ФОТОГАЛЬВАНИЧЕСКИЕ ЭФФЕКТЫ
В НИЗКОРАЗМЕРНЫХ СИСТЕМАХ - 1

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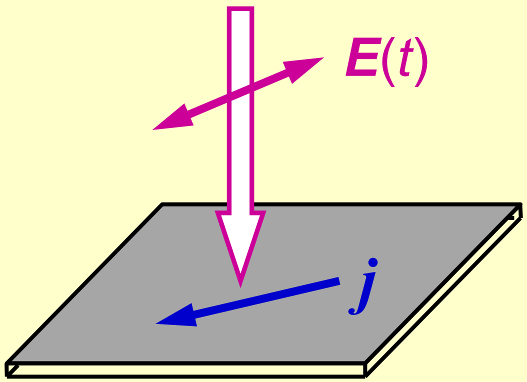
«Современные проблемы физики конденсированного состояния»

ОТКЛИК НА ВЫСОКОЧАСТОТНОЕ ЭЛЕКТРИЧЕСКОЕ ПОЛЕ



E поле электромагнитной волны

$$\boldsymbol{E}(\boldsymbol{r},t) = \boldsymbol{E}\exp(i\boldsymbol{q}\cdot\boldsymbol{r} - i\omega t) + \boldsymbol{E}^{*}\exp(-i\boldsymbol{q}\cdot\boldsymbol{r} + i\omega t)$$

$\boldsymbol{E}$ – комплексная амплитуда
$\boldsymbol{q}$ – волновой вектор
ω – частота

Электрический ток

линейный отклик   эффекты второго порядка

$$j_\alpha = \sum_\beta \sigma_{\alpha\beta} E_\beta + \sum_{\beta\gamma} P_{\alpha\beta\gamma} E_\beta E_\gamma^{*} + \sum_{\beta\gamma} D_{\alpha\beta\gamma} E_\beta E_\gamma + \dots$$

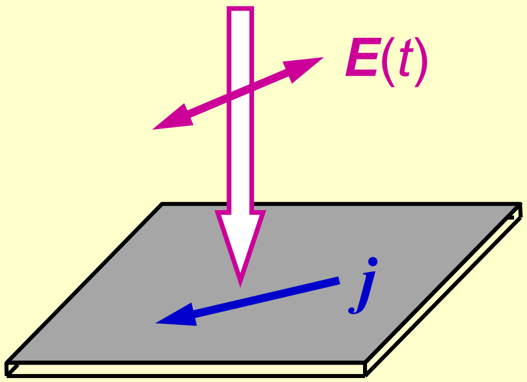
проводимость
поляризуемость

постоянный ток

ток на 2ω

ФОТОГАЛЬВАНИЧЕСКИЕ ЭФФЕКТЫ

Постоянный ток, квадратичный по амплитуде переменного поля



$$j_\alpha = \sum_{\beta\gamma} P_{\alpha\beta\gamma} E_\beta E_\gamma^*$$

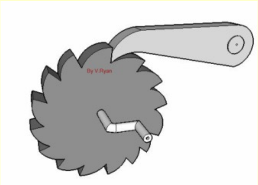
Пространственная инверсия:

$$\boldsymbol{j} \to -\boldsymbol{j}, \quad \boldsymbol{E} \to -\boldsymbol{E}$$

ФГЭ в средах без центра инверсии

Нелинейный транспорт, эффект «храповика» (ratchet), nonlinear Hall effect

Ratchet is a device that allows continuous linear or rotary motion in only one direction while preventing motion in the opposite direction.
http://en.wikipedia.org/wiki/Ratchet_(device)



Фотогальванические эффекты в оптике

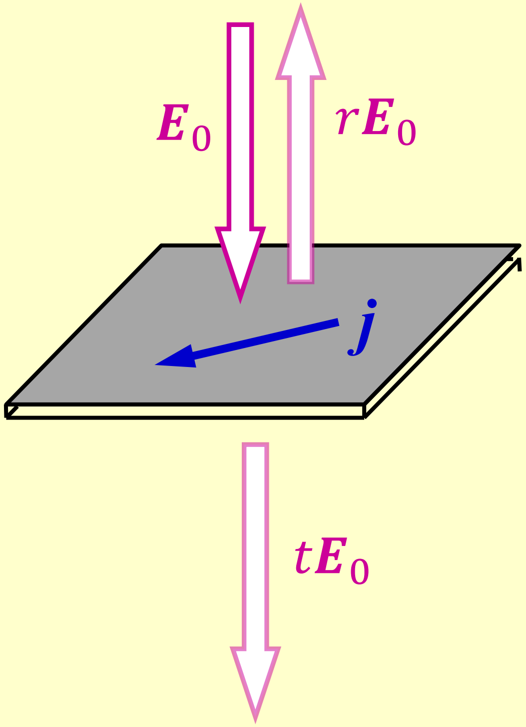
B.I. Sturman and V.M. Fridkin, The photovoltaic and photorefractive effects in noncentrosymmetric materials (Gordon and Breach Science Publishers, 1992)
E.L. Ivchenko, Optical spectroscopy of semiconductor nanostuctures (Springer, 2007)

