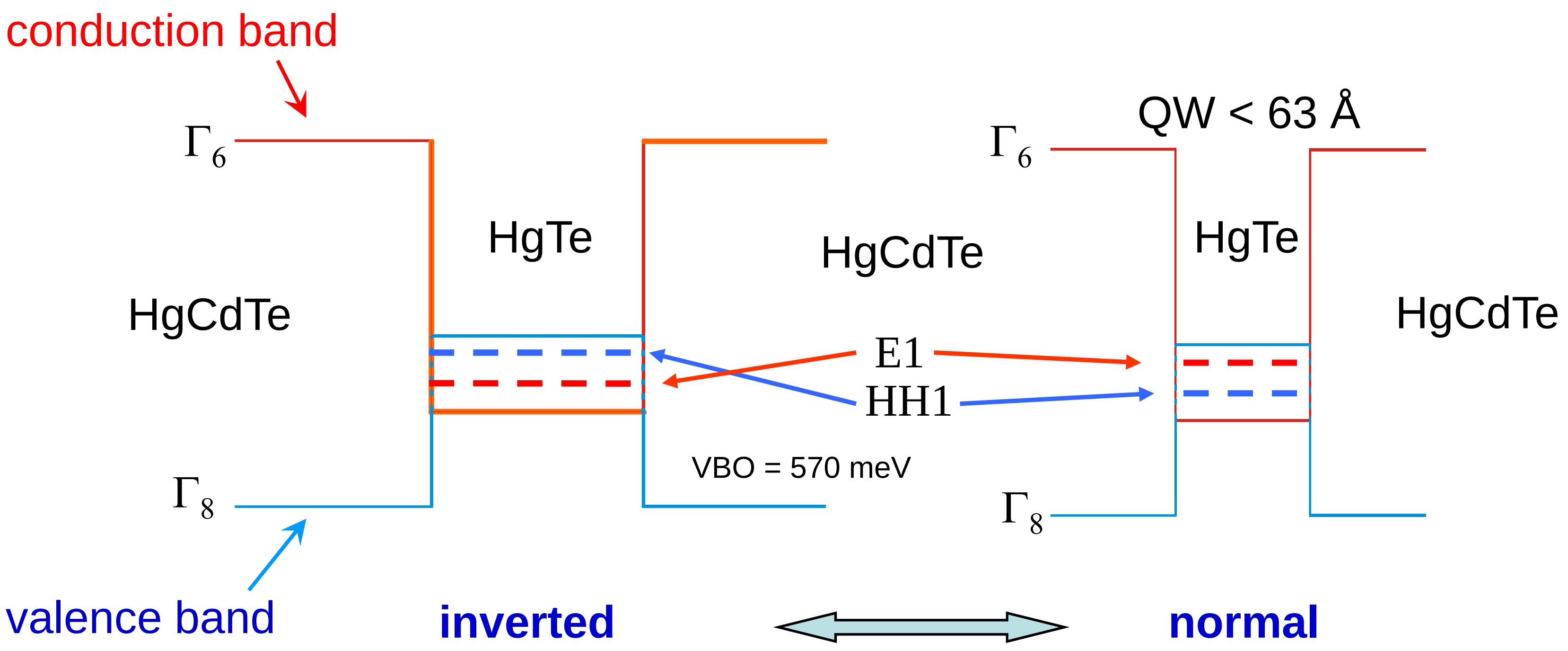
HgTe-Quantum Wells



VBO = 570 meV

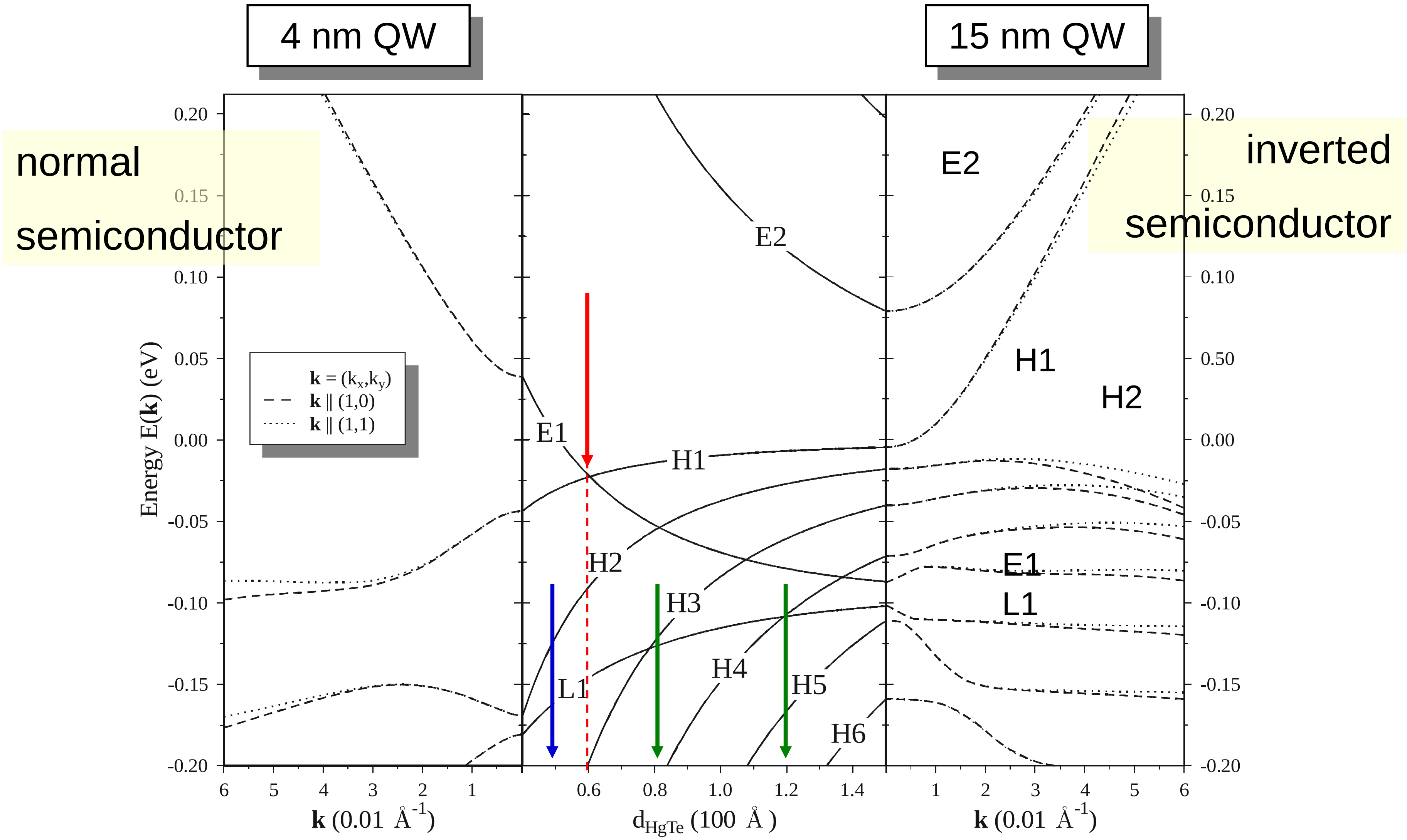
HgTe-Quantum Wells

Type-III QW



band structure

Band Gap Engineering

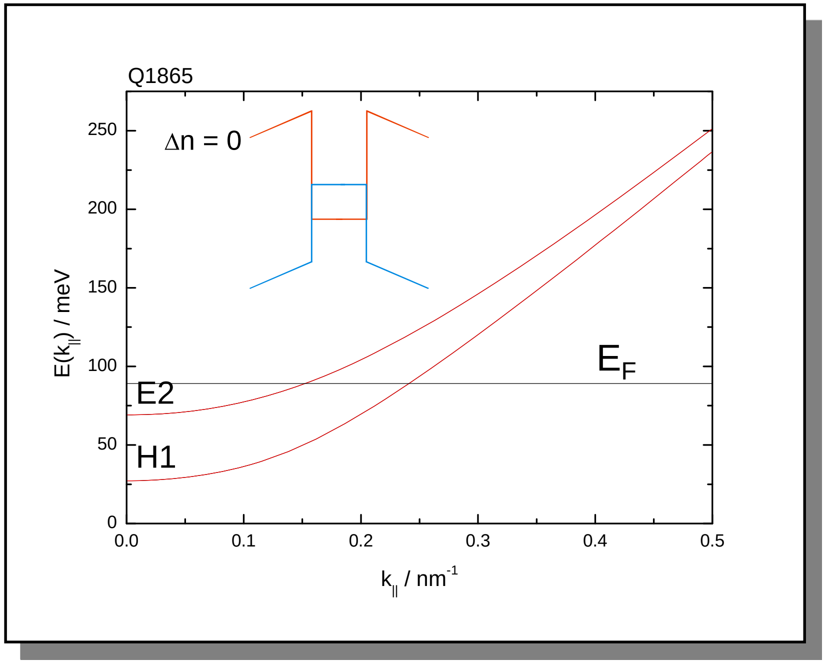


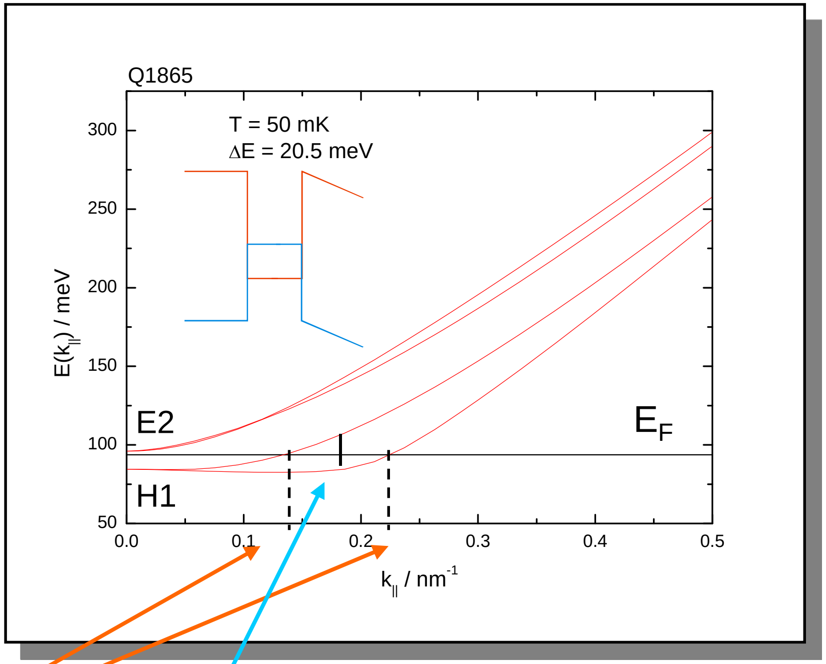
Rashba Spin-Orbit Splitting

8 x 8 **k·p** calculation

symmetric QW

asymmetric QW





E.G. Novik *et al*, PRB **72**, 035321 (2005)

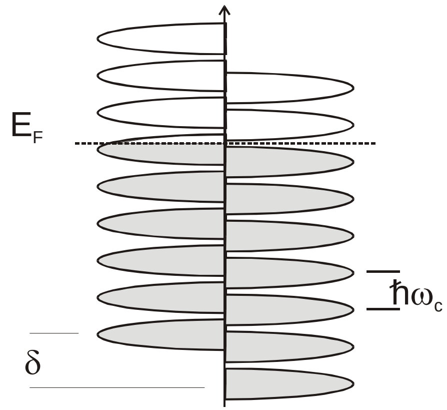
Δn

$\Delta_{R,\max}$ up to 30 meV

Y.S. Gu, et al., PRB 70, 115328 (2004)

Magneto-Transport

nodes in SdH:

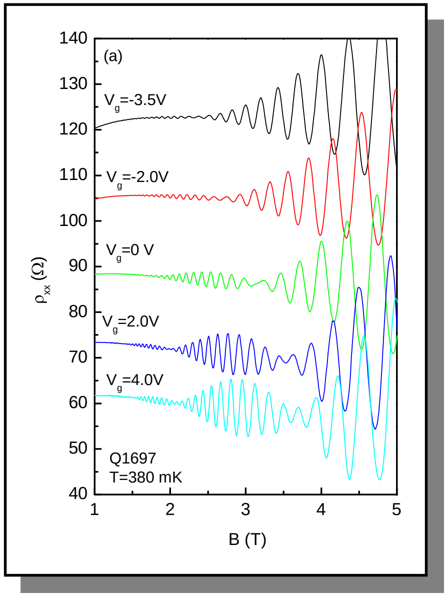


SdH-Amplitude:

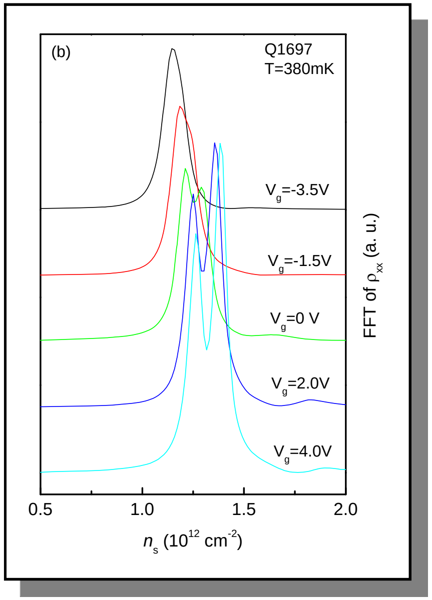
$$A \propto \cos(\pi \nu) \qquad \nu = \frac{\delta}{\hbar \omega_c}$$

Y.S. Gui et al., Europhys. Lett. **65**, 393 (2004)

SdH



FFT



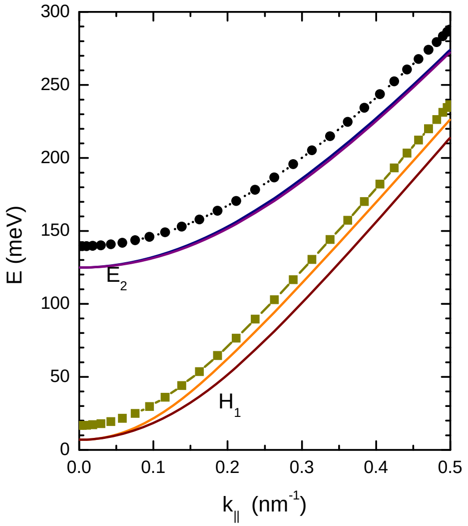
Rashba Spin-Splitting Energy

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

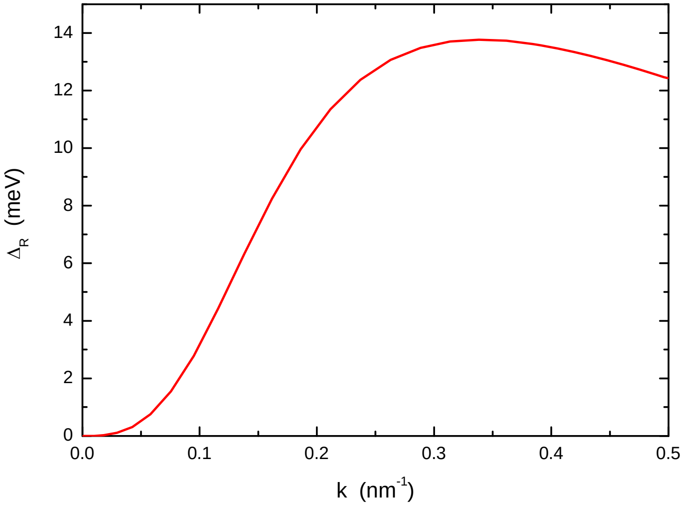
(for electron and light hole bands)

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

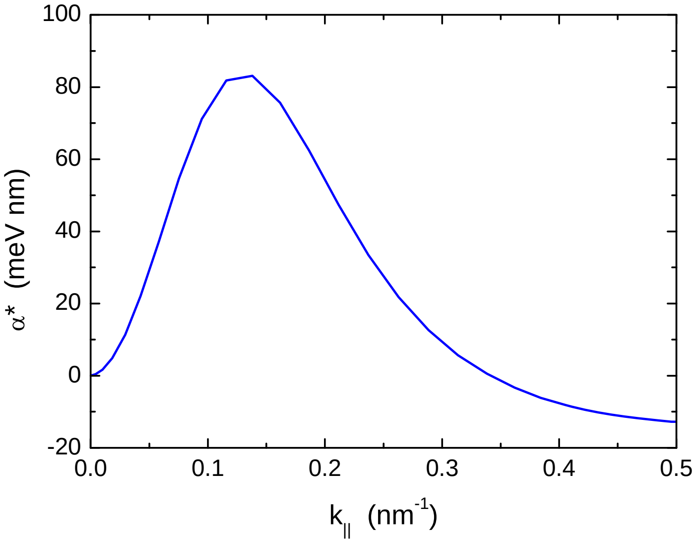
(for heavy hole bands)



