Cyclotron Resonance Induced Spin Polarized Photocurrents in Dirac Fermion Systems

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Joint work of:

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Introduction: nonlinear transport in Dirac fermions systems

- Electronic properties of Dirac fermions are in focus of current research.

- Graphene - the most detailed studied system so far

  - Large variety of fascinating linear electron transport effects

  - Furthermore, a number of *nonlinear transport effects*, where the response is *proportional to the higher powers of the field*, have been observed

    --> novel aspects of the light matter interaction

    --> access to various graphene properties

    for review see Glazov & Ganichev, Physics Reports 535, 101 (2014)

- Dirac fermions in the systems with large spin-orbit coupling, e.g. topological insulators. Spin properties are in focus.

  - only a few experiments aimed to nonlinear transport are reported

Introduction: nonlinear transport in Dirac fermion systems with large spin-orbit interaction (SOI)

Already first experiments demonstrated that photoelectrical phenomena can be efficiently used to study Dirac fermions in materials with large SOI even in "dirty" systems where conventional transport is often hindered by high bulk carrier density

McIver et al. Nature Nanotech. 7, 96 (2012)

P. Olbrich, S. Ganichev et al., Phys. Rev. Lett. 113, 096601 (2014)

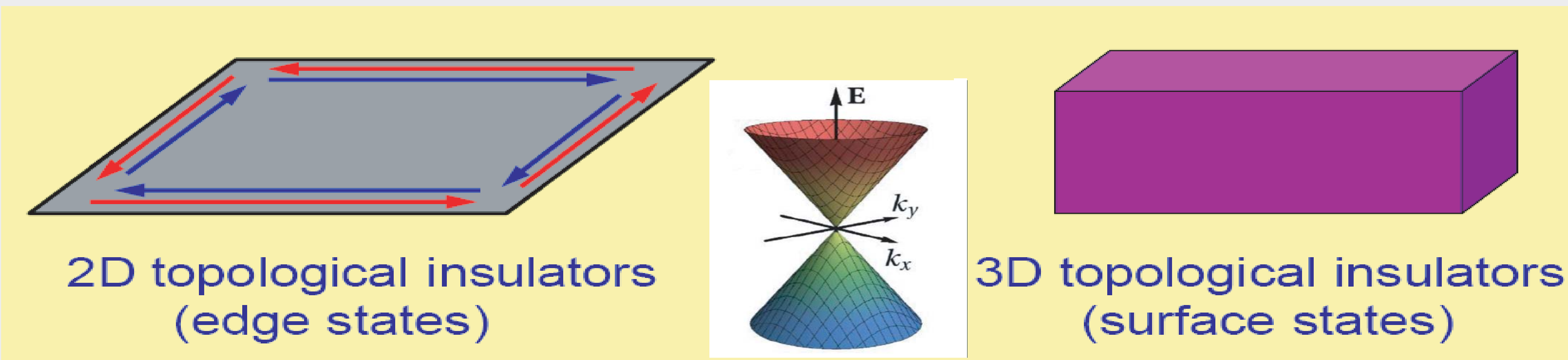
The talk overviews our studies of cyclotron resonance induced photocurrents in various HgTe-based Dirac fermion systems excited by terahertz electromagnetic radiation

We will show that a combination of photocurrents technique and cyclotron resonance provides a further access to study Dirac fermions physics

Dirac fermion systems in materials with strong spin orbit coupling

While graphene has a vanishingly small spin-orbit interaction and its band structure is determined by the coupling of electron momentum with a *pseudospin*, in materials with strong spin orbit interaction the energy dispersion corresponds to the linear coupling between *electron spin* and electron momentum k.

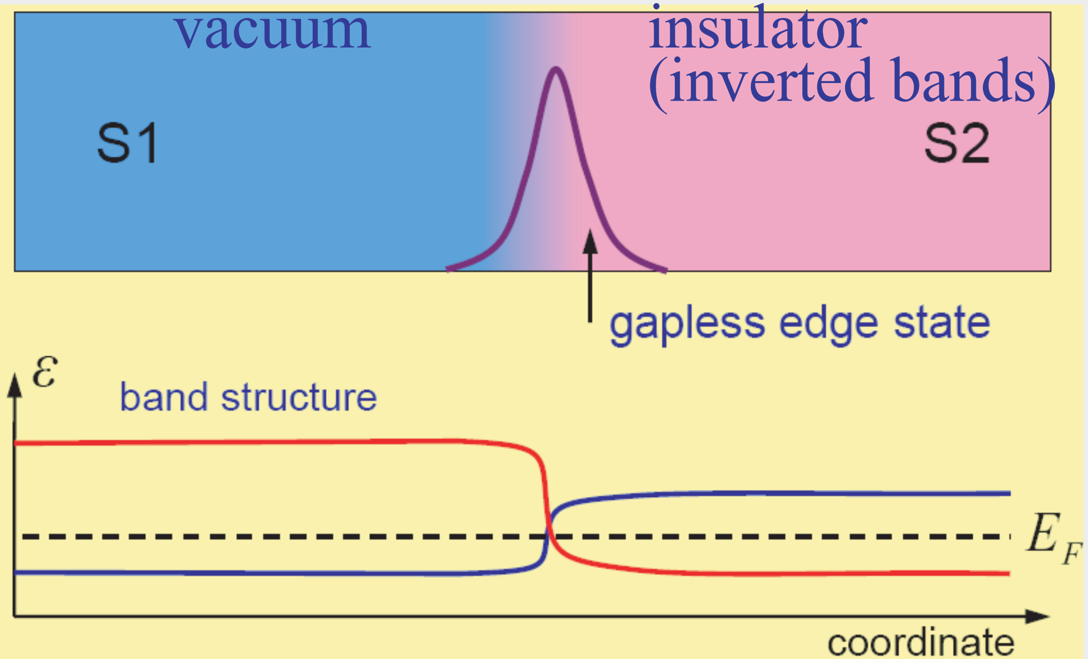
To important examples belong 2D and 3D topological insulators



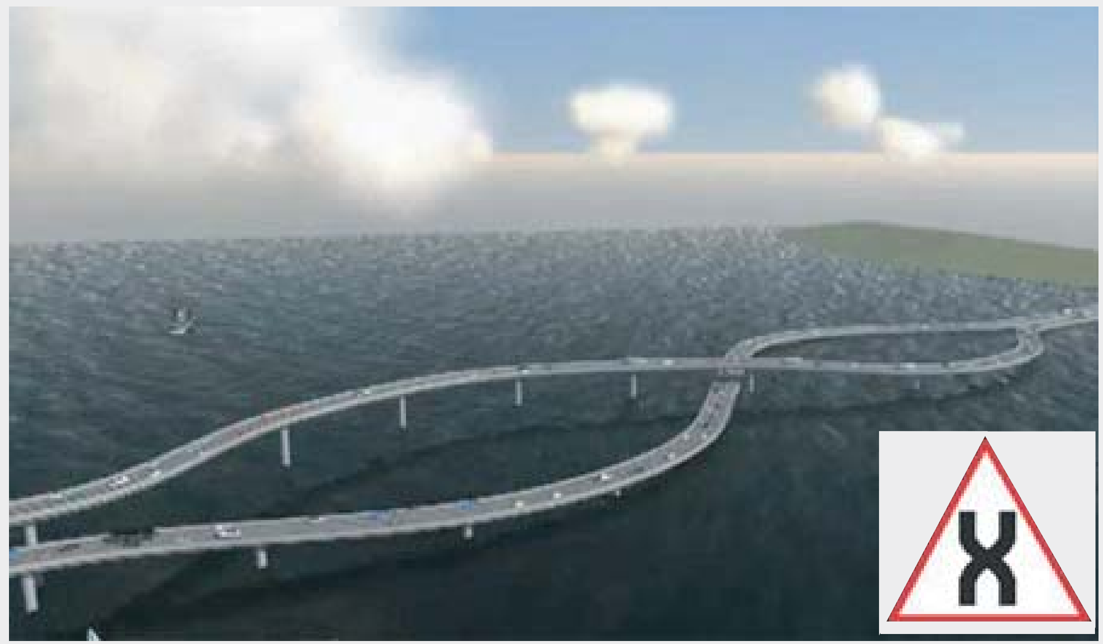
Reviews: M.Z. Hasan and C.L. Kane, Rev. Mod. Phys. 82, 3045 (2010)
X.-L. Qi and Sh.-Ch. Zhang, Rev. Mod. Phys. 83, 1057 (2011)

Topological insulators

The easiest way to describe a topological insulator is as an insulator with inverted band orders (conduction and valence bands are interchanged) that always has a condacting boundary when placed next to a vacuum or an ‘ordinary’ insulator.



Macroscopic realization of the order switch:
Hong-Kong/China - left to right traffic



Topological insulators

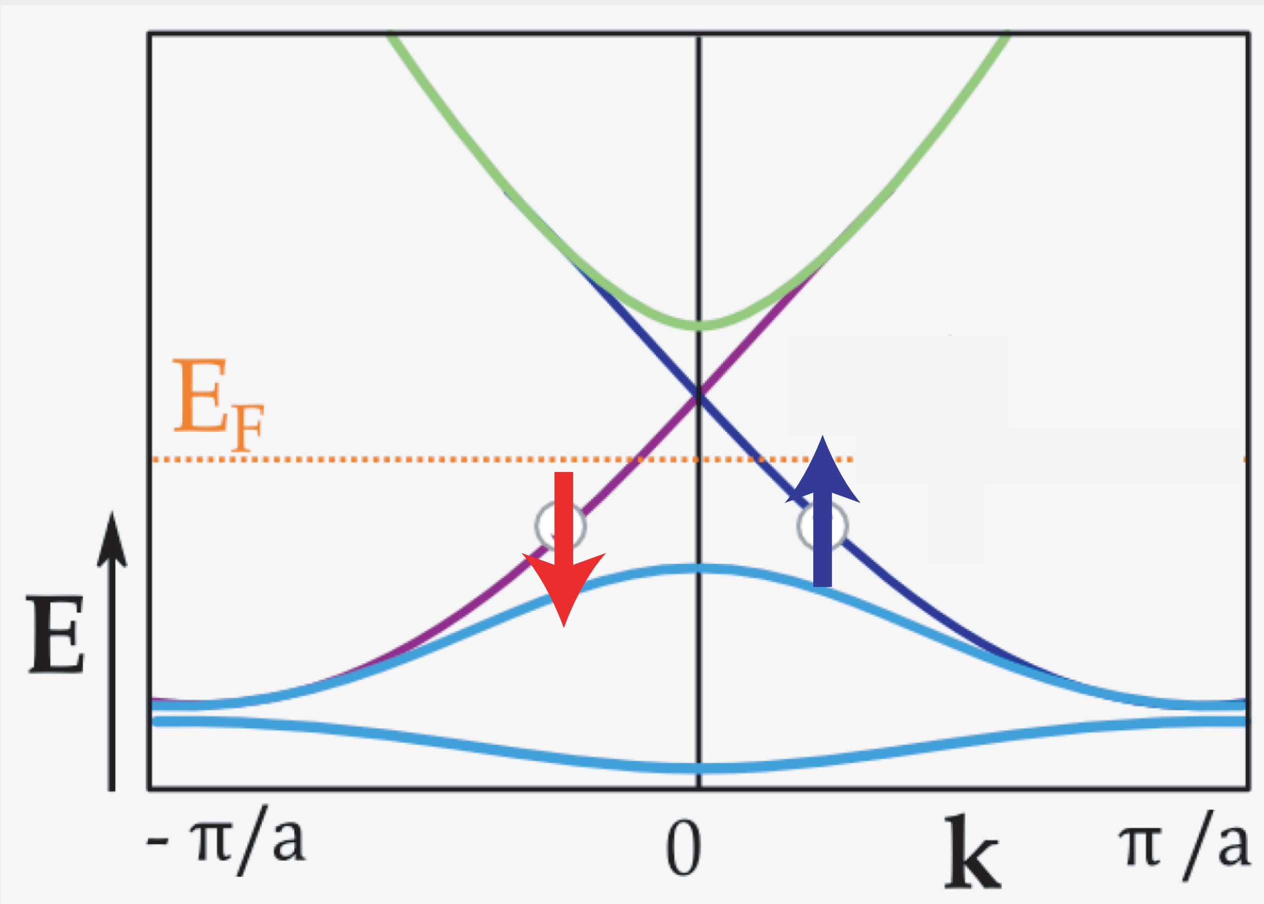
The edge states lying in the gap of the host material are described by the relativistic Dirac equation (1928)

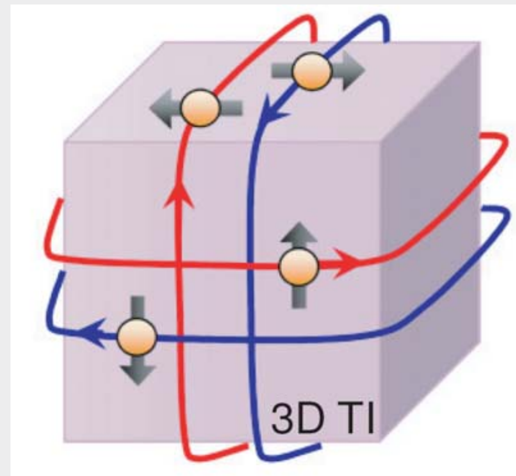
Surface states with a single Dirac cone:

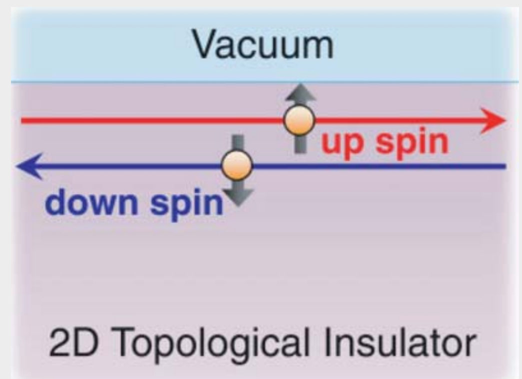
$$H_{\text{surf}}(k_x, k_y) = C + A_2(\sigma^x k_y - \sigma^y k_x).$$

X.-L. Qi and Sh.-Ch. Zhang, Rev. Mod. Phys. 83, 1057 (2011)

Electron momentum (k) and spin (σ) are linked which results in spin current and absence of the back scattering







Topological insulators and other materials

Typical examples of nontrivial topological insulators: Bi_2Se_3, Bi_2Te_3, Sb_2Te_3

Challenging task: to obtain clean, insulating bulk material

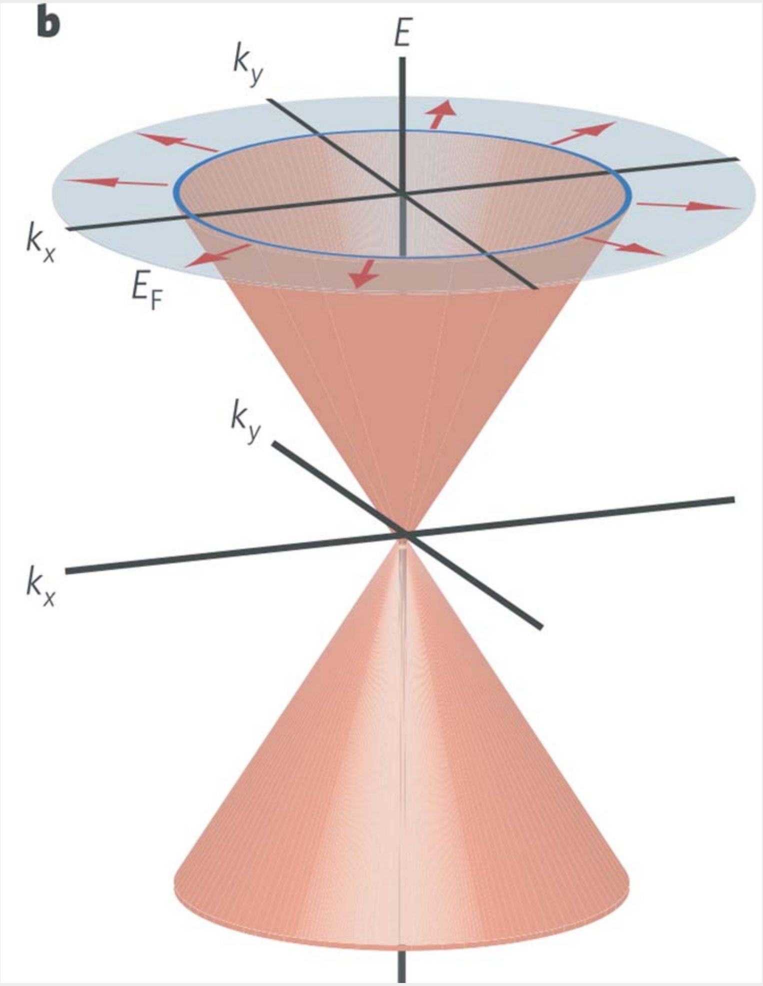
Very promissing system for realization of various Dirac fermion systems: *HgTe - based materials*

Topological insulators

- 2D edge states in HgTe based QWs (2D TI)
  König et al., Science318, 766 (2007)
- 3D TI made of strained bulk HgTe
  Brune et al, Phys. Rev. Lett. 106, 126803 (2011)
  Kozlov et al., Phys. Rev. Lett. 112, 196801(2014)
  Ganichev et al., arXiv (2015)

These materials do not belong to topological insulators

- Dirac fermions in QW with critical thickness
  Bernevig, et al. Science 314, 1757 (2006)
  Büttner, et al. Nature Phys. 7, 418 (2011)
  Ganichev et al. JETP Lett. 94, 816 (2011)
  Zholudev et al. Nanoscale Research Lett. 7, 534 (2012)
- Dirac fermions in specially designed HgCdTe
  Orlita, et al. Nature Phys. 10, 233 (2014)



Spin polarized electric current in HgTe QWs of critical thickness

Cyclotron Resonance of Dirac Ferions in HgTe Quantum Wells

Z. D. Kvon[a, b], S. N. Danilov[c], D. A. Kozlov[a, b, *], C. Zoth[c], N. N. Mikhailov[a], S. A. Dvoretskii[a], and S. D. Ganichev[c]

JETP Letters, 2011, Vol. 94, No. 11, pp. 816–819.