Основоположники теории:
В.И. Белиничер, Б.И. Стурман, М.В. Энтин, Л.И. Магарилл, Г.Е. Пикус, Е.Л. Ивченко

ПЛАН ЛЕКЦИИ

- Линейный отклик на электромагнитное поле
- Фотогальванические эффекты. Симметрийный анализ
- Линейный и циркулярный ФГЭ в 2D структурах
  - микроскопическая модель, эксперимент
  - магнитоиндуцированные эффекты
  - общее описание
  - токи, обусловленные энергетической и спиновой релаксацией
- Спиновые и долинные фототоки
- Основные результаты

LINEAR RESPONSE OF 2D SYSTEM



Incident field

$$\boldsymbol{E_0}(\boldsymbol{r},t) = \boldsymbol{E_0}\exp(i\boldsymbol{q}\cdot\boldsymbol{r} - i\omega t) + \mathrm{c.c.}$$

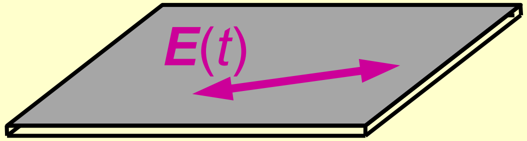
Linear response

$$\boldsymbol{j} = \sigma(\omega)\boldsymbol{E}$$

Amplitude reflection and transmission coefficient

$$r = -\frac{2\pi\sigma(\omega)/c}{1 + 2\pi\sigma(\omega)/c} \qquad t = \frac{1}{1 + 2\pi\sigma(\omega)/c}$$

2D ELECTRON GAS. DRUDE CONDUCTIVITY



In-plane electric field

$$\boldsymbol{E}_{\|}(t) = \boldsymbol{E}_{\|} e^{-i\omega t} + \text{c.c.}$$

Newton equation for the drift velocity

$$\frac{d\boldsymbol{v}_d}{dt} = \frac{e}{m^*}\boldsymbol{E}_{\|}(t) - \frac{\boldsymbol{v}_d}{\tau} \quad \Longrightarrow \quad \boldsymbol{v}_d = \frac{e\tau/m^*}{1 - i\omega\tau}\boldsymbol{E}_{\|} e^{-i\omega t} + \text{c.c.}$$

momentum relaxation time

Momentum relaxation time

$$1/\tau = \frac{2\pi}{\hbar}\sum_{\boldsymbol{k}'} \left\langle \left| V_{\boldsymbol{k}'\boldsymbol{k}} \right|^2 \right\rangle \left(1 - \cos\theta_{\boldsymbol{k}'\boldsymbol{k}}\right) \delta\left(\varepsilon_{\boldsymbol{k}} - \varepsilon_{\boldsymbol{k}'}\right)$$

matrix elements of scattering

Drude conductivity

$$\boldsymbol{\sigma}(\omega) = \frac{n_e e^2 \tau/m^*}{1 - i\omega\tau}$$

DRUDE MODEL. APPLICABILITY

Good conductivity

$$k_F l \gg 1 \ (E_F \tau / \hbar \gg 1)$$

$$\sigma_0 = \frac{n_e e^2 \tau}{m^*} = \frac{\nu m^* E_F}{2\pi\hbar^2} \frac{e^2 \tau}{m^*} = \frac{\nu}{2\pi} \frac{e^2}{\hbar} \frac{E_F \tau}{\hbar} \gg \frac{e^2}{h}$$

$$\frac{h}{e^2} \approx 25 \ \mathrm{k\Omega}$$

ν spin/valley degeneracy

von Klitzing constant

Classical range of frequencies

$$\hbar\omega \ll E_F$$

Otherwise, quantum description, e.g., Kubo formula

- Indirect optical transitions (scattering assisted)
- Direct optical transitions

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SYMMETRY CONSIDERATION

Photogalvanic effects (PGEs)

$$j_\alpha = \sum_{\beta\gamma} P_{\alpha\beta\gamma} E_\beta E_\gamma^*$$

Further analysis

$$j_\alpha = \sum_{\beta\gamma} L_{\alpha\beta\gamma} \frac{E_\beta E_\gamma^* + E_\gamma E_\beta^*}{2} + \sum_\beta C_{\alpha\beta} \underbrace{i[\boldsymbol{E} \times \boldsymbol{E}^*]_\beta}_{\text{axial vector}} \propto P_{circ}$$

linear ratchet or linear PGE
(piezoelectric systems)

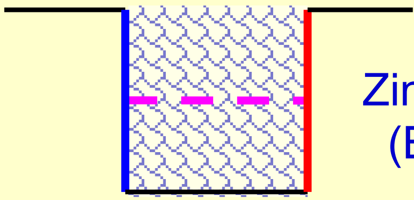
$LiNbO_3$:Fe A.M. Glass et al. (1974)
Theory V.I. Belinicher et al. (1976)
E.M. Baskin et al. (1977)

circular ratchet or circular PGE
(gyrotropic systems)

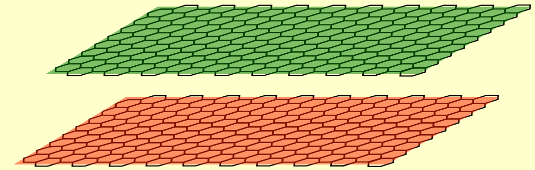
Pred. E.L. Ivchenko, G.E. Pikus (1978)
V.I. Belinicher (1978)
Exper in bulk Te V.M. Asnin at el (1978)

