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EP 3
PD Dr. H. Buhmann

Spin Hall Effects in HgTe Quantum Well Structures

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(slides with unpublished results have been removed!)

Presented at the PITP/SpinAps Asilomar Conference in June 2007

PiTP

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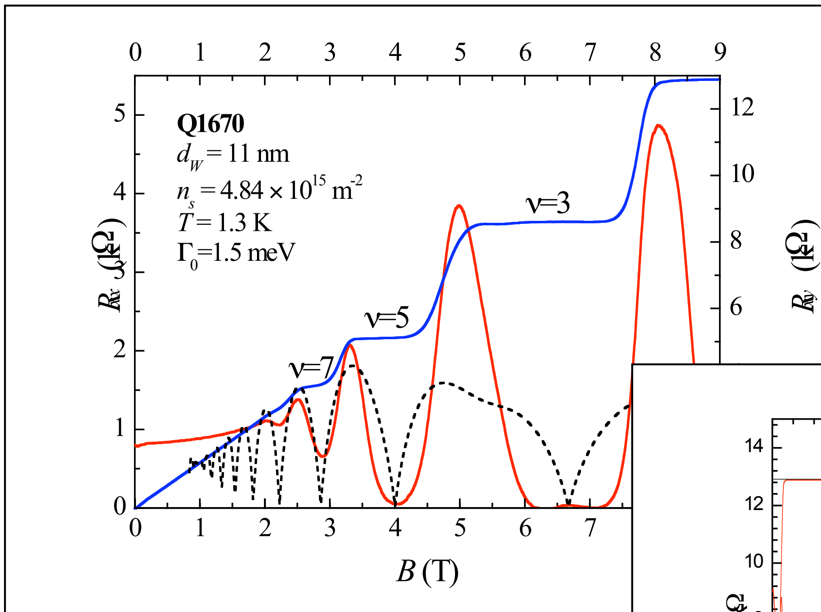
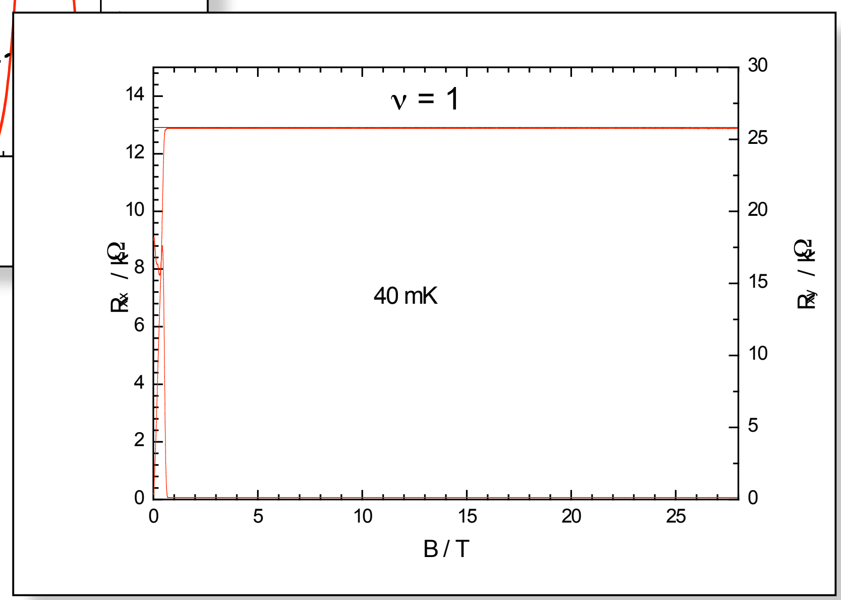
Anomalous Quantum Hall Effect

PD Dr. H. Buhmann

in dilute magnetic semiconductor quantum wells



2% Mn

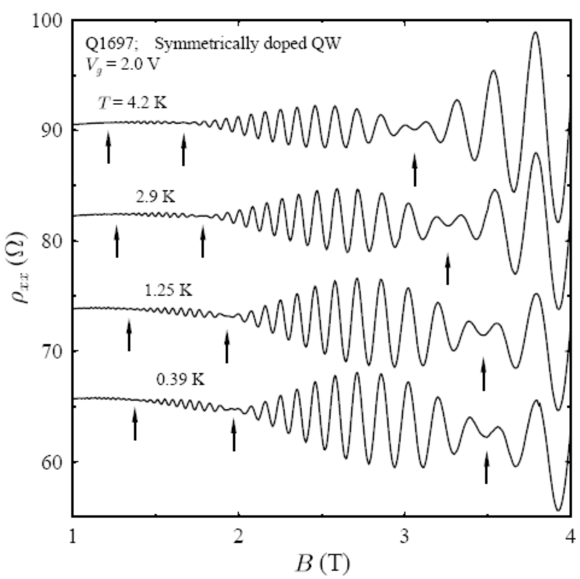


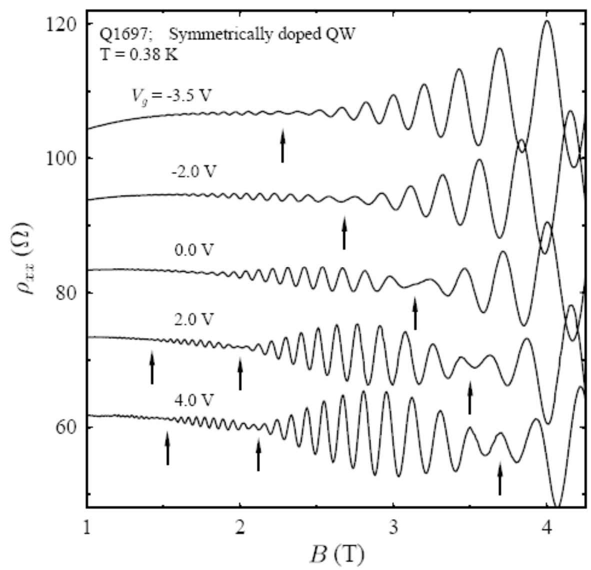
H. Buhmann *et al.*, Apl. Phys. Lett. **86**, 212104 (2005)

Interplay of Rashba, Zeeman and Landau splitting in a magnetic two-dimensional electron gas

Y. S. Gui(*), C. R. Becker(**), J. Liu, V. Daumer, V. Hock,
H. Buhmann and L. W. Molenkamp

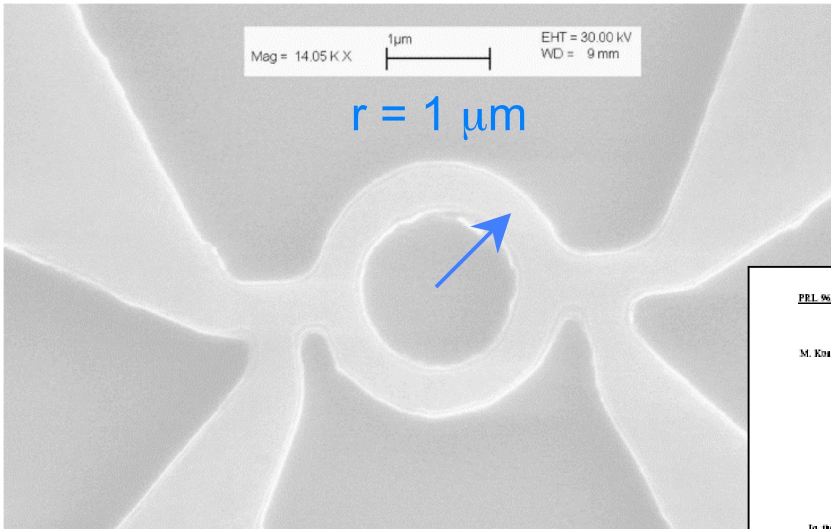
Europhys. Lett., 65, 393 (2004)



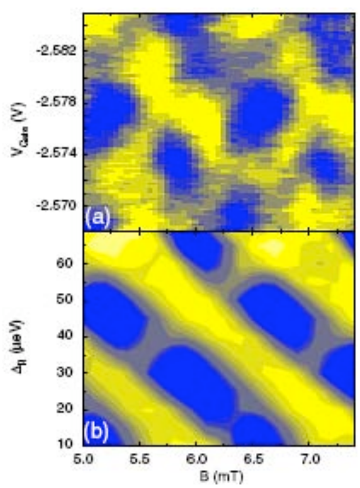


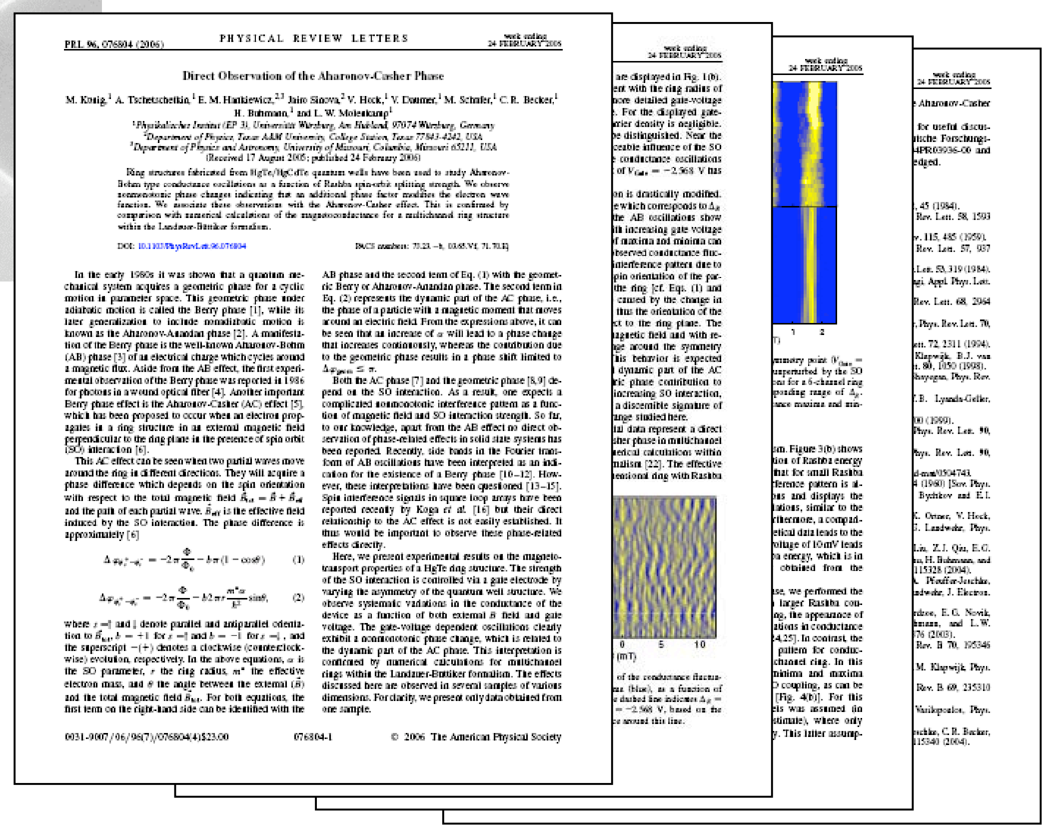
Spin Interference Effect

Direct Observation of the Aharonov-Caser Phase



M.König, AT, EMH, JS, VH, VD, MS, CRB, **HB**, and LWM, PRL **96**, 076804 (2006).




PRL 96, 076804 (2006) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2006

Direct Observation of the Aharonov-Casher Phase

M. König,[1] A. Tschetschetkin,[1] E. M. Hankiewicz,[2,3] Jairo Sinova,[2] V. Hock,[1] V. Daumer,[1] M. Schäfer,[1] C. R. Becker,[1] H. Buhmann,[1] and L. W. Molenkamp[1]

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[3]Department of Physics and Astronomy, University of Missouri, Columbia, Missouri 65211, USA
(Received 17 August 2005; published 24 February 2006)

Ring structures fabricated from HgTe/HgCdTe quantum wells have been used to study Aharonov-Bohm type conductance oscillations as a function of Rashba spin-orbit splitting strength. We observe nonmonotonic phase changes indicating that an additional phase factor modifies the electron wave function. We associate these observations with the Aharonov-Casher effect. This is confirmed by comparison with numerical calculations of the magnetoconductance for a multichannel ring structure within the Landauer-Büttiker formalism.

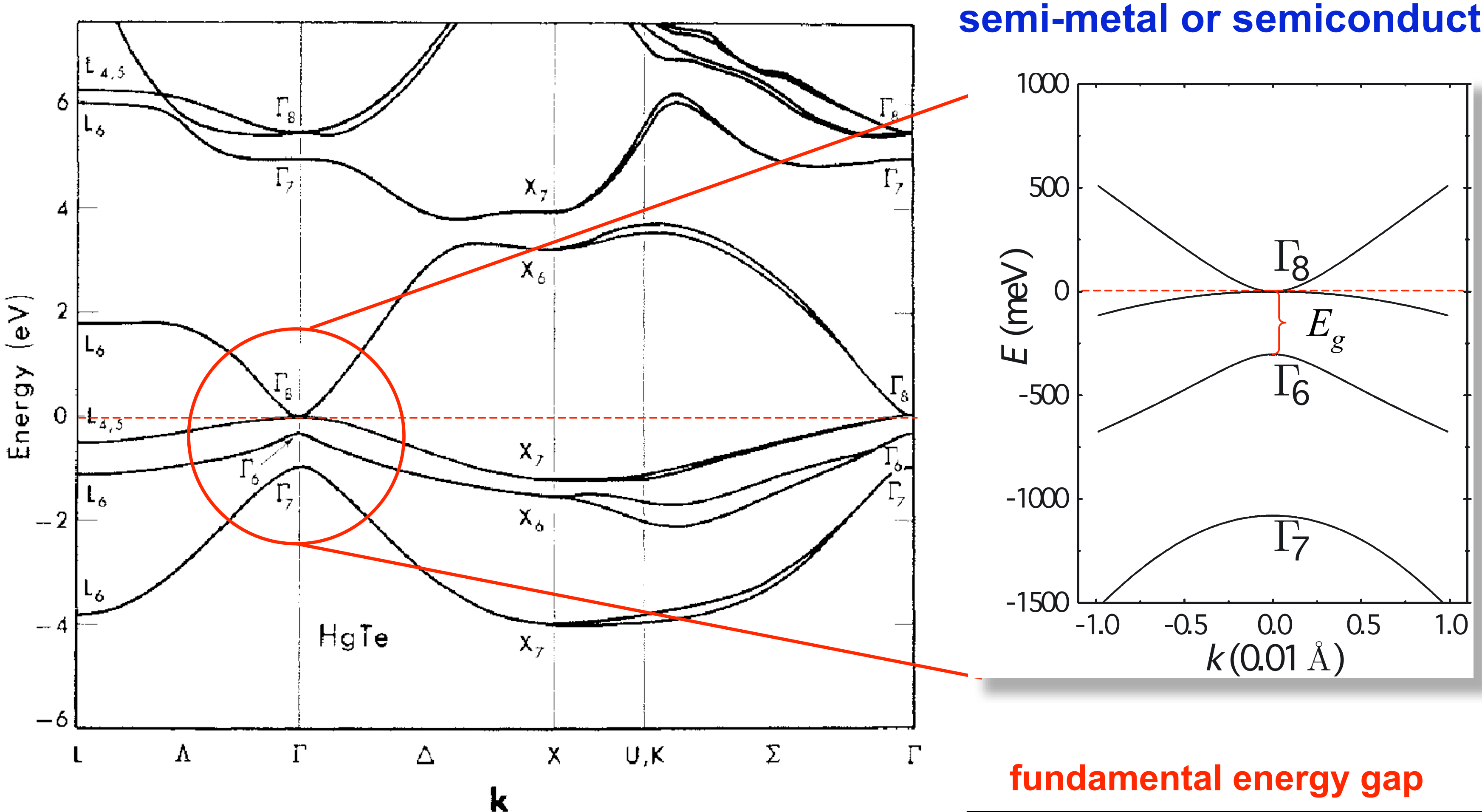
DOI: 10.1103/PhysRevLett.96.076804 PACS numbers: 73.23.-b, 03.65.Vf, 71.70.Ej