PHYSICAL REVIEW B **87**, 235439 (2013)

Giant photocurrents in a Dirac fermion system at cyclotron resonance

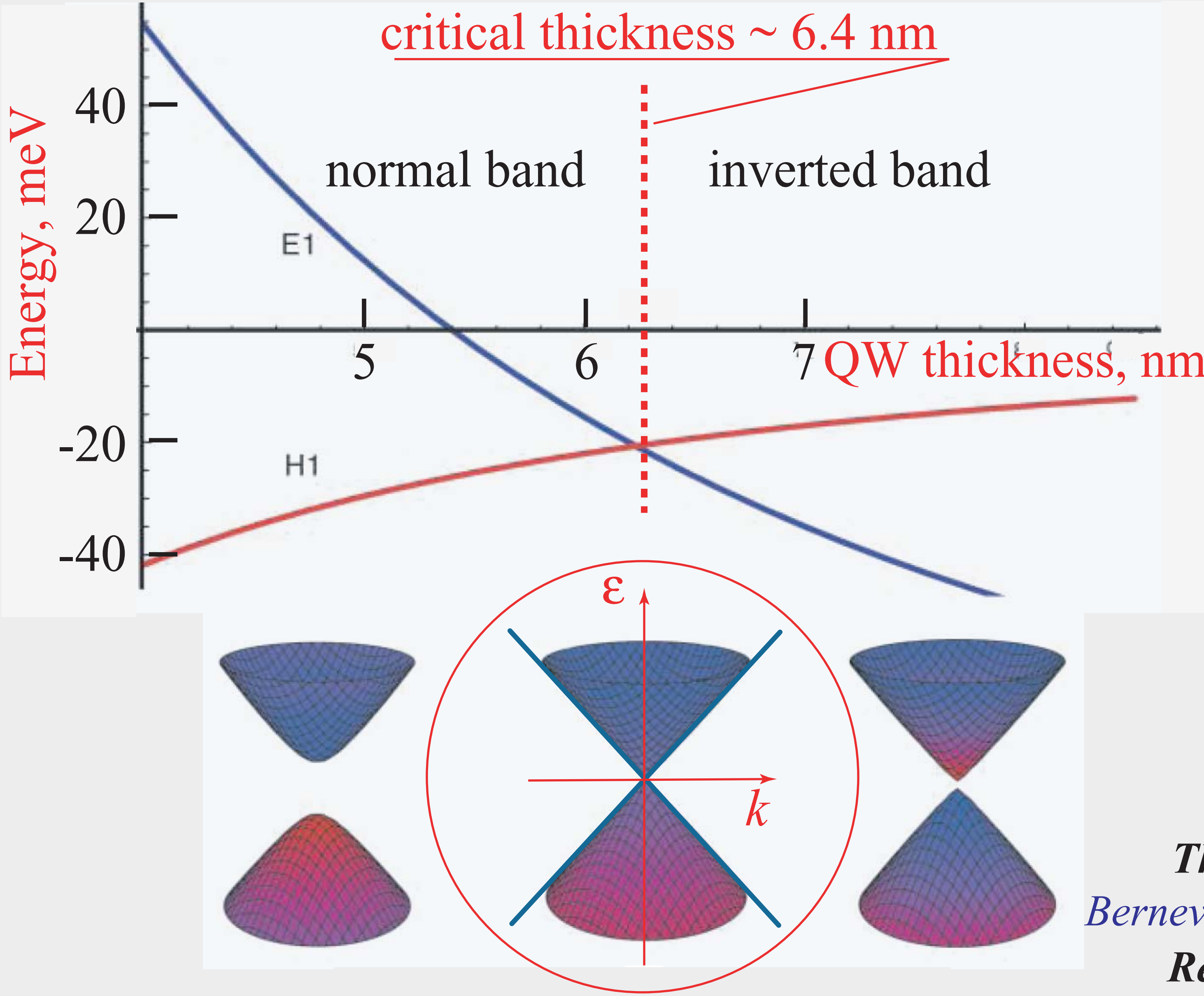
P. Olbrich,[1] C. Zoth,[1] P. Vierling,[1] K.-M. Dantscher,[1] G. V. Budkin,[2] S. A. Tarasenko,[2] V. V. Bel'kov,[2] D. A. Kozlov,[3] Z. D. Kvon,[3] N. N. Mikhailov,[3] S. A. Dvoretsky,[3] and S. D. Ganichev[1]

PHYSICAL REVIEW B **90**, 205415 (2014)

Quantum oscillations of photocurrents in HgTe quantum wells with Dirac and parabolic dispersions

C. Zoth,[1] P. Olbrich,[1] P. Vierling,[1] K.-M. Dantscher,[1] V. V. Bel'kov,[2] M. A. Semina,[2] M. M. Glazov,[2] L. E. Golub,[2] D. A. Kozlov,[3,4] Z. D. Kvon,[3,4] N. N. Mikhailov,[3] S. A. Dvoretsky,[3] and S. D. Ganichev[1]

HgTe QW systems



- at the critical QW thickness d_c the band structure changes from normal to inverted
- at $d = d_c$ the QWs are characterized by a Dirac linear energy dispersion

Theory:

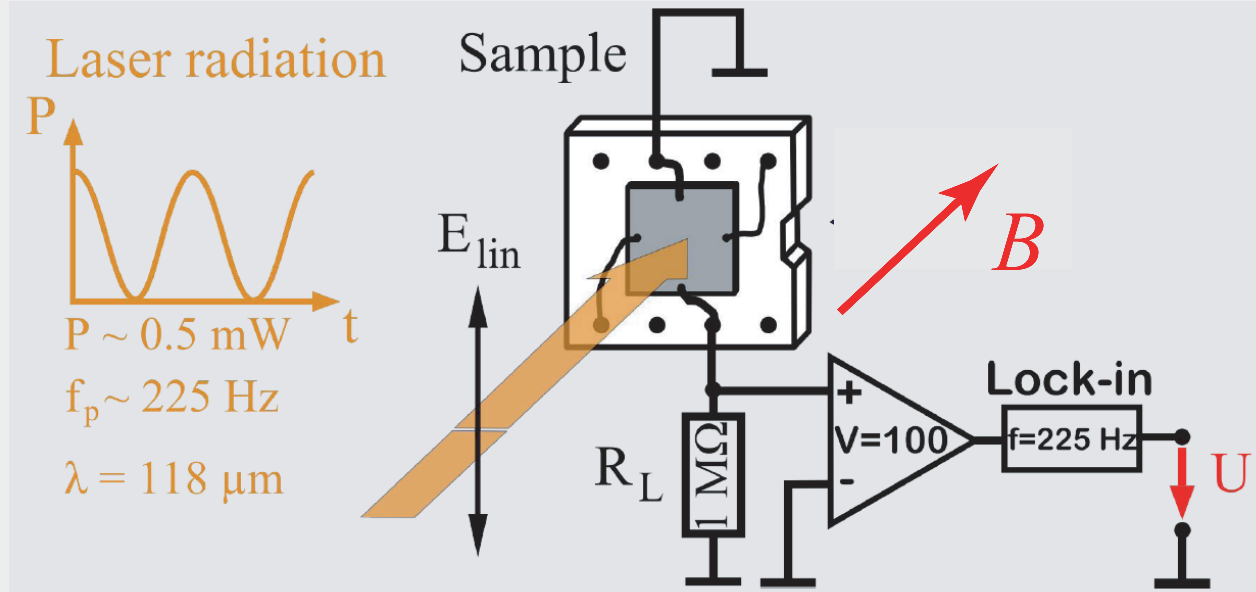
Bernevig, et al. Science ***314****, 1757 (2006)*

Realization:

Büttner, et al. Nature Phys. 7, 418 (2011)

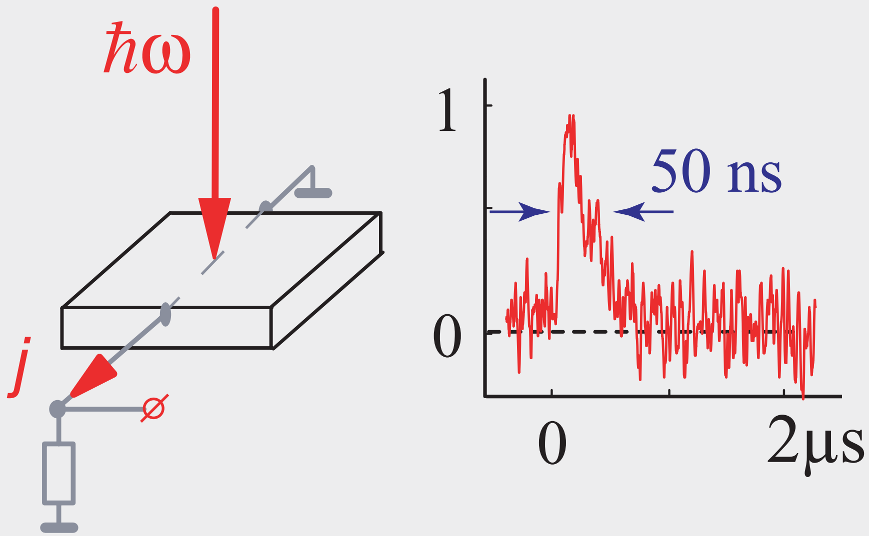
Ganichev et al. JETP Lett. ***94****, 816 (2011)*

Experimental geometry

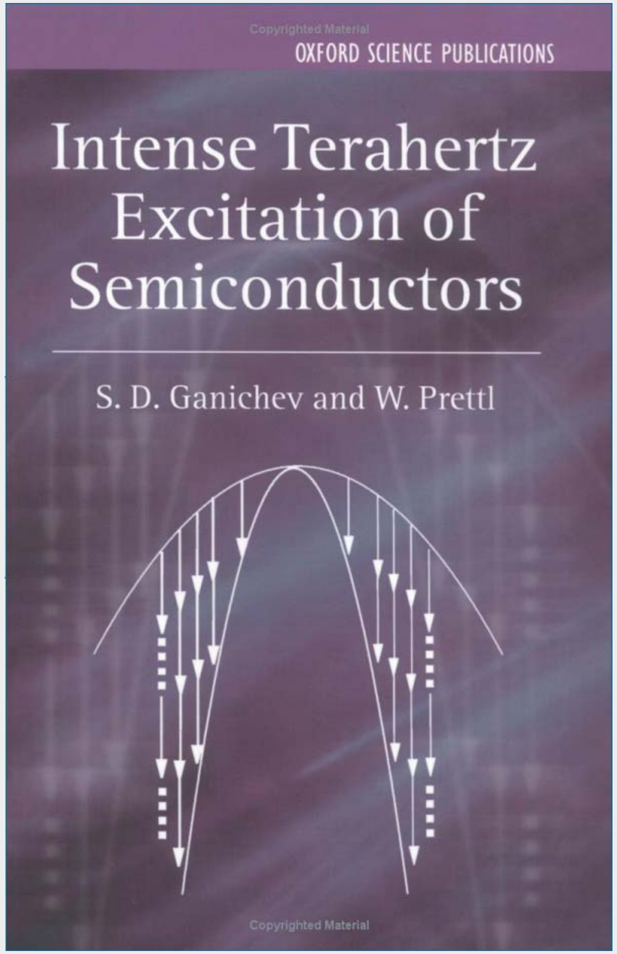


- Excitation: - cw molecular THz laser
  - λ =118 μm (ħω ~10 meV), 184 μm and 432 μm
  - circular or linear polarized
  - power P ~ 10 mW
  - laser spot diameter about 1 mm
- Signal: - voltage drop over load resistance (R_L ~ 1 MΩ or 50 Ω)
  - standard lock-in technique
- Temperature: 4.2 - 60 K
- Magnetic field: up to 7 T

Experimental geometry



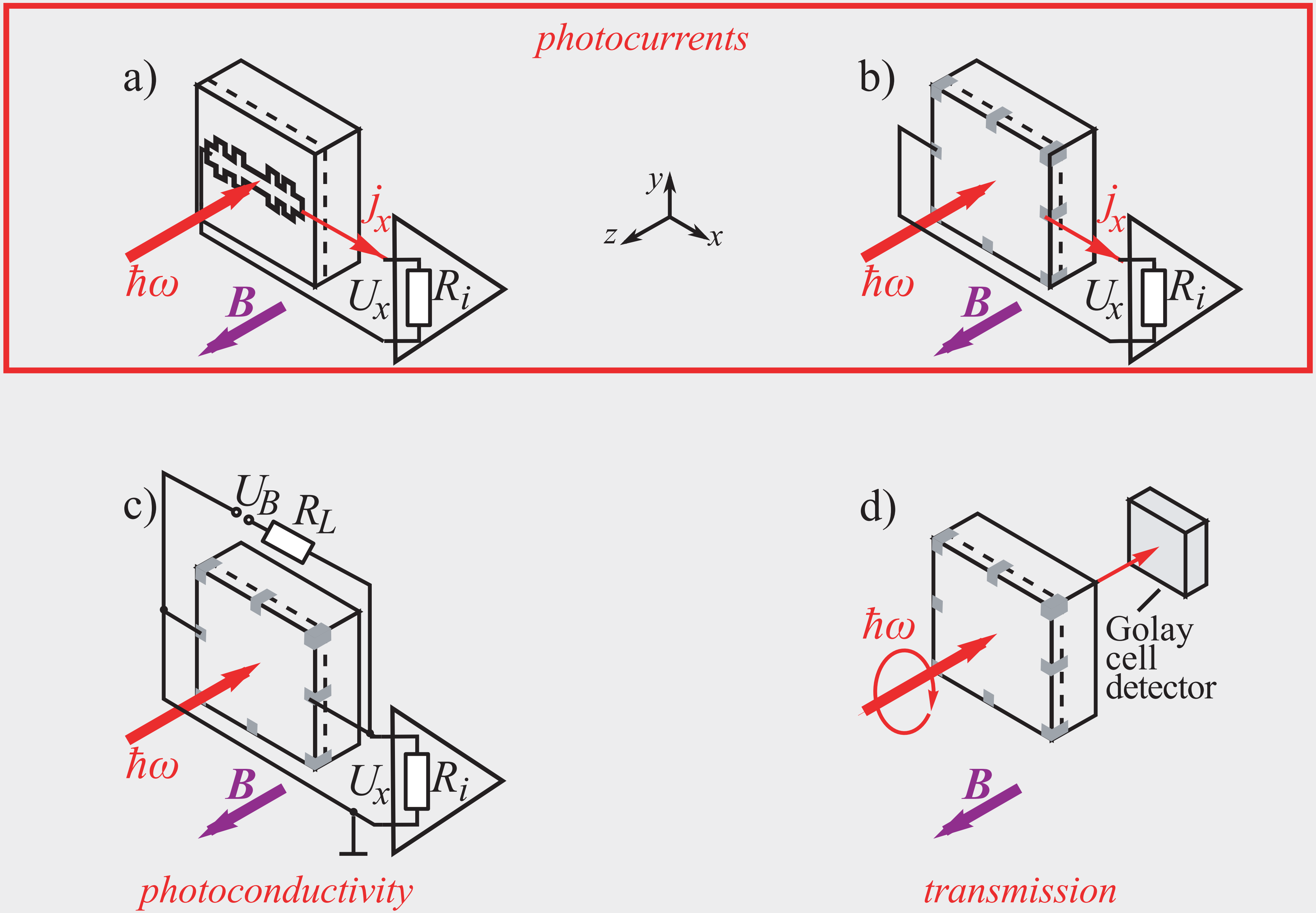
for details see:



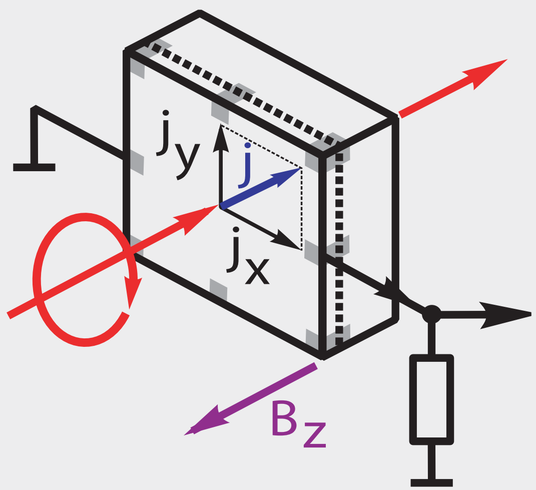
- Excitation:
  - pulsed molecular THz laser
  - λ = 76, 90, 148, 280, 385, 496 μm
  - pulse duration ~ 50 ns, power P ~ 10 kW

- Signal: - voltage drop over load resistance (R_L ~ 50 Ω)
  - no bias voltage
  - digital oscilloscope

Photocurrents induced in HgTe QW of critical thickness

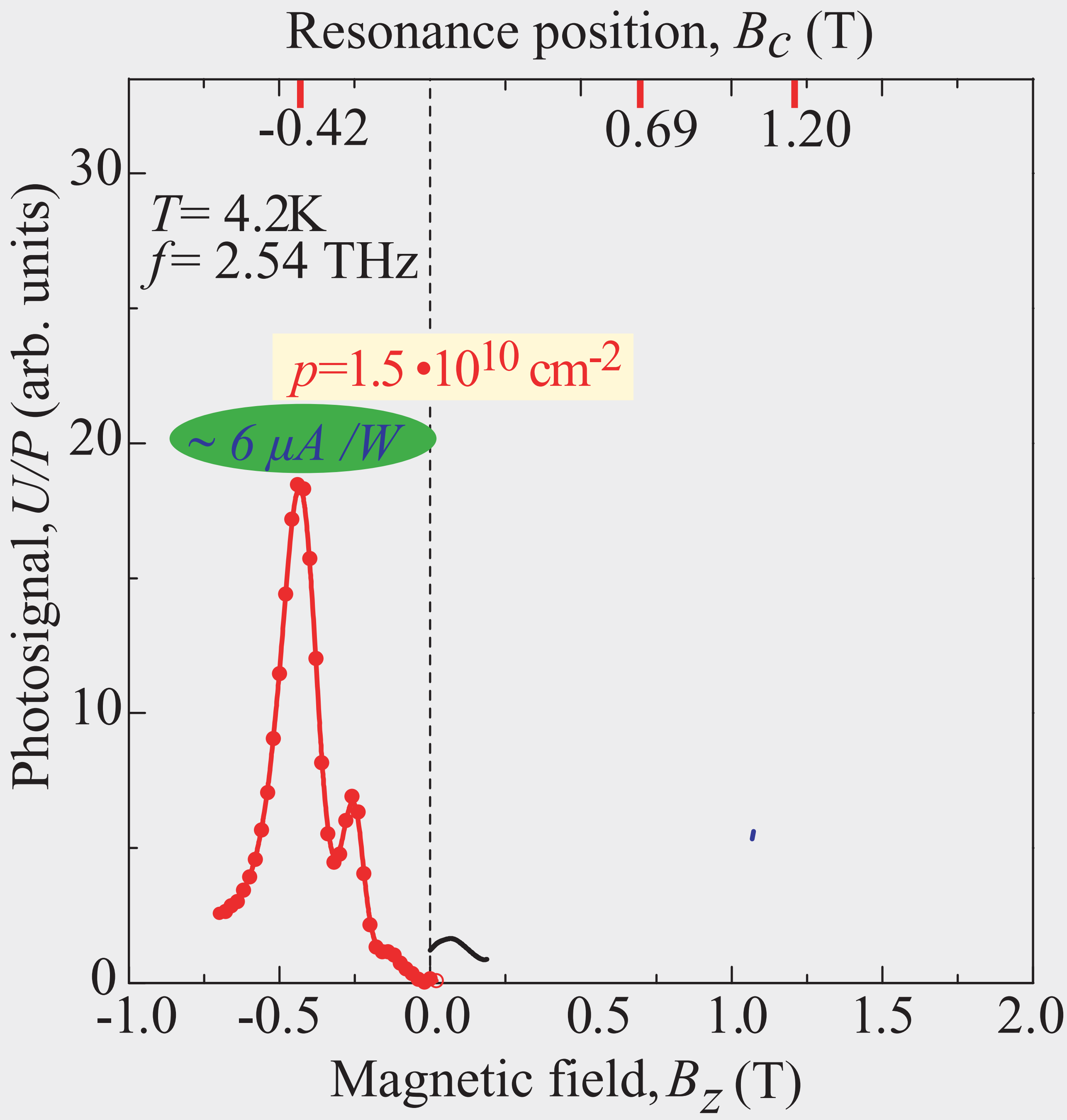


Resonant photocurrent in HgTe of critical thickness

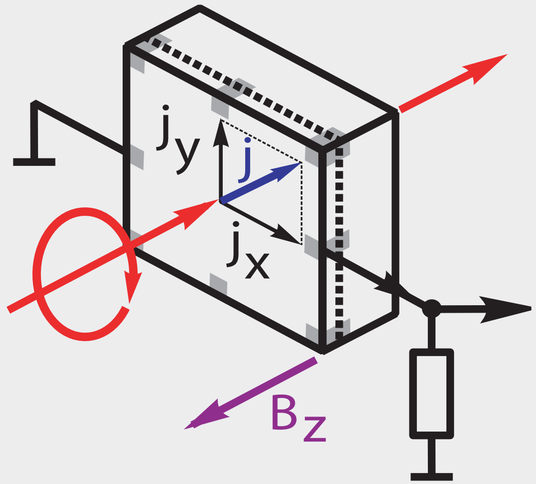


Illuminating QW with rid handed circularly polarized radiation we observed a current by two orders of magnitudes larger than that at zero B-field.

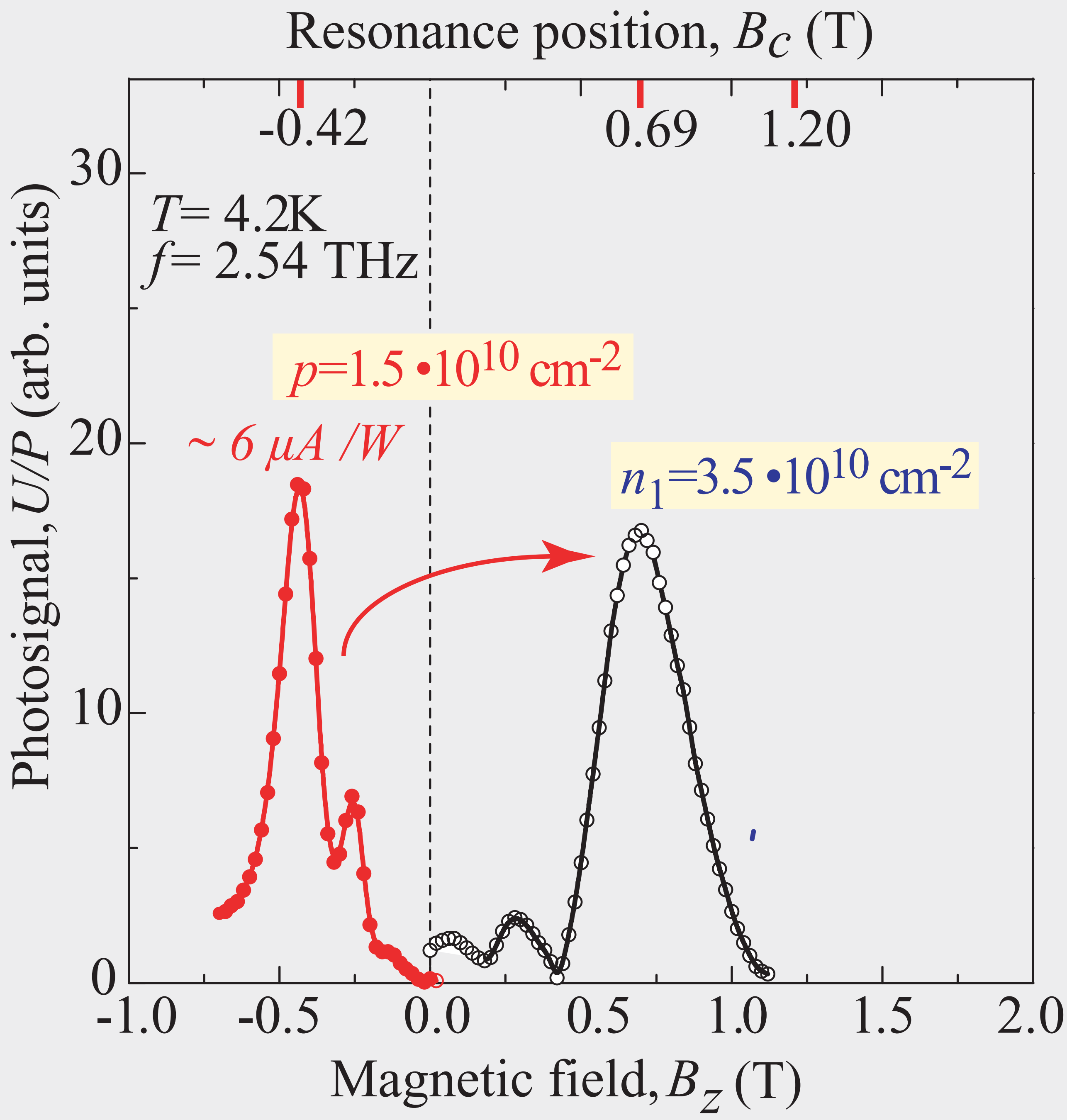
Very small value of the resonance fields - 0.4 T !



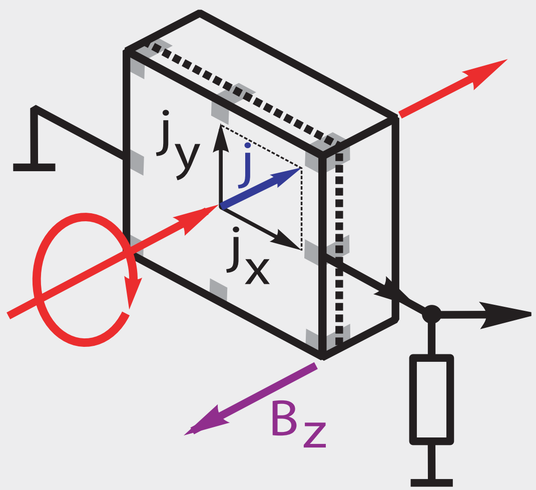
Resonant photocurrent in HgTe of critical thickness



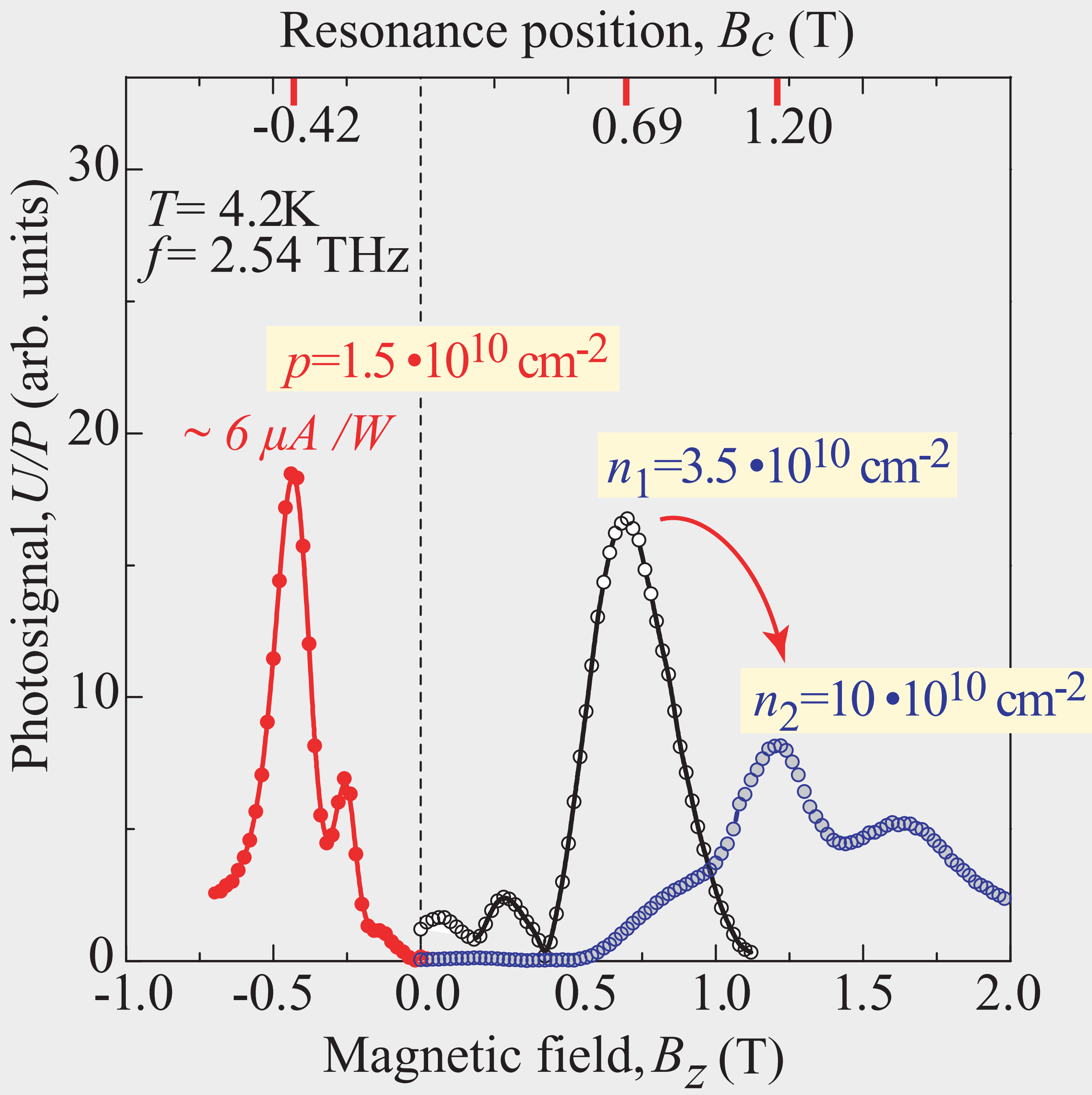
By changing the carrier type due to optical doping the resonance jumps to positive *B*-fields