Rashba Energy Δ_R



Rashba Coefficient α

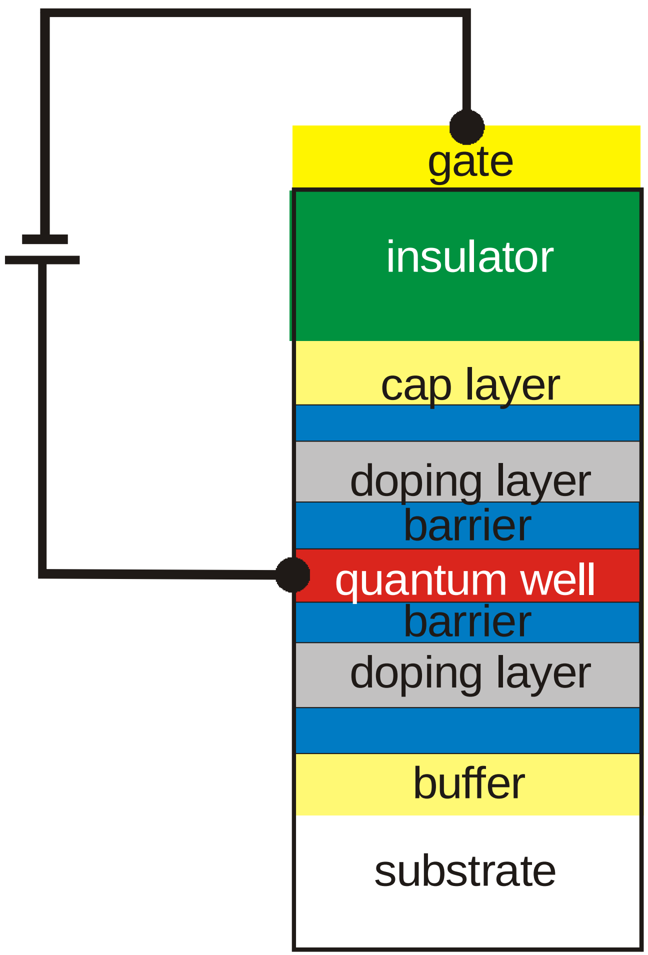


Y.S. Gui, et al., PRB 70, 115328 (2004)
E.G. Novik, *et al*, PRB **72**, 035321 (2005)

Layer Structure

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

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



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

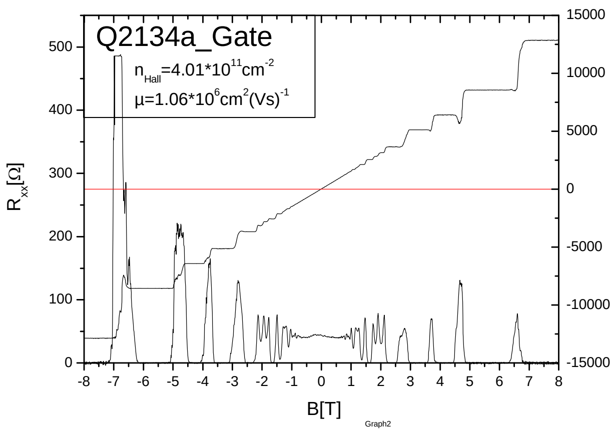
10 nm HgCdTe x = 0.7

9 nm HgCdTe with I

10 nm HgCdTe x = 0.7

25 nm CdTe

CdZnTe(001)



symmetric or asymmetric doping

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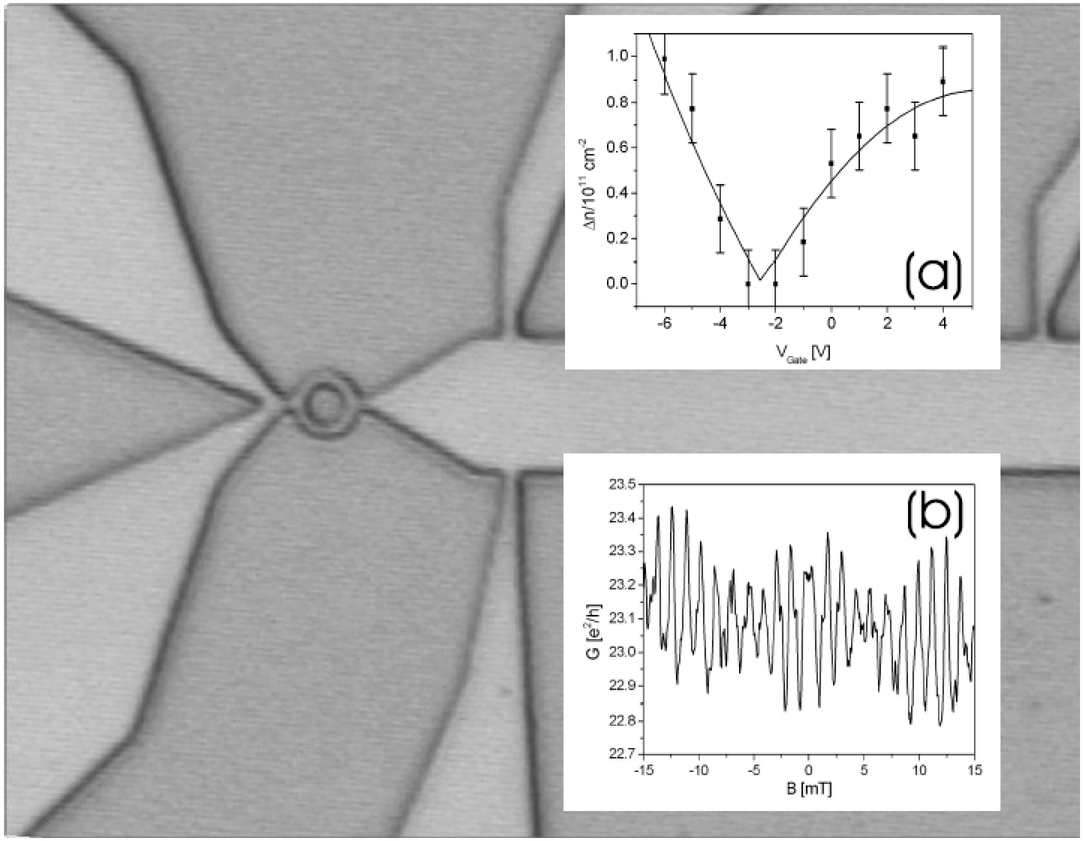
HgTe Ring-Structures



Three phase factors:

Aharonov-Bohm

Berry

Aharonov-Casher

$$\Delta\varphi_{\psi_s^+ - \psi_s^-} = -2\pi\frac{\Phi}{\Phi_0} - b\pi(1 - cos\theta)$$

$$\Delta\varphi_{\psi_s^+ - \psi_{\bar{s}}^-} = -2\pi\frac{\Phi}{\Phi_0} - b2\pi r\frac{m^*\alpha}{\hbar^2}sin\theta$$