HgTe-Quantum Well Structures

HgTe

band structure

semi-metal or semiconductor



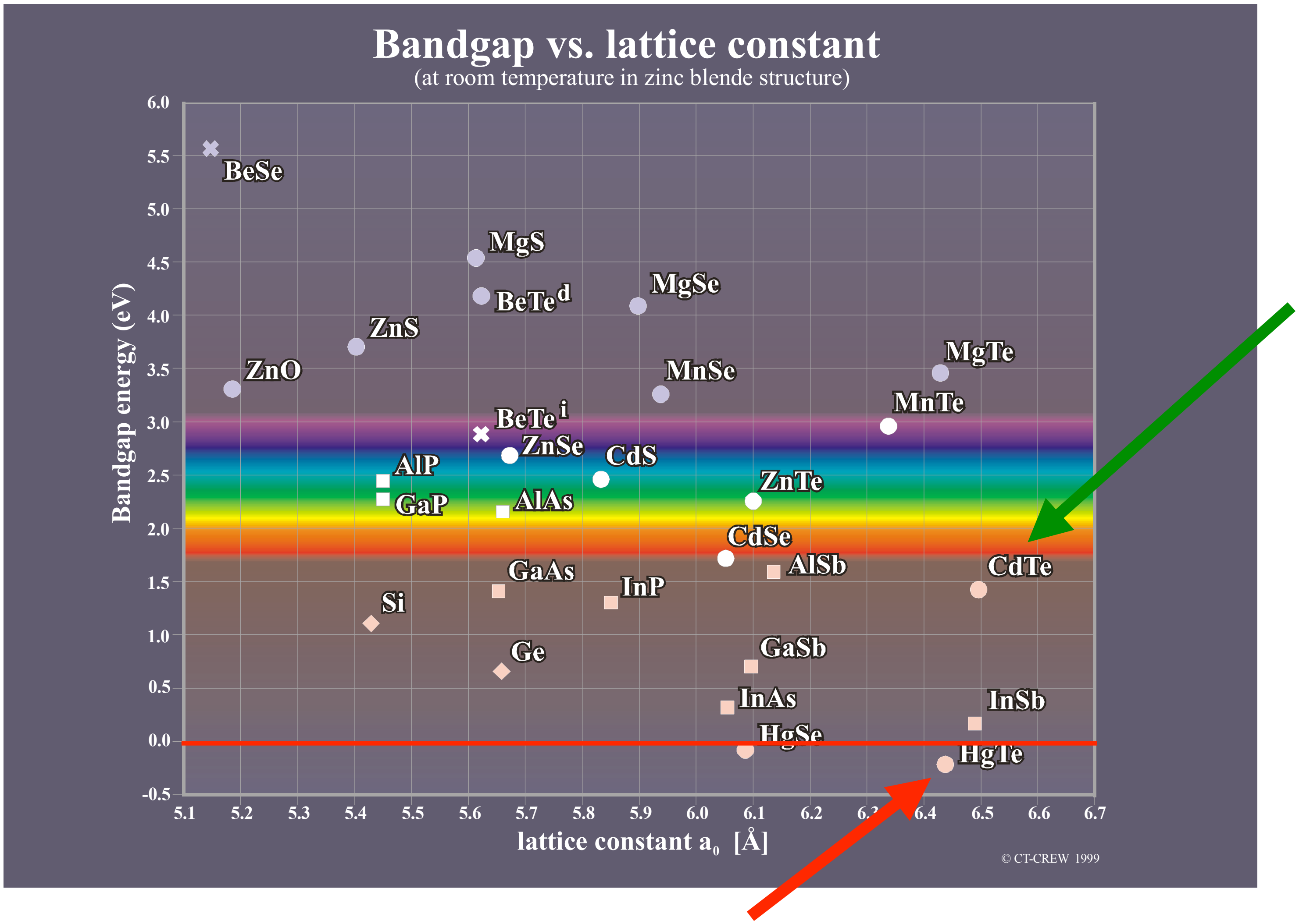
D.J. Chadi et al. PRB, 3058 (1972)