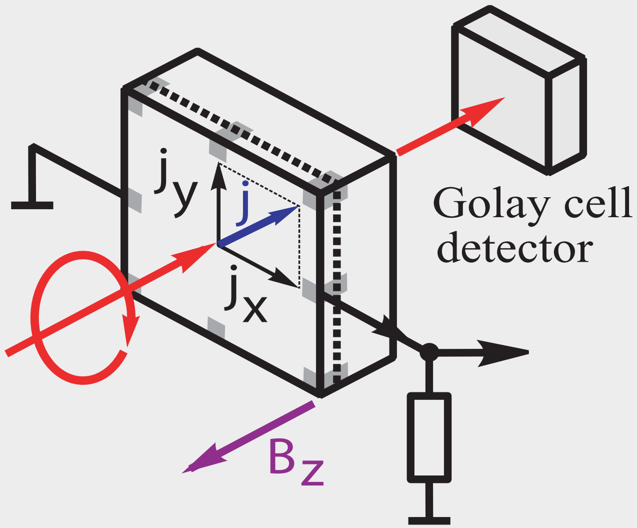
Resonant photocurrent in HgTe of critical thickness



Further increase of carrier density strongly shifts resonance to higher *B*-fields

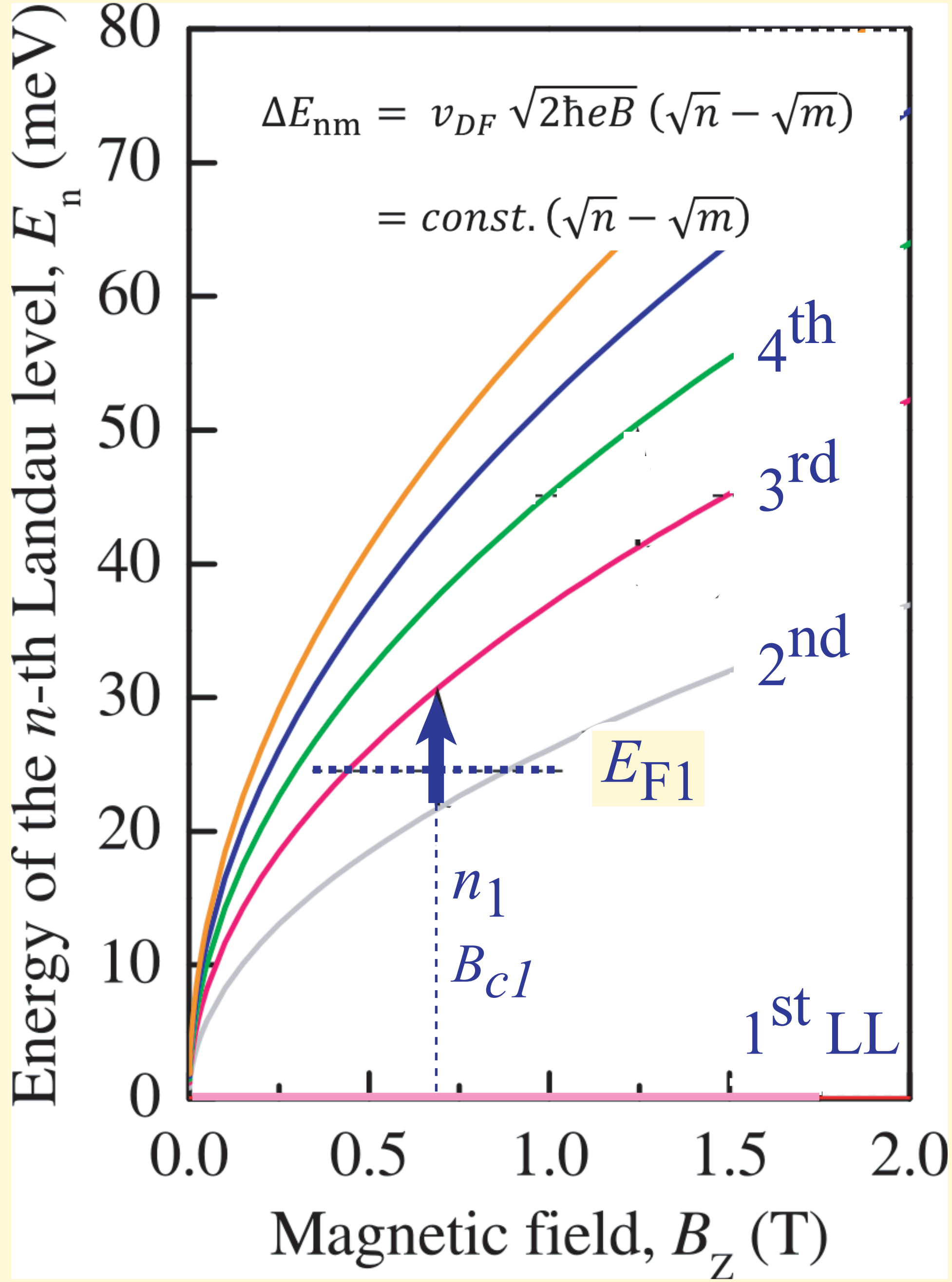


Resonant photocurrent in HgTe of critical thickness

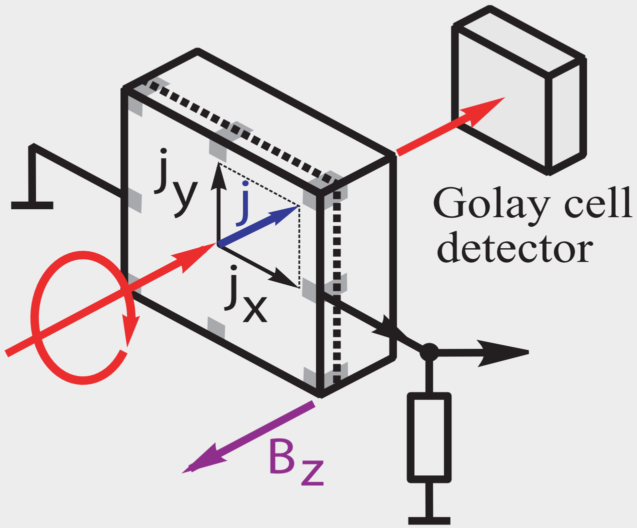


Density dependence of the CR position is charactteristic for Dirac fermions with the non-equidistant Landau levels

CR position allowed us to measure the average electron velocity which is 7.2 10^5 m/s and agrees well with the calculations of Bernevig et al.



Resonant photocurrent in HgTe of critical thickness



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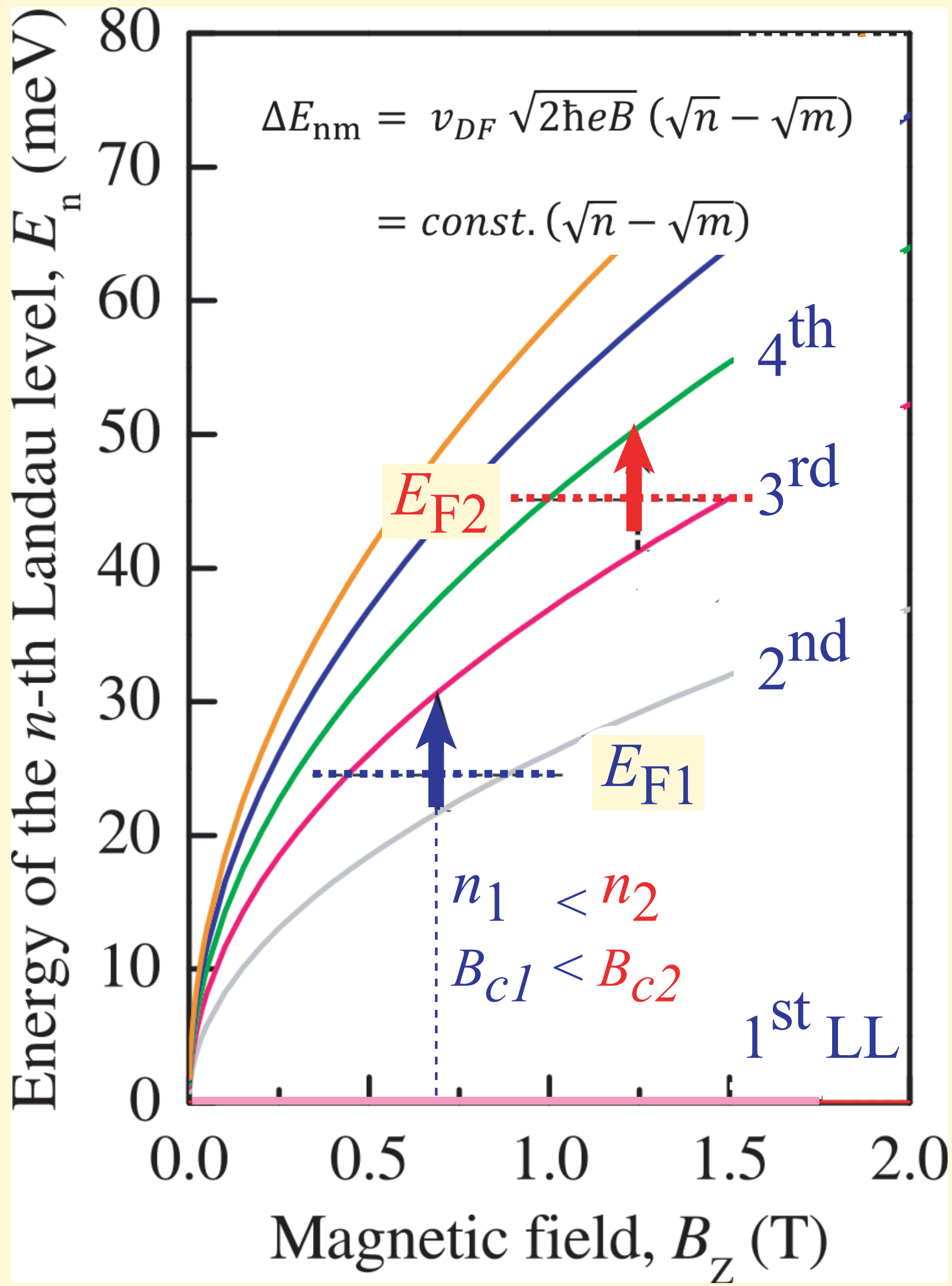
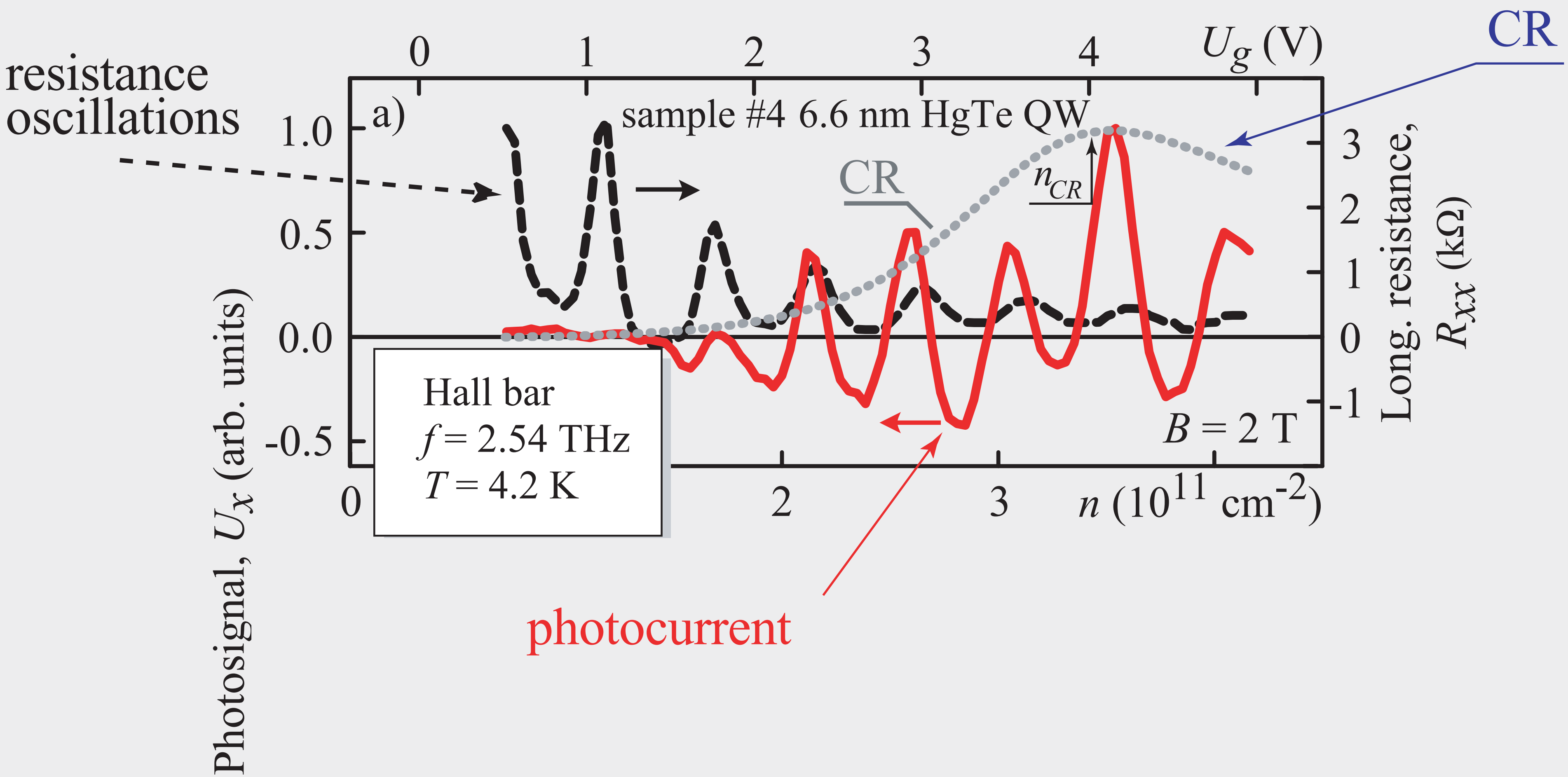
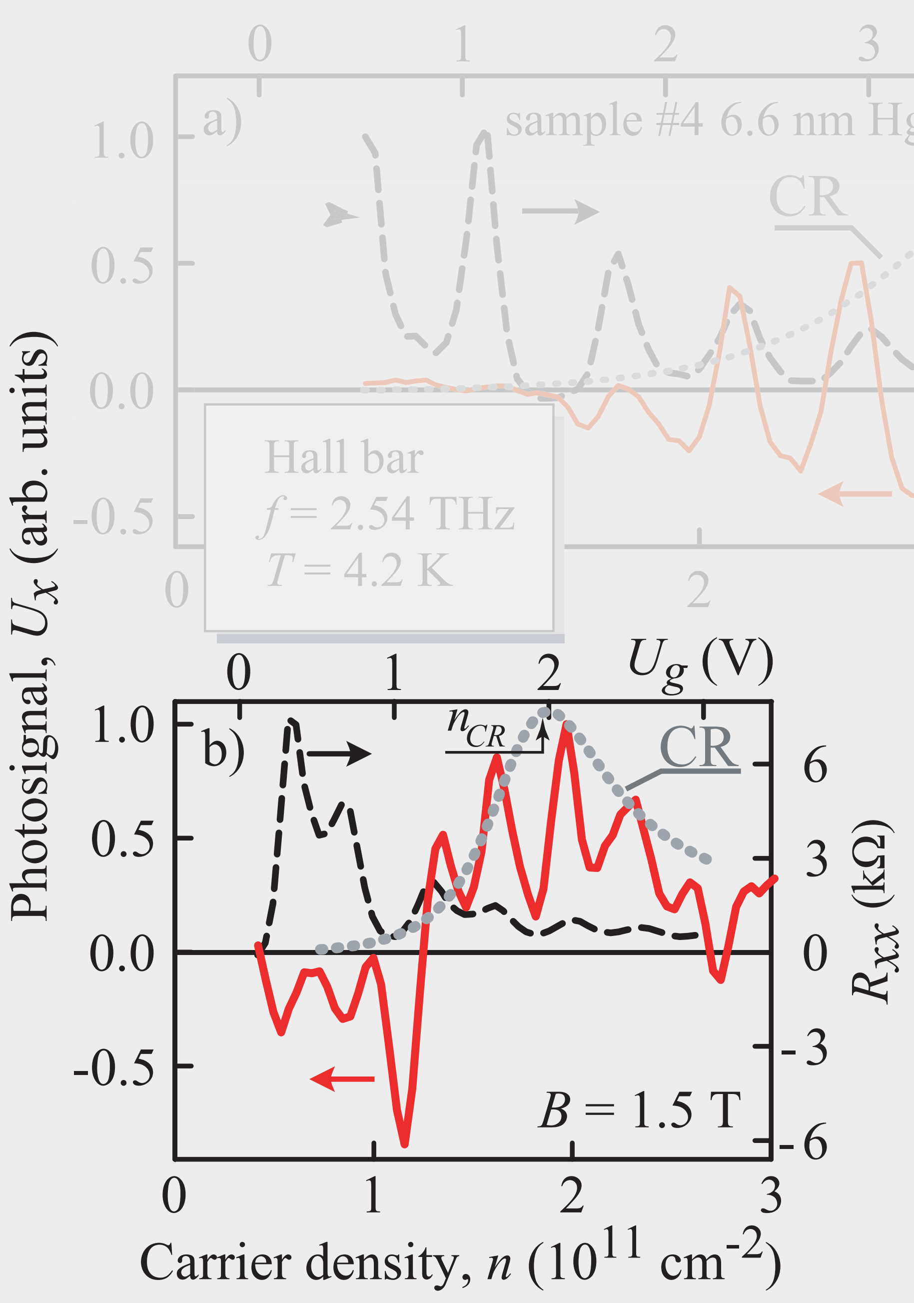