SPACE INVERSION ASYMMETRY IN 2D SYSTEMS

Bulk (or 2D "bulk") inversion asymmetry (BIA)

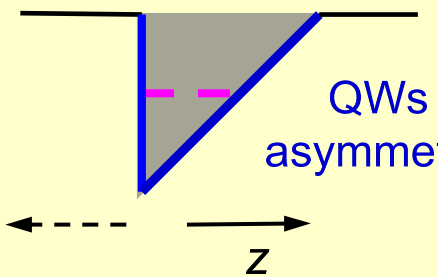


Zinc-blende QWs
(BIA and IIA)

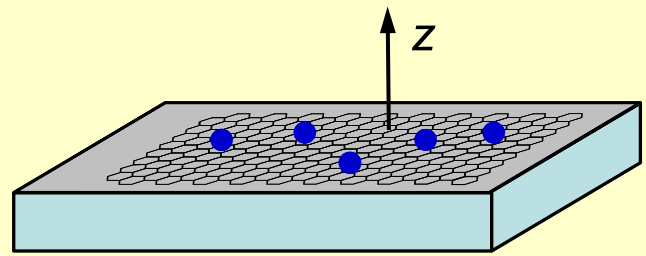


TMDC monolayers (D_{3h} group)
MoS_2, $MoSe_2$, WSe_2, …

Structure inversion asymmetry (SIA)

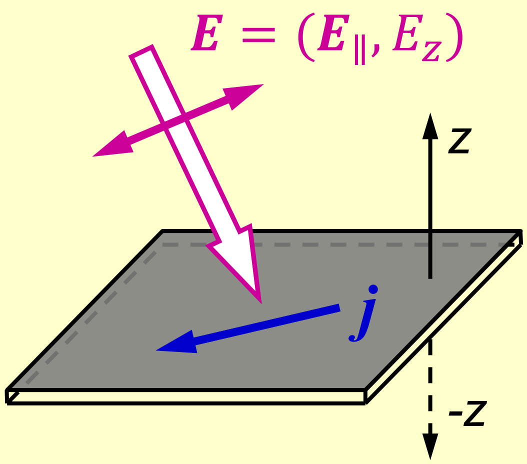


QWs with
asymmetric profile



2D crystal on substrate, special stacks

RATCHET TRANSPORT
DUE TO STRUCTURE INVERSION ASYMMETRY



E_z is invariant

$\boldsymbol{j}$ and $\boldsymbol{E}_{\|}$ transform in a similar way

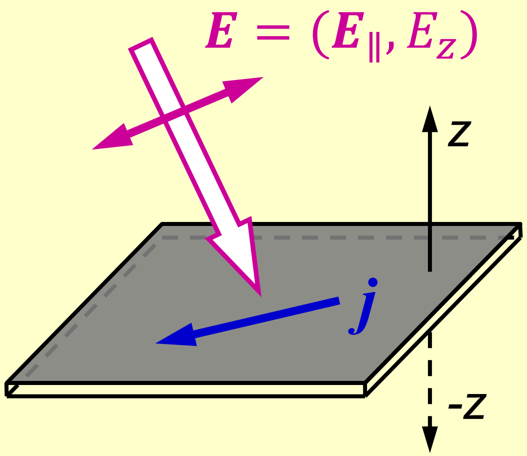
Density of dc electric current

$$\boldsymbol{j} = L(\boldsymbol{E}_{\|} E_z^* + E_z^* \boldsymbol{E}_{\|}^*) + C\, i(\boldsymbol{E}_{\|} E_z^* - E_z^* \boldsymbol{E}_{\|}^*)$$

linear ratchet circular ratchet

oblique incidence of radiation is required

(I) AC CURRENT BY IN-PLANE COMPONENT $E_{\|}$



In-plane ***E***-field component

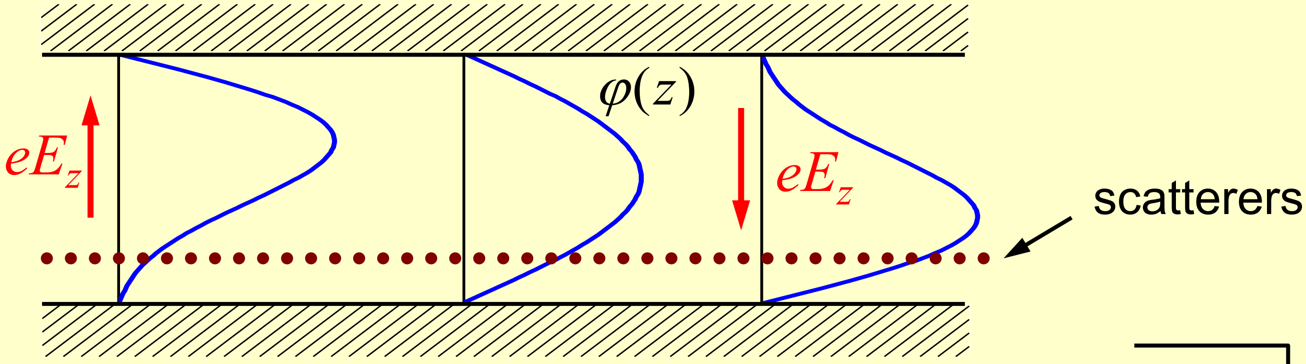
$$\boldsymbol{E}_{\|}(t) = \boldsymbol{E}_{\|} e^{-i\omega t} + \text{c.c.}$$