fundamental energy gap

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

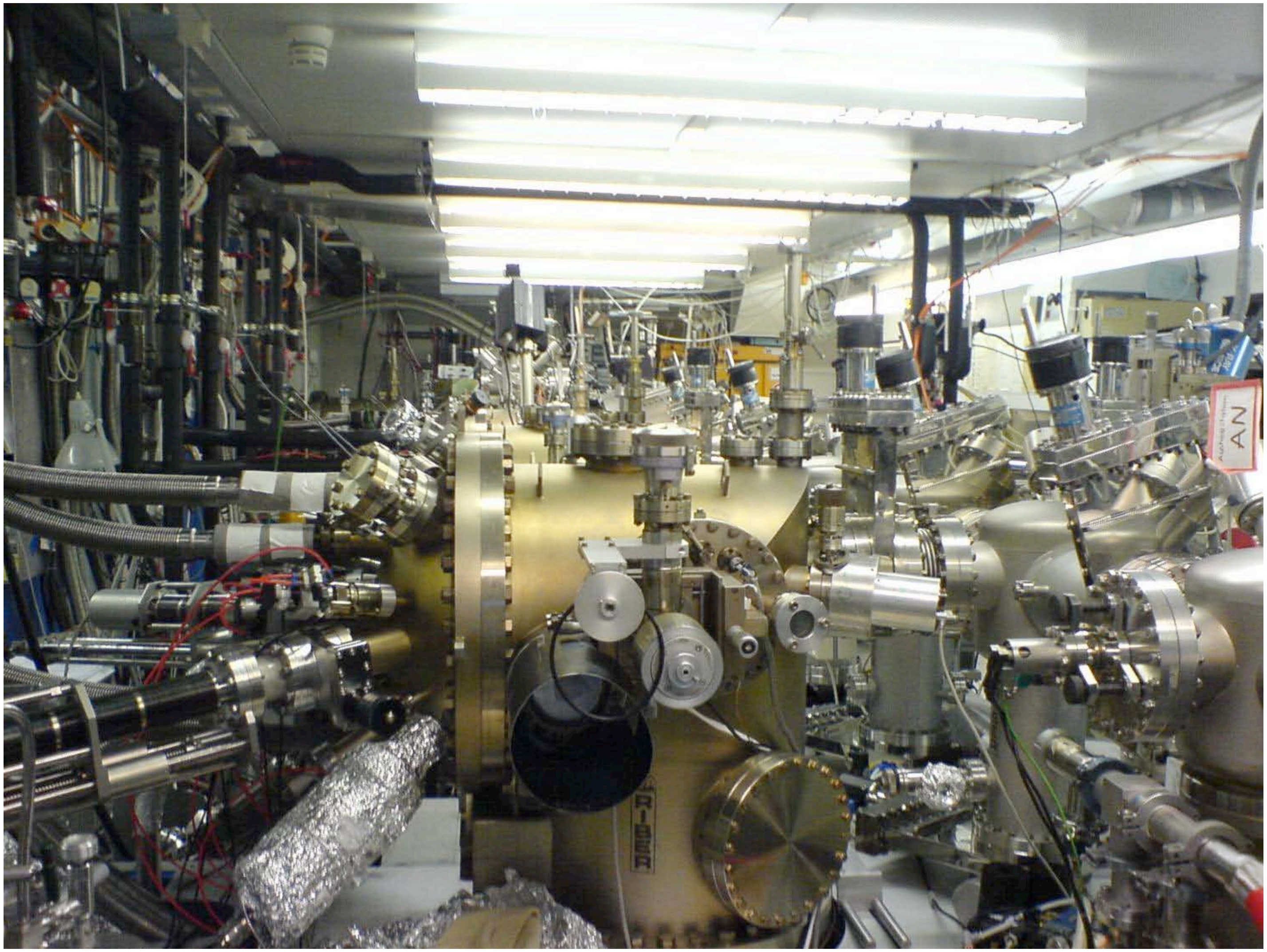
HgTe-Quantum Wells

MBE-Growth

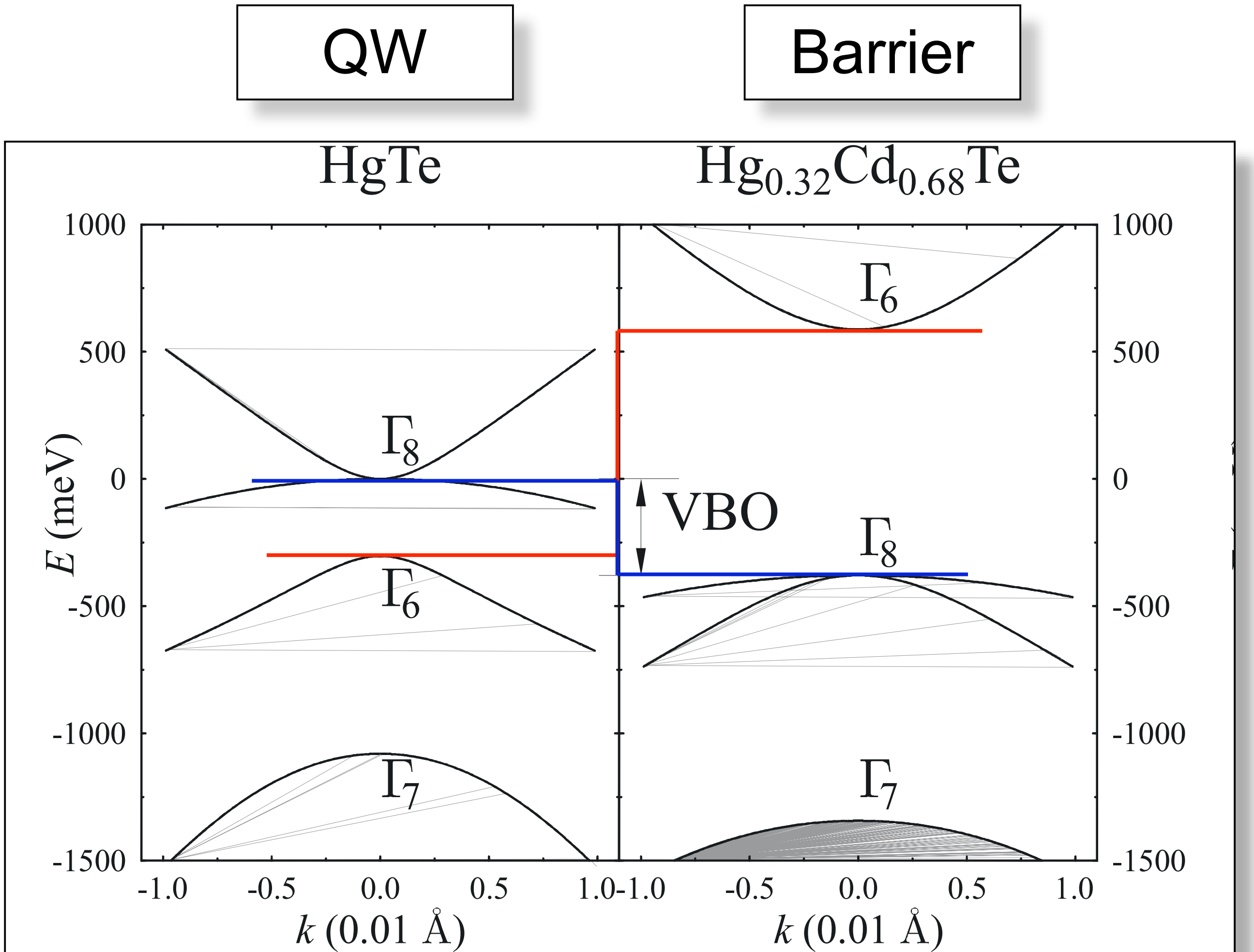


HgTe-Quantum Wells

MBE-Growth Chamber



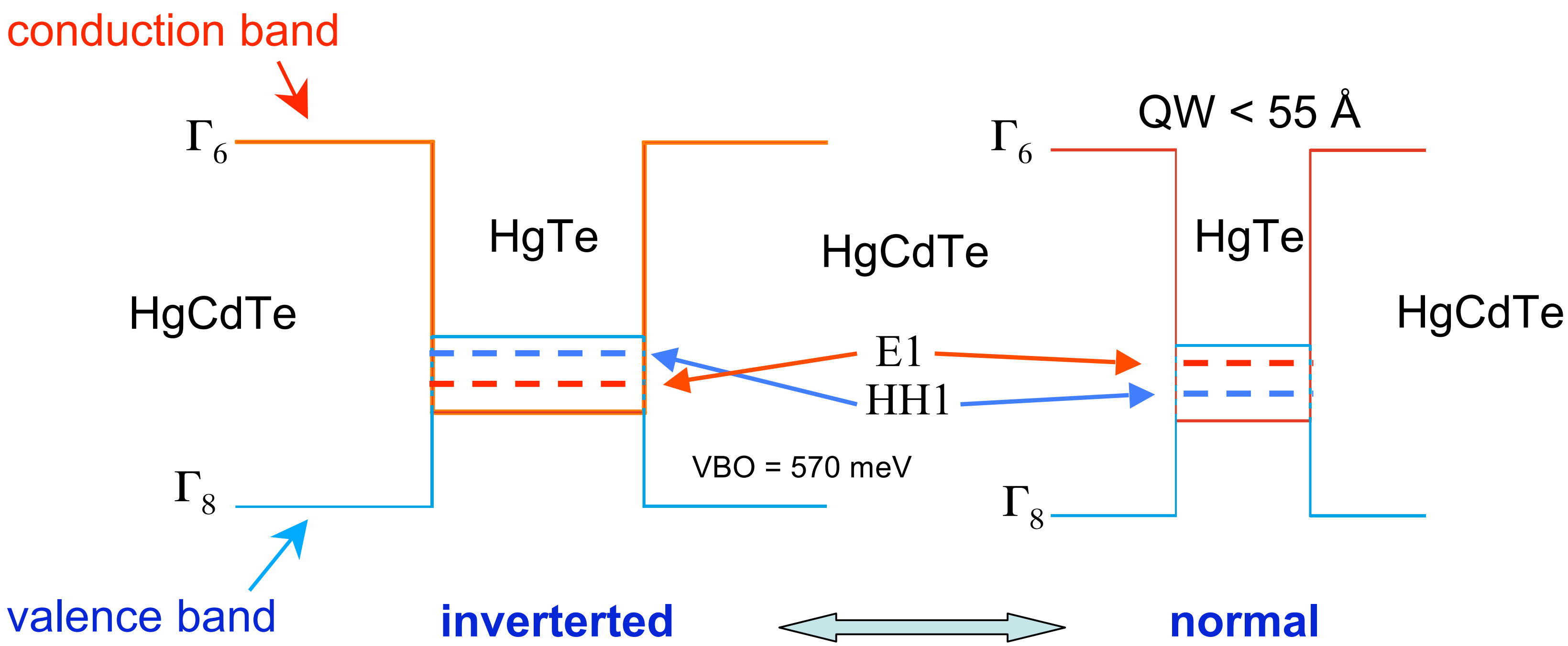
HgTe-Quantum Wells



VBO = 570 meV

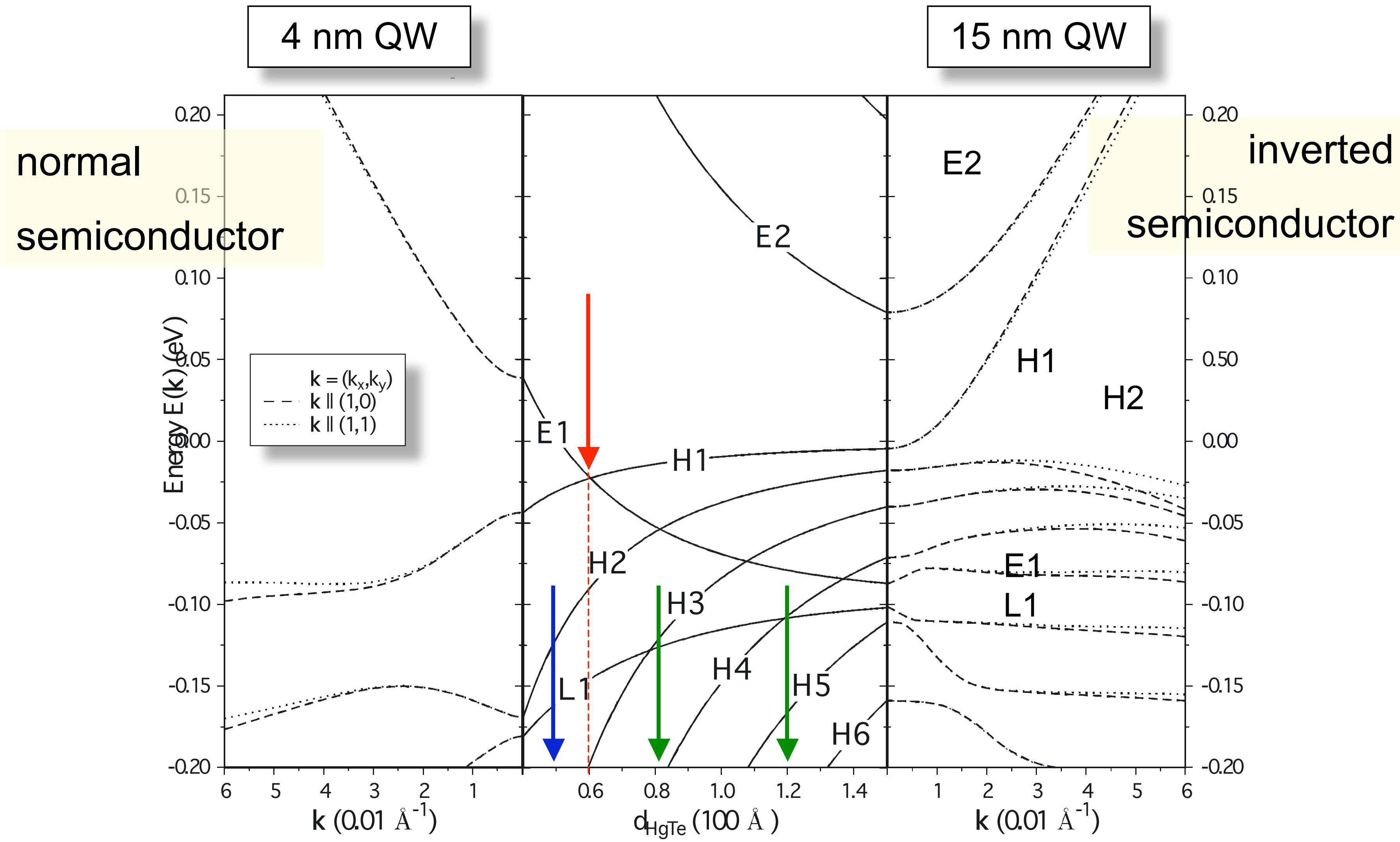
HgTe-Quantum Wells

Typ-III QW

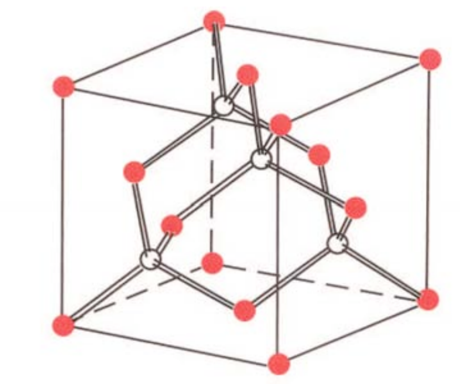


band structure

Band Gap Engineering

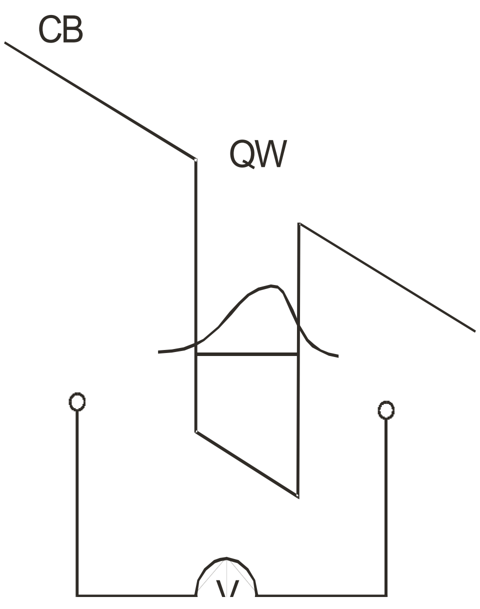


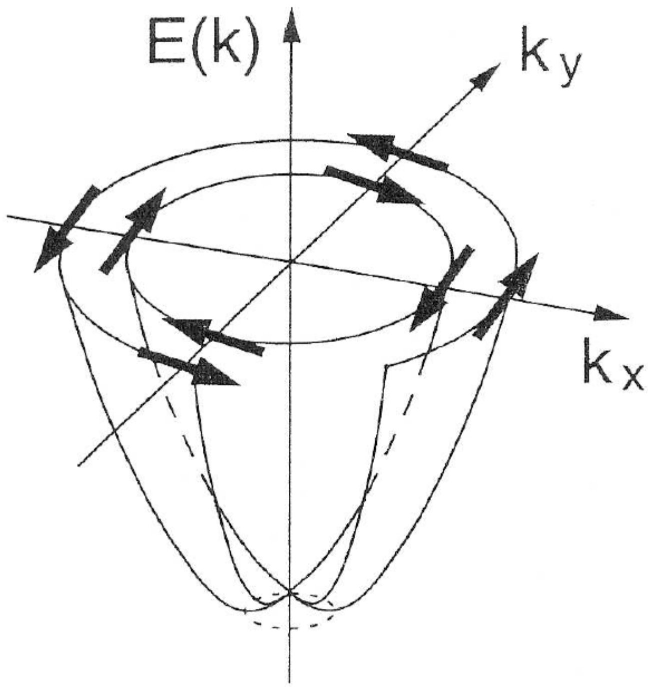
Rashba Spin-Orbit Interaction



structural inversion asymmetry (SIA)

$$H_R = \alpha_R(\sigma_x k_y - \sigma_y k_x)$$





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

(for electron and light hole bands)

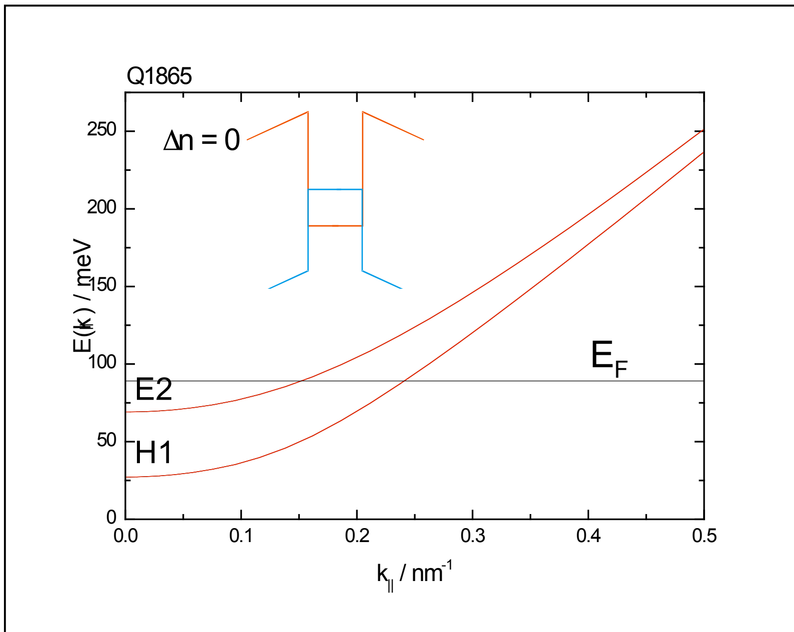
$$E^{\pm} = E_i + \frac{\hbar^2 k_{\|}^2}{2m^*} \pm \beta k_{\|}^3$$

(for heavy hole bands)

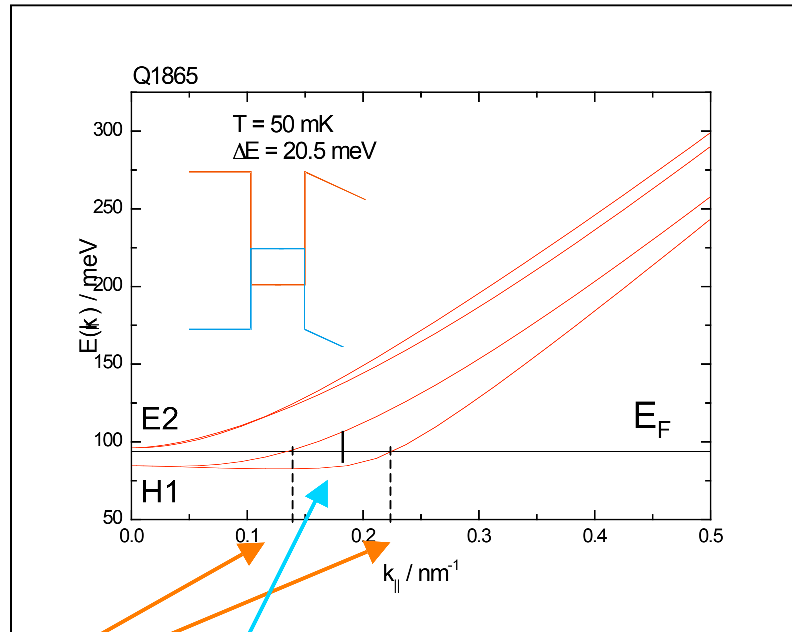
Rashba Spin-Orbit Splitting

8 x 8 **k·p** calculation

symmetric QW



asymmetric QW



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

Δn

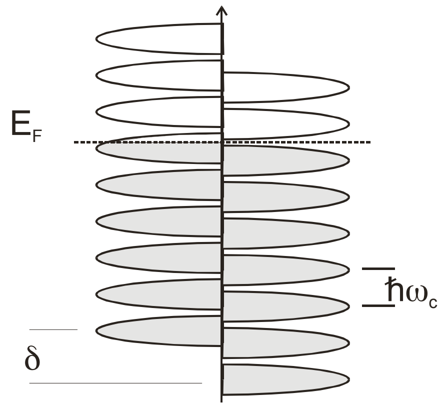
$\Delta_{R,max}$ up to 30 meV

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

Magneto-Transport

PD Dr. H. Buhmann

nodes in SdH:

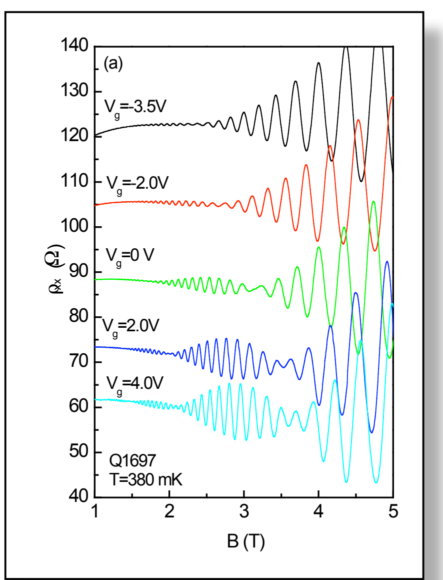


SdH-Amplitude:

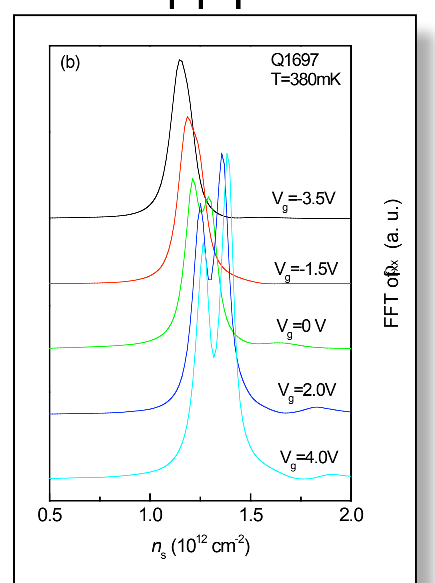
$$A \propto \cos(\pi \nu) \qquad \nu = \frac{\delta}{\hbar \omega_c}$$

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

SdH



FFT



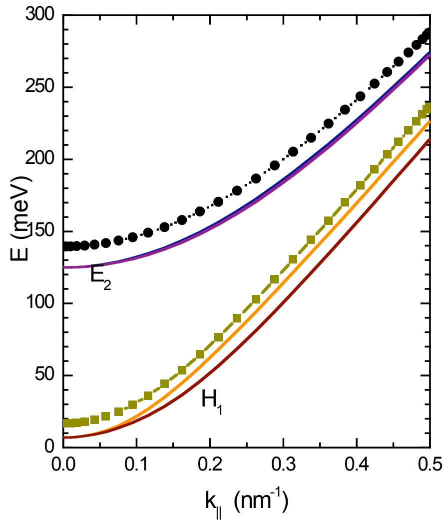
Rashba Spin-Splitting Energy

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

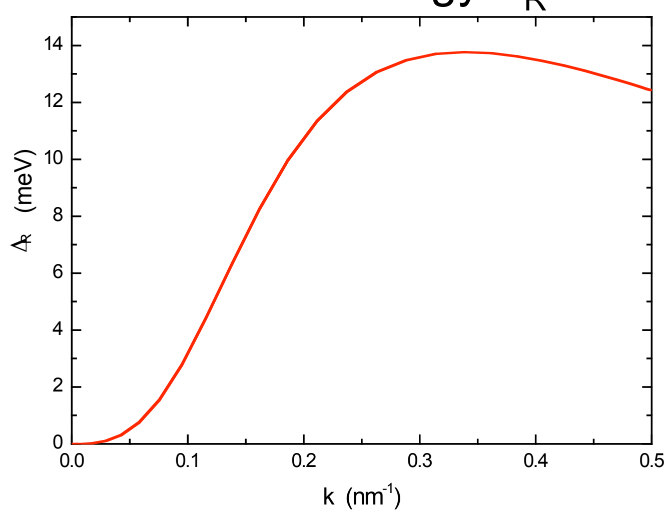
(for electron and light hole bands)

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

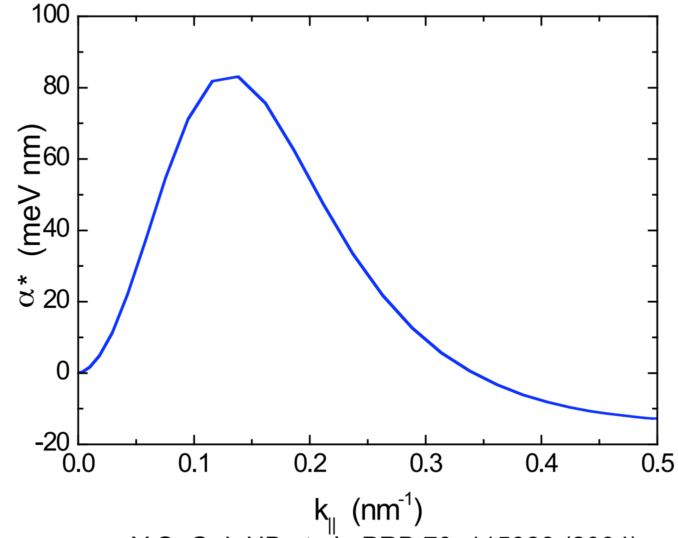
(for heavy hole bands)