Photocurrents induced in HgTe QW of critical thickness

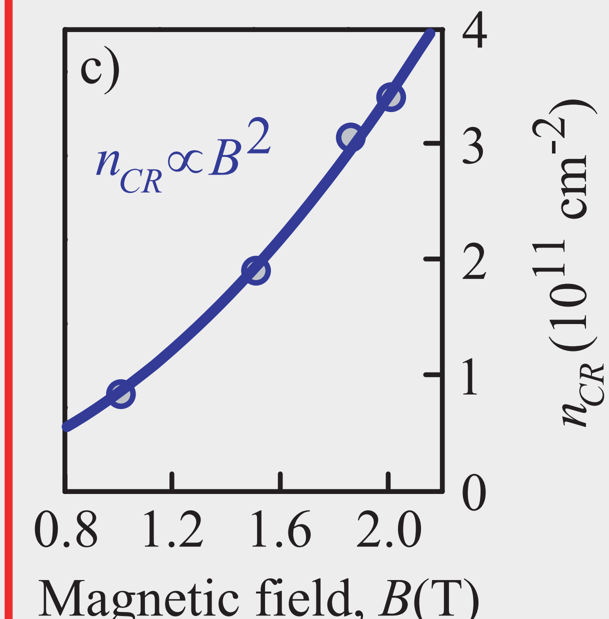


In the systems with linear dispersion CR can be excited at fixed magnetic field and radiation frequency by varying the carrier density. Photocurrent shows 1/B oscillations

Photocurrents induced in HgTe QW of critical thickness



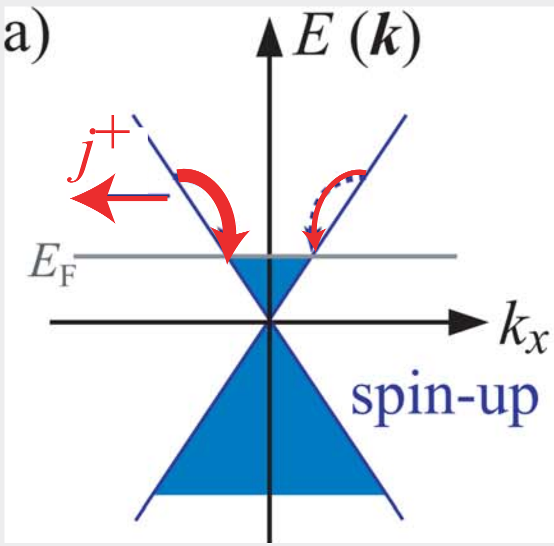
CR resonance density changes with B-field



Origin of the resonant photocurrent

- Strong electron gas heating due to cyclotron resonance --> energy relaxation
- Spin and momentum dependent scattering of electrons (transition from state $\boldsymbol{k}$ to $\boldsymbol{k}'$)
  In gyrotropic media like HgTe QWs scattering:

$$\hat{V}(\boldsymbol{k}',\boldsymbol{k}) = \hat{V}_0(\boldsymbol{k}',\boldsymbol{k}) + \hat{V}_{spin}(\boldsymbol{k}',\boldsymbol{k}) \quad \text{where} \quad \hat{V}_{spin}(\boldsymbol{k}',\boldsymbol{k}) \propto [(\boldsymbol{k}'+\boldsymbol{k}) \times \sigma]$$



The relaxation rates for say spin-up electrons with positive and negative k are different.
The scattering asymmetry results in the flux j^+

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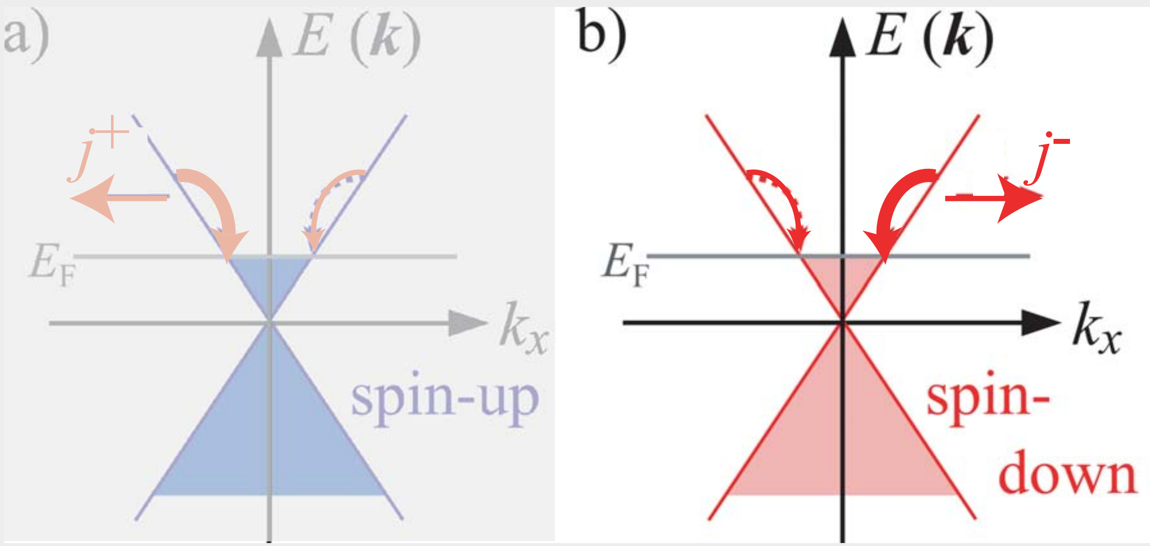
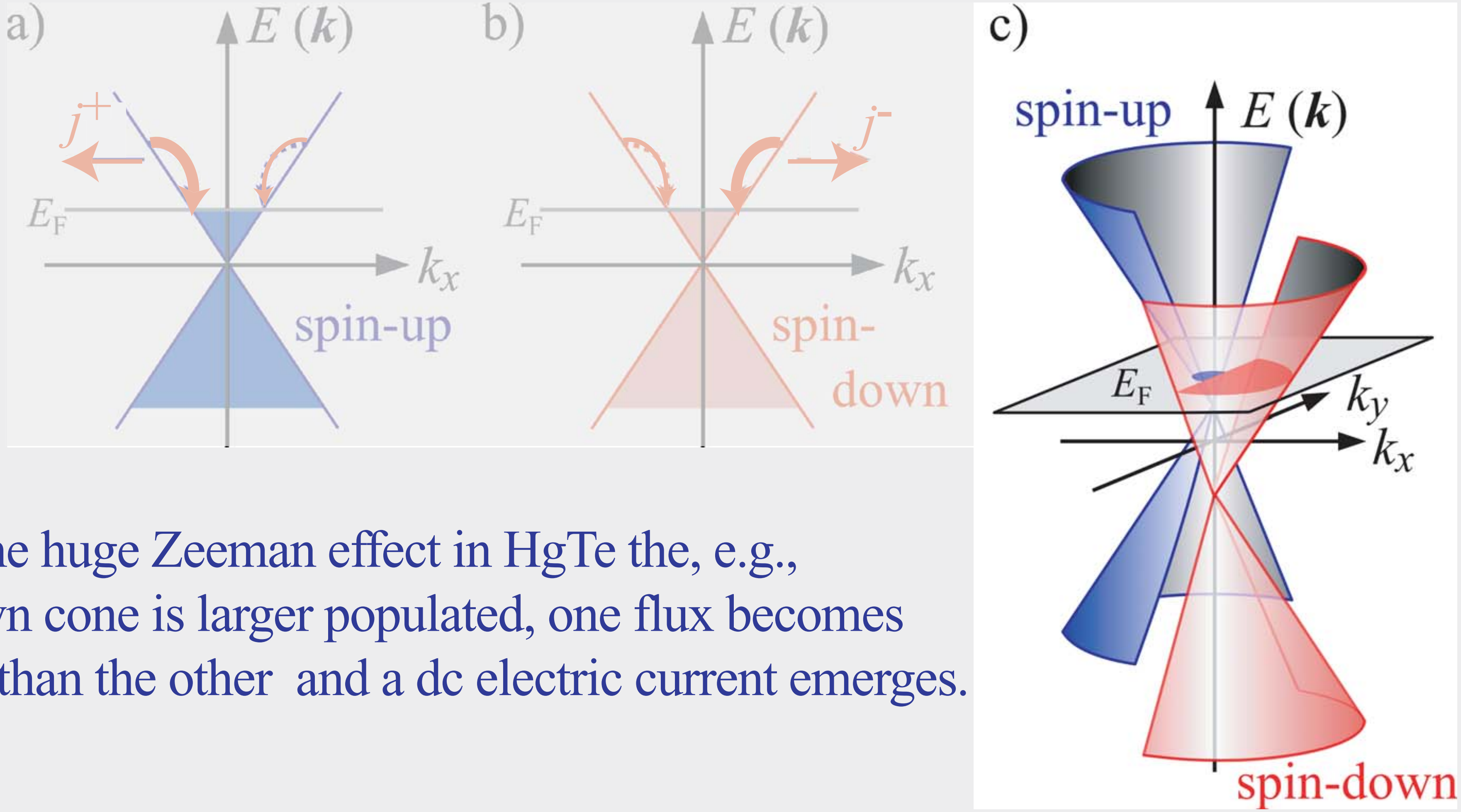


The relaxation rates for say spin-up electrons with positive and negative k are different.
The scattering asymmetry results in the flux j^+
For the spin-down spin sigma and the corresponding flux j^- have opposite signs

Origin of the resonant photocurrent

- Strong electron gas heating due to cyclotron resonance --> energy relaxation
- Spin and momentum dependent scattering of electrons (transition from state $\boldsymbol{k}$ to $\boldsymbol{k}'$)
  In gyrotropic media like HgTe QWs scattering:

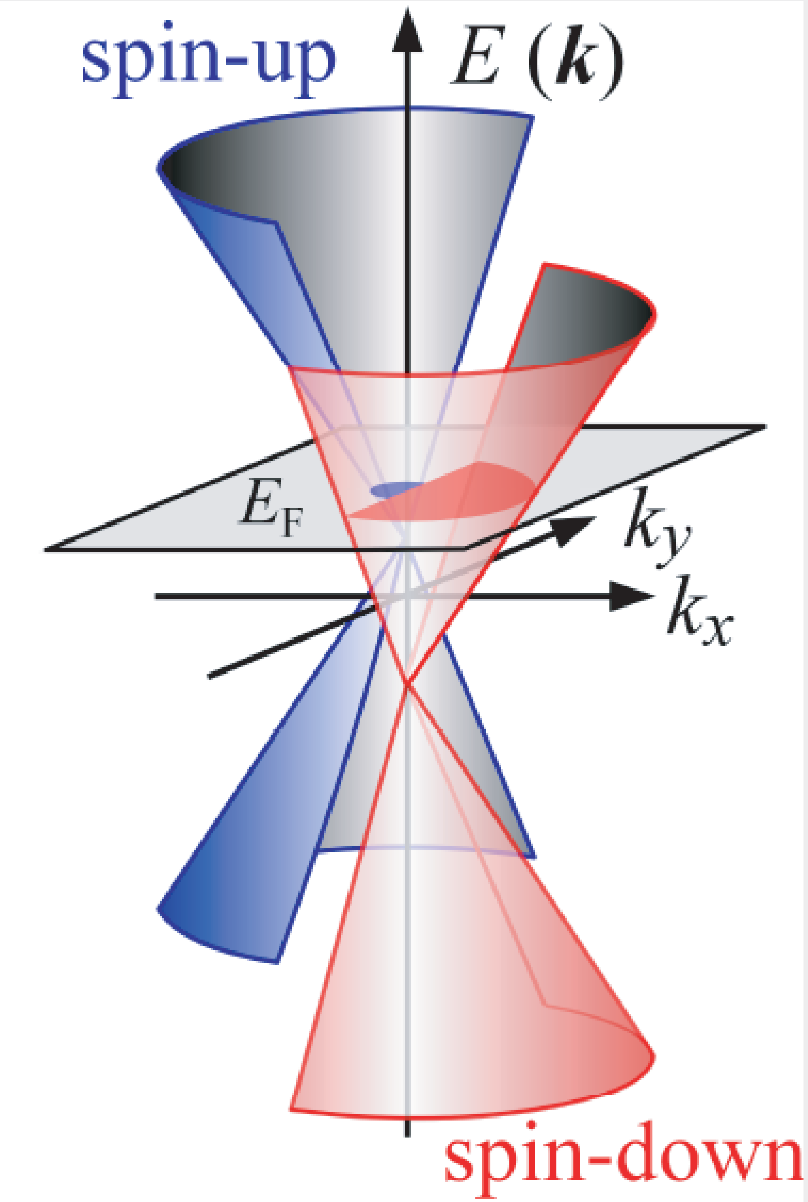
$$\hat{V}(\boldsymbol{k}',\boldsymbol{k}) = \hat{V}_0(\boldsymbol{k}',\boldsymbol{k}) + \hat{V}_{spin}(\boldsymbol{k}',\boldsymbol{k}) \quad \text{where} \quad \hat{V}_{spin}(\boldsymbol{k}',\boldsymbol{k}) \propto [(\boldsymbol{k}'+\boldsymbol{k})\times\sigma]$$



Due to the huge Zeeman effect in HgTe the, e.g., spin-down cone is larger populated, one flux becomes stronger than the other and a dc electric current emerges.