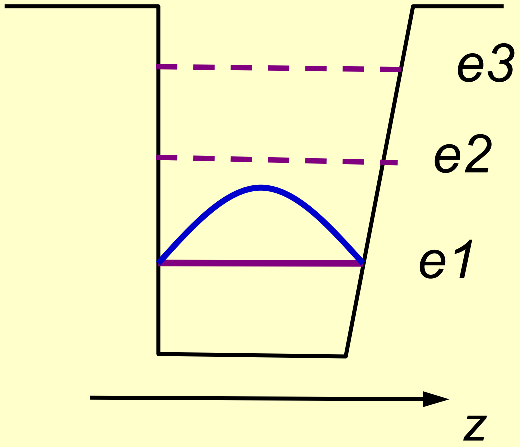
Equation for the drift velocity of electrons

$$\frac{d\boldsymbol{v}_d}{dt} = \frac{e}{m^*}\boldsymbol{E}_{\|}(t) - \frac{\boldsymbol{v}_d}{\tau} \quad \Longrightarrow \quad \boldsymbol{v}_d = \frac{e\tau/m^*}{1 - i\omega\tau}\boldsymbol{E}_{\|} e^{-i\omega t} + \text{c.c.}$$

momentum relaxation time

(II) OSCILLATIONS OF ELECTRON MOBILITY BY E_z





Admixture of excited subbands

Function of size quantization

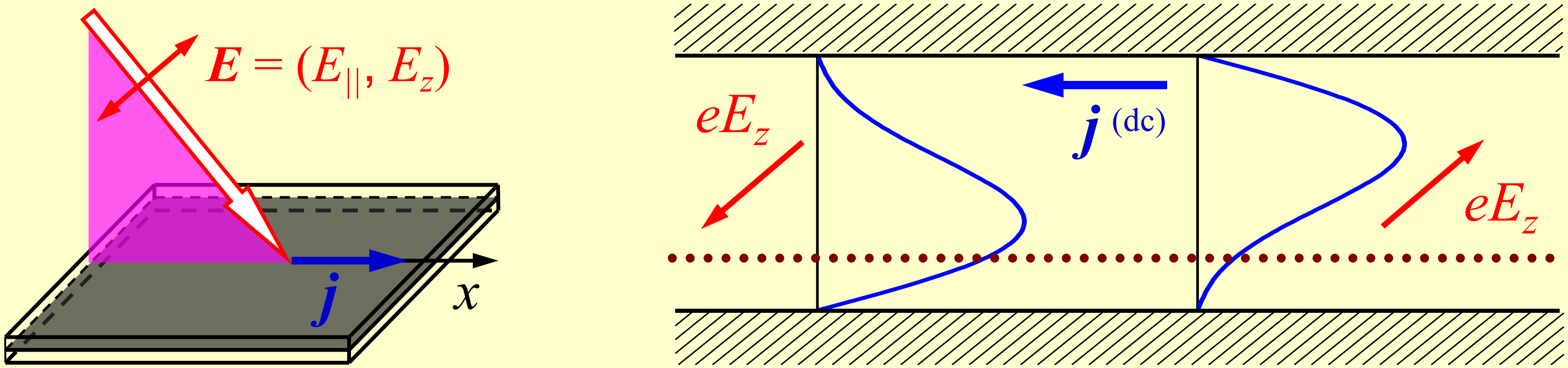
$$\varphi(z) = \varphi_1(z) + eE_z(t)\sum_{n\neq 1}\frac{z_{n1}}{\varepsilon_{n1}}\varphi_n(z)$$