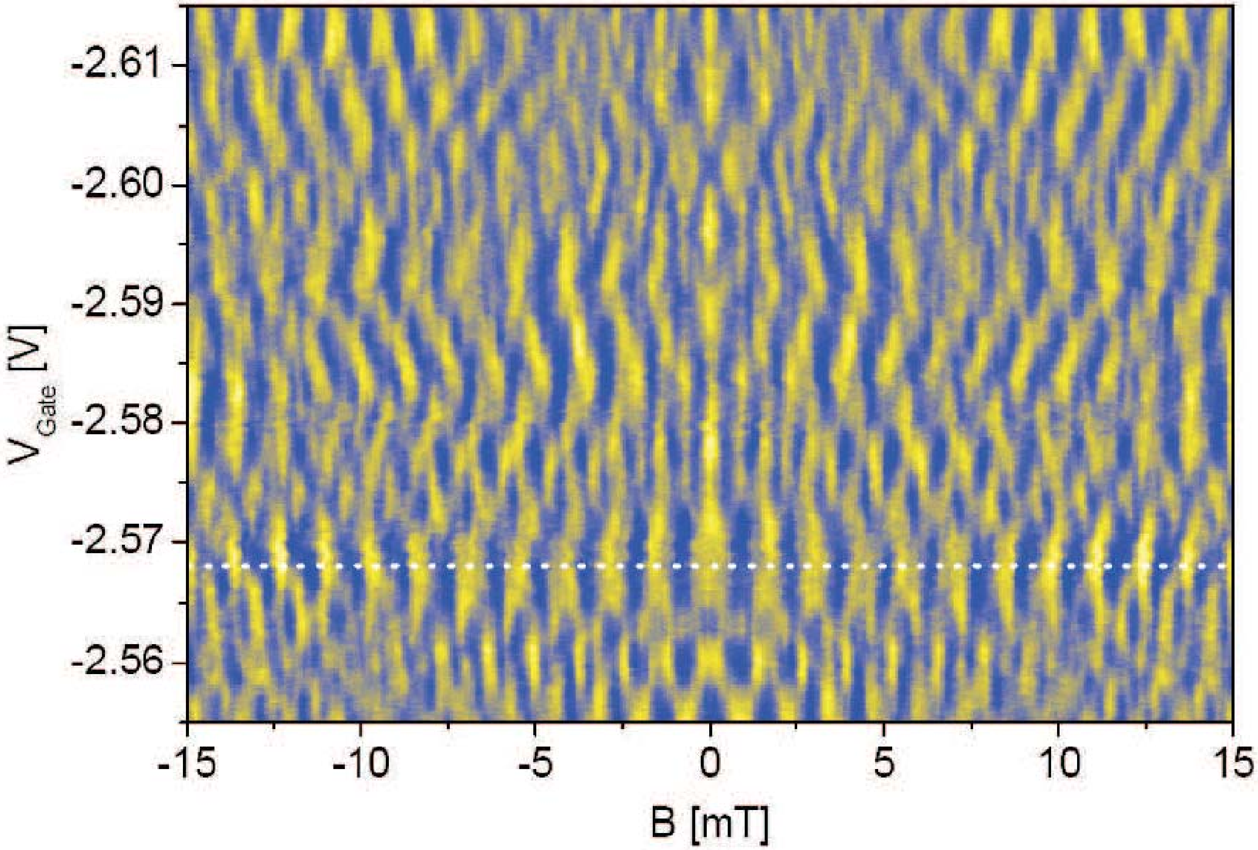
$s = \uparrow$ and $\downarrow$,

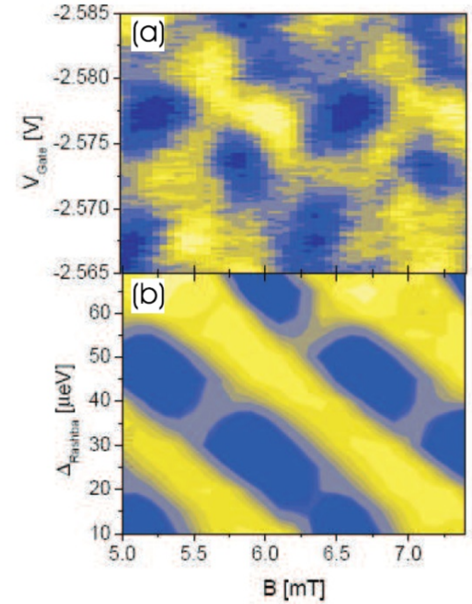
parallel and anti-parallel to B_{tot}

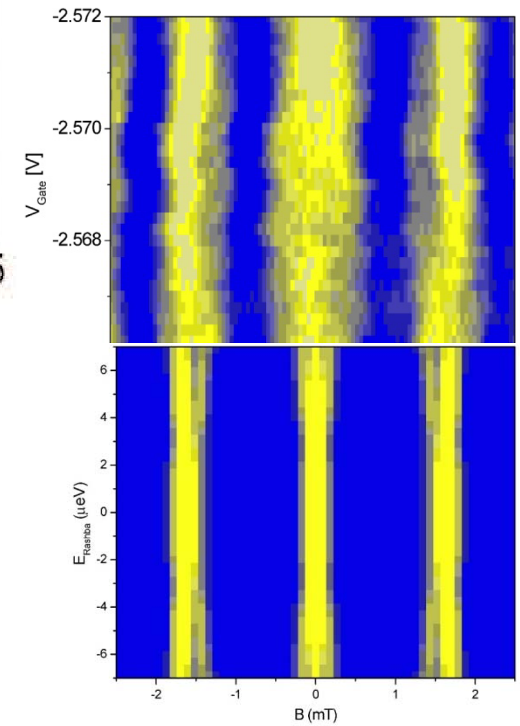
$b = \pm 1$ for $\uparrow, \downarrow$

$\theta \prec B_{ext}, B_{tot}; \quad B_{tot} = B_{ext} + B_{eff}$

HgTe Ring-Structures







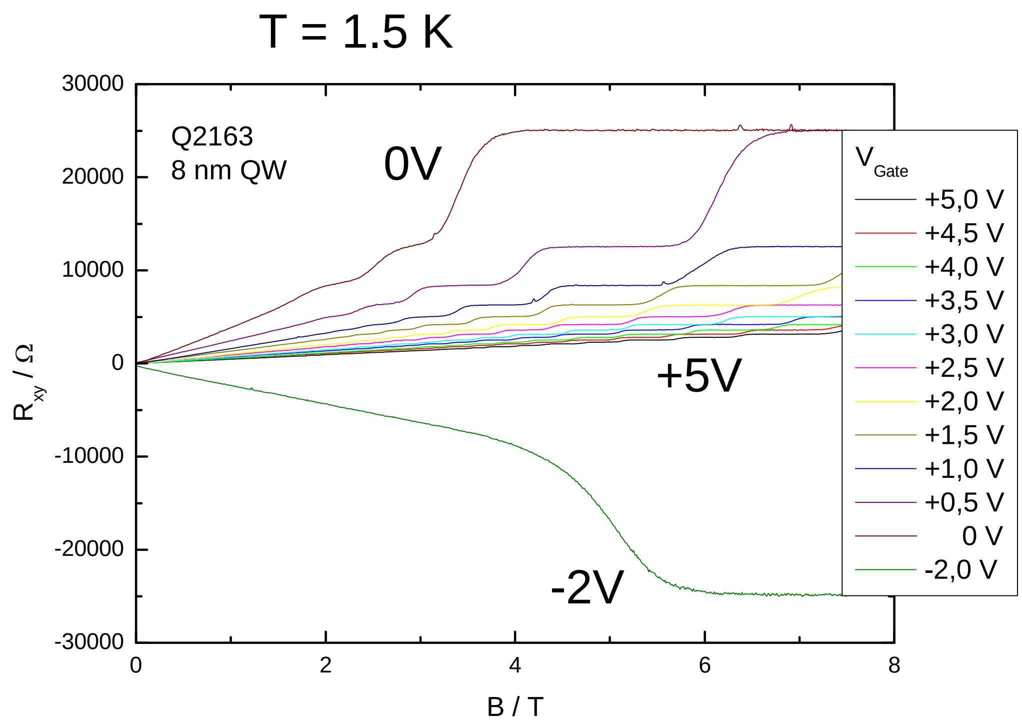
Modeling E. Hankiewicz, J. Sinova,

Concentric Tight Binding Model (a la Nikolic)+ B-field

M. König et al., Phys. Rev.Lett. **96**, 76804 (2006).

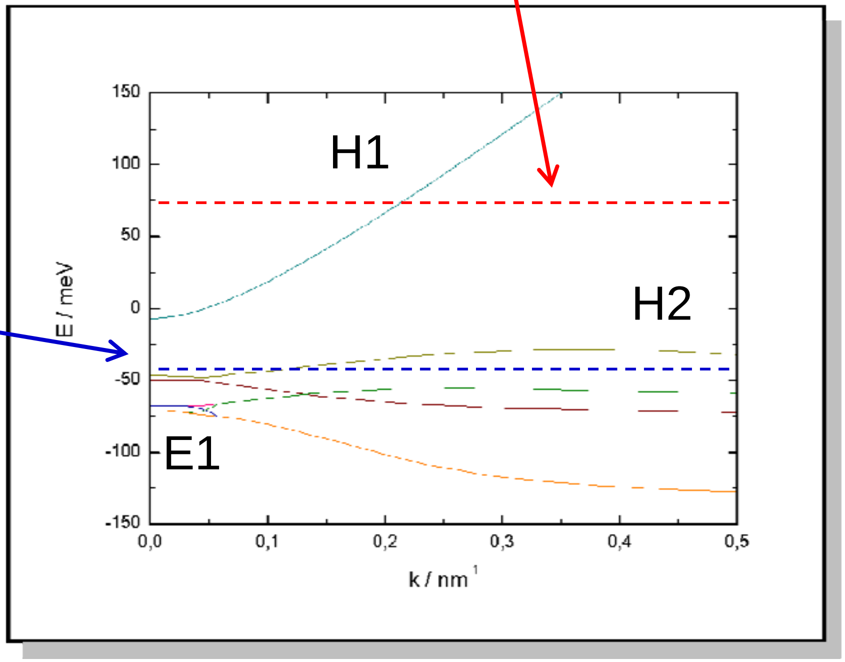
Gated
Low Carrier Densities
Samples

n to *p* transitions

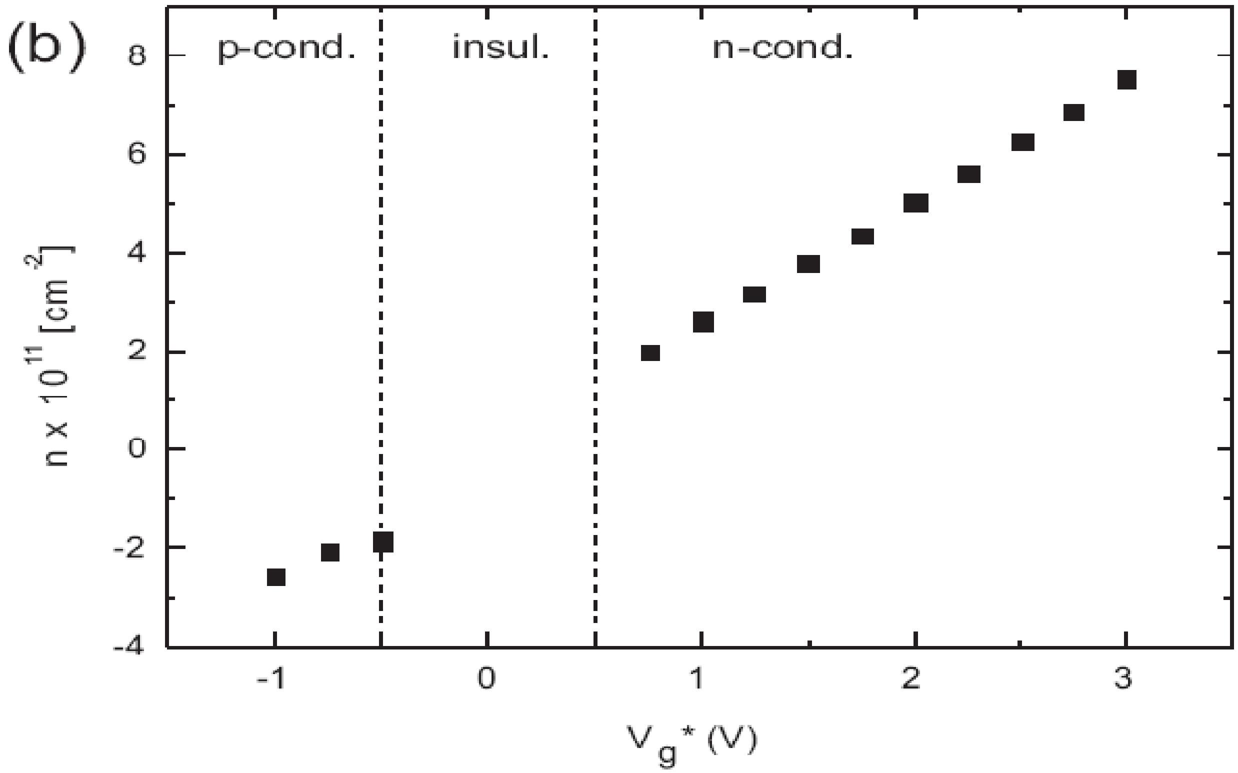


n_{max} = 1.35 x 10^{12} cm^{-2}

p_{max} = 3.2 x 10^{11} cm^{-2}

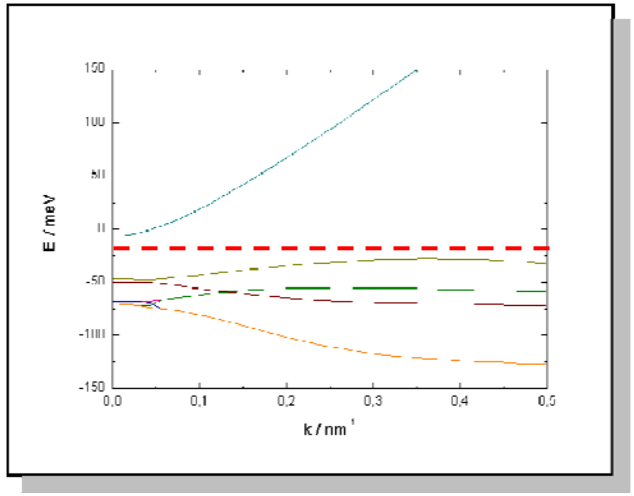


n to *p* transitions



Gate voltage versus carrier density

Magneto-Resistance in the insulating regime



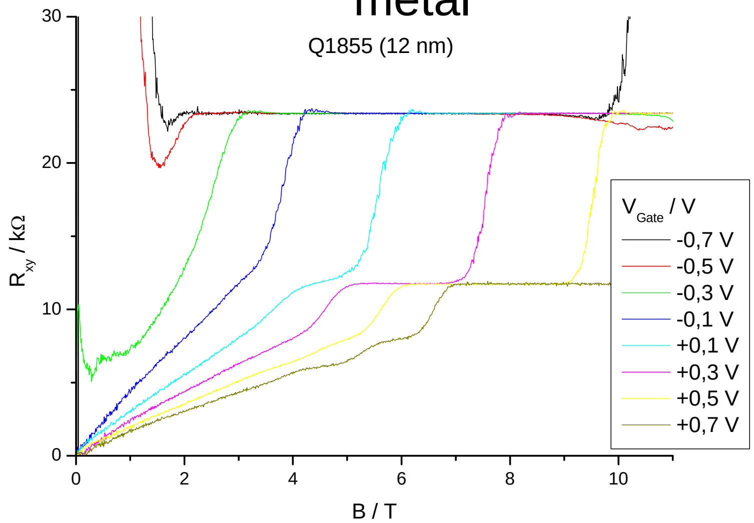
Hall

SdH

insulator

metal

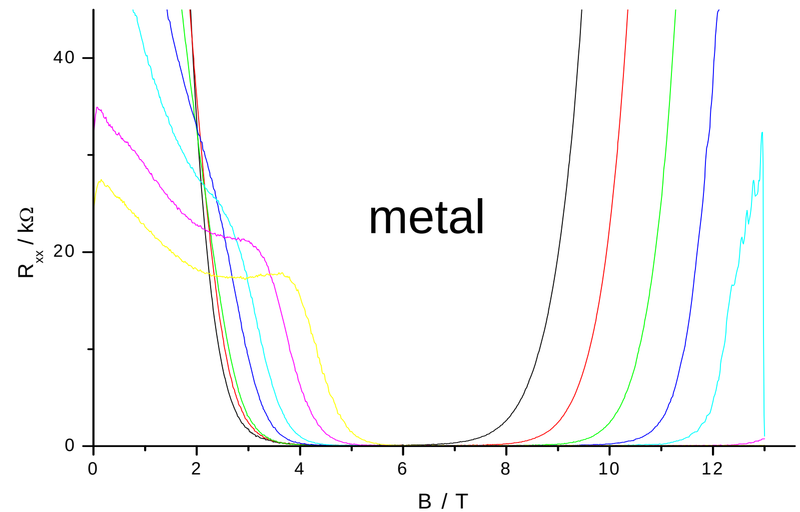
insulator



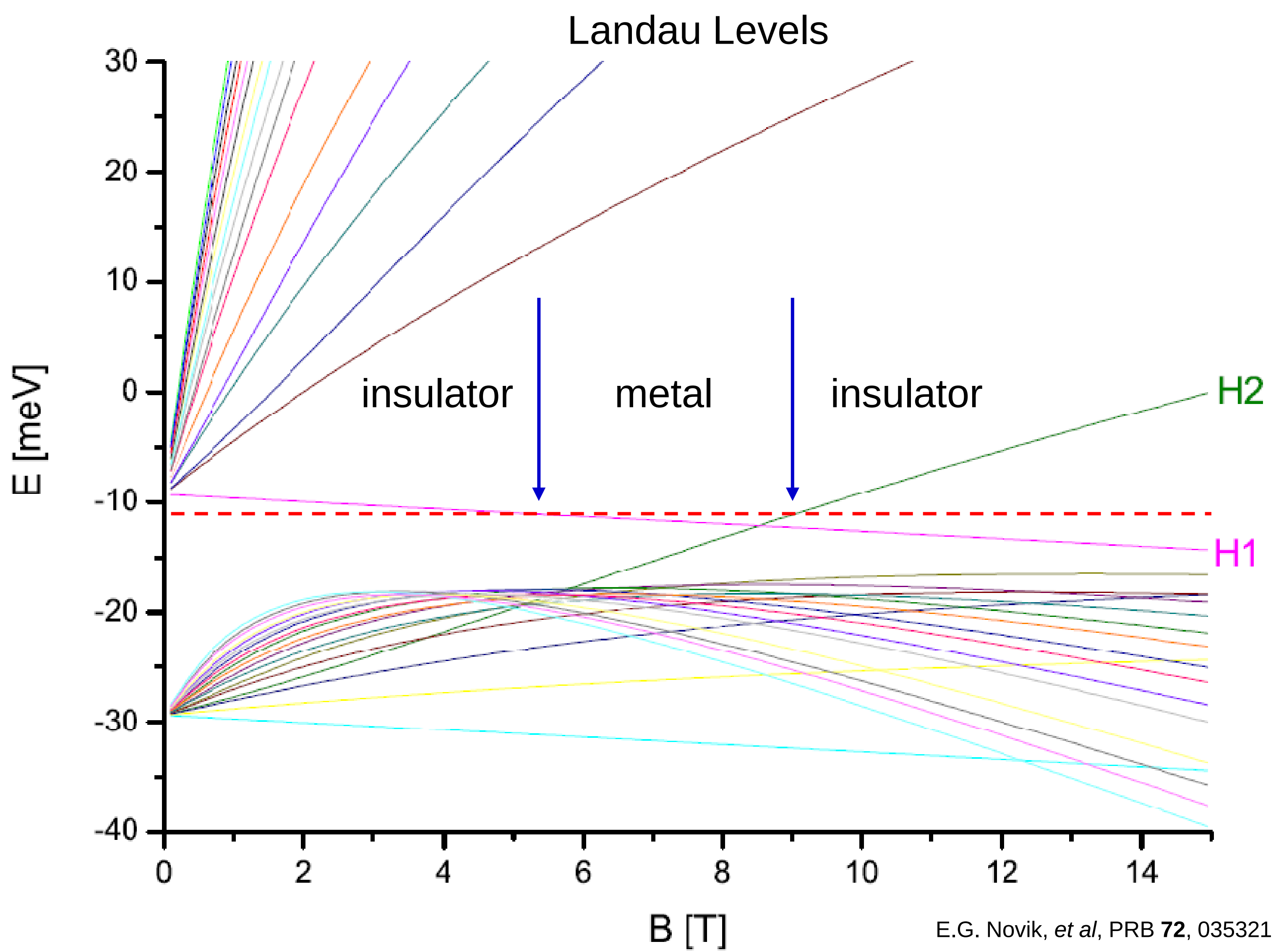
insulator

insulator

metal

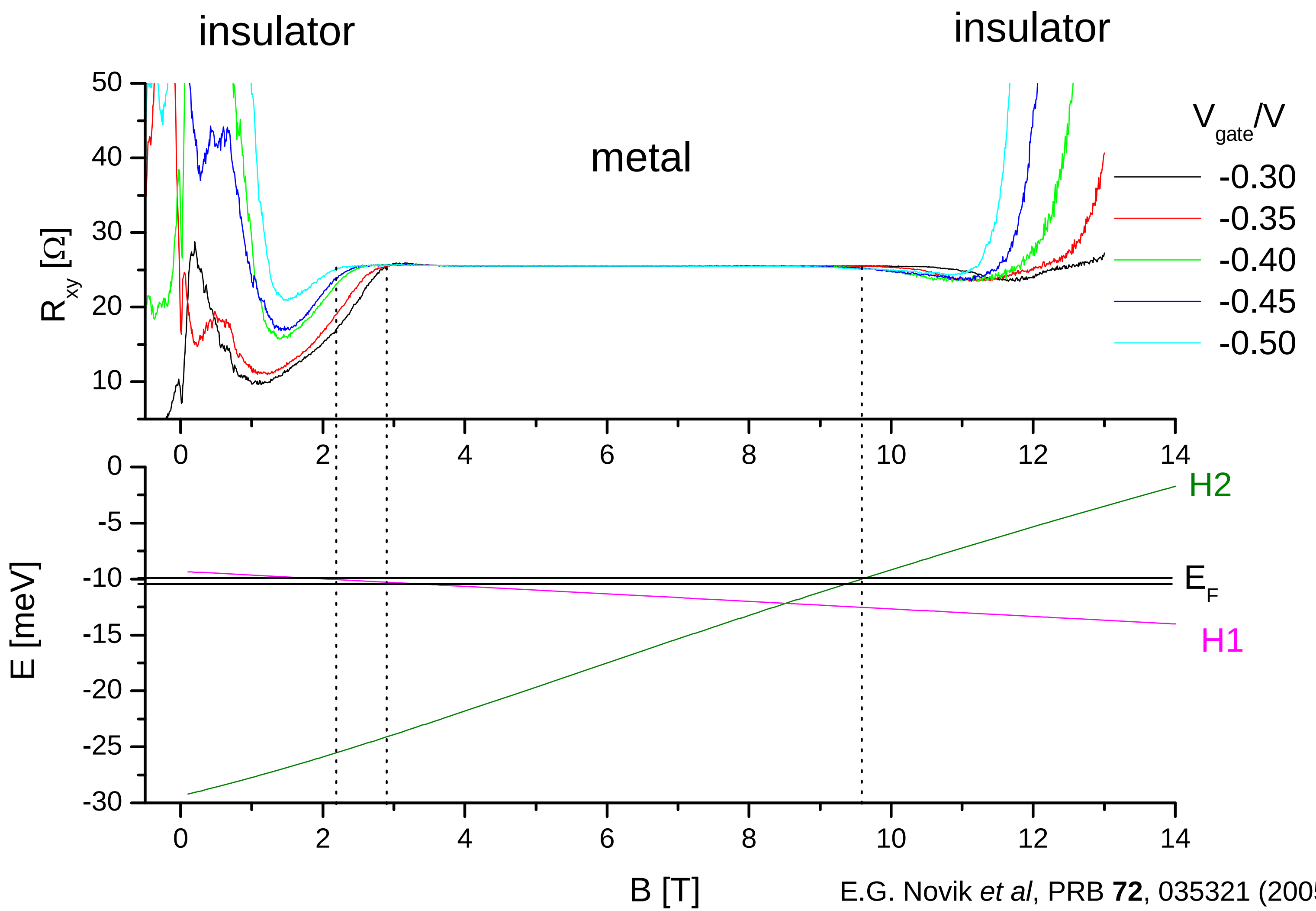


Insulator-Metal-Insulator Transition



E.G. Novik, *et al*, PRB **72**, 035321 (2005)