Microscopic theory

The developed theory yields



the current

$$|j| = |\frac{ev\sin(2\theta)}{2\sqrt{2}E_F\omega_c}\frac{g\mu_0 B}{E_F}\xi I\eta|$$

and voltage

$$U = |j\frac{\omega_c\tau_p a}{\sigma}|$$

with

$$\eta = \frac{2e^2E_F}{c\hbar^2 n_\omega}\frac{\tau_p}{1+(\omega-\omega_c)^2\tau_p{}^2}$$

absorbance in vicinity of CR

and

$$\sigma = e^2E_F\tau_p/2\pi\hbar^2$$

conductivity at zero field

current j ~ radiation absorption (η)
SOI strength (ξ)
Zeeman splitting ($g\mu_0 B$)

Microscopic theory

The observed photocurrent oscillations, similarly to the de Haas–van Alphen and Shubnikov–de Haas effects, stem from the consecutive crossings of Fermi level by Landau levels.

$$j_x = j_n + j_\mu$$

spin polarization due to Zeeman effect

$$j_n = \frac{2e\zeta c\beta |E_0|^2}{|B|} S_z n \mu(\omega)$$

$$\mu(\omega) = [\mu_+(\omega) + \mu_-(\omega)]/2$$

$$j_\mu = \frac{e\zeta c\beta |E_0|^2}{|B|} n \frac{\mu_+(\omega) - \mu_-(\omega)}{2}$$

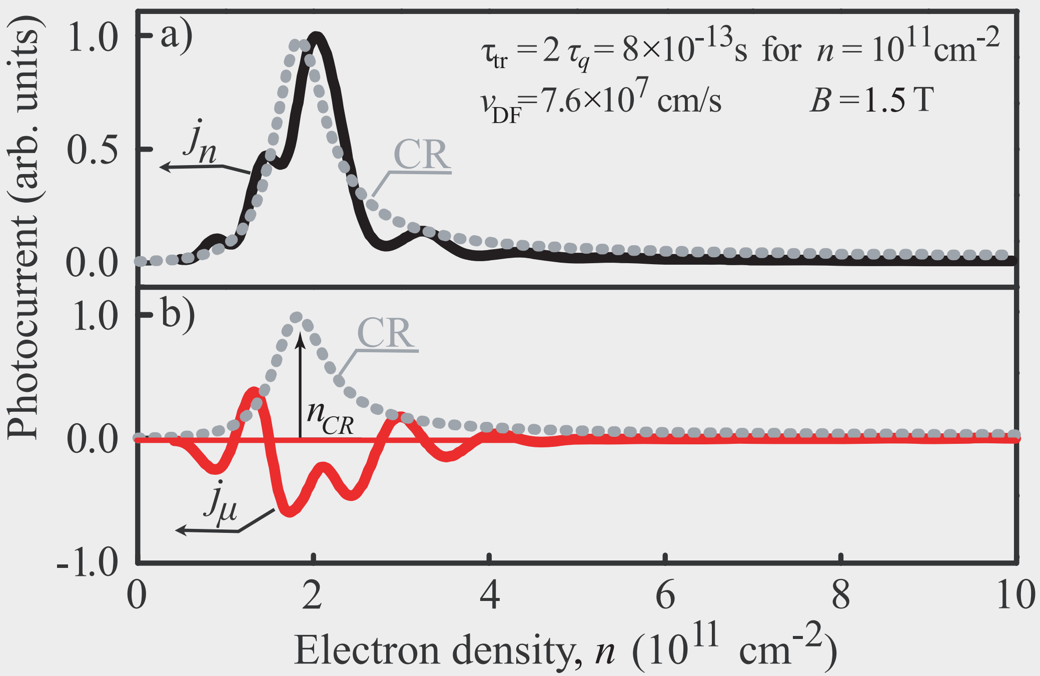
mobilities in each spin branch

Asymmetry of scattering
$$\zeta = \frac{2\mathrm{Re}(V_0 V_1^*)}{|V_0|^2} \frac{k}{v(k)}$$

Absorbance
$$\sigma_\pm(\omega) = |e| n_\pm \mu_\pm(\omega)$$

$$\sigma(\omega) = \frac{e^2 n^* \tau_{\mathrm{tr}}^*}{2m_c^* [1 + (\omega - \omega_c^* \eta)^2 \tau_{\mathrm{tr}}^{*2} \eta^2]}$$

Photocurrents induced in HgTe QW of critical thickness



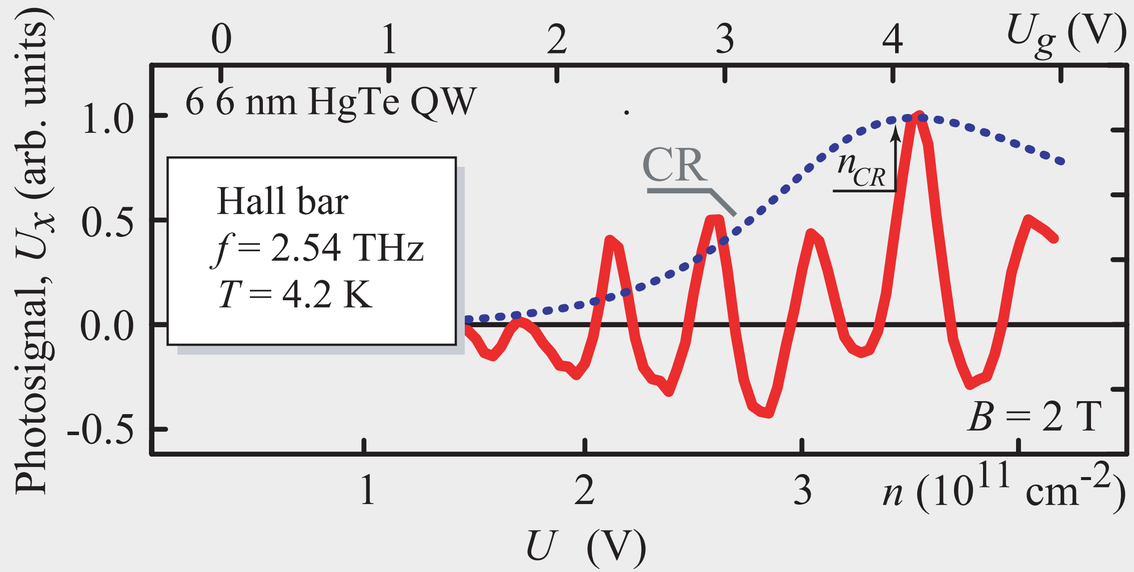
$$j_x = j_n + j_\mu,$$

$$j_n = \frac{2e\zeta c\beta|E_0|^2}{|B|} S_z n\mu(\omega),$$

Zeeman spin polarization

$$j_\mu = \frac{e\zeta c\beta|E_0|^2}{|B|} n \frac{\mu_+(\omega) - \mu_-(\omega)}{2}$$

Stem from periodic variation of the occupations of spin-up and spin-down subbands and electron scattering rates



Theory exactly describes the experiment. Observation of de Haas van Alpen contribution supports Zeemen effect induced spin polarization origin of the cyclotron induced photocurrent in Dirac Fermions systems,

Spin polarized electric current in HgTe TI systems

3D TI

Cyclotron Resonance Assisted Photocurrents in Surface States of a 3D Topological Insulator Based on a Strained High Mobility HgTe Film

K.-M. Dantscher,[1] D.A. Kozlov,[2,3] P. Olbrich,[1] C. Zoth,[1] P. Faltermeier,[1] M. Lindner,[1] G.V. Budkin,[4] S.A. Tarasenko,[4,5] V.V. Belkov,[4] Z.D. Kvon,[2,3] N.N. Mikhailov,[2] S.A. Dvoretsky,[2] D. Weiss,[1] B. Jenichen,[6] and S.D. Ganichev[1]

arXiv cond-mat:1503.06951 (2015)

2D TI

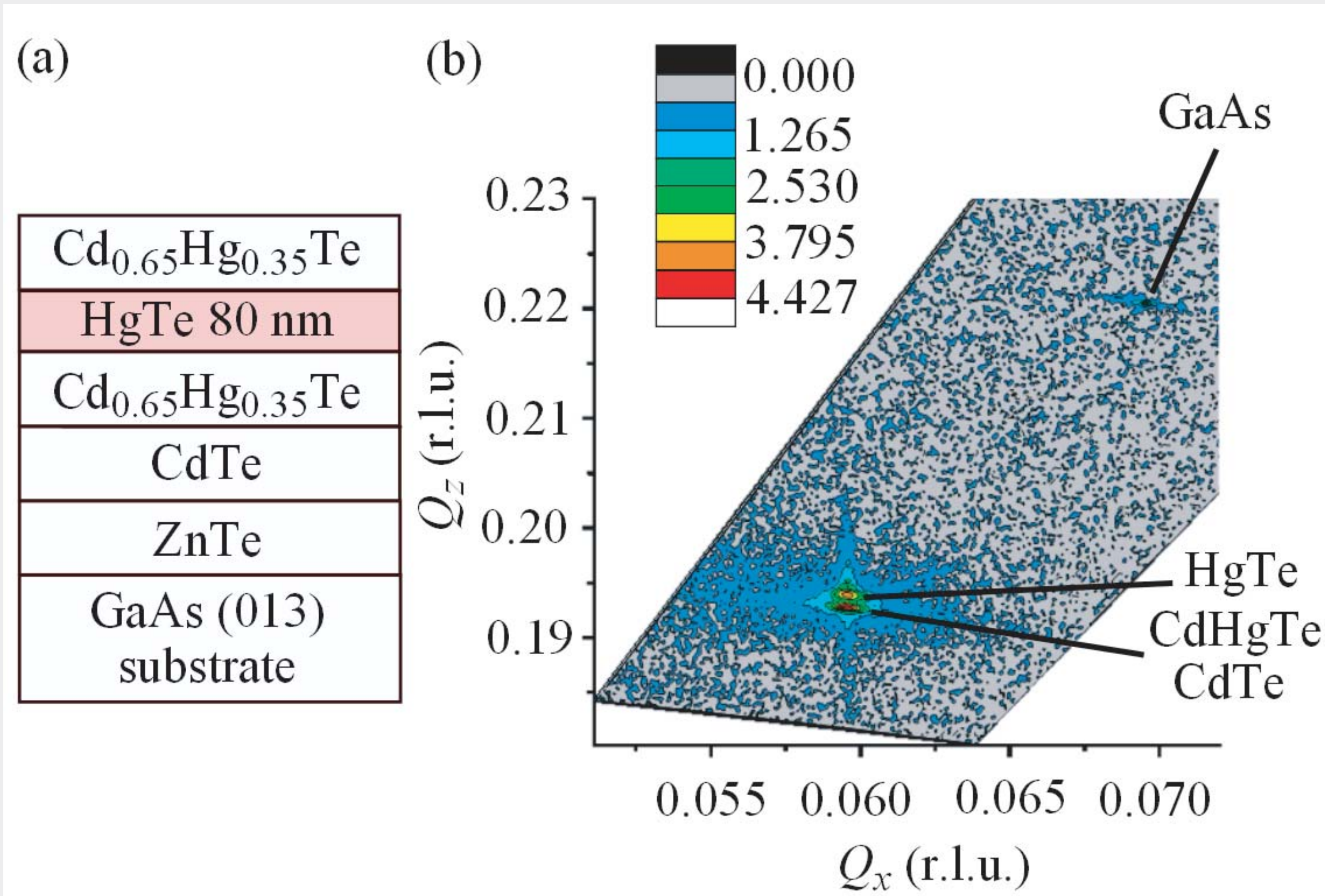
Terahertz Electron Transport in a Two-Dimensional Topological Insulator in a HgTe Quantum Well

Z. D. Kvon[a, b], K. M. Dantscher[c], C. Zoth[c], D. A. Kozlov[a, b, *], N. N. Mikhailov[a, b], S. A. Dvoretsky[a], and S. D. Ganichev[c]

JETP Letters, 2014, Vol. 99, No. 5, pp. 290–294. © Pleiades Publishing, Inc., 2014.

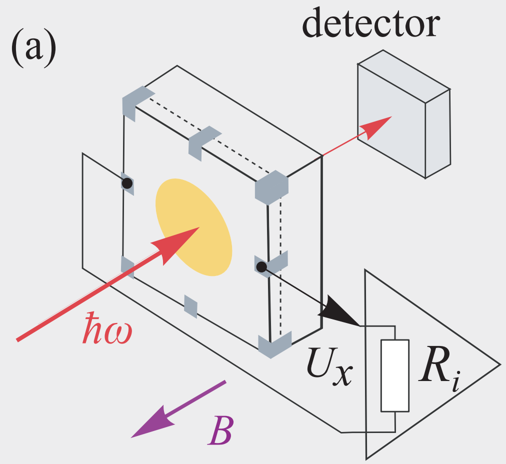
Samples: strained 80 nm film HgTe TI

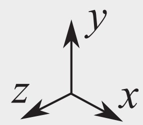
Samples: - 80 nm HgTe QW MBE grown on (013)-oriented GaAs substrate
- Fully strained as checked by X-rays
- Dirac surface states are chareacterized by transport measurements (details - talk of Dieter Weiss)

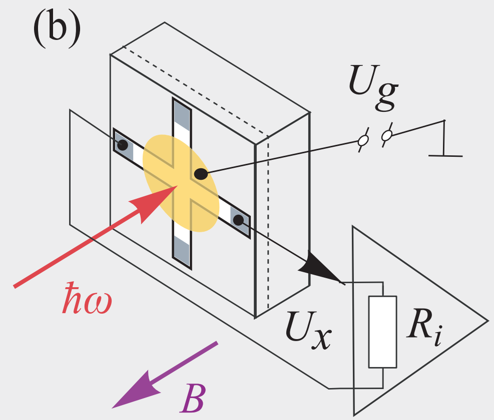


Experimental geometry

Radiation THz sources and methods are the same as in the first part of the talk







large area ungated samples:
simultaneous measurements
of photocurrent and transmission

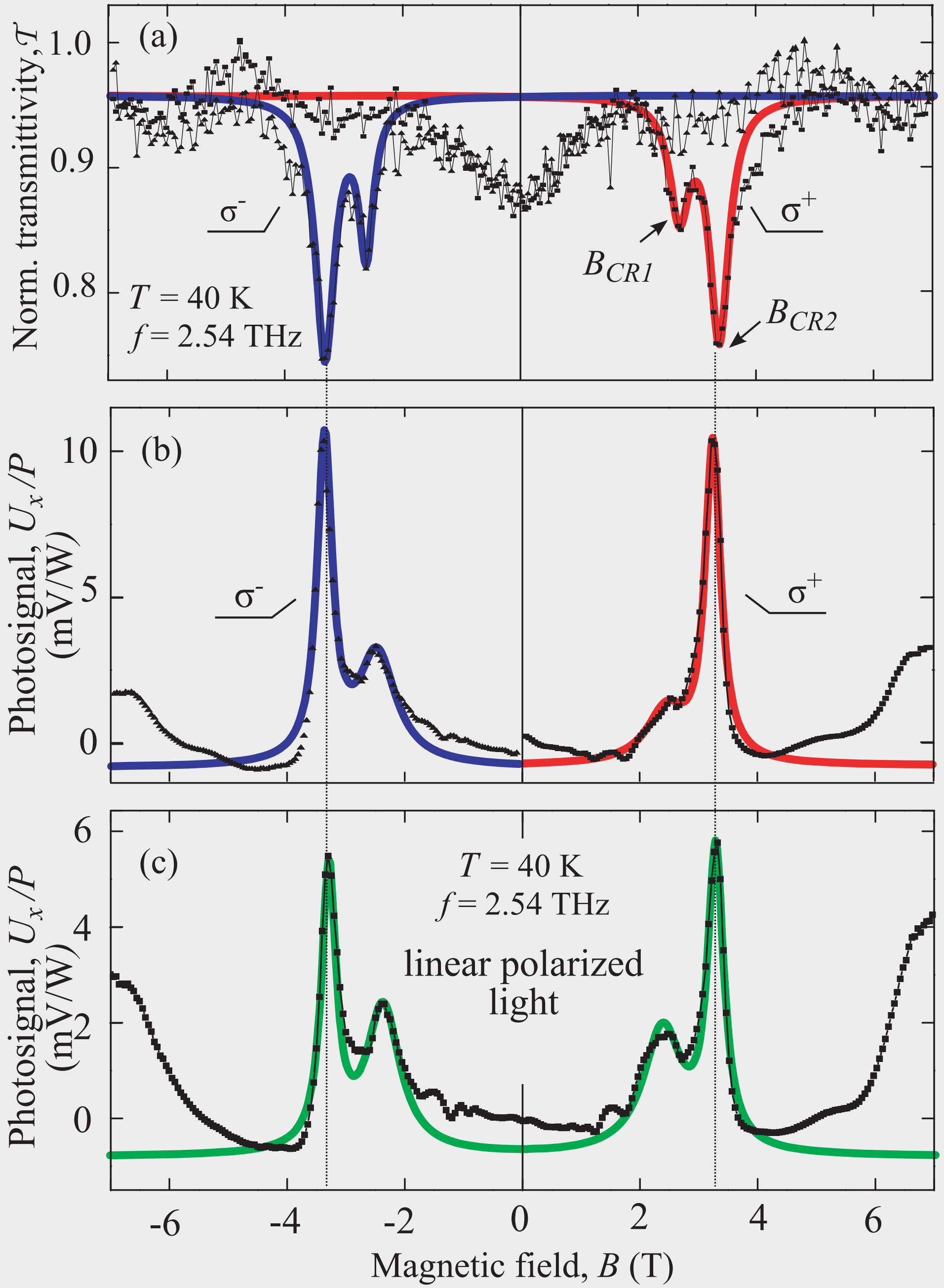
small area crossed gated samples:
measurements of photocurrent
upon gate voltage variation