Momentum relaxation time

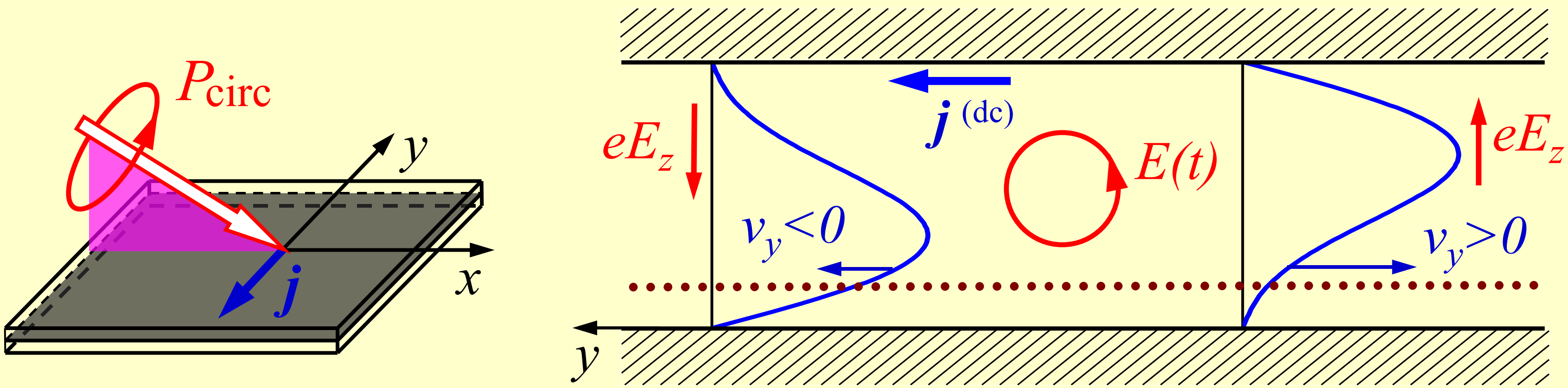
$$\frac{1}{\tau(t)} = \frac{1}{\tau_0}\left(1 + 4eE_z(t)\sum_{n\neq 1}\frac{z_{n1}\xi_n}{\varepsilon_{n1}}\right), \qquad \xi_n = \langle V_{11}V_{1n}\rangle / \langle V_{11}^2\rangle$$

MECHANISMS OF LINEAR AND CIRCULAR RATCHET

(a) Linearly polarized field



(b) Circularly polarized field



MICROSCOPIC THEORY. QUASI-CLASSICAL APPROACH

Newton equation for the drift velocity

$$\frac{d\boldsymbol{v}_d(t)}{dt} = \frac{e\boldsymbol{E}_{\parallel}(t)}{m^*} - \frac{\boldsymbol{v}_d(t)}{\tau(t)}$$

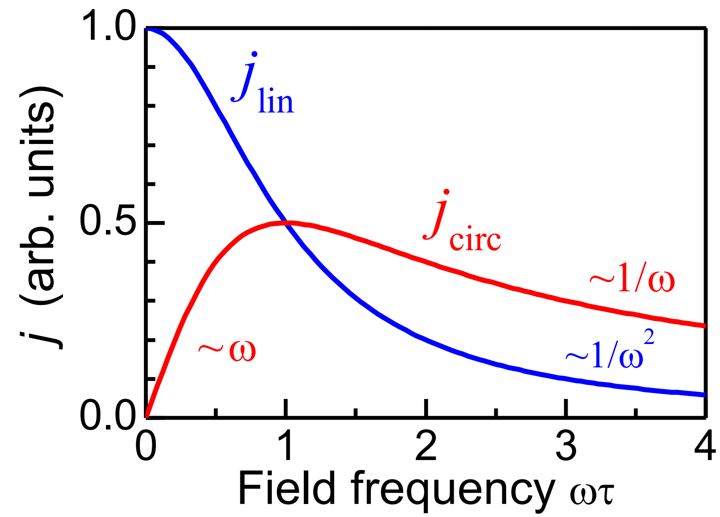
Momentum relaxation time

$$\frac{1}{\tau(t)} = \frac{1}{\tau_0} + \varsigma\, eE_z(t)$$

Electric current

$$\boldsymbol{j}(t) = e\boldsymbol{v}_d(t)N_e$$

Frequency dependence of dc current



DC current

$$\boldsymbol{j} = -N_e \frac{\varsigma e^3 \tau_0^2}{m^*}\left[\frac{\boldsymbol{E}_{\parallel}E_z^* + \boldsymbol{E}_z E_{\parallel}^*}{1+(\omega\tau_0)^2} + i\omega\tau_0 \frac{\boldsymbol{E}_{\parallel}E_z^* - \boldsymbol{E}_z E_{\parallel}^*}{1+(\omega\tau_0)^2}\right]$$

Linear ratchet   Circular ratchet

S.A.T., Phys. Rev. B **83**, 035313 (2011)

ЗАДАЧА

Генерация второй гармоники

Уравнение Ньютона для дрейфовой скорости

$$\frac{d v_d(t)}{dt} = \frac{e\boldsymbol{E}_{\parallel}(t)}{m^*} - \frac{v_d(t)}{\tau(t)}$$

Электрическое поле

$$\boldsymbol{E}(t) = \boldsymbol{E}\exp(-i\omega t) + \text{c. c.}$$

Время релаксации по импульсу

$$\frac{1}{\tau(t)} = \frac{1}{\tau_0} + \varsigma\, eE_z(t)$$

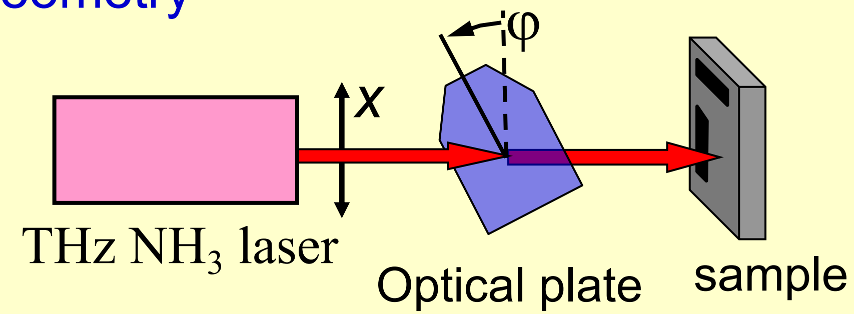
Плотность электрического тока

$$\boldsymbol{j}(t) = e\boldsymbol{v}_d(t)N_e \qquad \boldsymbol{j}(t) = \left(\boldsymbol{j}_1 \mathrm{e}^{-\mathrm{i}\omega t} + \text{c. c.}\right) + \boldsymbol{j}_{\mathrm{dc}} + \left(\boldsymbol{j}_2 \mathrm{e}^{-2\mathrm{i}\omega t} + \text{c. c.}\right)$$