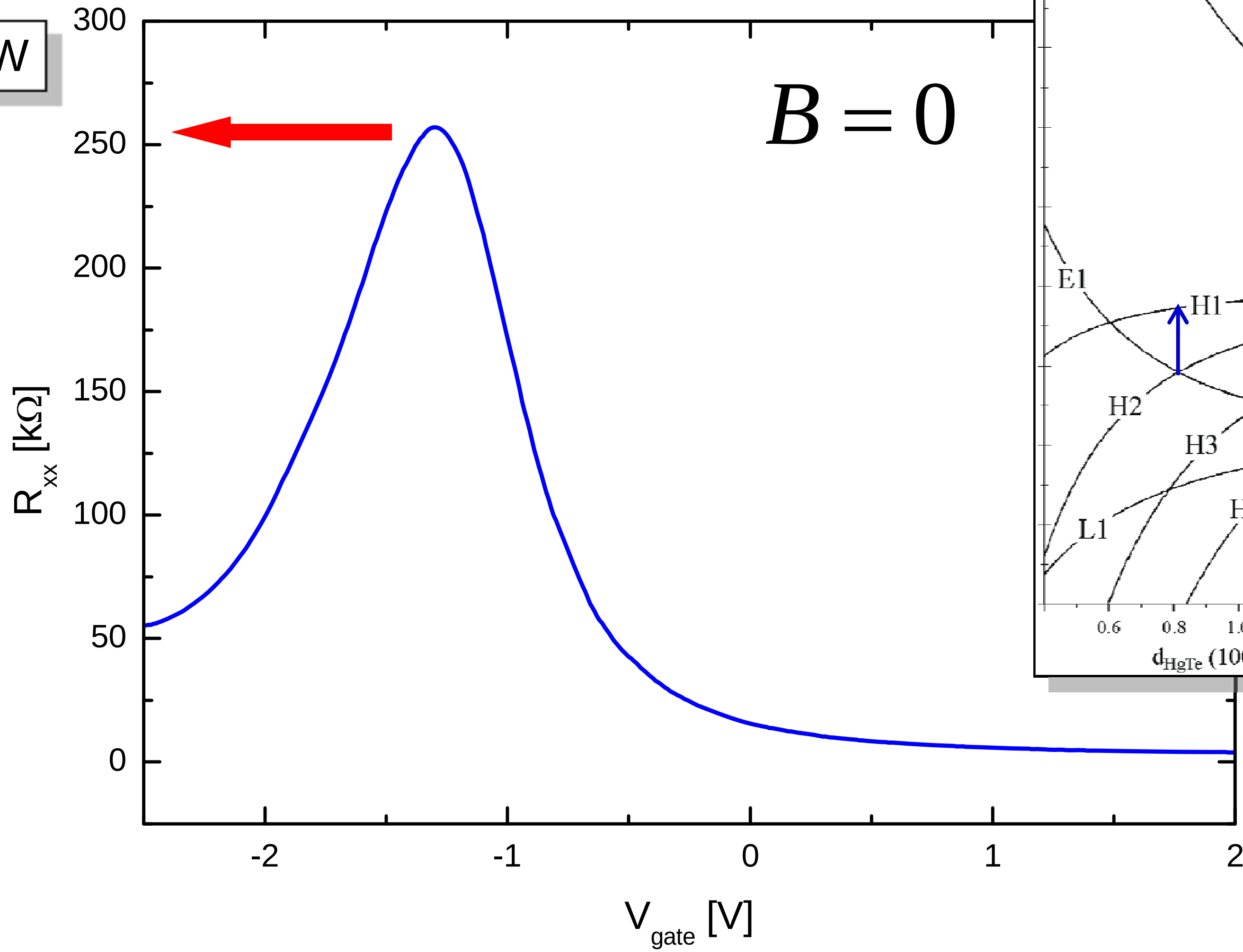
Insulator-Metal-Insulator Transition

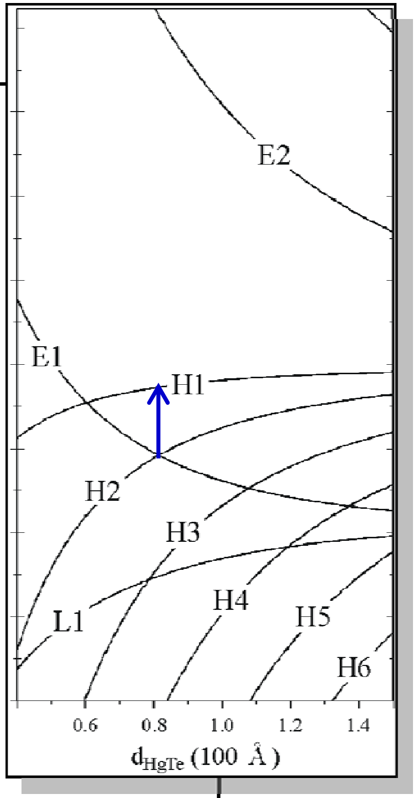


E.G. Novik *et al*, PRB **72**, 035321 (2005) ,
M. König et al., Science, (2007).
DOI: 10.1126/science.1148047 (Online Sept. 20, 2007)

Finite conductance in the insulating regime

8 nm QW



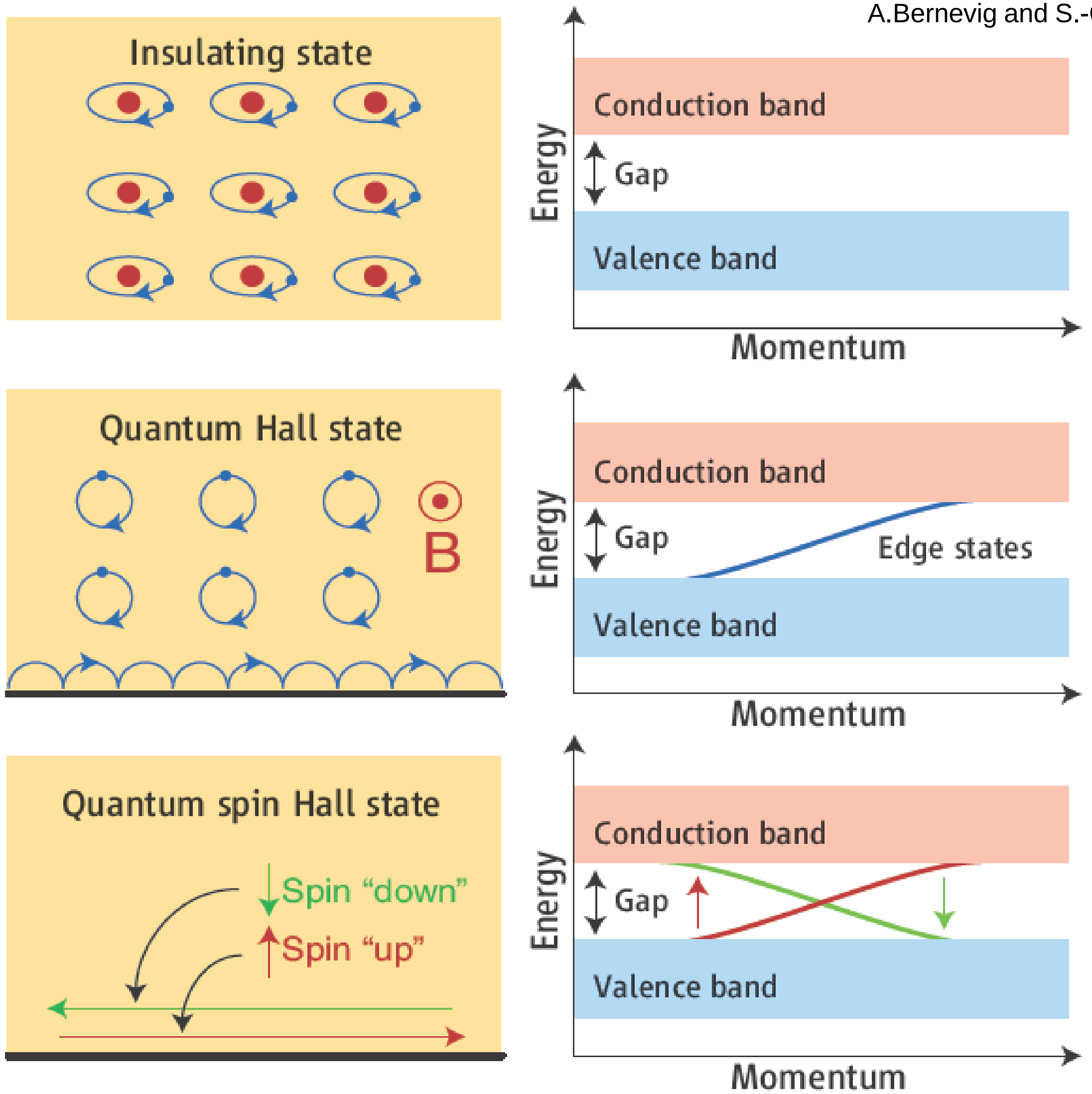


8 nm QW
largest
thermal gap

QSH insulator

Topological Quantization

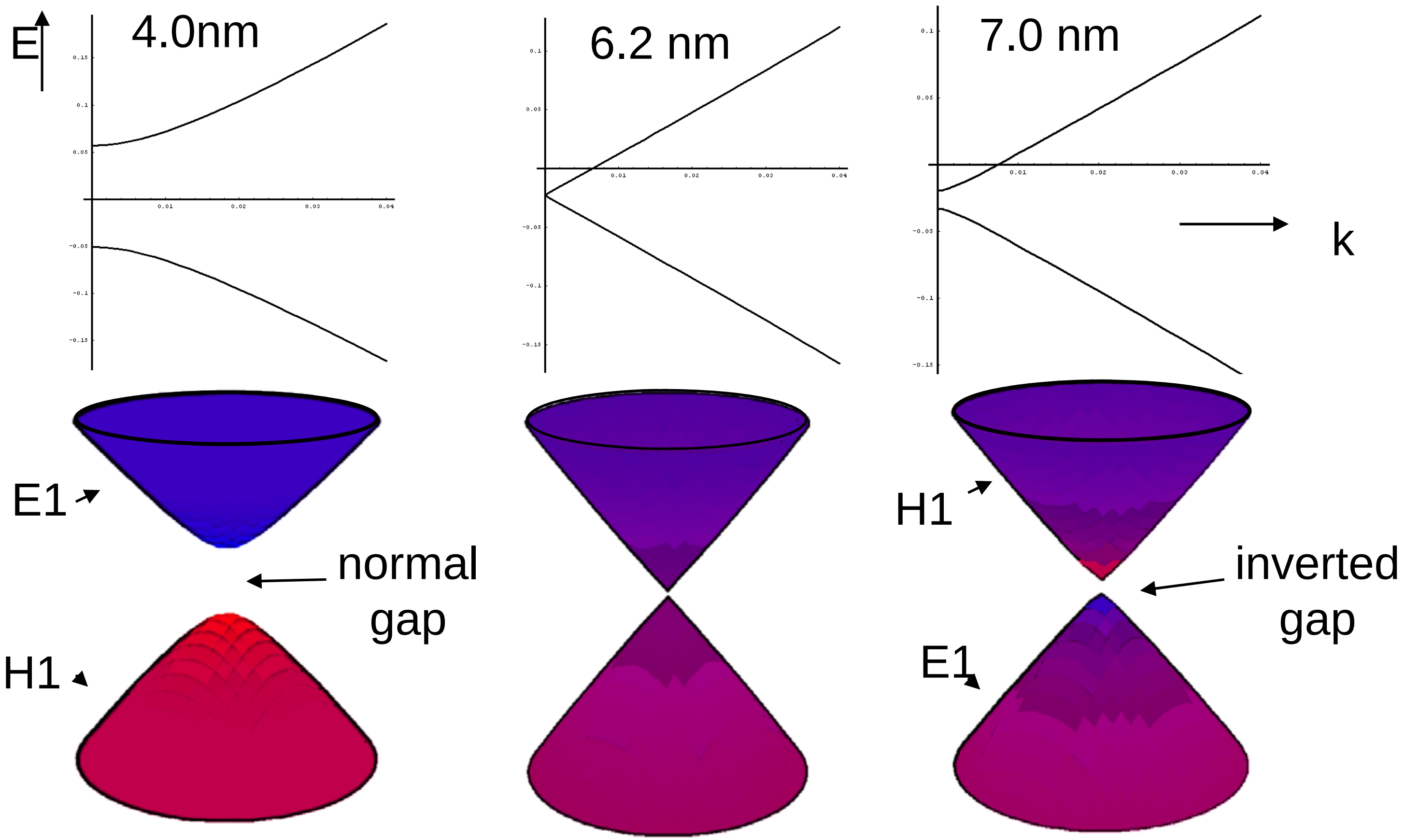
C.L.Kane and E.J.Mele, PRL **95**, 146802 (2005)
C.L.Kane and E.J.Mele, PRL **95**, 226801 (2005)
A.Bernevig and S.-C. Zhang, PRL **96**, 106802 (2006)



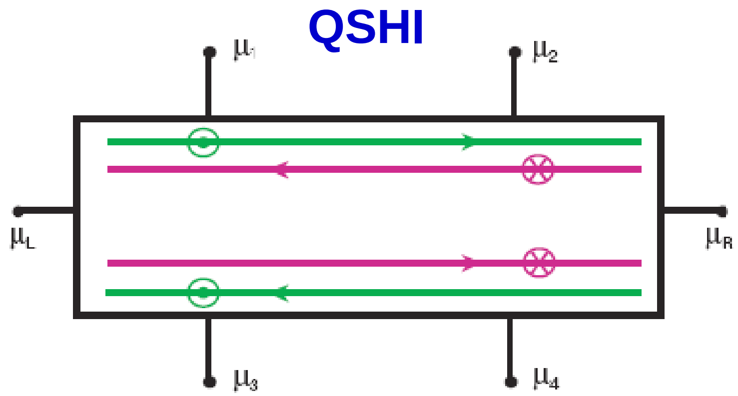
C.L.Kane and E.J. Mele, Science **314,** 1692 (2006)

Bandstructure HgTe

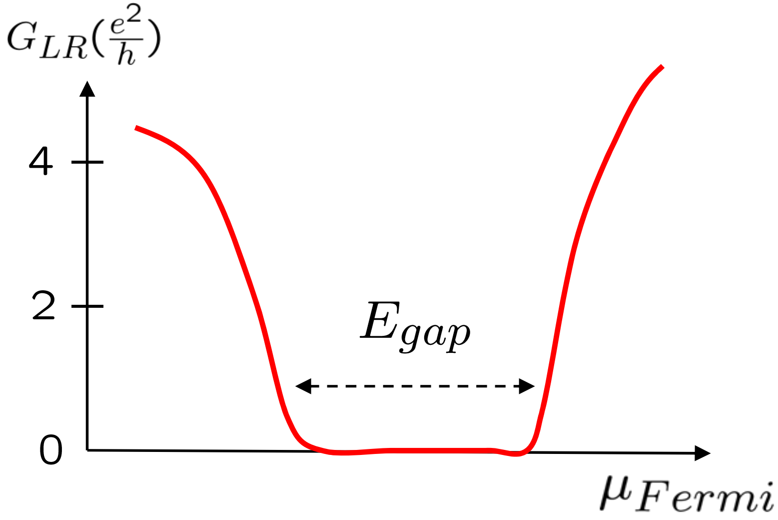
B.A Bernevig, T.L. Hughes, S.C. Zhang, Science **314**, 1757 (2006)