Rashba Energy Δ_R



Rashba Coefficient α

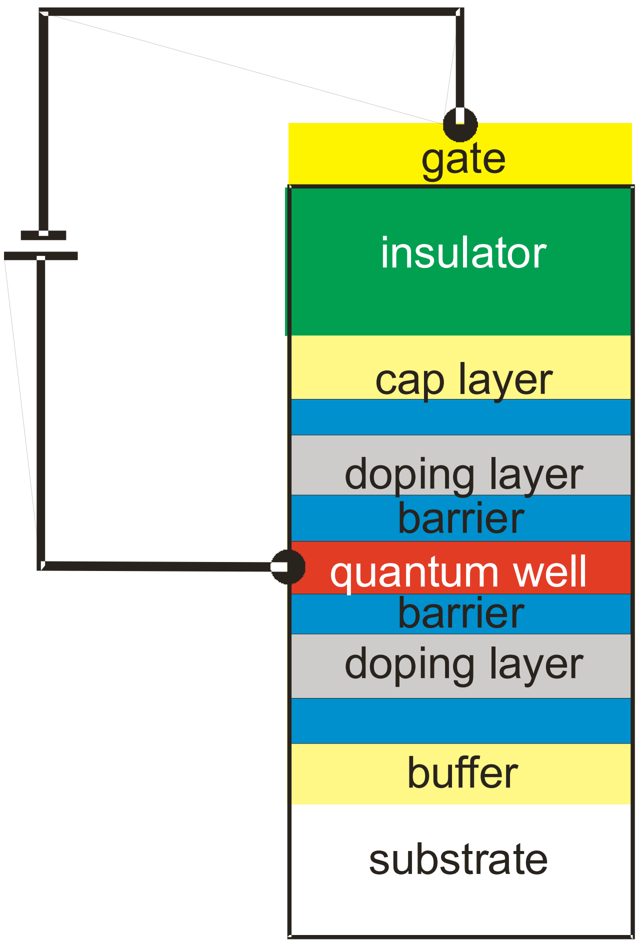


Y.S. Gui, HB et al., PRB 70, 115328 (2004)
E.G. Novik, HB, *et al*, PRB **72**, 035321 (2005)

Layer Structure

Carrier densities: n_s = 1x10^{11} ... 2x10^{12} cm^{-2}

Carrier mobilities: μ = 1x10^5 ... 1x10^6 cm^2/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

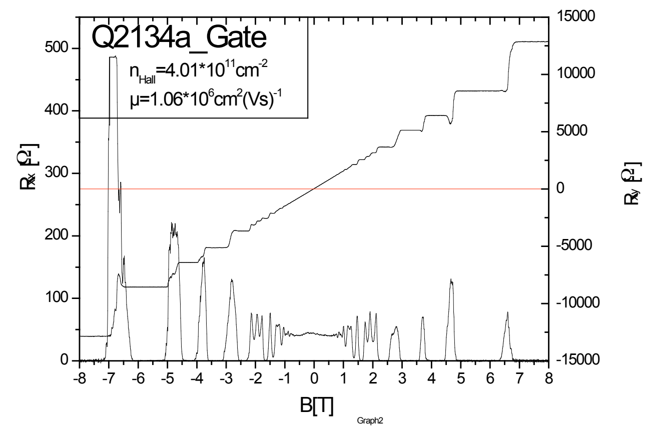
10 nm HgCdTe x = 0.7

9 nm HgCdTe with I

10 nm HgCdTe x = 0.7

25 nm CdTe

CdZnTe(001)