Определить амплитуду тока на удвоенной частоте

EXPERIMENT

Experimental geometry



Electron channel on Si

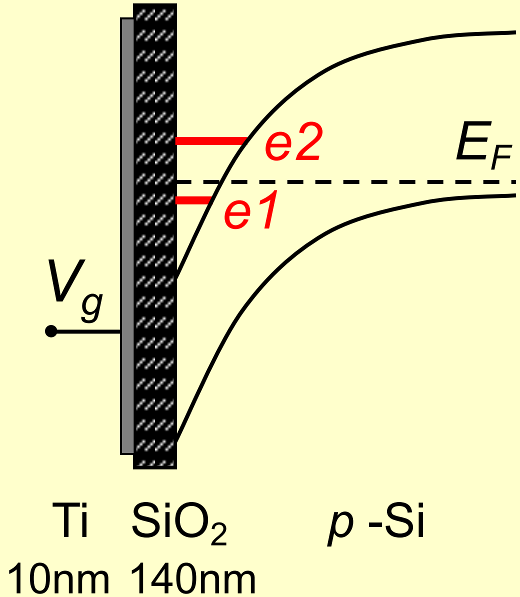
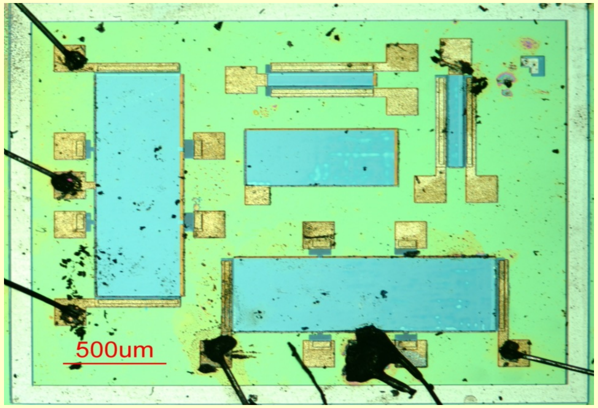
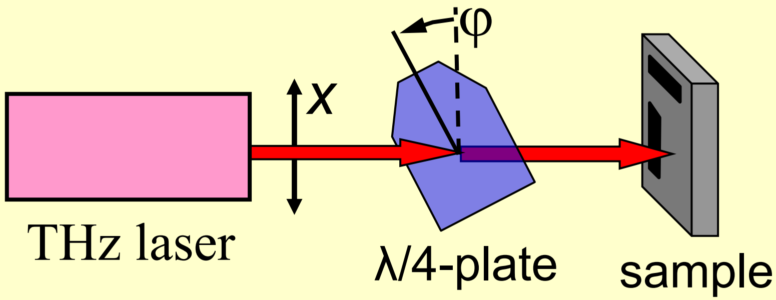


Photo of sample



Samples: Z.D. Kvon (Novosibirsk)
Experiment: S.D. Ganichev et al. (Regensburg)