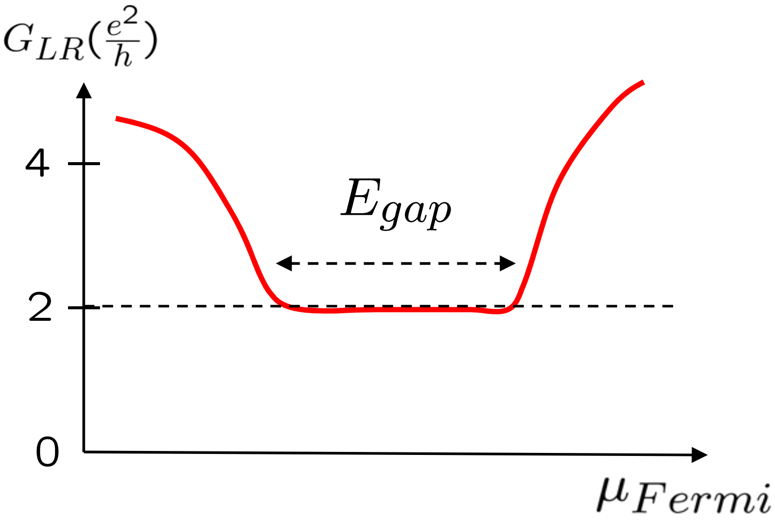
Experimental Signature



normal insulator state



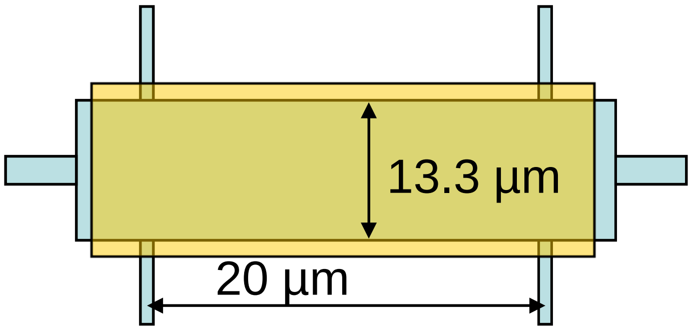
$d < d_c$, normal regime



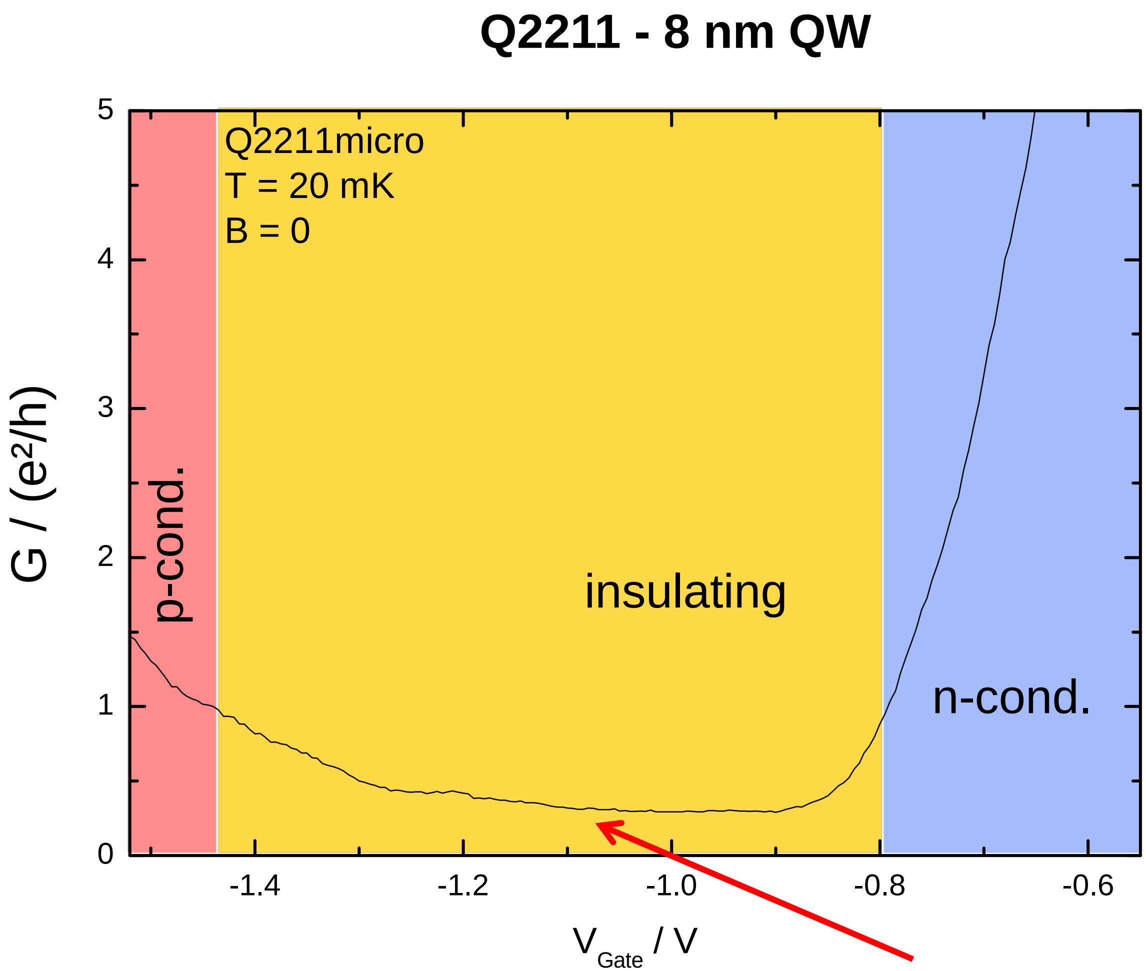
$d > d_c$, inverted regime

QSHE-Measurement

sample layout



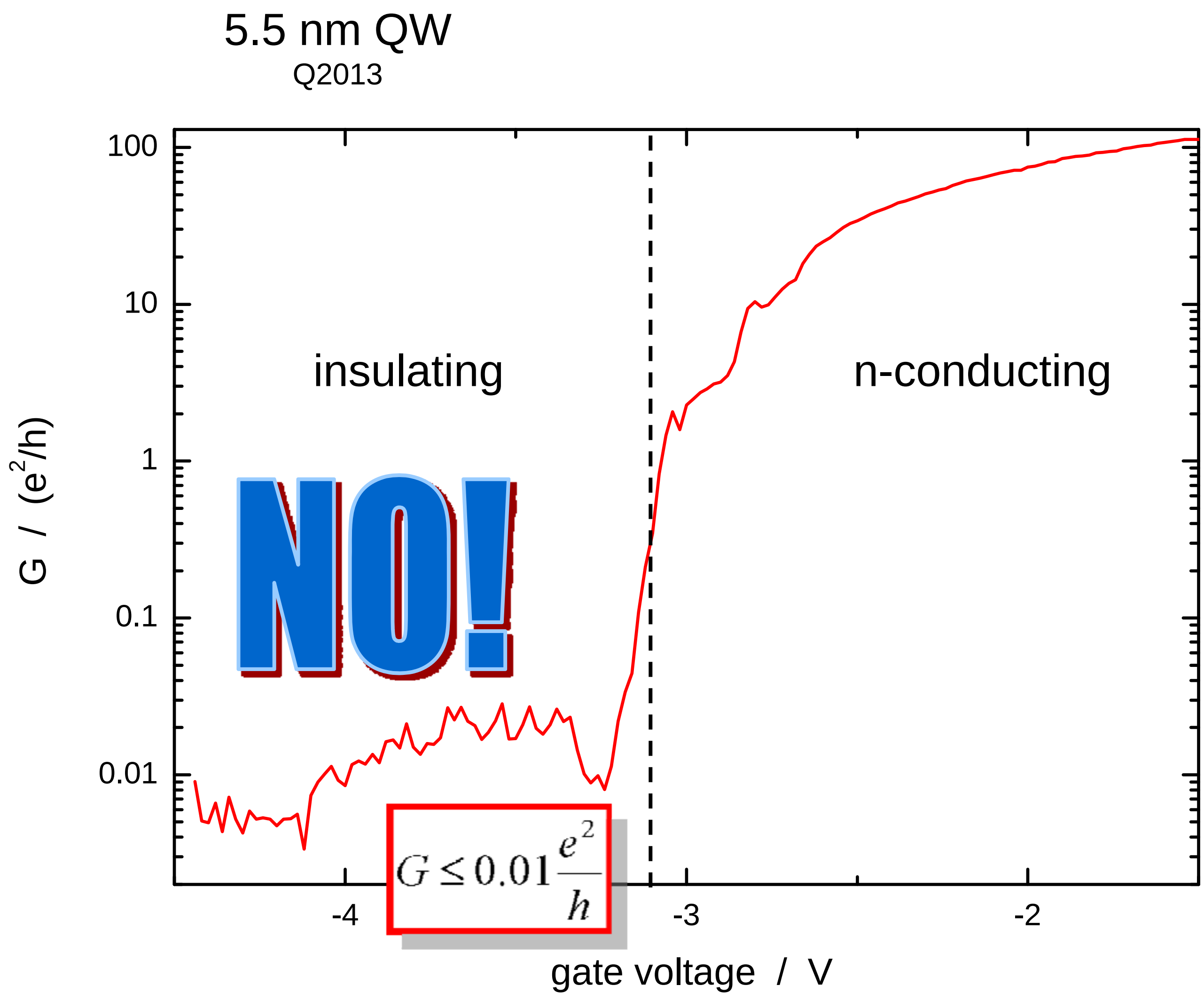
QSHE in inverted HgTe-QWs?



$$G \approx 0.3 \ldots 0.5 \frac{e^2}{h}$$

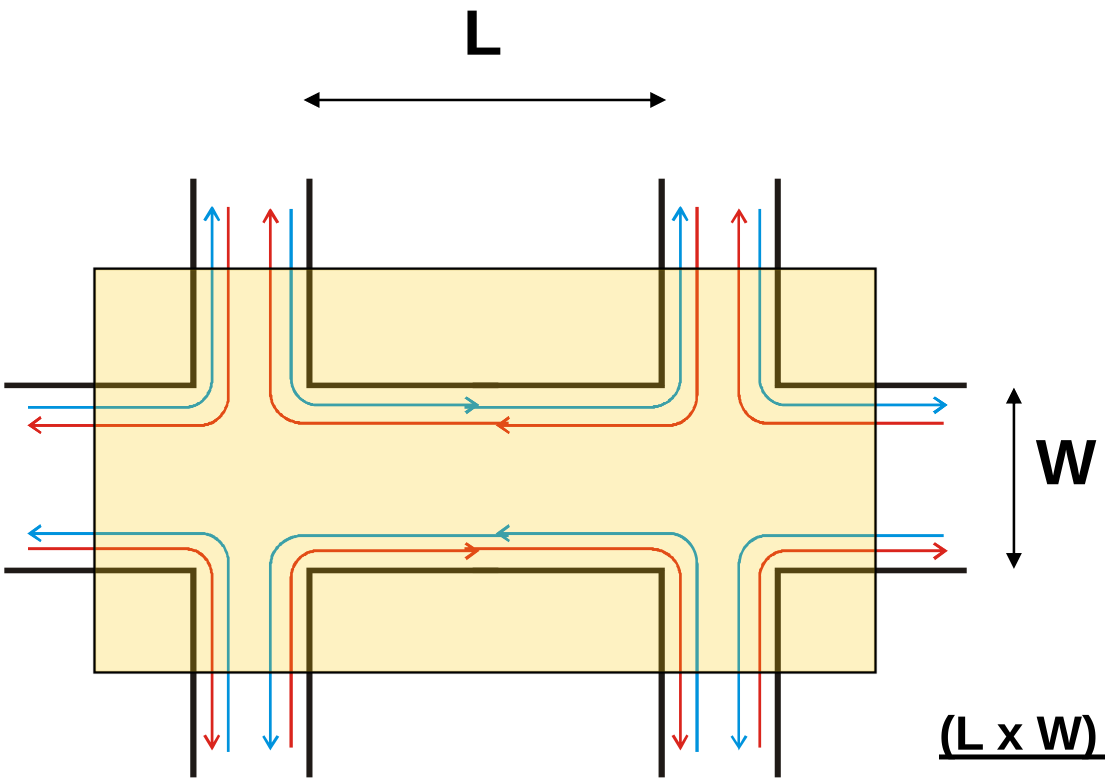
20 micron long bars:
finite conductance in the insulating regime

QSHE in normal HgTe-QWs?



$$G \leq 0.01\frac{e^2}{h}$$

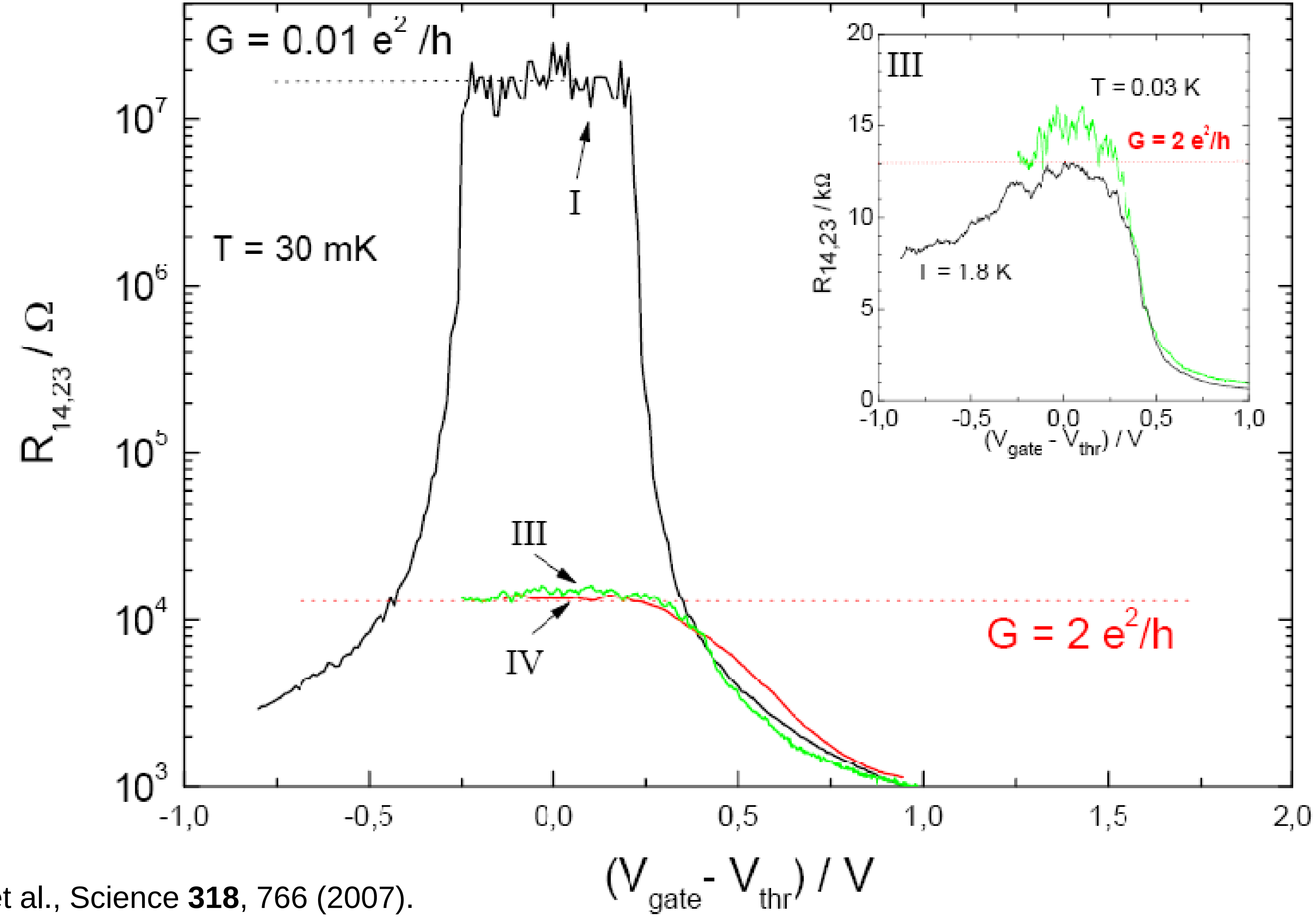
Smaller Samples



(L x W) μm

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

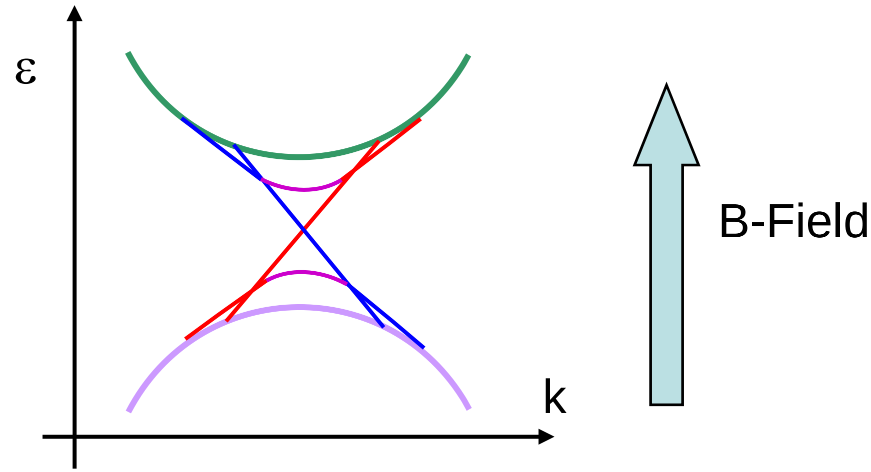
Observation of QSHI state in short samples