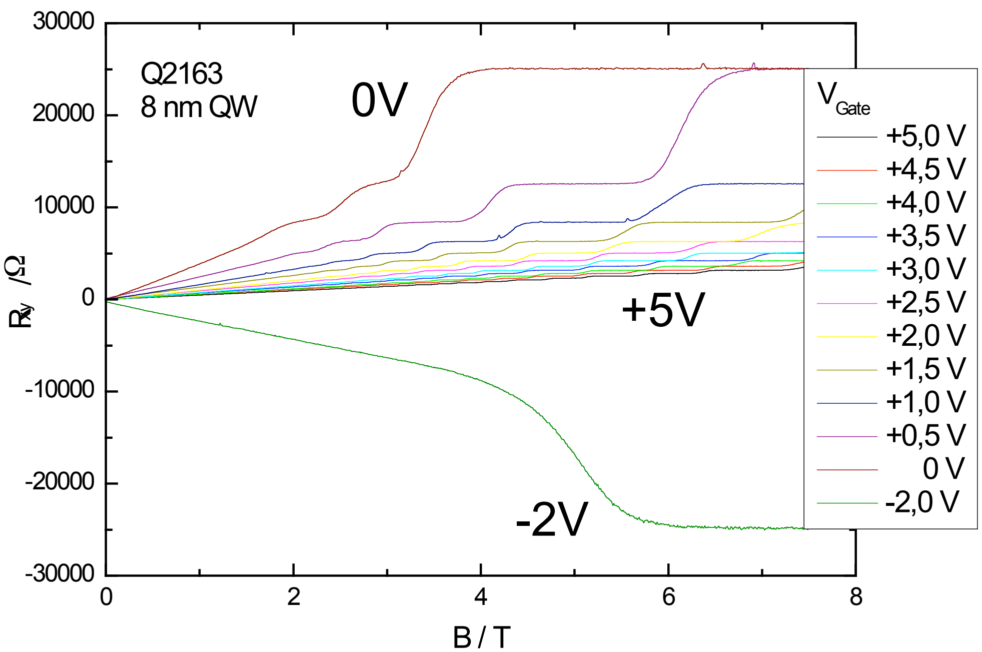


symmetric or asymmetric doping

Gated
Low Carrier Densities
Samples

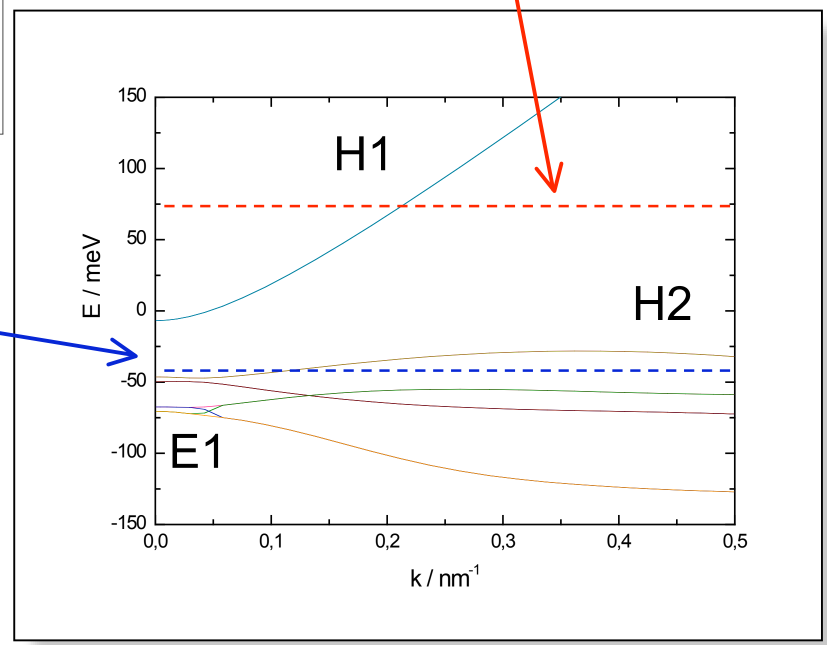
n to *p* Transitions

T = 1.5 K

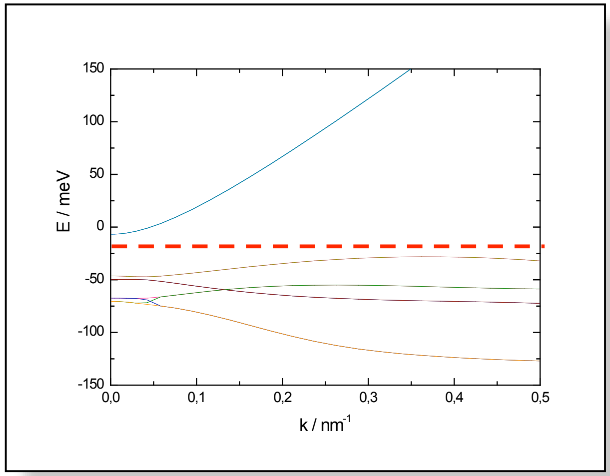


n_{max} = 1.35 x 10^{12} cm^{-2}

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



Magneto-Resistance in the insulating regime



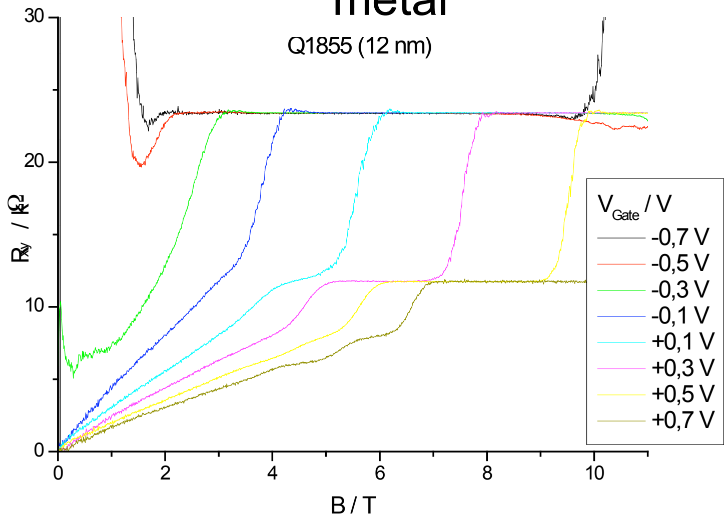
Hall

SdH

insulator

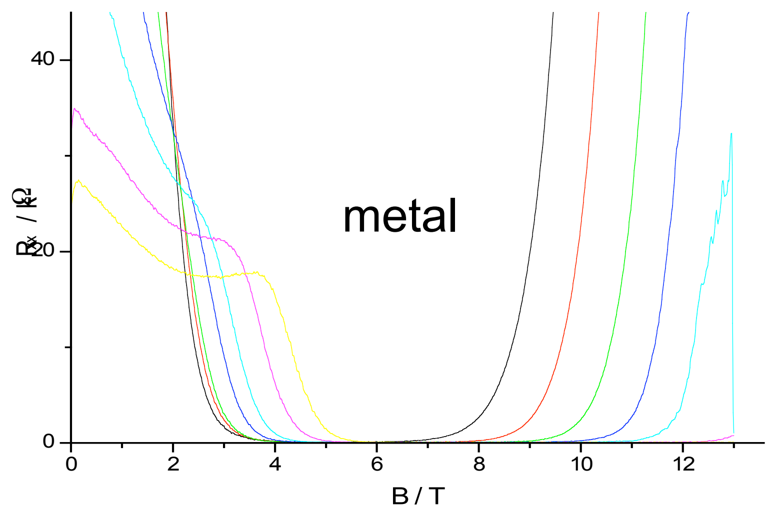
metal

insulator



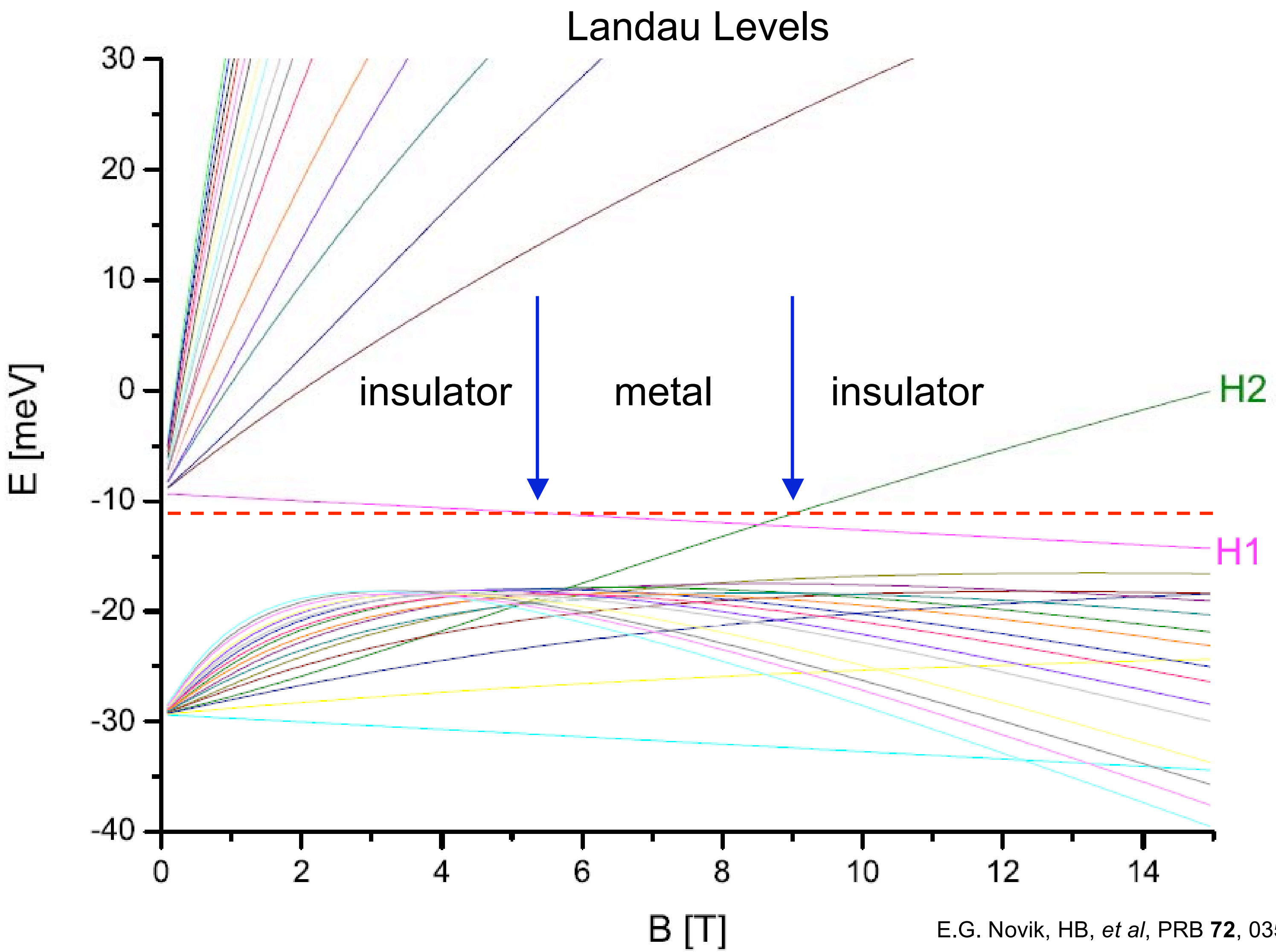
insulator

insulator



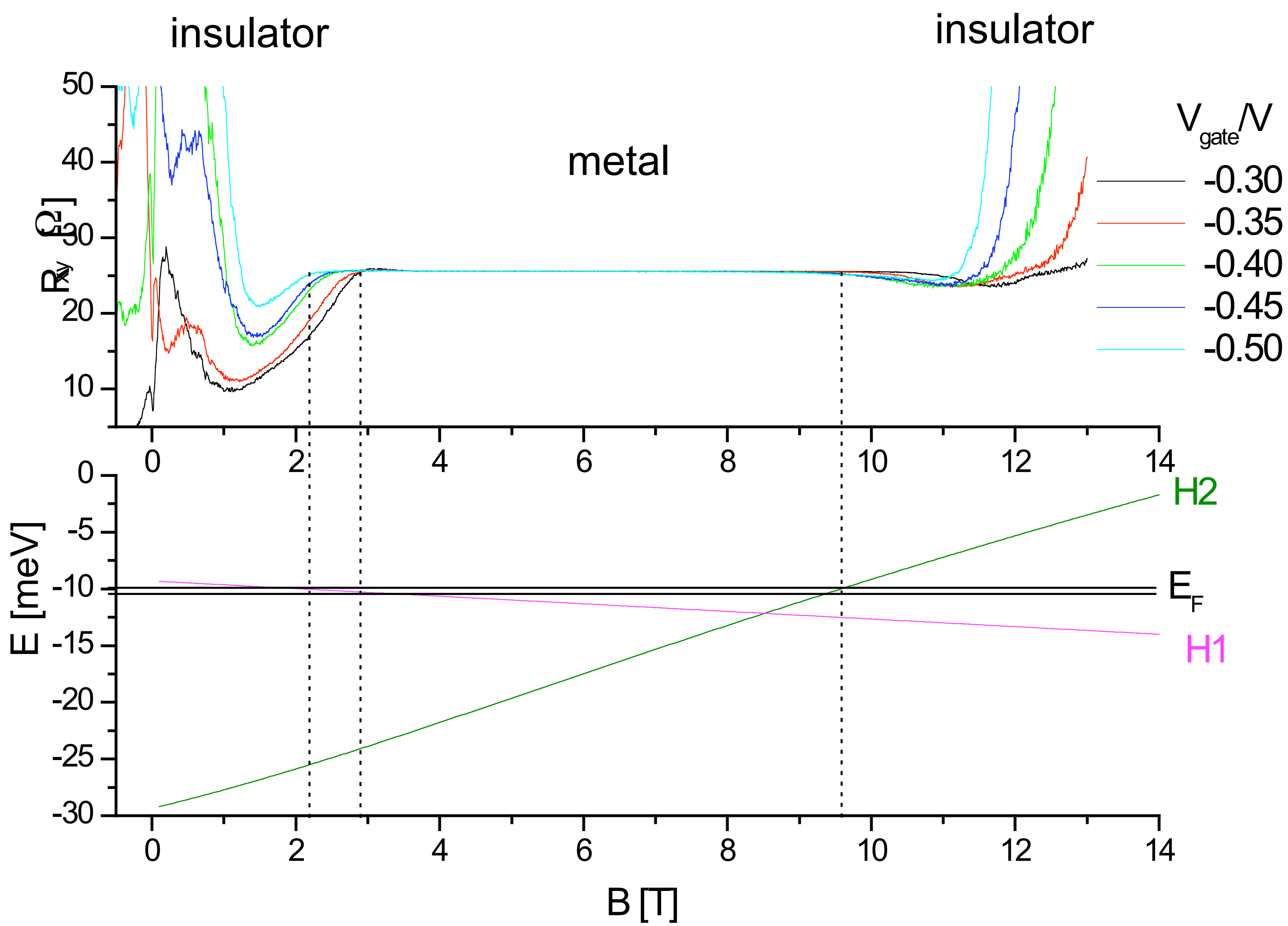
$$B \neq 0$$

Insulator-Metal-Insulator Transition



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

Insulator-Metal-Insulator Transition

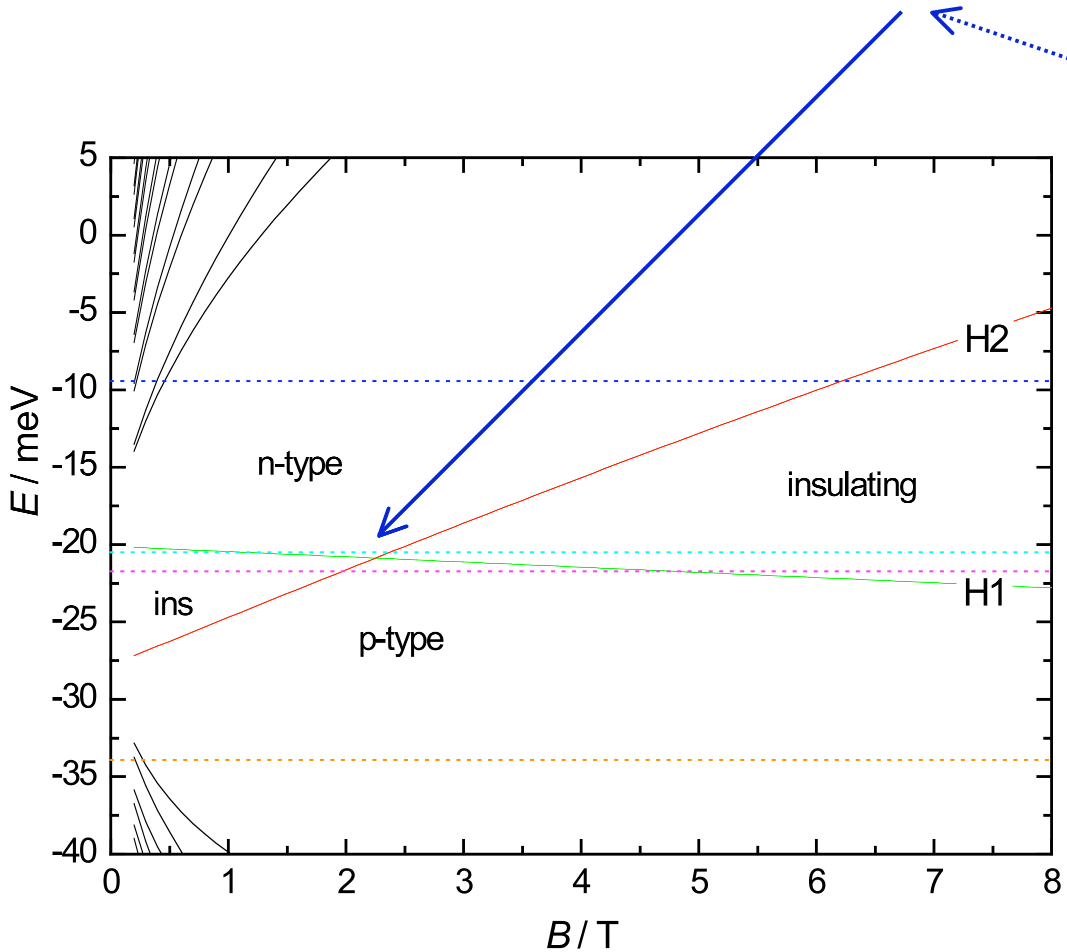


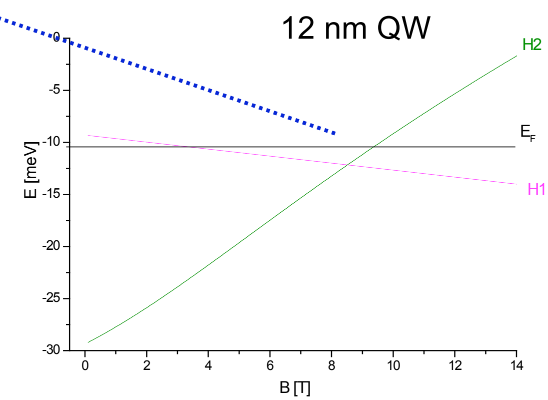
E.G. Novik, HB, *et al*, PRB **72**, 035321 (2005)

Insulator-Metal-Insulator Transition

6.5 nm QW

(shifts the LL crossing to lower magnetic fields)



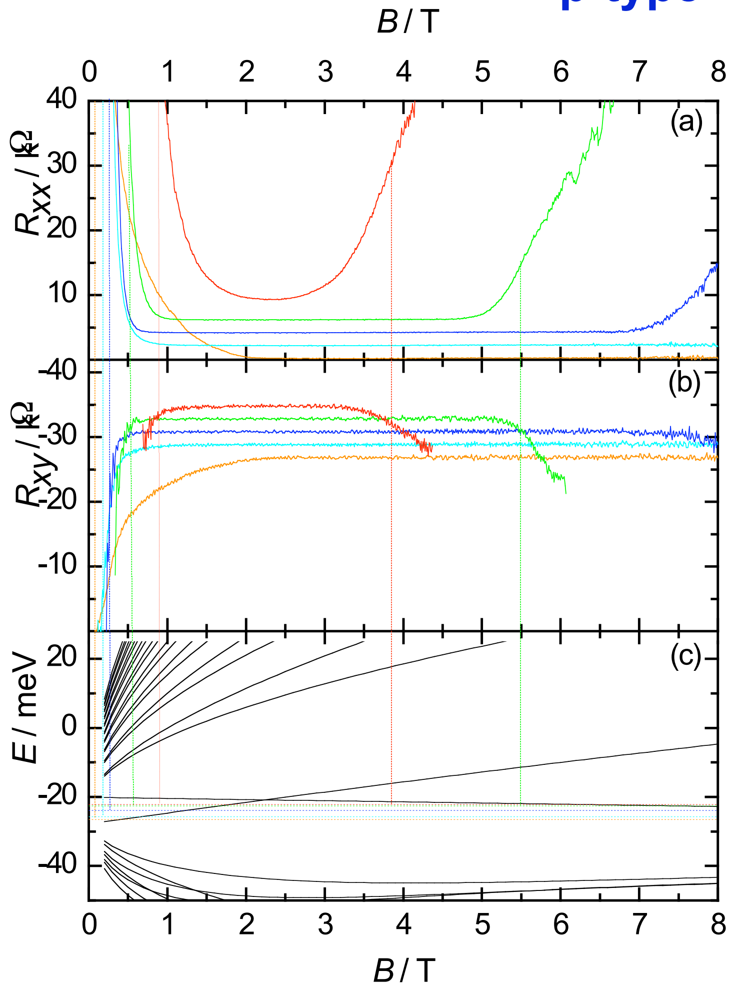


E.G. Novik, HB, *et al*, PRB **72**, 035321 (2005)