EXPERIMENT: λ/4 OPTICAL PLATE



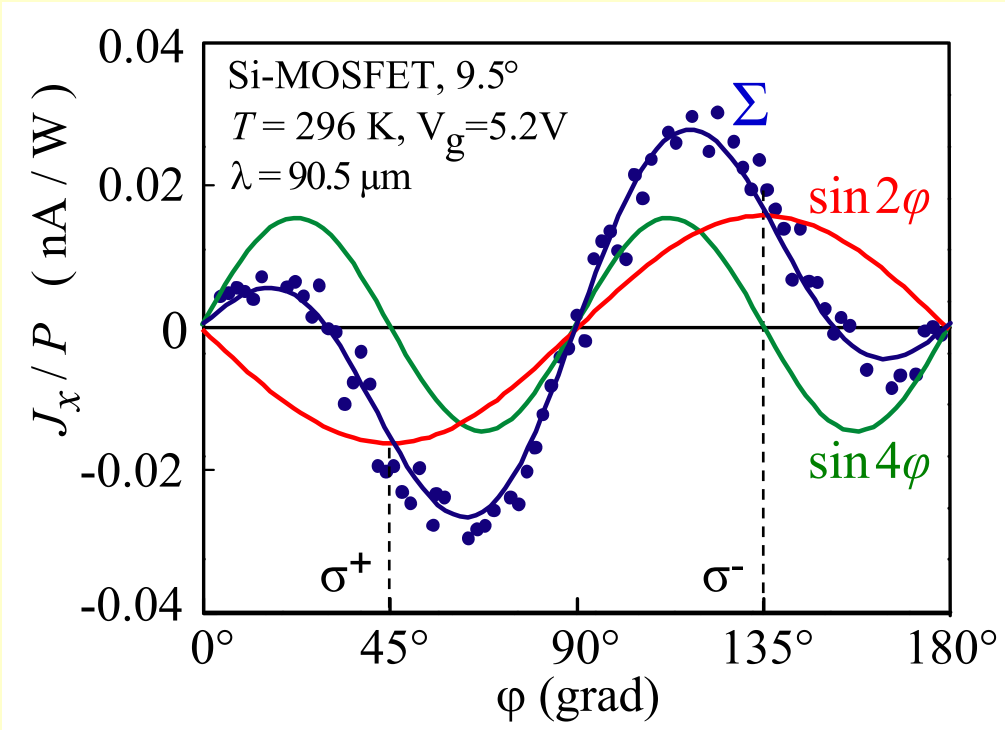
Polarization of THz radiation

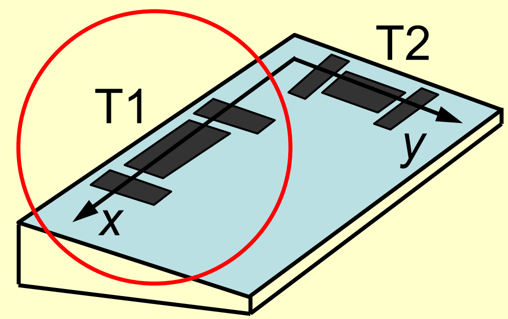
$$P_{circ} = \sin 2\varphi$$

$$P_{lin} = \cos^2 2\varphi$$

$$P'_{lin} = (1/2)\sin 4\varphi$$

Polarization dependence of photocurrent

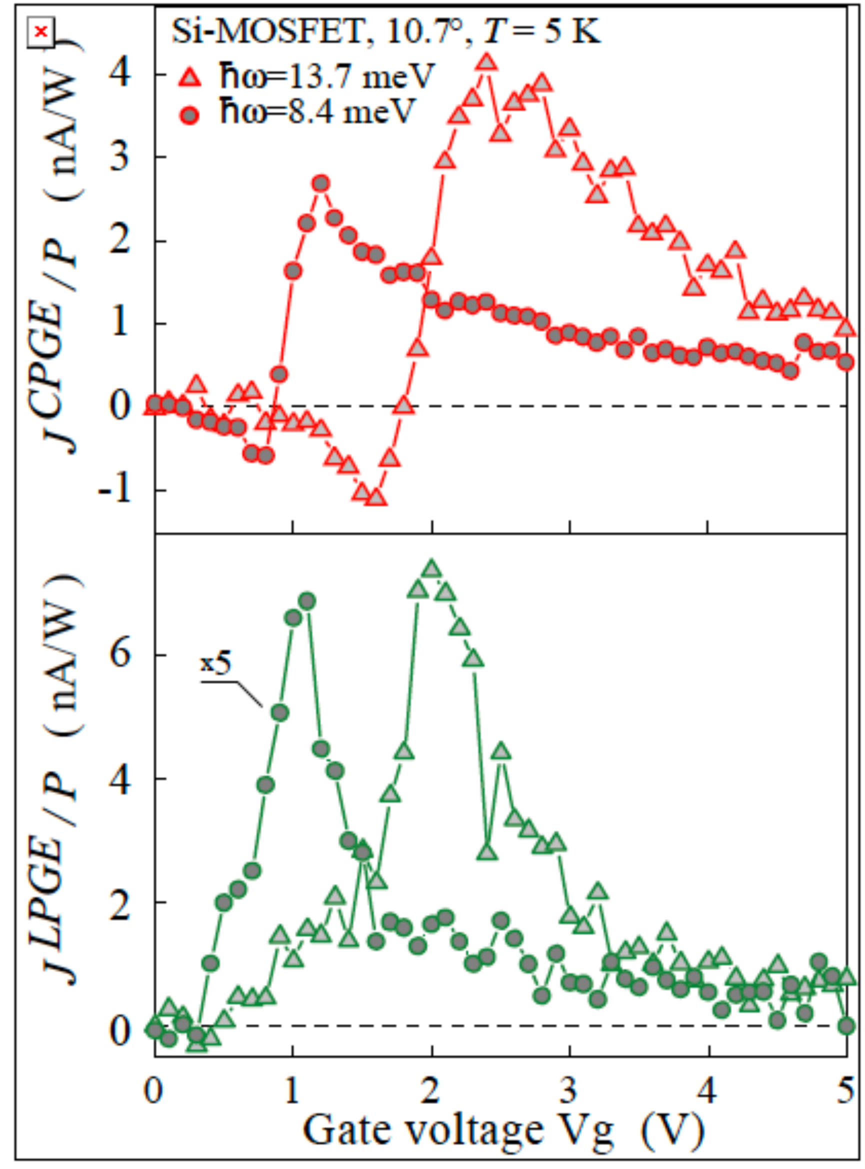




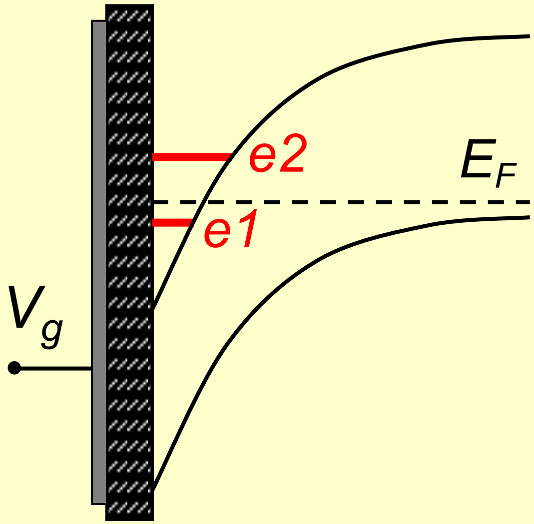
Electron channel
on Si surface (Si-MOSFET)

P. Olbrich et al.,
Phys. Rev. B (R) (2009)

EXPERIMENT: DEPENDENCE ON GATE VOLTAGE



2D electron gas on Si surface

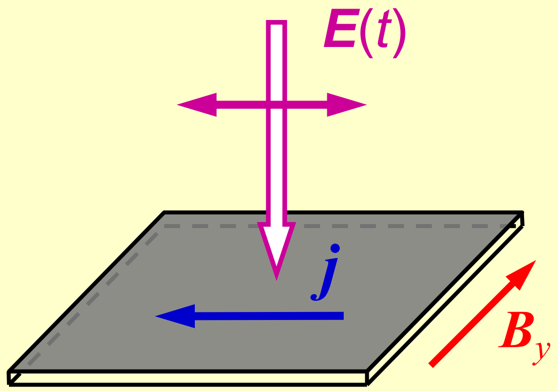


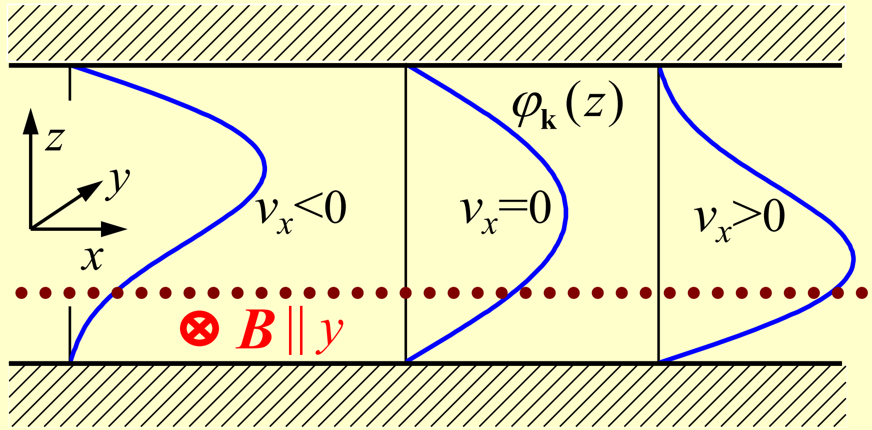
Intersubband resonance

$$\hbar\omega = \varepsilon_{21}$$

P. Olbrich et al.,
Phys. Rev. B (R) (2009)