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

Magnetoconductance: Smoking gun for helical edge states

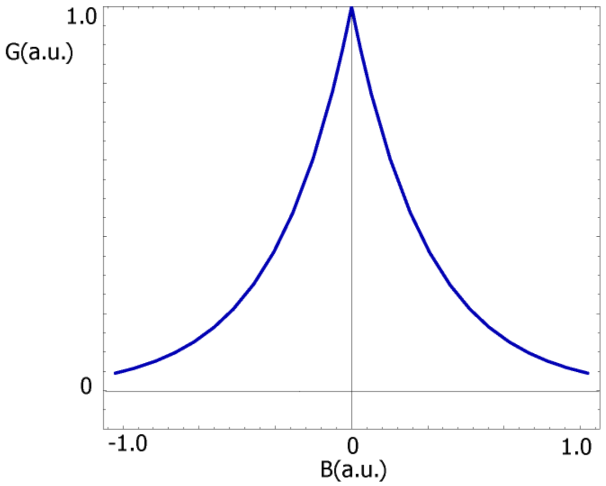
The crossing of the helical edge states is protected by the TR symmetry. TR breaking term such as the Zeeman magnetic field causes a singular perturbation and will open up a full insulating gap:



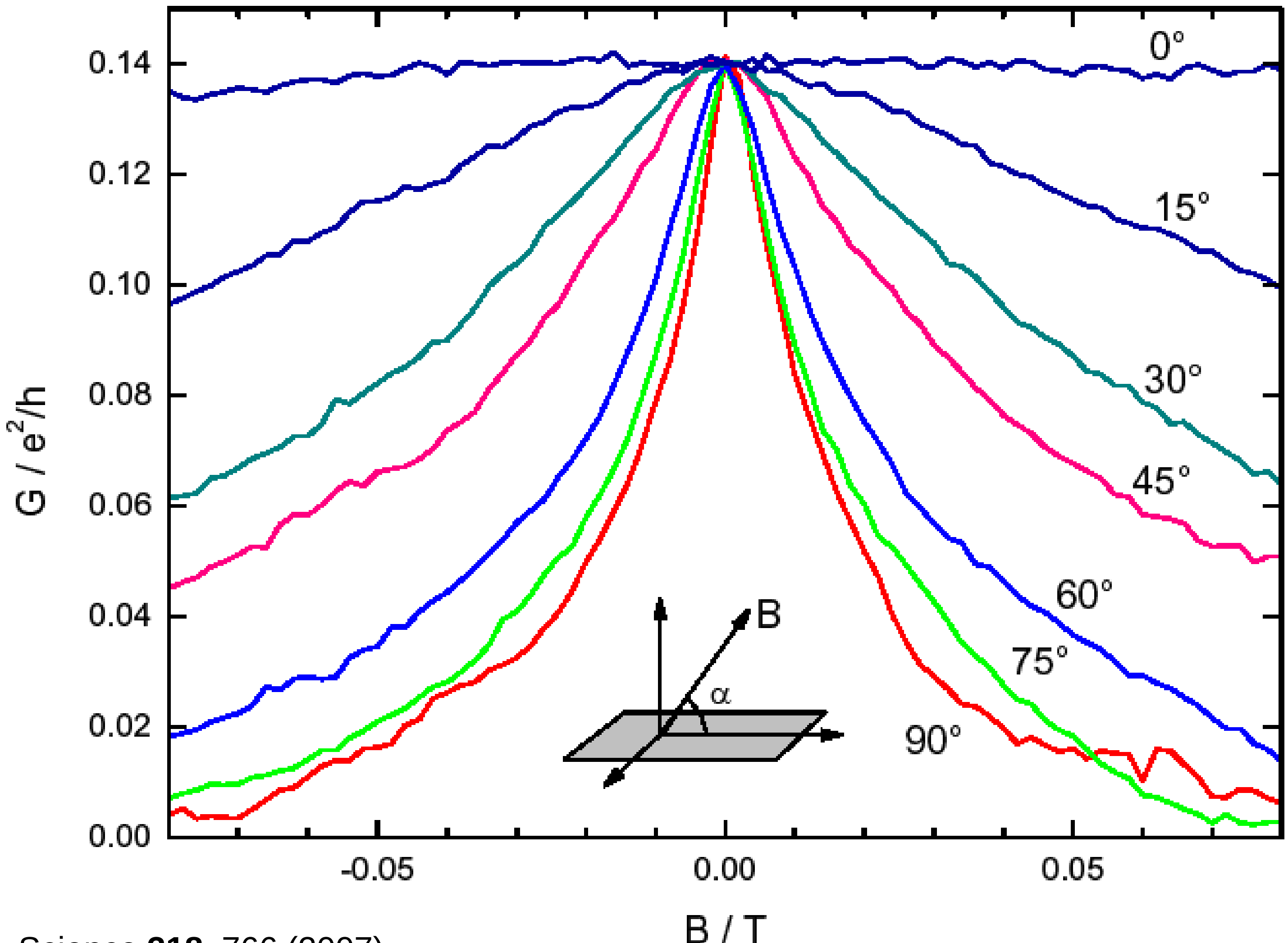
$$E_g \propto g|B|$$

Conductance now takes the activated form:

$$G \propto f(T) e^{-g|B|/kT}$$



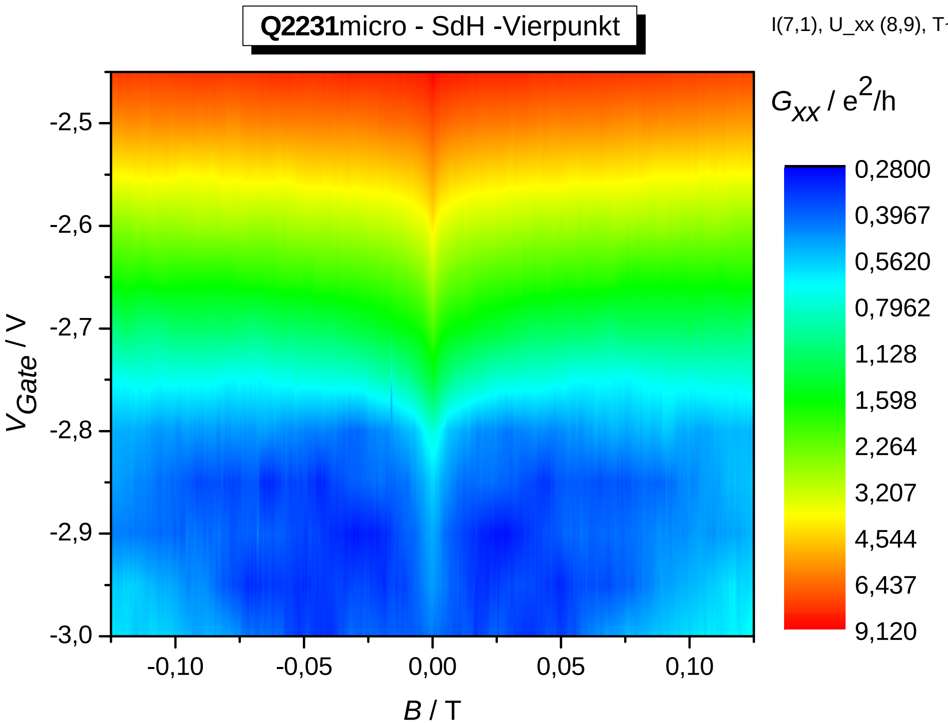
Angular dependence of the magneto-conductance



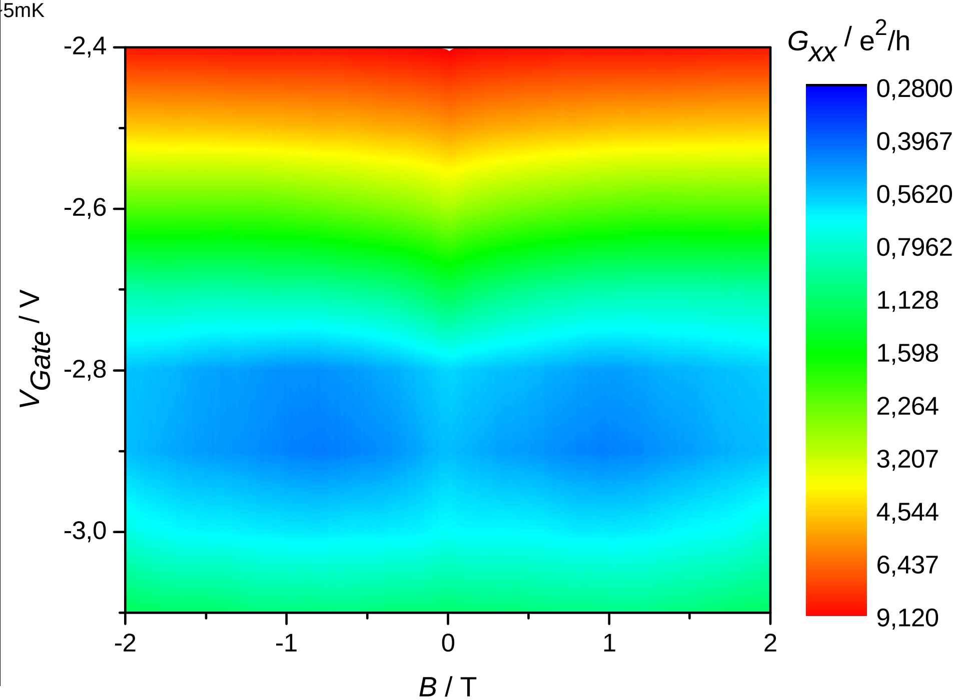
M. König et al., Science **318**, 766 (2007).

Magnetic field dependence

perpendicular



in plane



similar magnetic field behavior but on a different scale,
anisotropy due to high Fermi velocity and small gap.

Intrinsic SHE in Metals

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Spin-Hall Effect

EP 3

VOLUME 83, NUMBER 9 PHYSICAL REVIEW LETTERS 30 AUGUST 1999

Spin Hall Effect

J. E. Hirsch

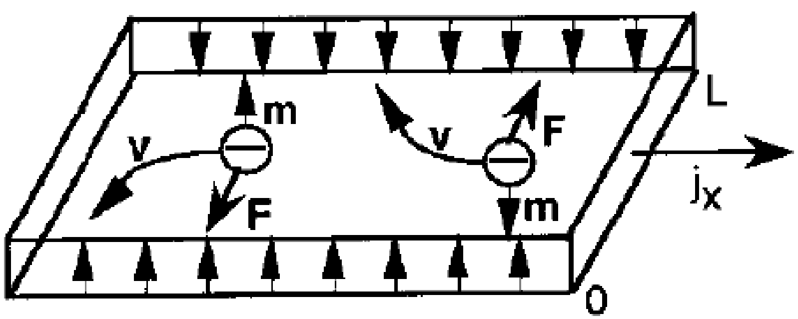
Department of Physics, University of California, San Diego, La Jolla, California 92093-0319

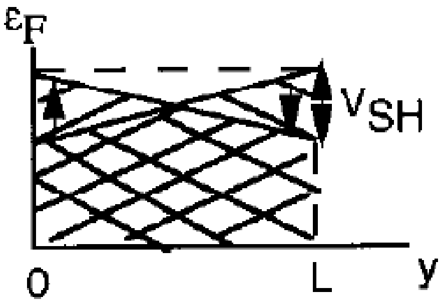
(Received 24 February 1999)

It is proposed that when a charge current circulates in a paramagnetic metal a transverse spin imbalance will be generated, giving rise to a "spin Hall voltage." Similarly, it is proposed that when a spin current circulates a transverse charge imbalance will be generated, giving rise to a Hall voltage, in the absence of charge current and magnetic field. Based on these principles we propose an experiment to generate and detect a spin current in a paramagnetic metal.

PACS numbers: 72.15.Gd, 73.61.At

Spin Hall effect

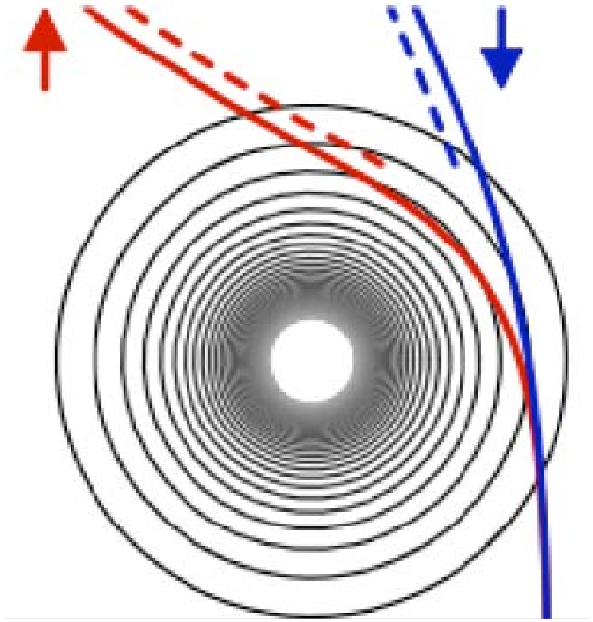




Spin-Hall Effect

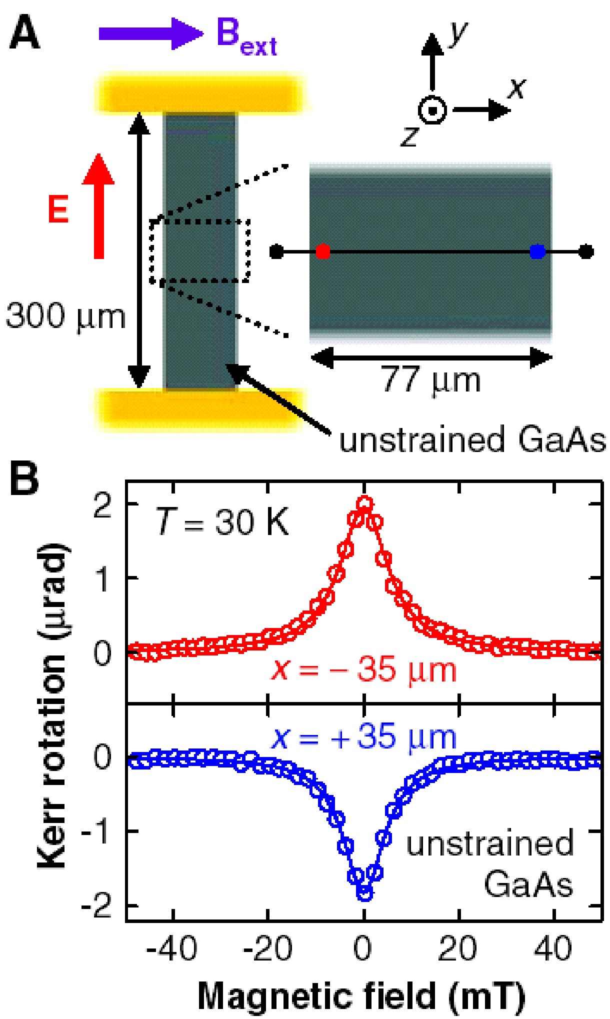
1. Extrinsic Spin Hall Effect: spin-dependent scattering at impurities

- skew scattering
- side jump effect

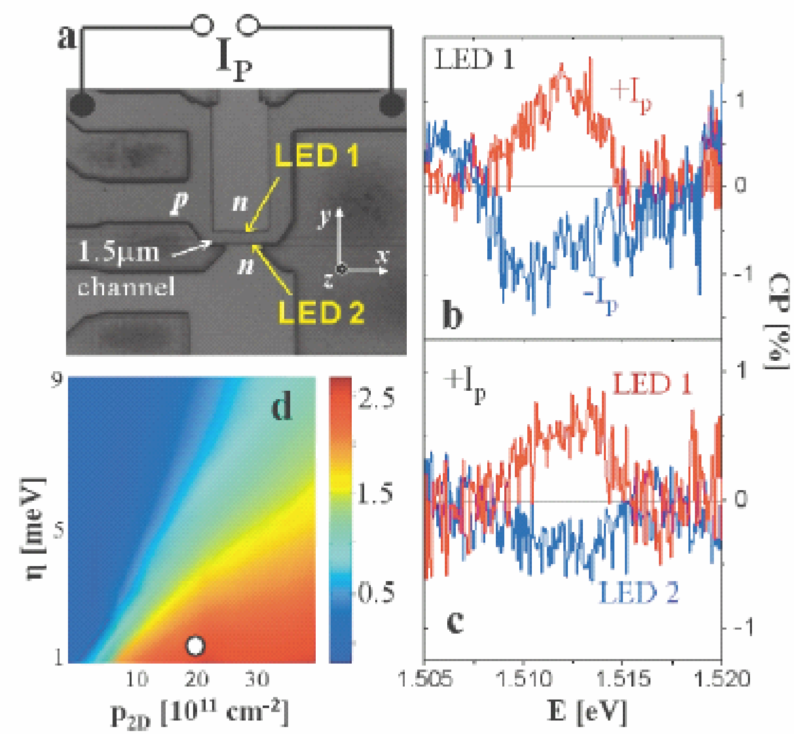


Spin-Hall Effect

optical detection



Kato et al. Science 306, 1910 (2004)