Strained 80 nm film HgTe topological insulator

Transmission for right and left handed circularly polarized light

Photocurrent for right and left handed circularly polarized light

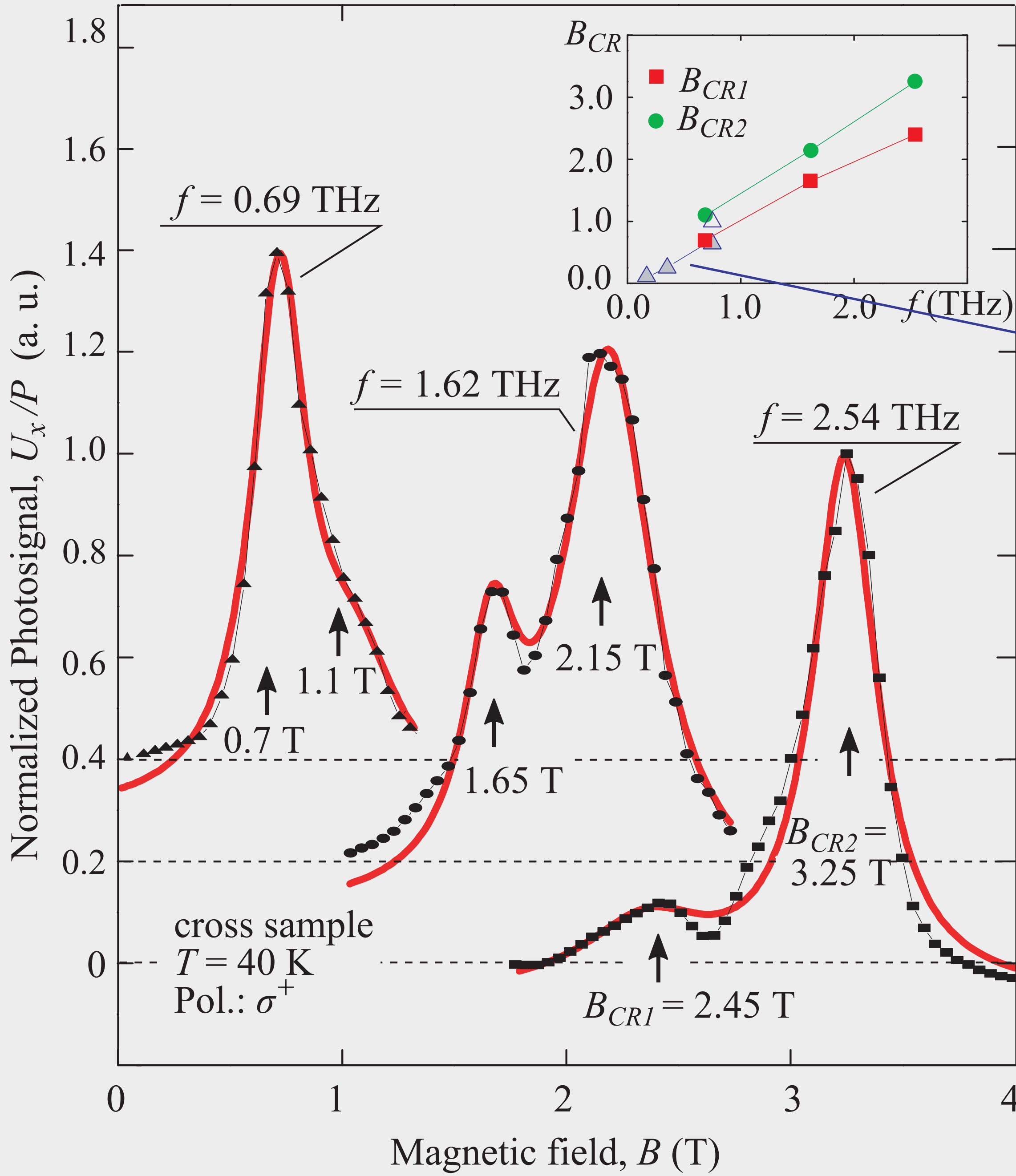
Photocurrent for linearly polarized light



f = 2.54 THz

Photocurrent: variation of light frequency

Scales linearly with frequency



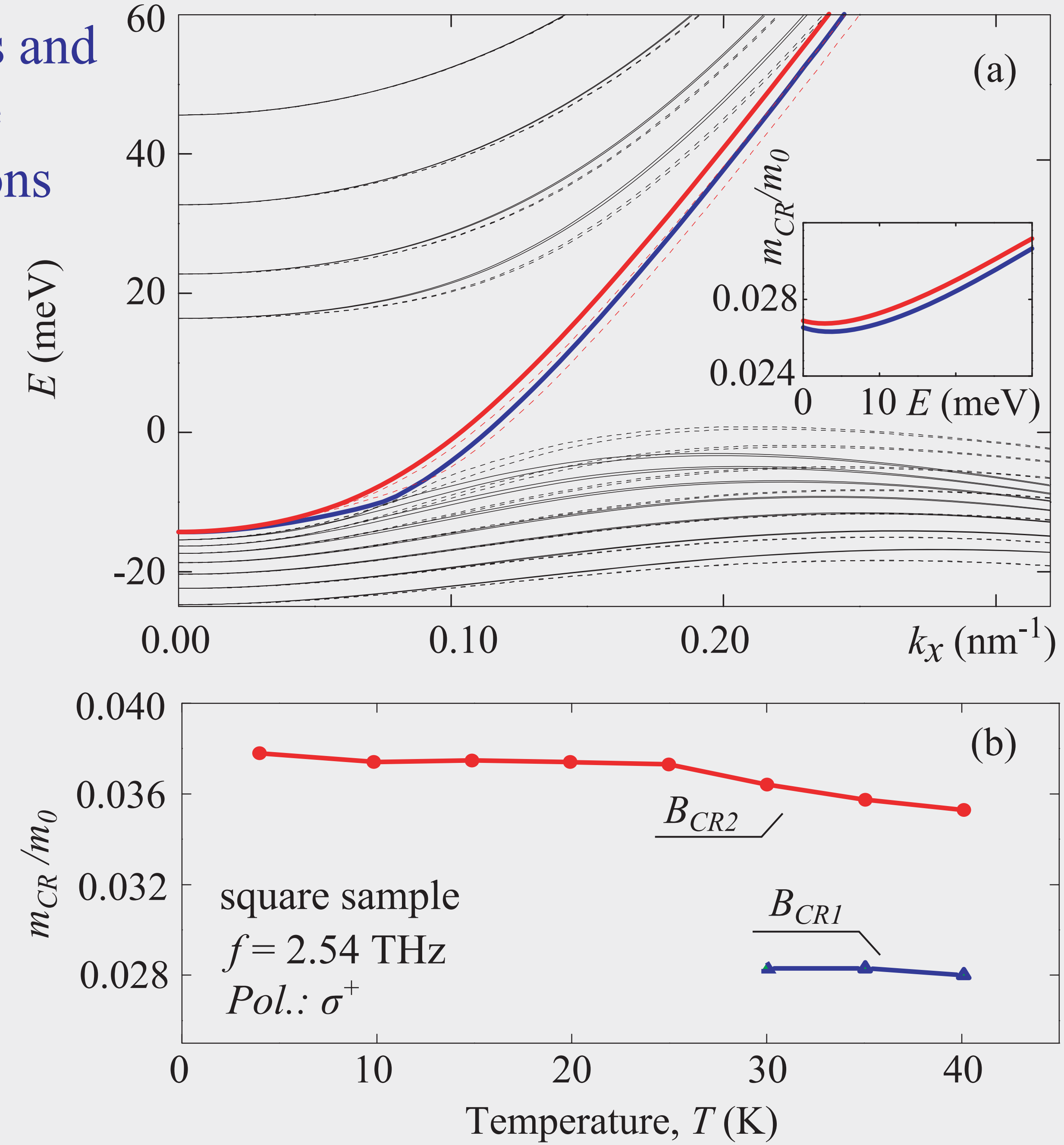
Triangles are microwave data on surface states CR

from Shavaev et al. Semicond. Sci. Technol. 27, 124004 (2012)

Cyclotron masses of surface electrons

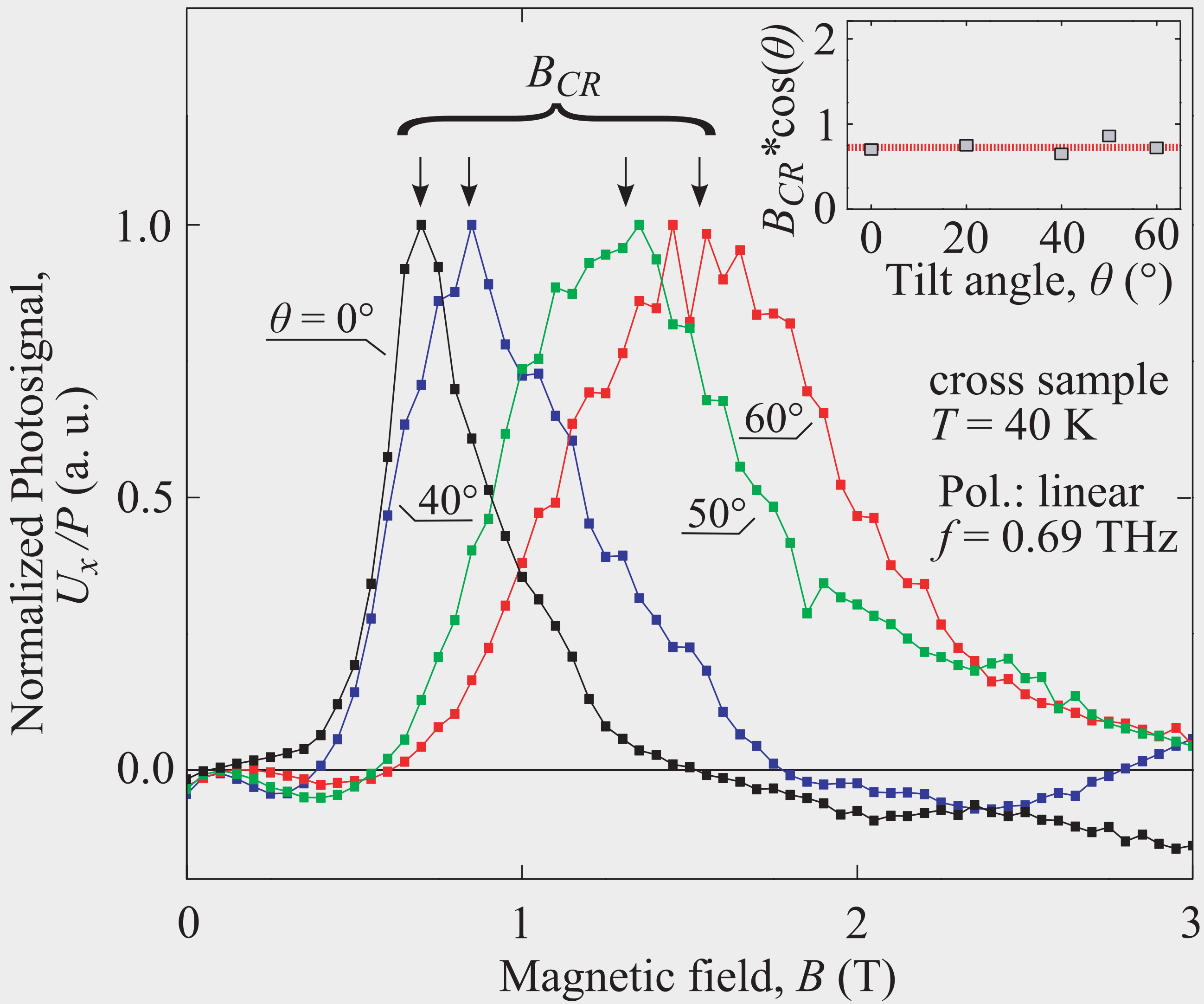
Surface states cyclotron masses and their temperature behaviour are in agreement with the estimations from kp theory.

Note that bulk masses are two times larger



Tilted magnetic fields: 2D electrons

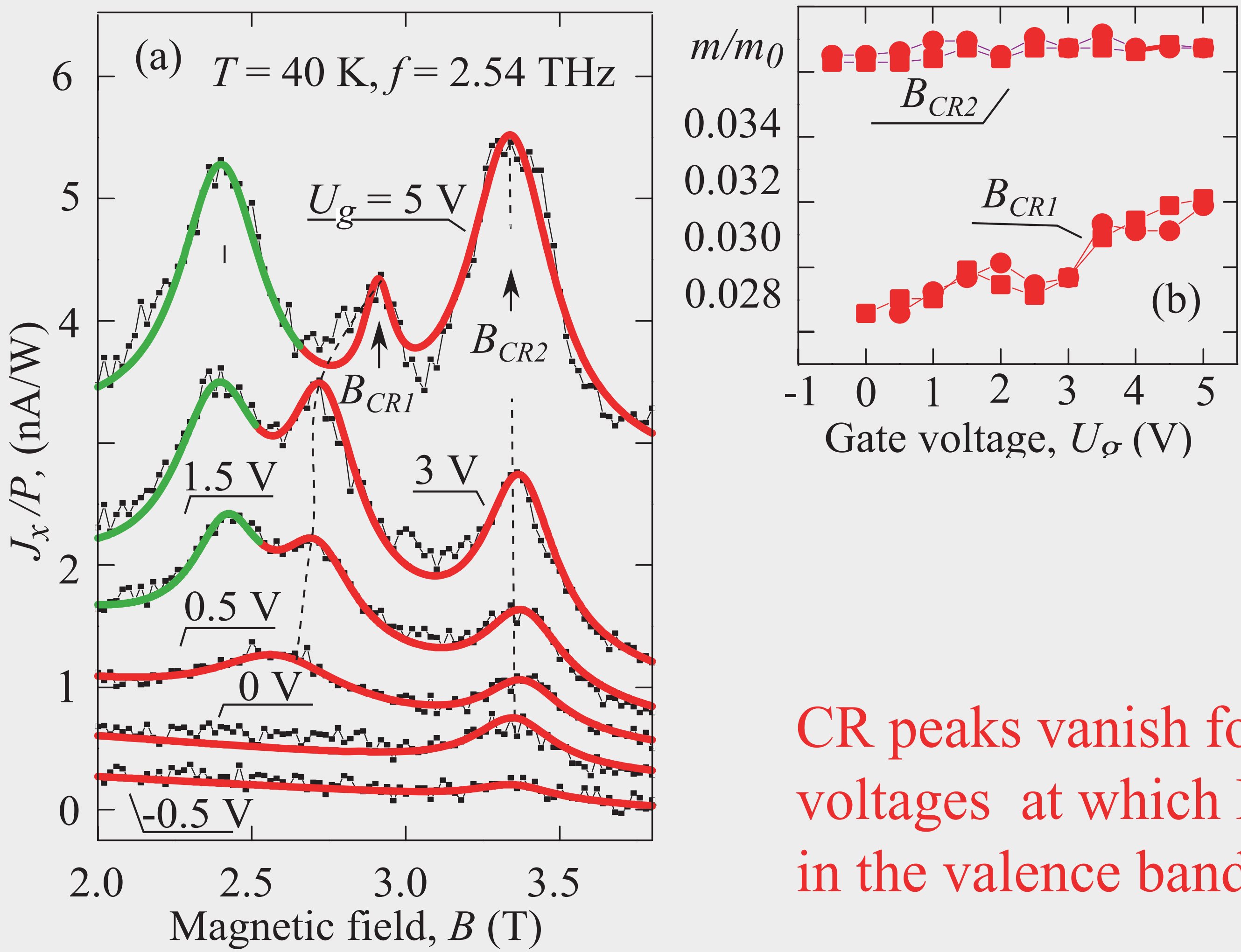
Experiments with tilted magnetic fields show that resonances vanish for fields parallel to the surface --> 2D electrons



Gate dependence

Position of the resonance CR1 depends on the gate voltage varying from 2.6 T to 3 T --> top surface state

Position of the resonance CR1 is independent of Vg (3.3 T) --> bottom surface state