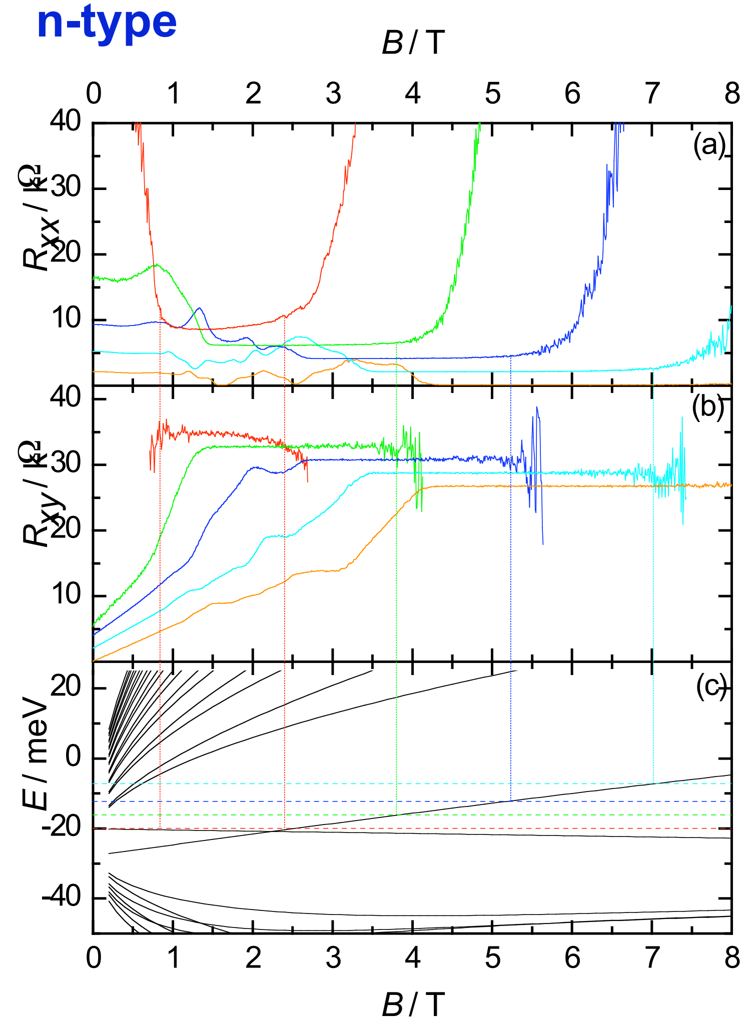
Insulator-Metal-Insulator Transition

6.5 nm QW

p-type

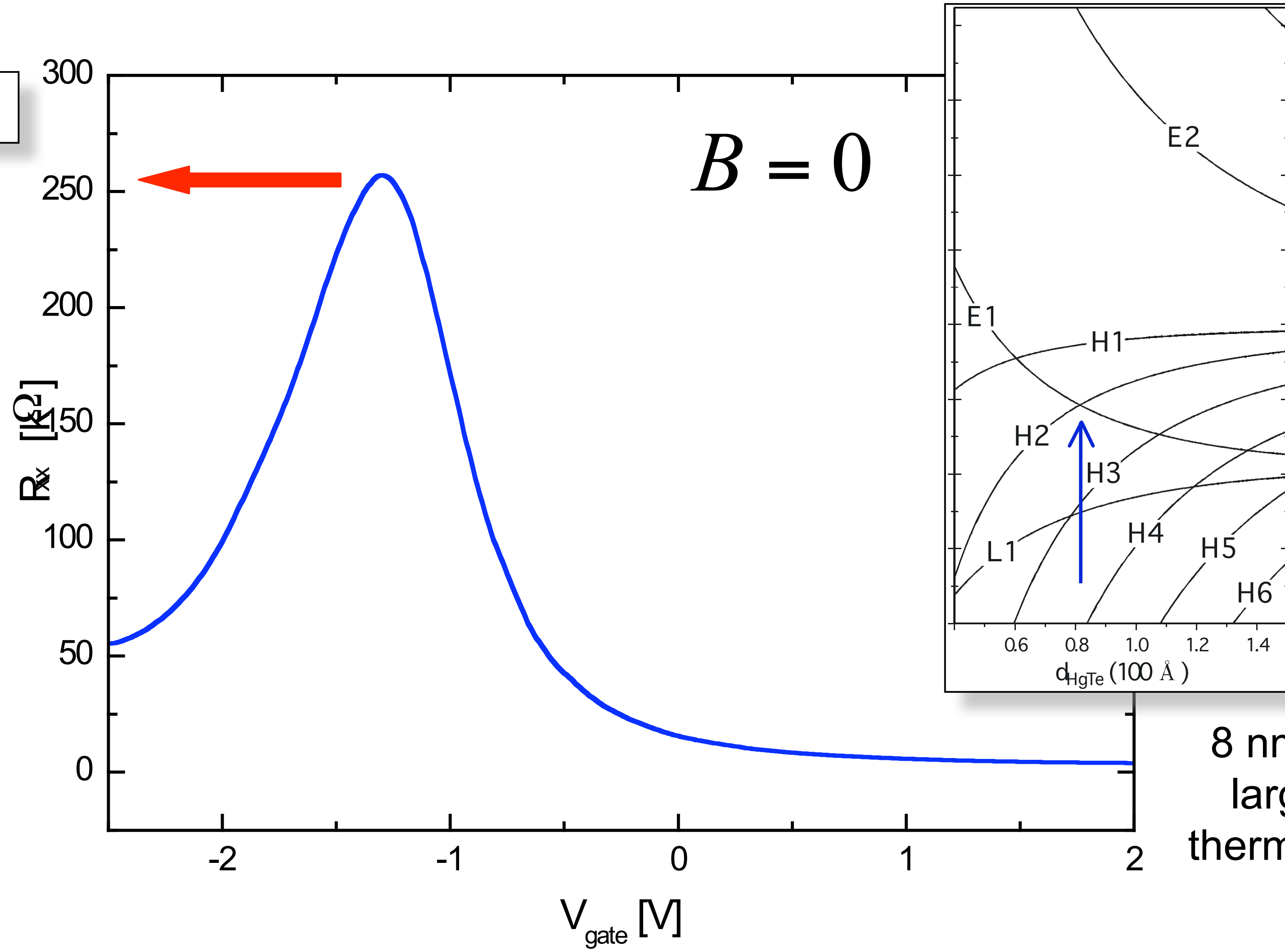


n-type



Finite conductance in the insulating regime

8 nm QW

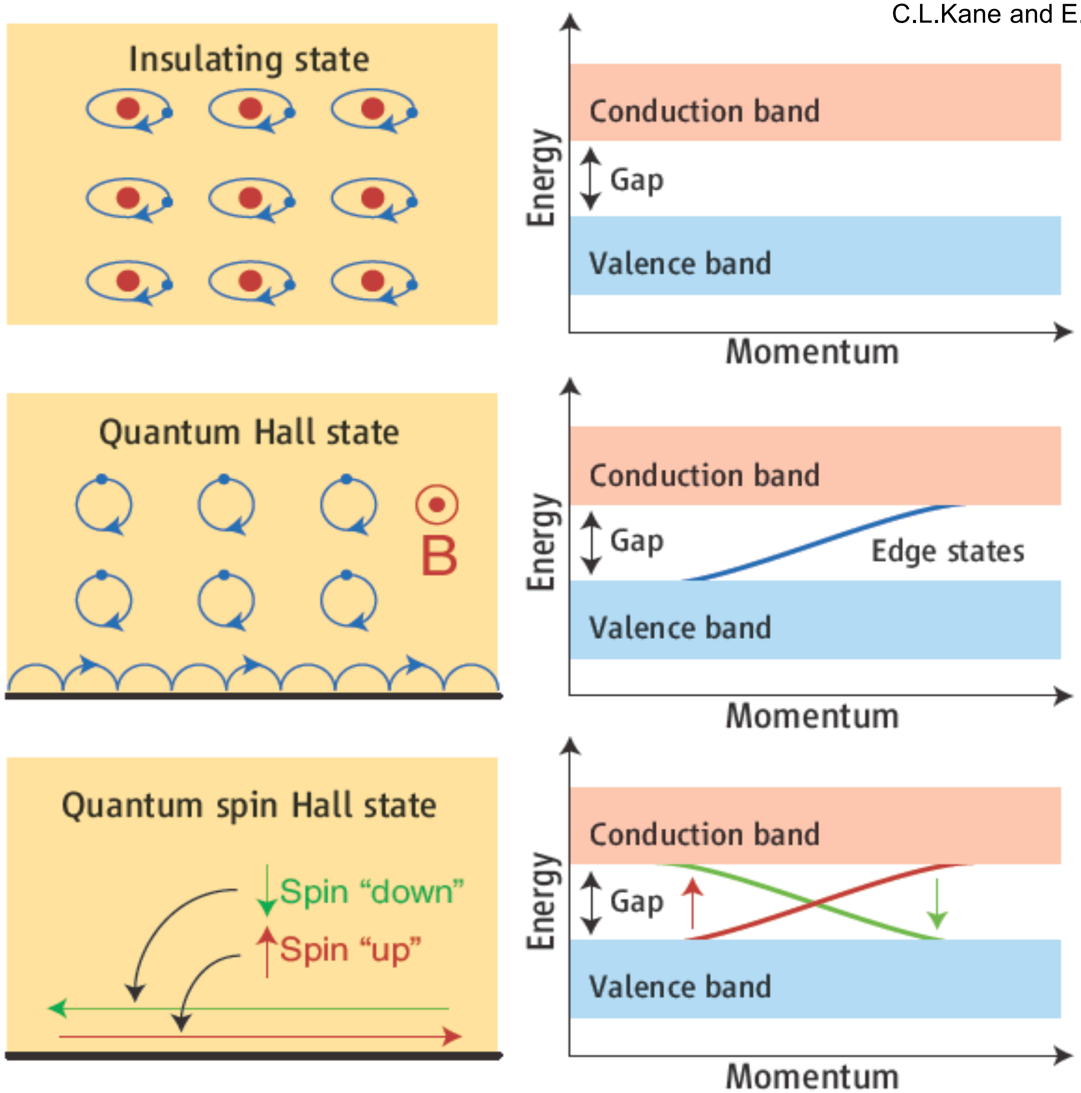


8 nm QW
largest
thermal gap

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)

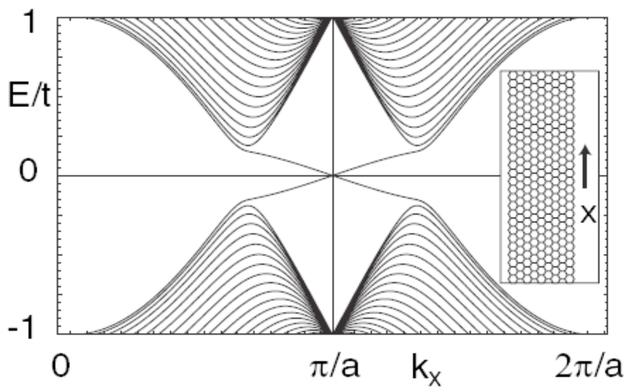


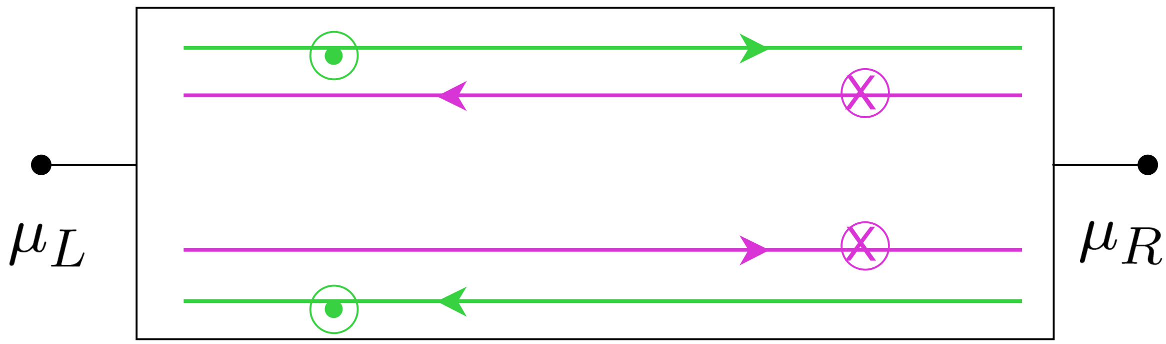
C.L.Kane and E.J. Mele, Science **314,** 1692 (2006)

Topological Quantization

C.L.Kane and E.J.Mele, PRL **95**, 146802 (2005)
C.L.Kane and E.J.Mele, PRL **95**, 226801 (2005)

Graphene edge states

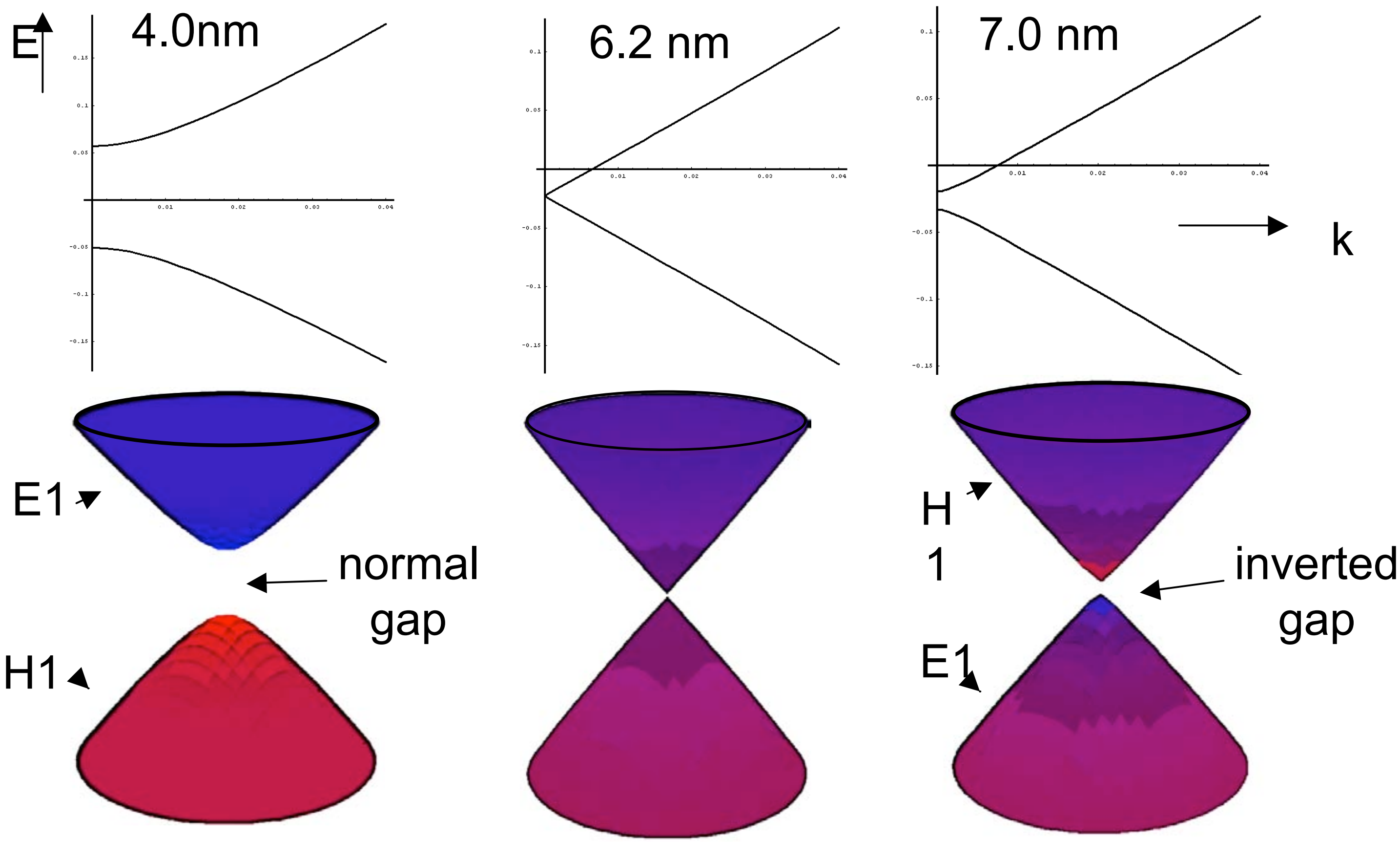




Conductance: $G = \frac{2e^2}{h}$

Bandstructure HgTe

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



Experimental Signature

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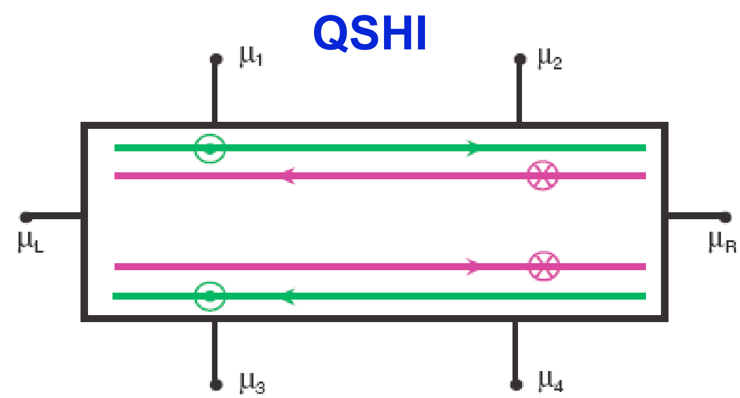
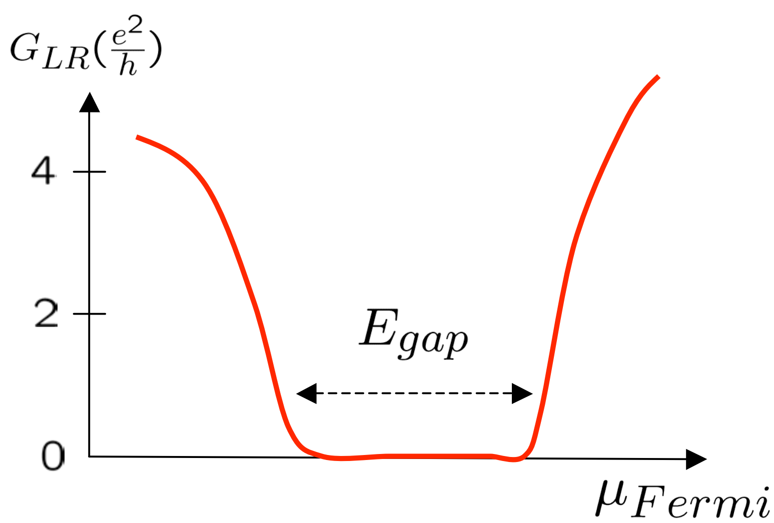
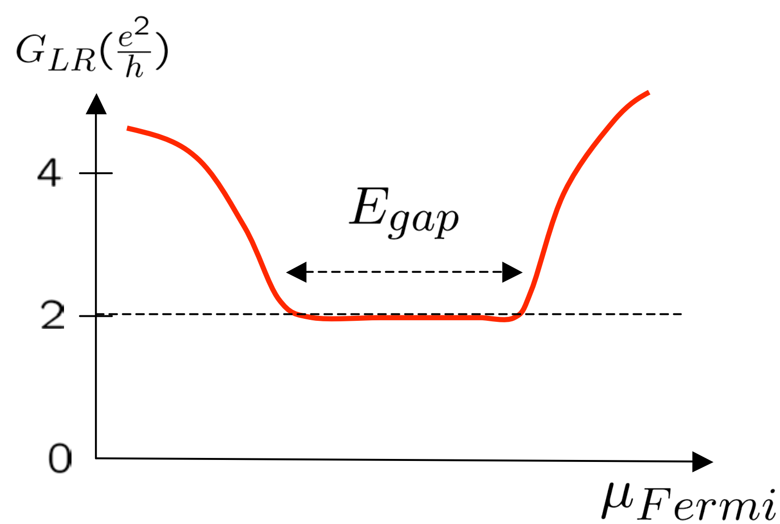


normal insulator state



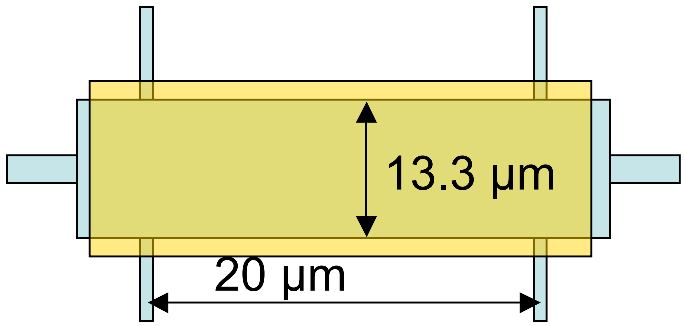
$d < d_c$, normal regime



$d > d_c$, inverted regime

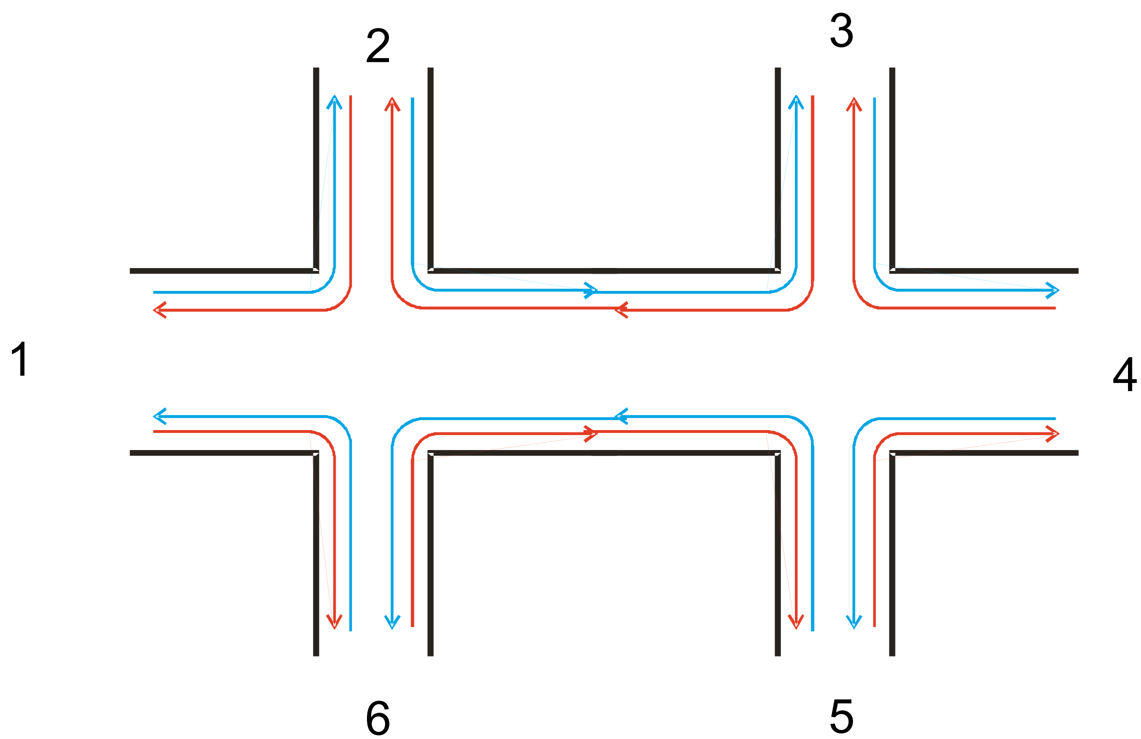
QSHE-Measurement

sample layout



Multi-Terminal Probe

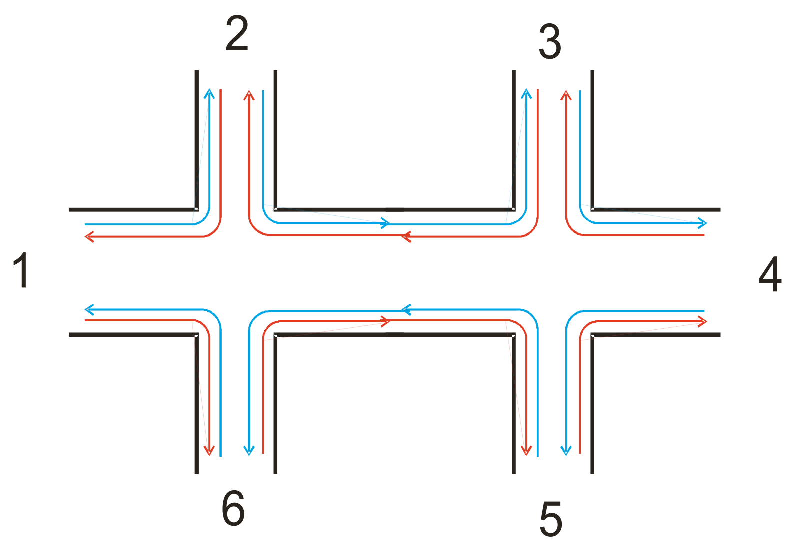
PD Dr. H. Buhmann



$$\frac{R_{2t}}{R_{4t}} \approx 2.6$$

measurements show that 4-termial conductance is comparable to 2-terminal

Multi-Terminal Probe



$$T = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

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

generally

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

X.L. Qi (Stanford Univ.)