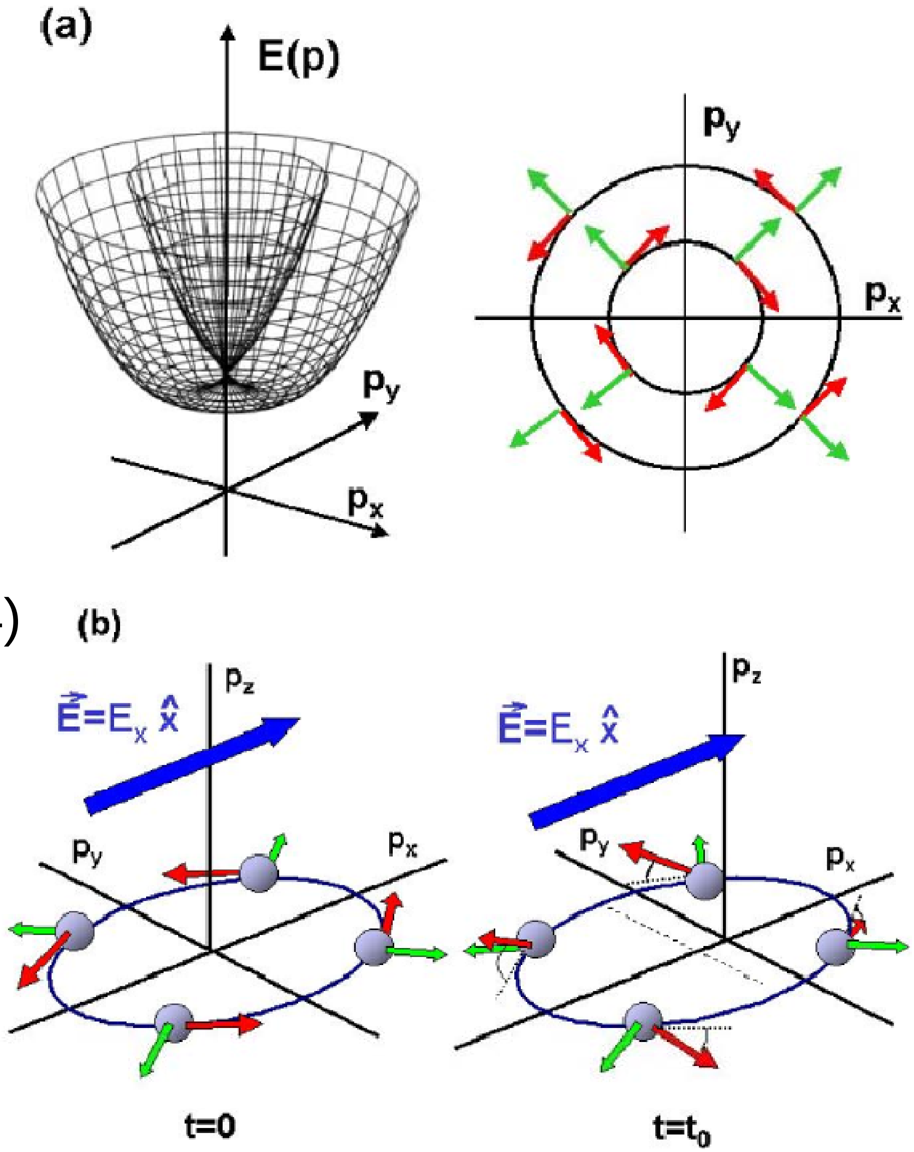
Wunderlich et al. PRL 94, 47204 (2005)

Spin-Hall Effect

Intrinsic SHE

Rashba effect

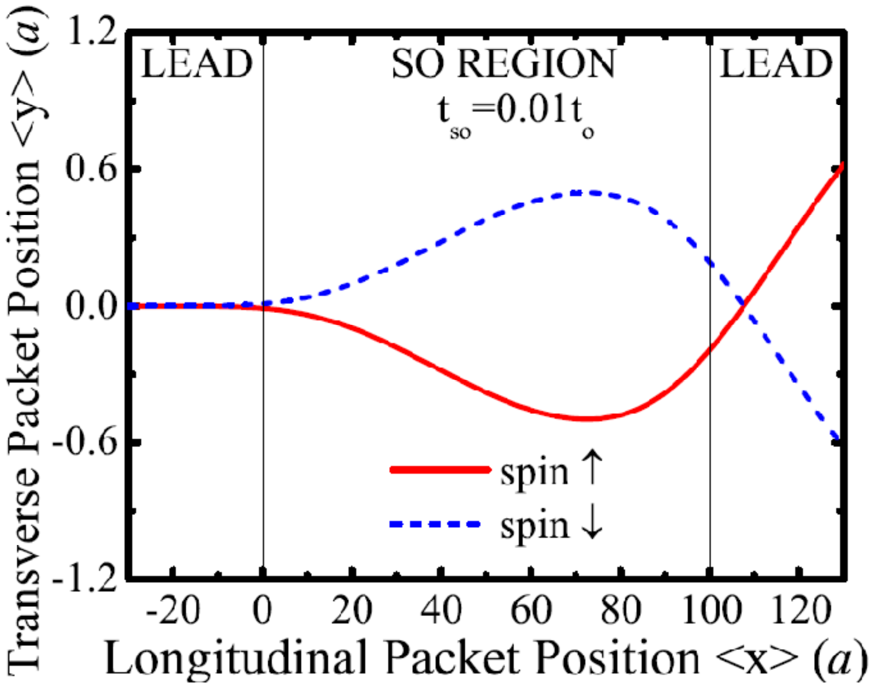
J.Sinova et al.,
Phys. Rev. Lett. **92**, 126603 (2004)



Spin-Orbit Force

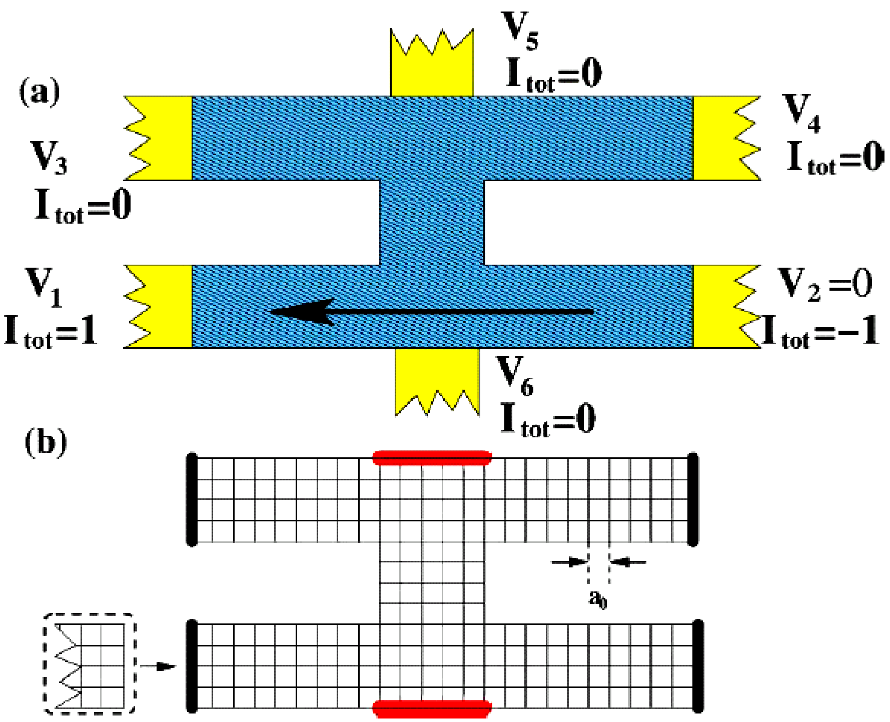
$$\hat{\mathbf{F}}_H = m^* \frac{d\mathbf{r}_H^2}{dt^2} = \frac{m^*}{\hbar^2}[\hat{H}, [\hat{\mathbf{r}}_H, \hat{H}]]$$

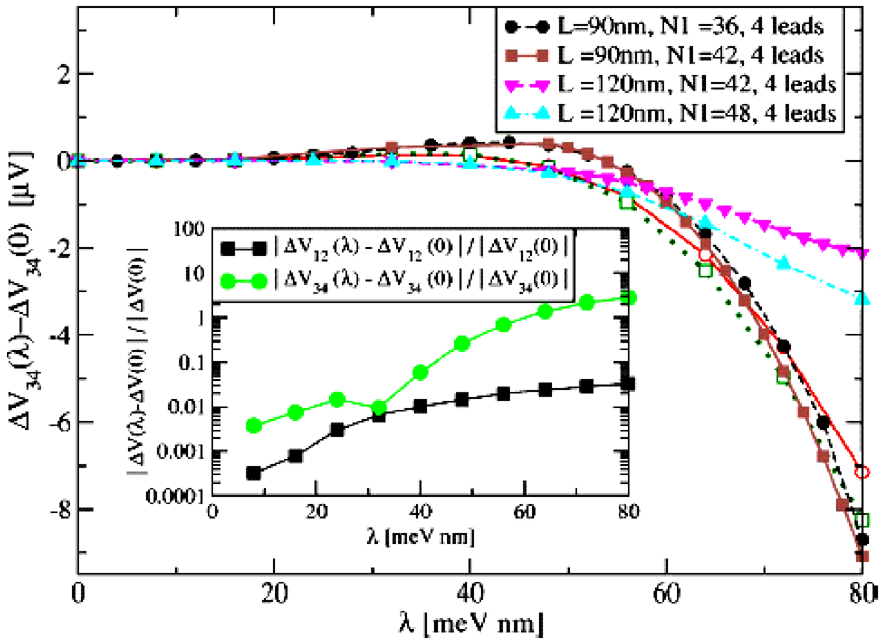
$$= \frac{2\alpha^2 m^*}{\hbar^3}(\hat{\mathbf{p}}_H \times \mathbf{z}) \otimes \hat{\sigma}_H^z - \frac{dV_{\mathrm{conf}}(\hat{y}_H)}{d\hat{y}_H}\mathbf{y}$$



H-bar for detection of Spin-Hall-Effect

(electrical detection through inverse SHE)



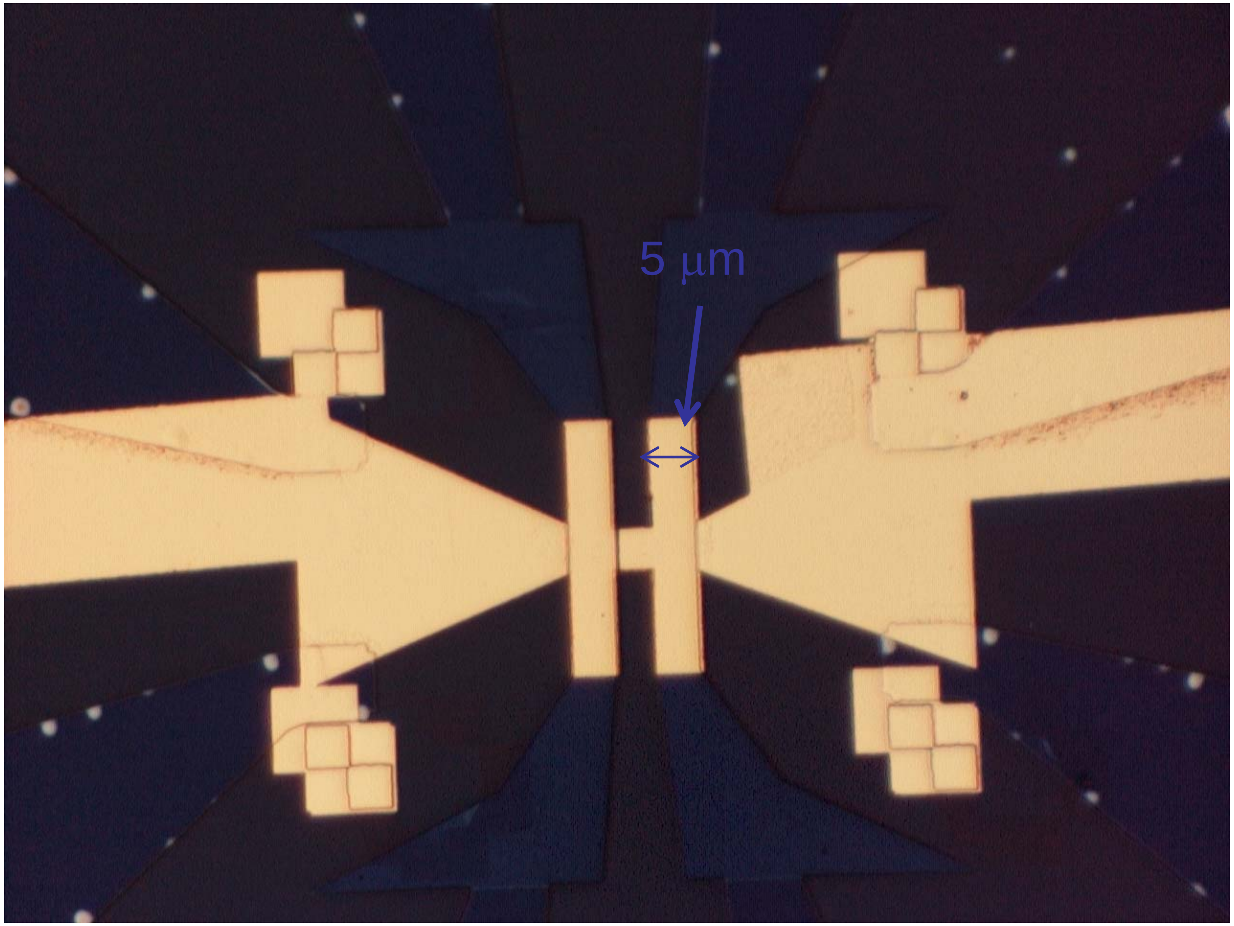


E.M. Hankiewicz et al ., PRB **70**, R241301 (2004)

Original gated H-bar sample (2004)