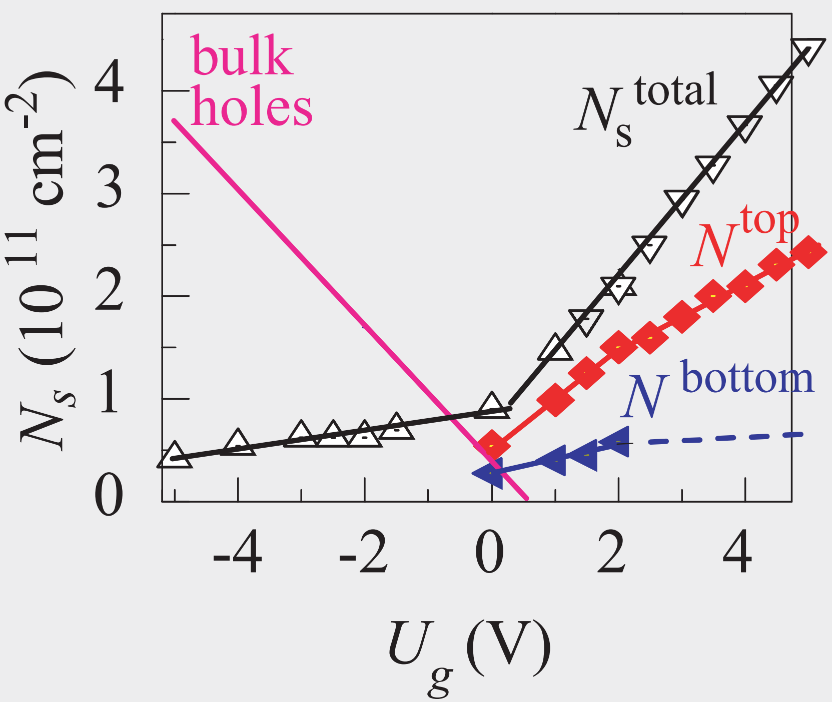


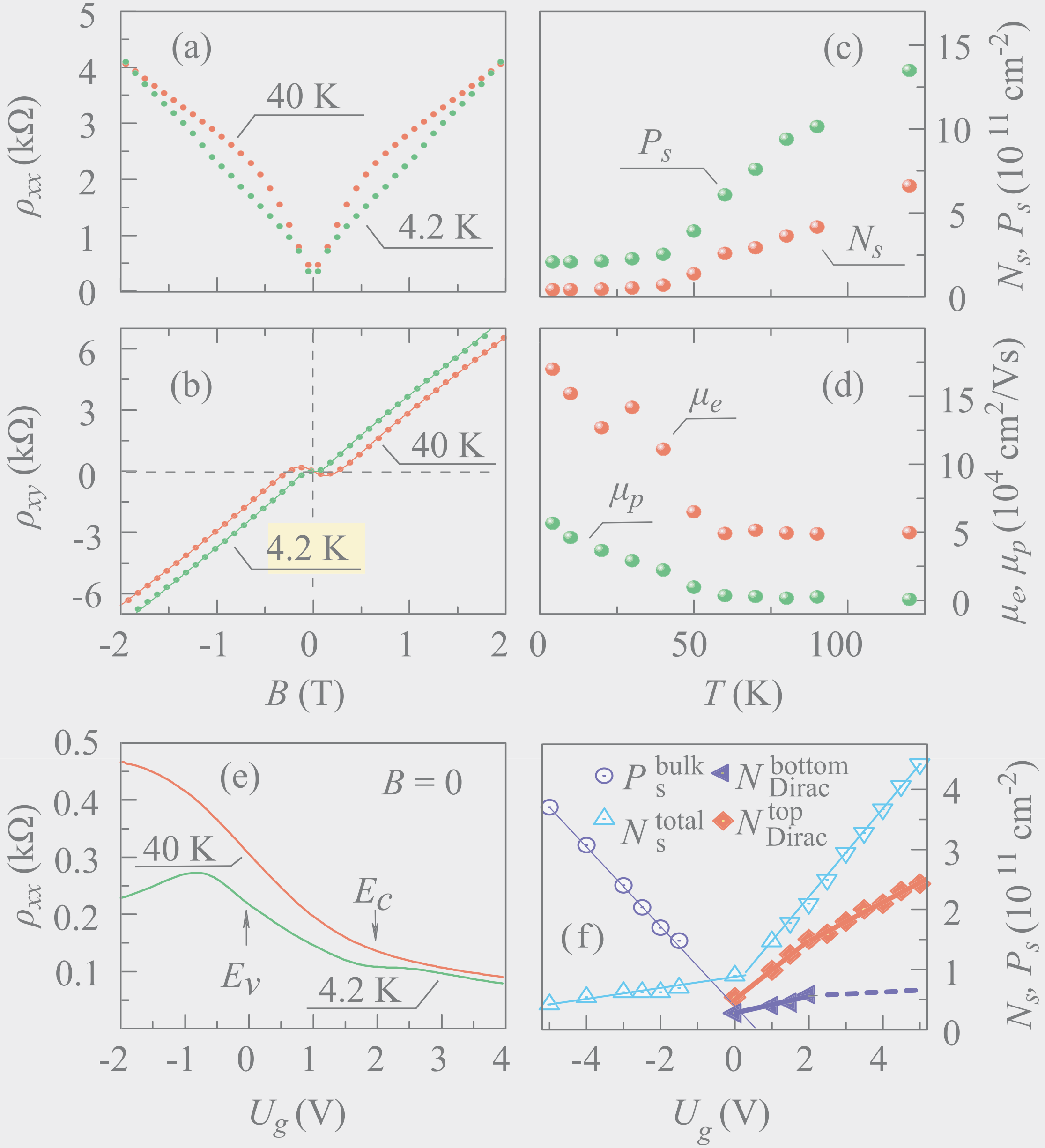
CR peaks vanish for negative gate voltages at which Fermi energy is in the valence band

Transport data

Data show:

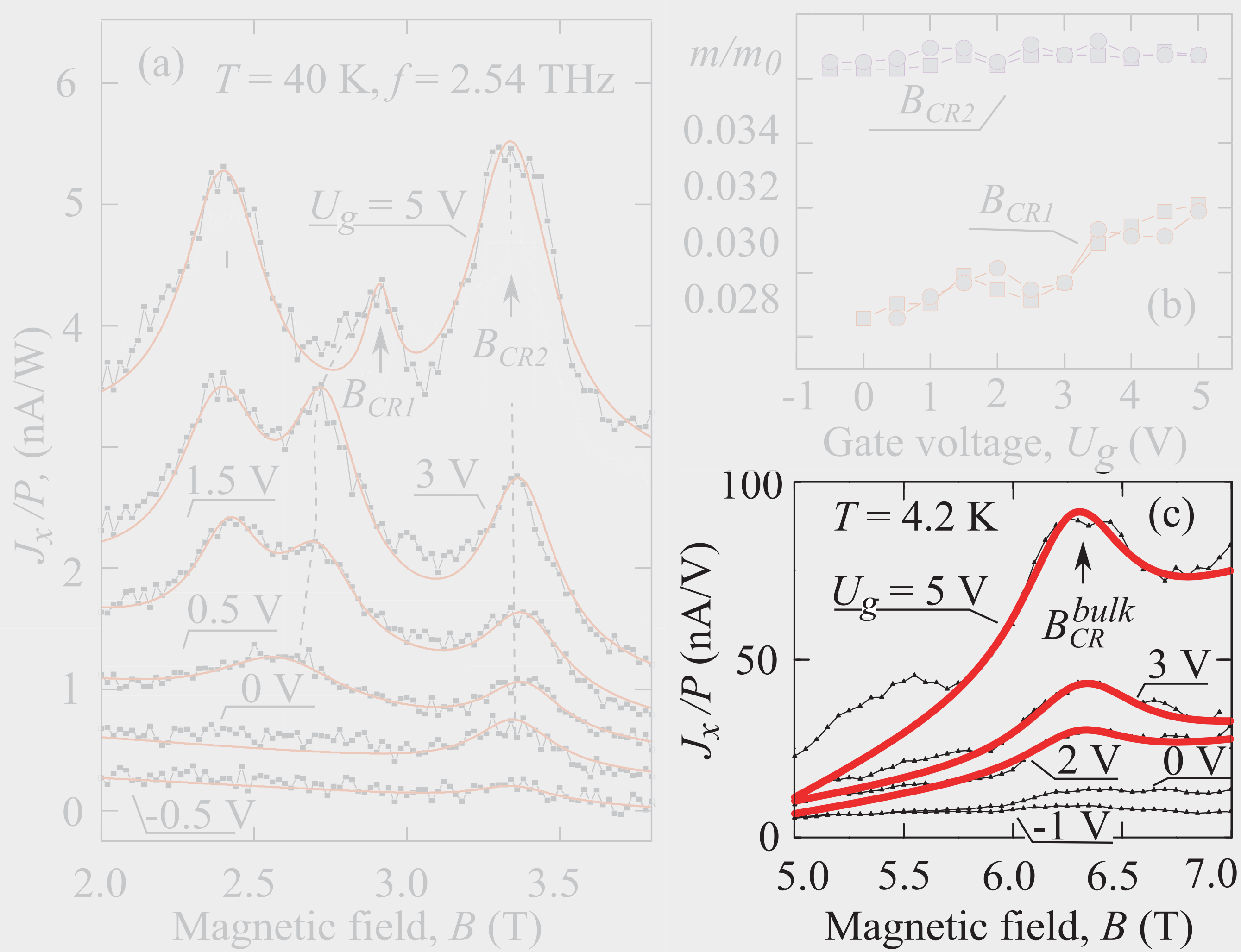
- gate and temperature dependences of surface states electron/hole densities
- change of carrier type upon variation of the gate voltage
- position of the valence and conduction band edges





Gate dependence

For gate voltages larger than 1.5V a CR on bulk electrons is detected at B = 6.3 T



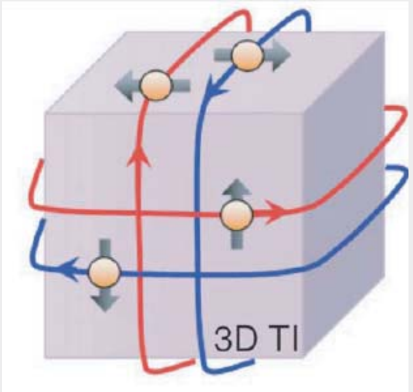
Origin of the resonant photocurrent in TI

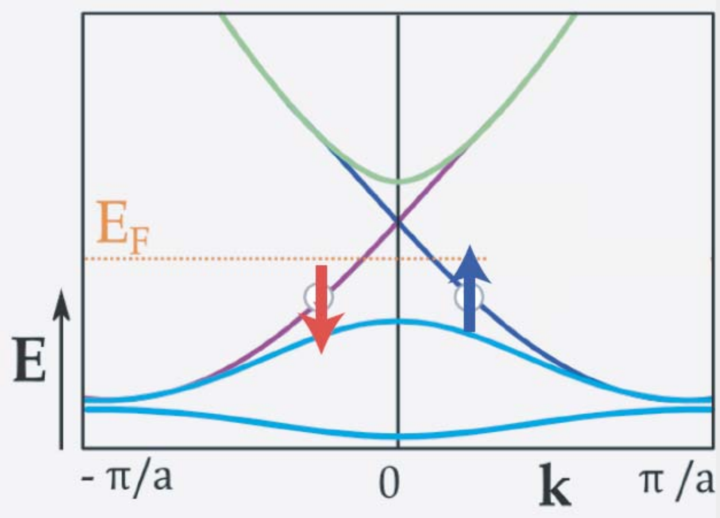
As overall behaviour of the photocurrent is similar to that detected in 6.6 nm QW it would be natural to assume that the physical mechanism of the current is just the same

However, in TI states are spin nondegenerated and Zeeman effect does not lead to spin polarization making previously discussed mechanism impossible

--> orbital mechanism of the photocurrent formation

(*also possible, but less effective in 6.6nm QWs with huge spin polarization due to Zeeman effect*)



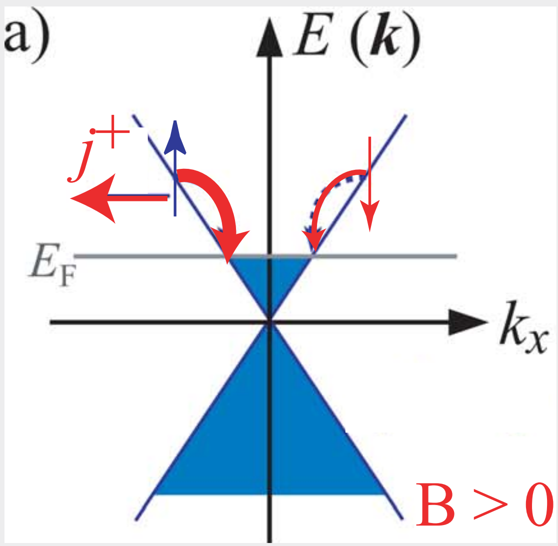


Origin of the resonant photocurrent in TI

- Strong electron gas heating due to cyclotron resonance --> energy relaxation
- Magnteic field and momentum dependent scattering (transition from state ***k*** to ***k***')

In gyrotropic media like surface states of HgTe 3D TI scattering:

$$\hat{V}(\boldsymbol{k}',\boldsymbol{k}) = \hat{V}_0(\boldsymbol{k}',\boldsymbol{k}) + \hat{V}_{orb.}(\boldsymbol{k}',\boldsymbol{k}) \quad \text{where} \quad \hat{V}_{orb.}(\boldsymbol{k}',\boldsymbol{k}) \propto [(\boldsymbol{k}'+\boldsymbol{k}) \times \boldsymbol{B}]$$



For fixed polarity of magnetic field (say +) the relaxation rates for electrons with positive and negative ***k*** are different.

The scattering asymmetry results in the spin polarized photocurrent j^+

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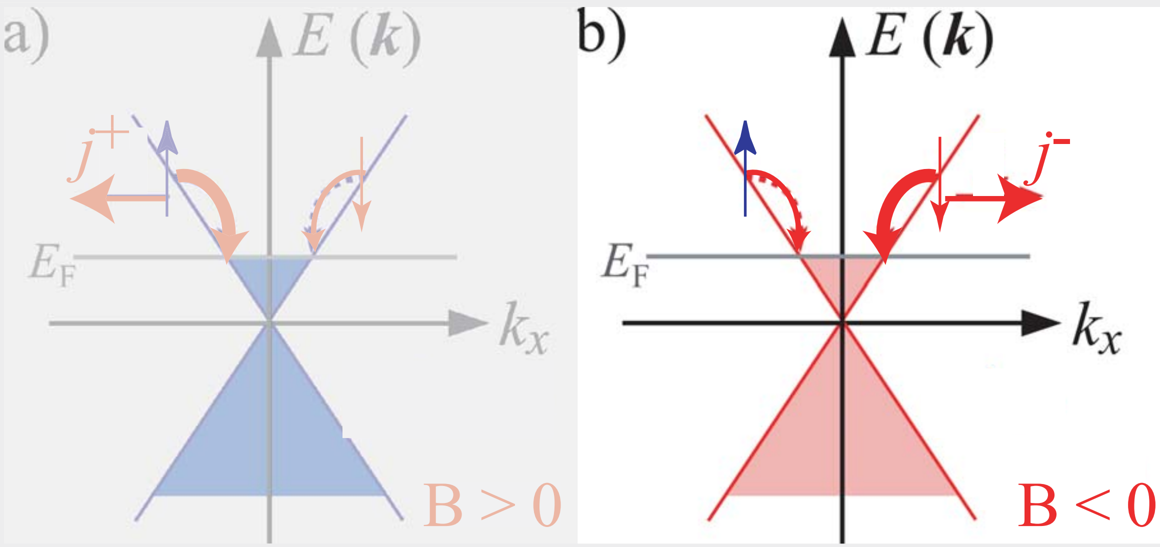

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The scattering asymmetry results in the spin polarized photocurrent j^+
For negative ***B*** the corresponding spin polarized current j^- will have opposite sign

Terahertz Center
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Summary

- Spin polarized current due to spin and/or magnetic field dependent scattering
- Experimental determination of the electron velocity in HgTe DF system
- Photocurrents --> studying CR in small gated structures
- Quantum oscillations in Dirac fermion systems
- Possible access to Rashba/Dresselhaus spin orbit coupling in DF systems

NEWS:
http://www.physik.uni-regensburg.de/forschung/ganichev/