$$\left(G_{4t,\mathrm{exp}} \approx 1.9 \frac{e^2}{h} \right)$$

$$\Rightarrow \frac{R_{2t}}{R_{4t}} = 3 \quad (\approx 2.6)_{\mathrm{exp}}$$

QSHI

Summary 1:

signatures for QSH insulator state
for inverted HgTe QW
micro-structures

multi-terminal resistance
corresponds to expected values for
helical edge states

SHE

Spin-Hall Effect

VOLUME 83, NUMBER 9 PHYSICAL REVIEW LETTERS 30 AUGUST 1999

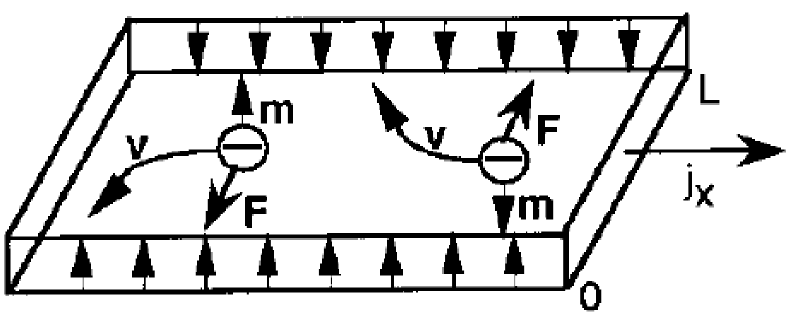
Spin Hall Effect

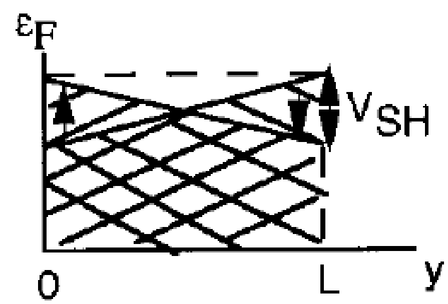
J. E. Hirsch
Department of Physics, University of California, San Diego, La Jolla, California 92093-0319
(Received 24 February 1999)

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

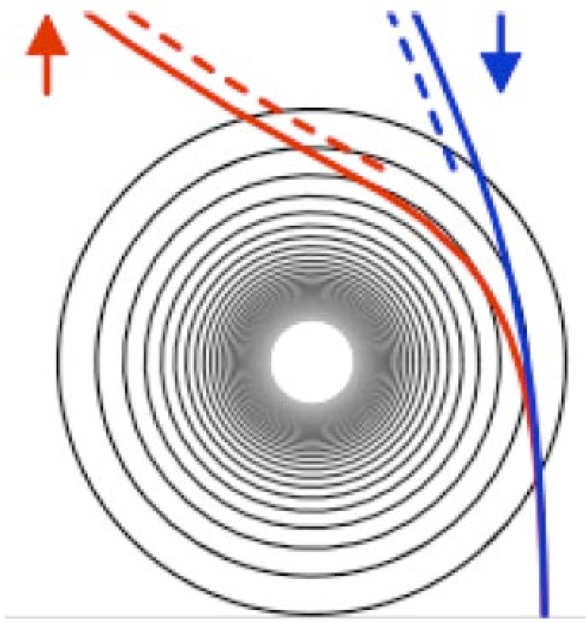




Spin-Hall Effect

extrinsic

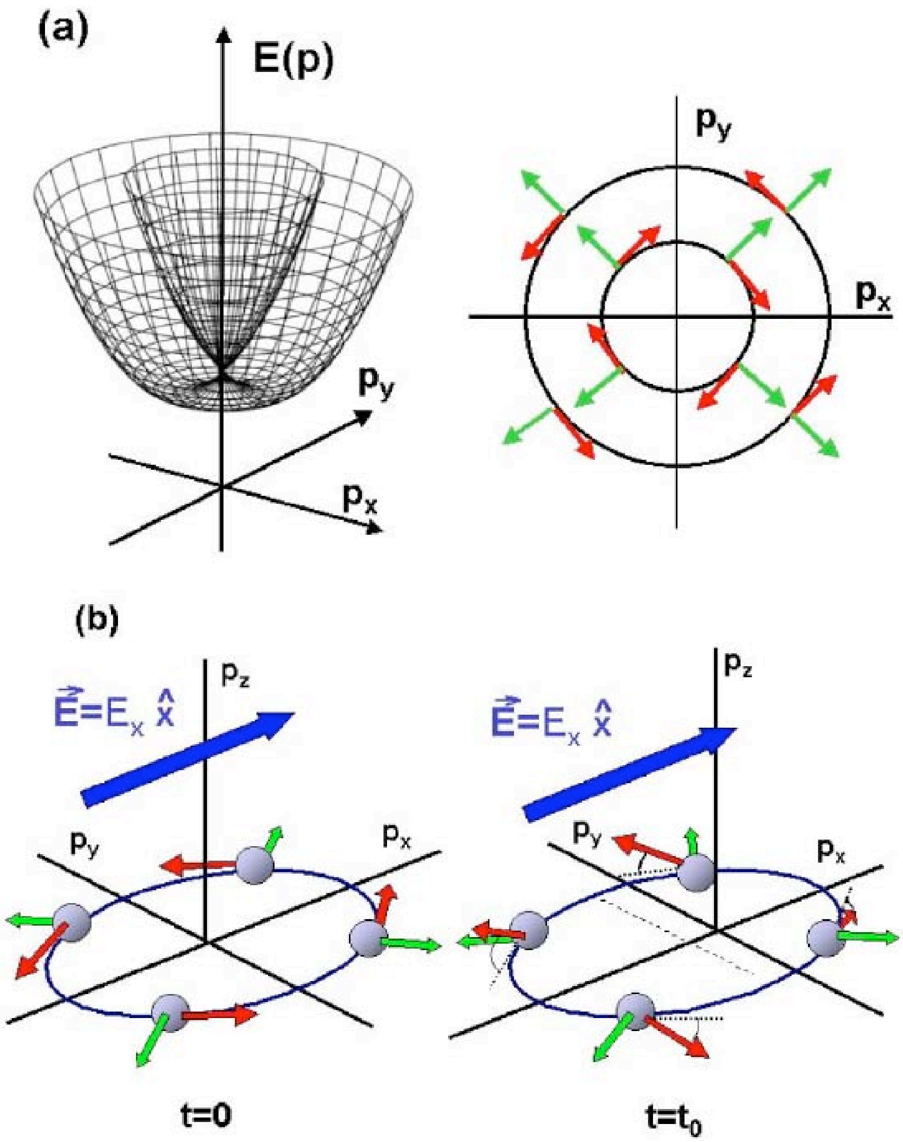
- skew scattering
- side jump effect



Spin-Hall Effect

2. Intrinsic SHE

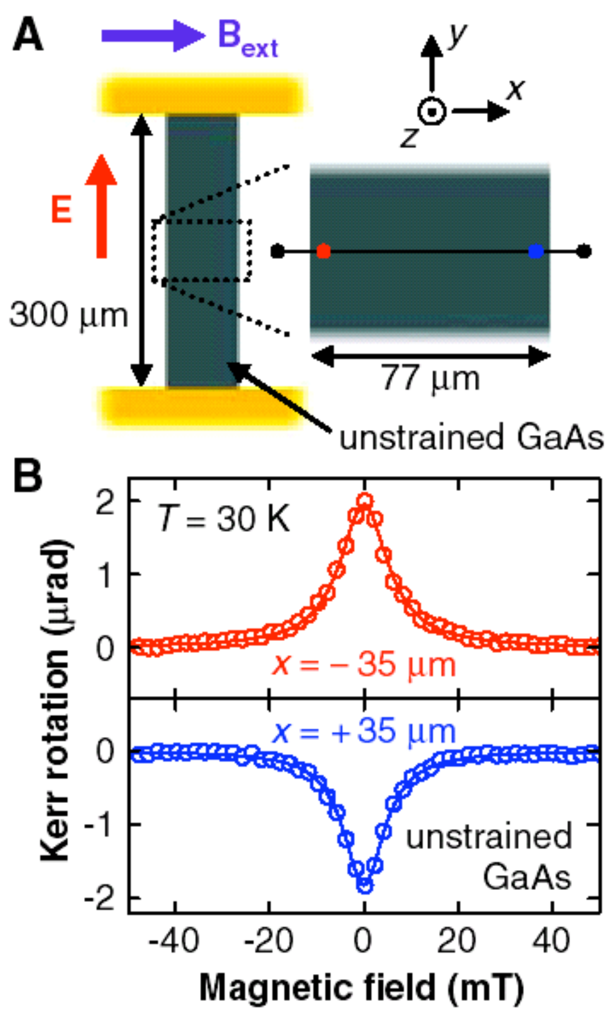
Rashba effect



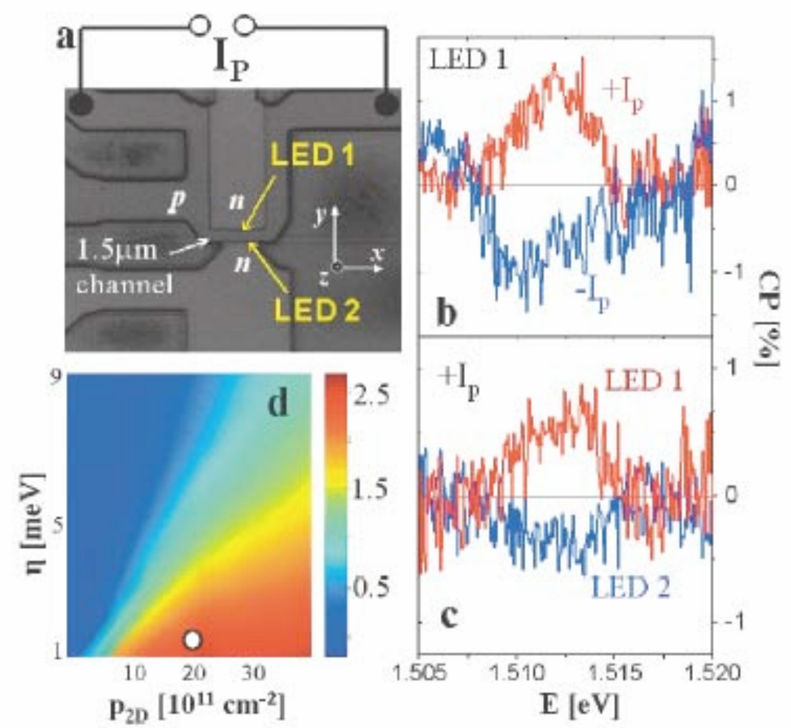
J.Sinova et al.,
Phys. Rev. Lett. **92**, 126603 (2004)

Spin-Hall Effect

optical detection



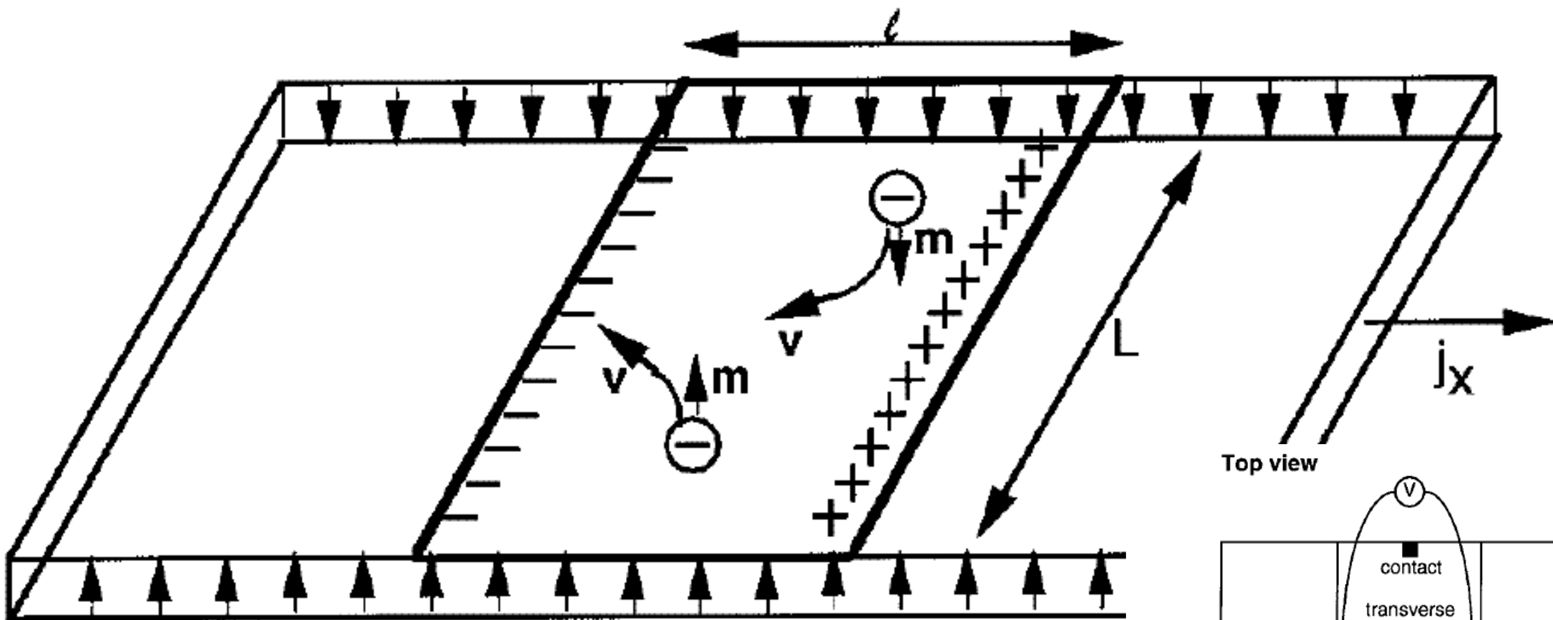
Kato et al. Science 306, 1910 (2004)