HgTe-QW

Δ_R = 5-15 meV



Gate-
Contact

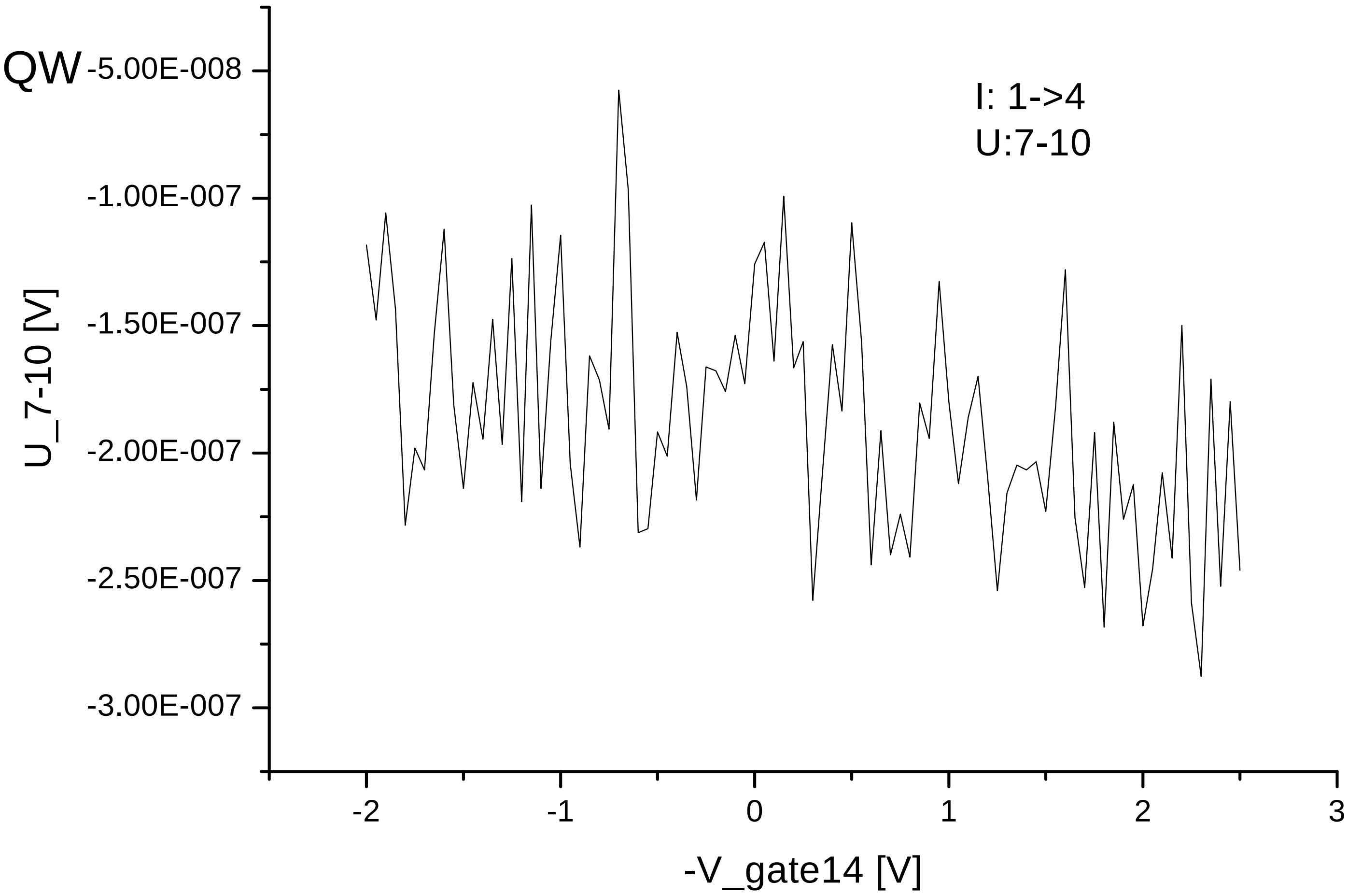
ohmic Contacts

High density Sample

Symmetric HgTe-QW

Δ_R = 0-5 meV

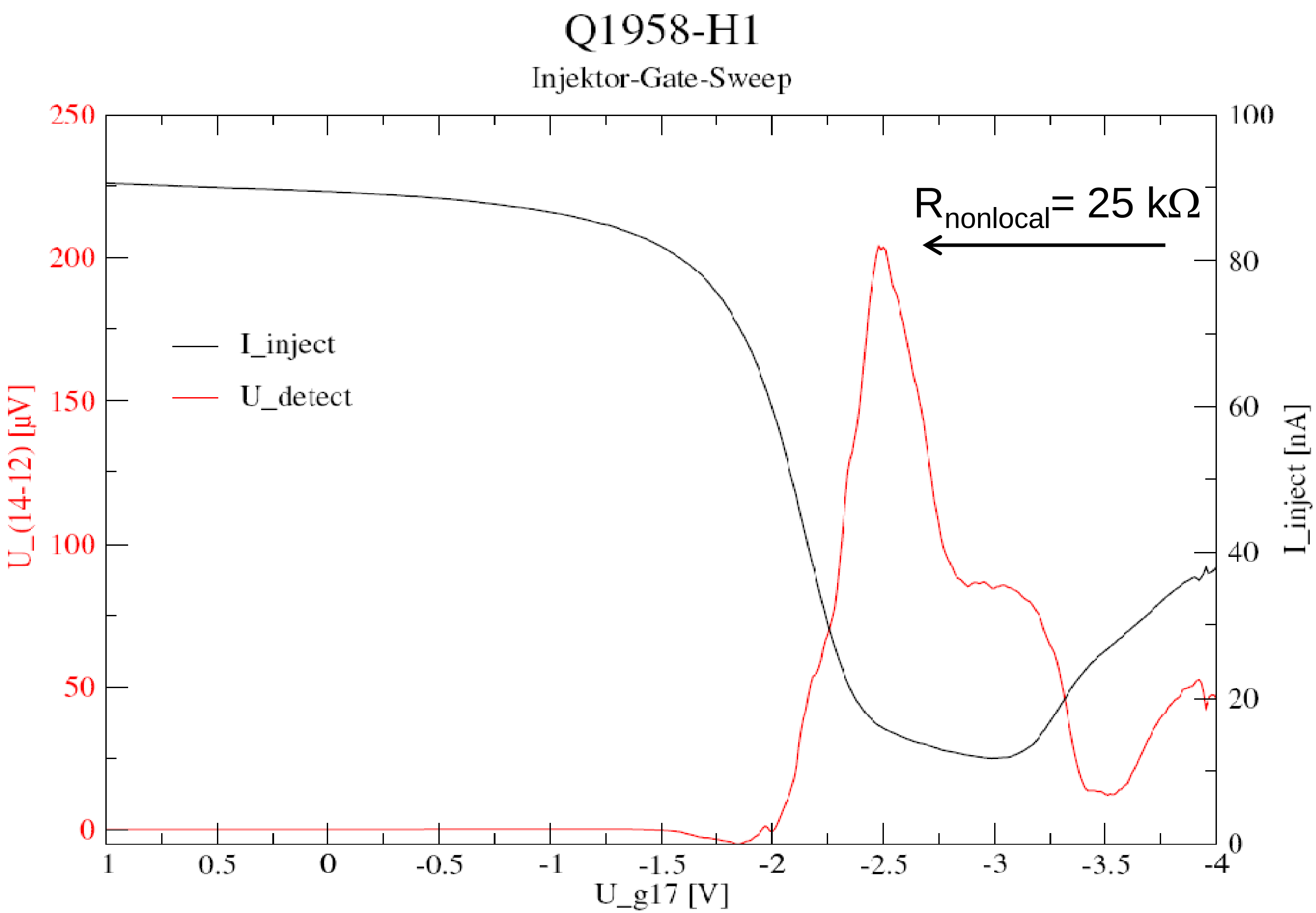
Signal less than 10^{-4}



Sample is diffusive:

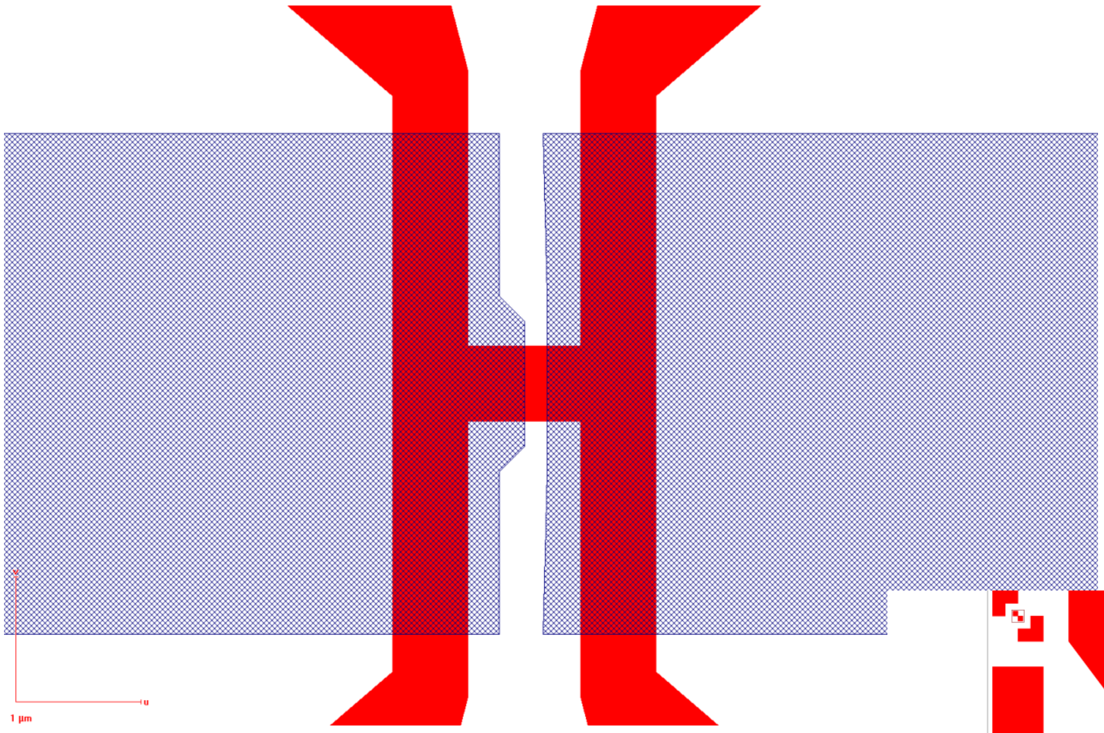
Vertex correction kills SHE (J. Inoue et al., Phys. Rev. B **70**, 041303 (R) (2004)).

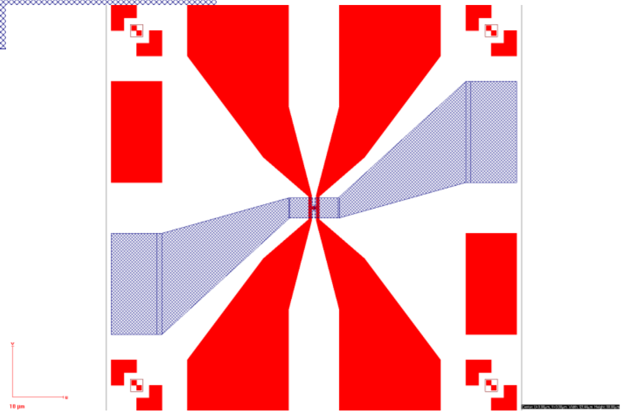
Low-Doped Sample (2004)



QSHE and iSHE as spin injector and detector

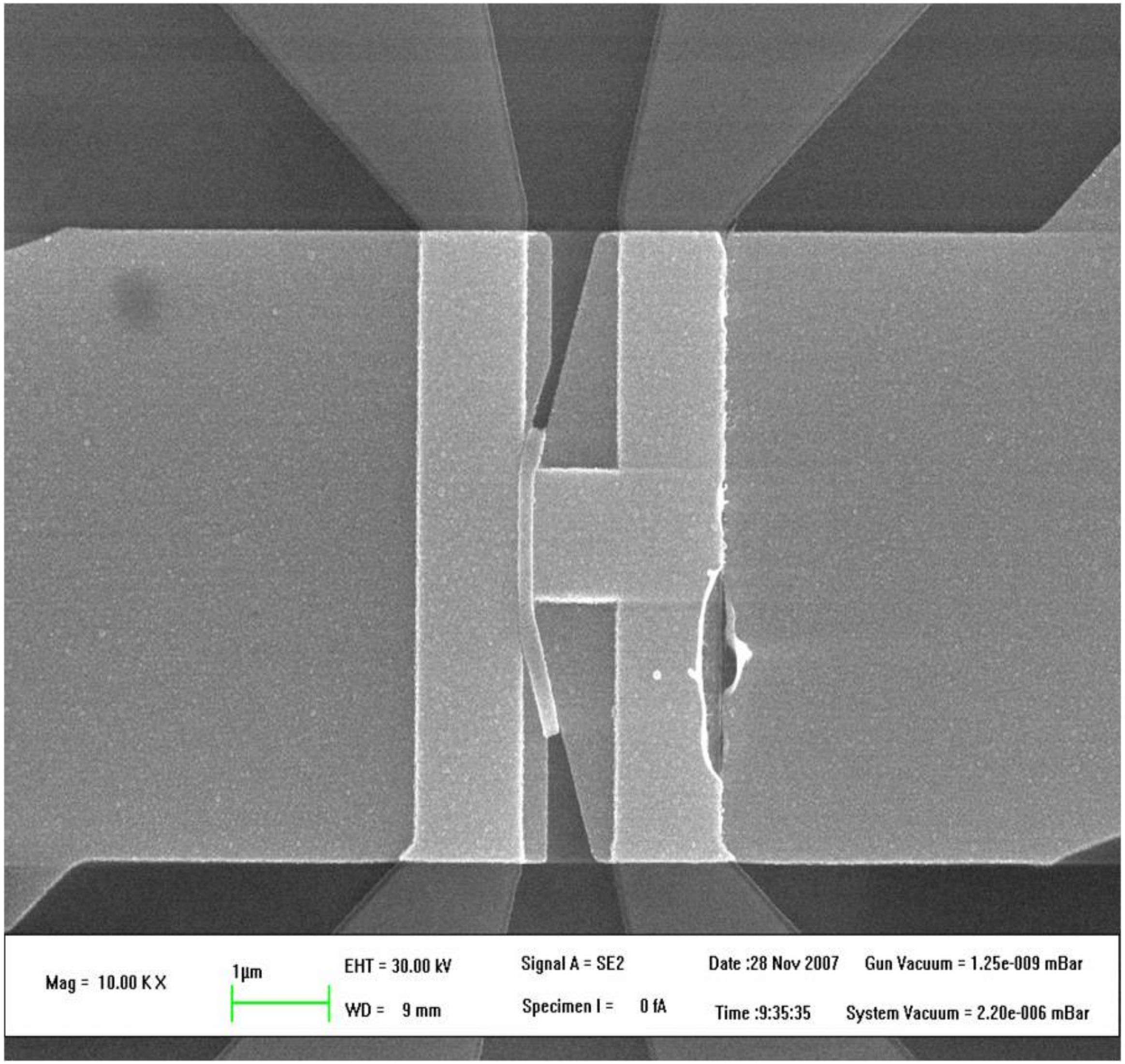
Q2315 HX

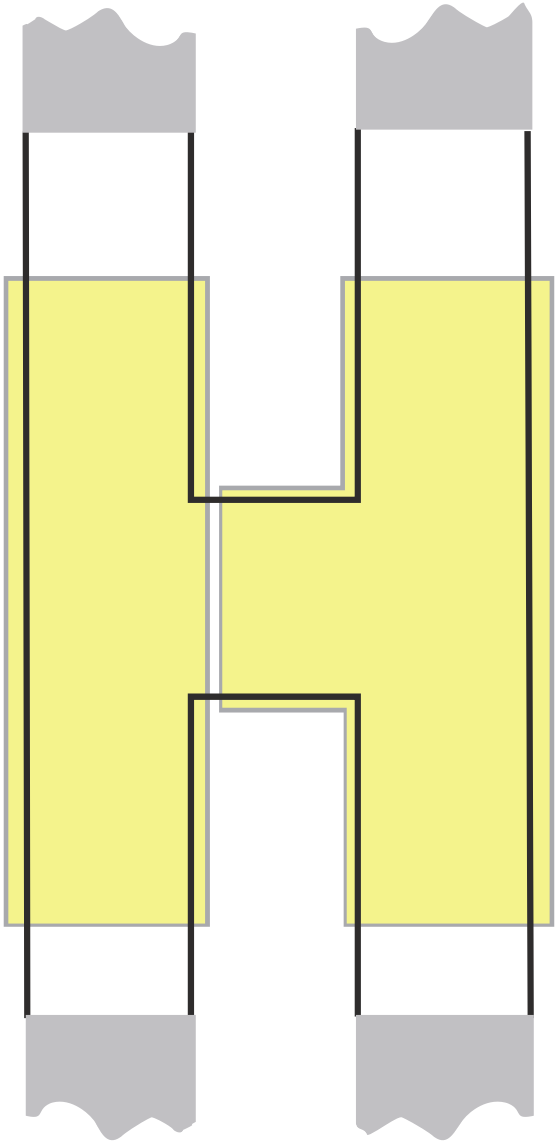




750 nm

Split Gate H-Bar





Conclusions

- HgTe Quantum wells: strong Rashba, normal and inverted semiconductors
- High mobility, gate-able through the bandgap
- First observation quantum SHI
- Clear evidence for non-local transport through edge channels
- First evidence for intrinsic SHE in metals

Collaborators:
Charlie Becker, Christoph Brüne, Hartmut Buhmann, Markus König, Andreas Roth, Volkmar Hock

Theory: Alina Novik, Manuel Schmidt, Ewelina Hankiewicz ,
Gerrit E.W. Bauer (Delft), Junichiro Inoue (Nagoya), Jairo Sinova (TAMU),
Shoucheng Zhang (Stanford), Sasha Finkel'stein (Weizmann/TAMU)

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