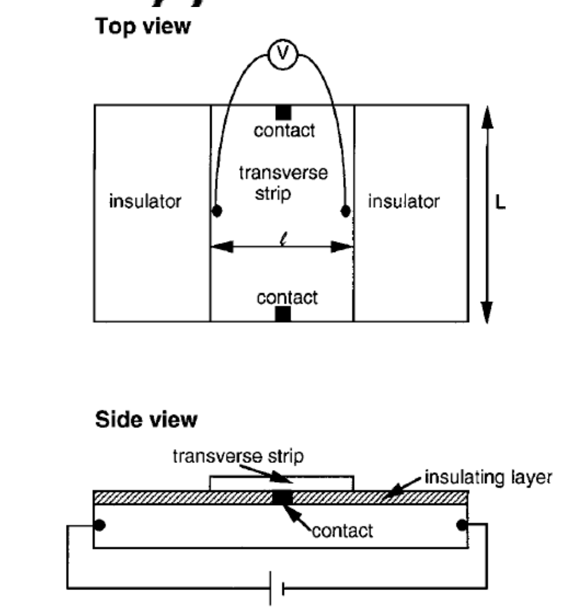


Wunderlich et al. PRL 94, 47204 (2005)

Spin-Hall Effect

electrical detection



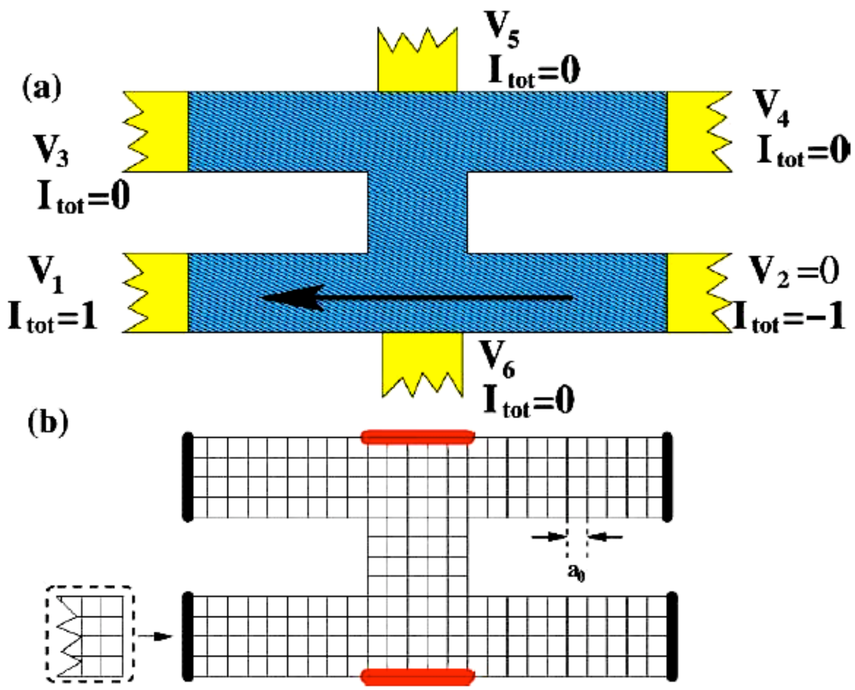


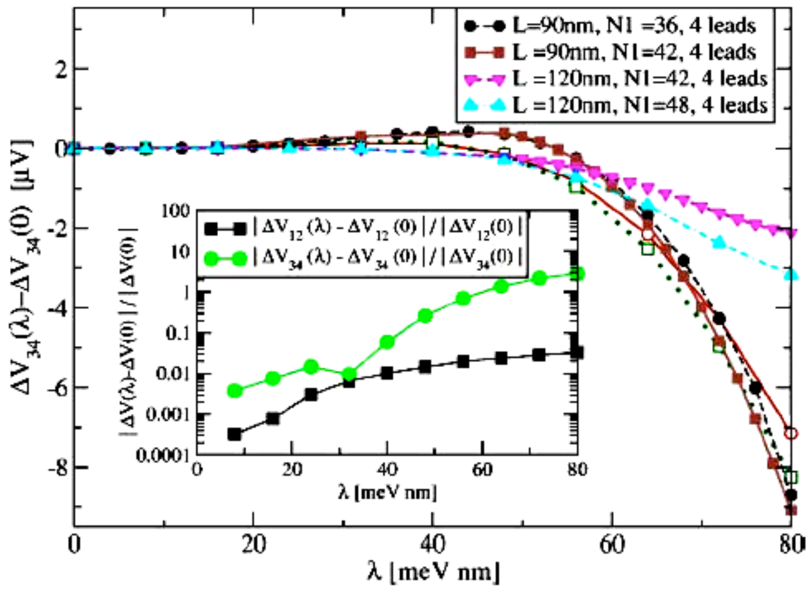
SHE^{-1}

Hirsch PRL **83**, 1834 (1999)

Spin-Hall Effect

electrical detection



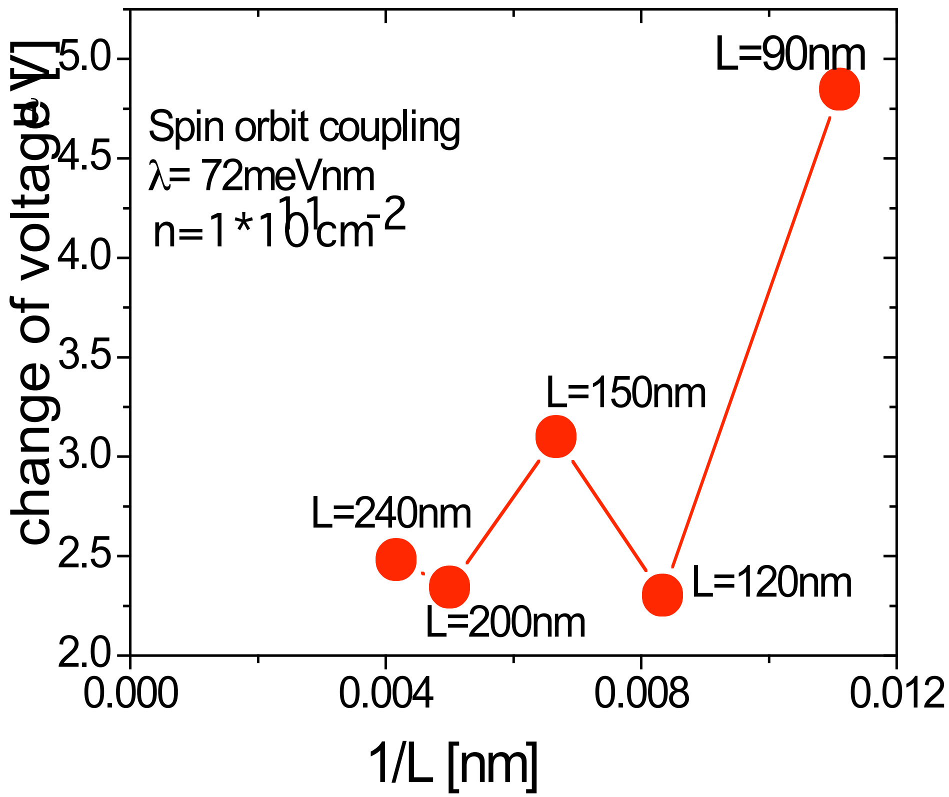


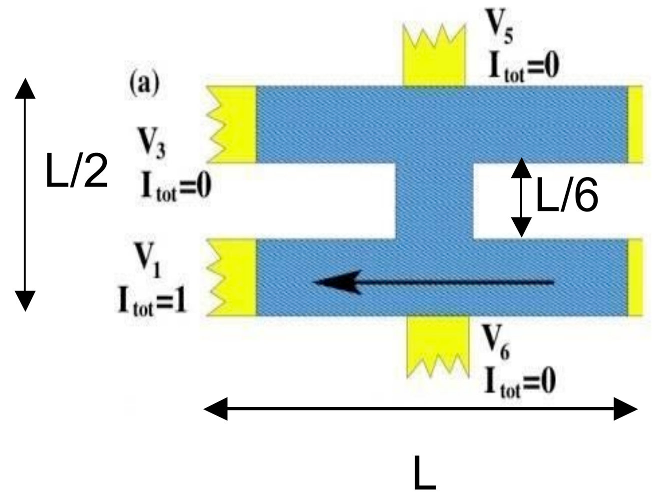
E.M. Hankiewicz et al . PRB 70, 241301 (2004)

Spin-Hall Effect

PD Dr. H. Buhmann

Scaling of H-samples with the system size

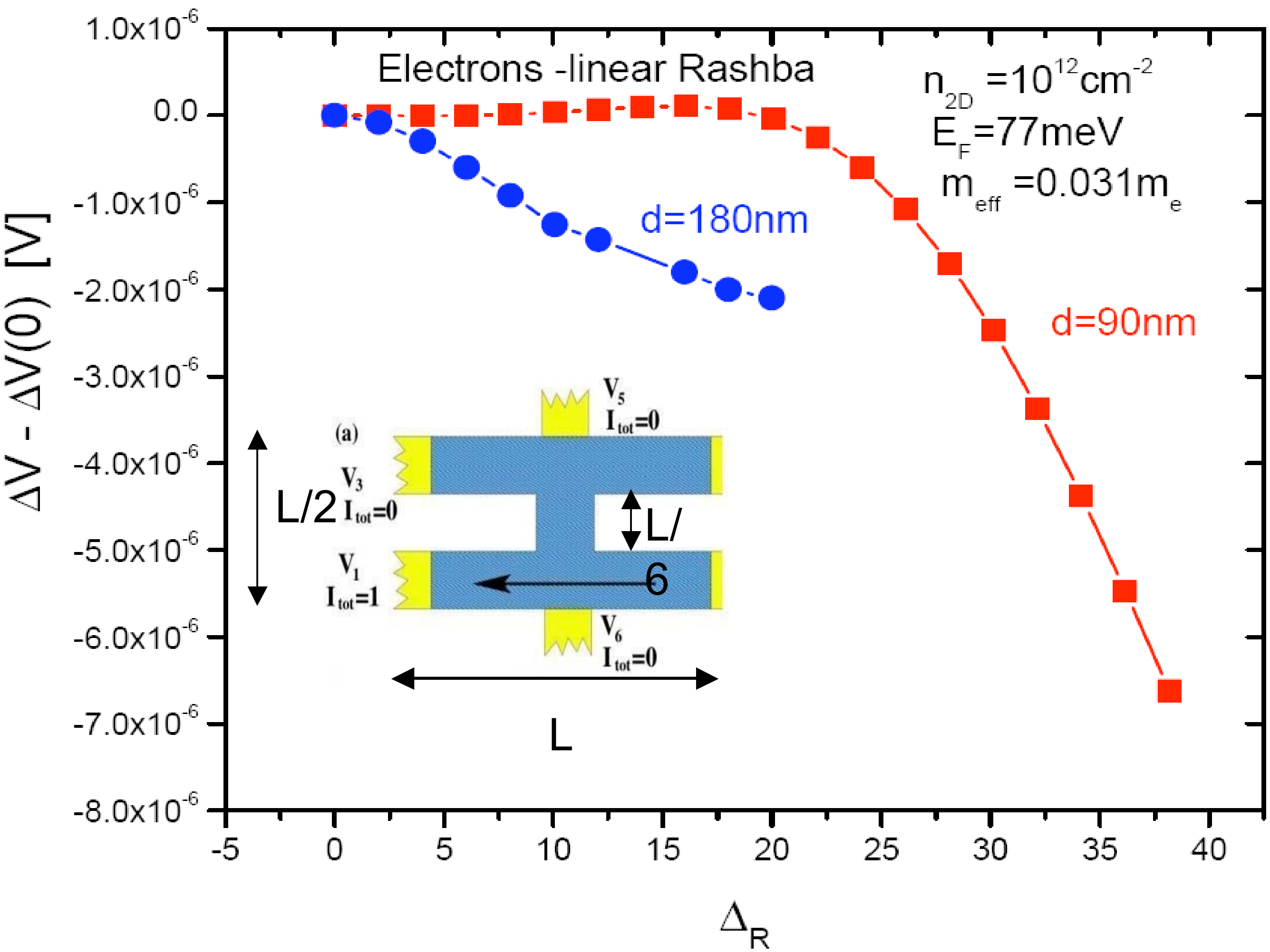




Oscillatory character of voltage difference with the system size.

Spin-Hall Effect

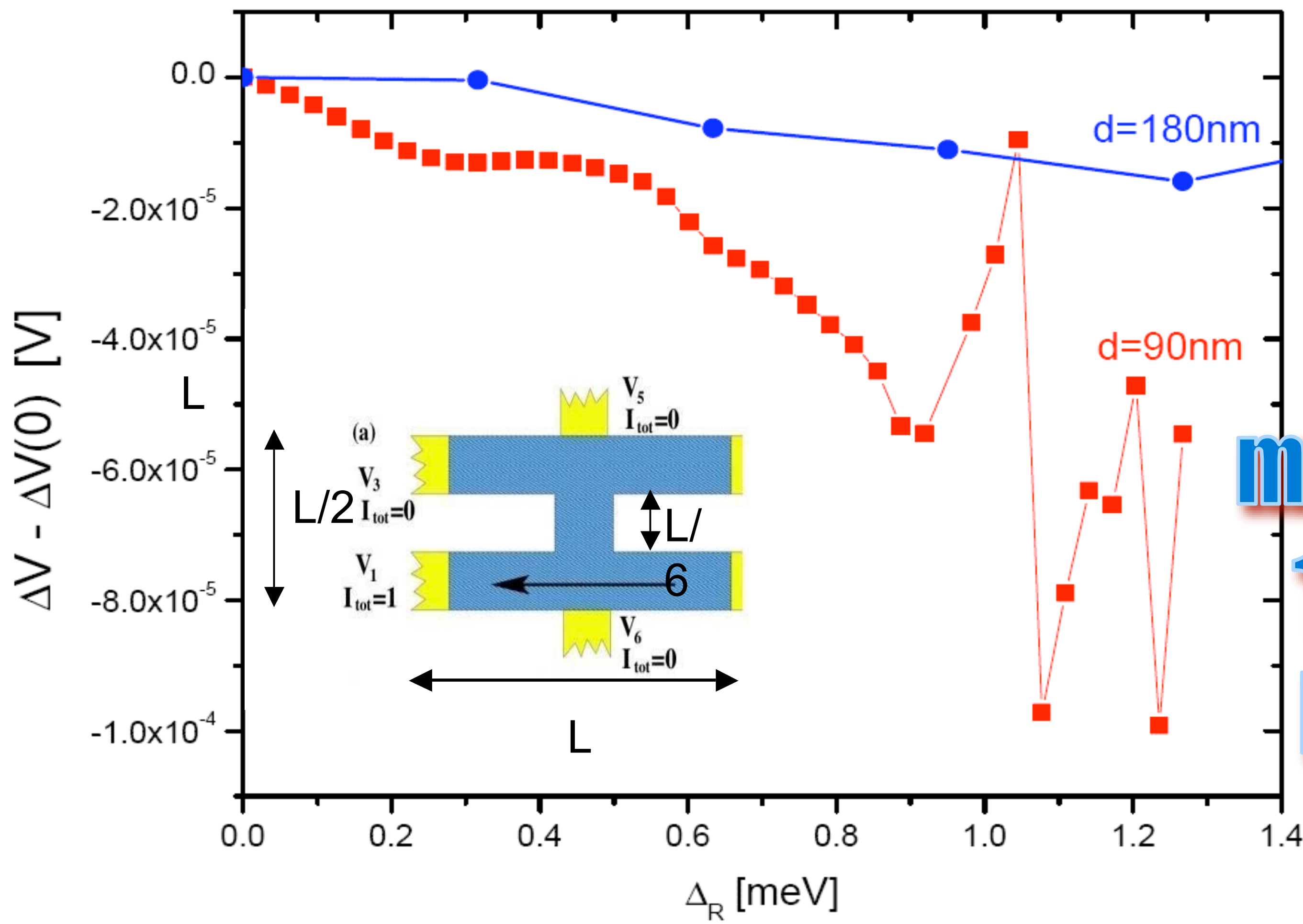
calculated voltage signal
for electrons



Measurement

calculated voltage signal

Holes -cubic Rashba



more than 10 time larger!

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S.C. Zhang (Stanford Univ.)
X.L. Qi (Stanford Univ.)