MAGNETIC QUANTUM RATCHET EFFECT



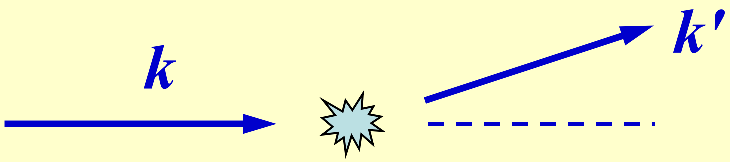


Up and down shift of electron density by Lorentz force

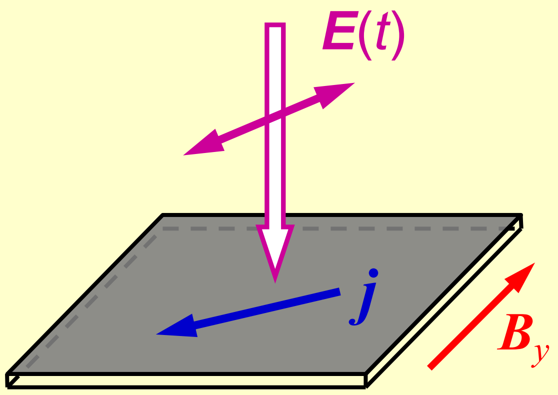
Probability of electron scattering ***k*** → ***k'***

$$W_{k'k} = W_0 + w_{\text{asym}}[B_x(k_y + k'_y) - B_y(k_x + k'_x)]$$

Asymmetry in scattering by static defects and phonons



MICROSCOPIC THEORY



Kinetic equation for distribution function $f(\boldsymbol{p},t)$

$$\frac{\partial f}{\partial t} + e\boldsymbol{E}_{\parallel}(t)\cdot\frac{\partial f}{\partial \boldsymbol{p}} = \mathrm{I}\{f\}$$

Collision integral

$$\mathrm{I}\{f(\boldsymbol{p})\} = \sum_{\boldsymbol{p}'}\left[W_{\boldsymbol{p}\boldsymbol{p}'}f(\boldsymbol{p}') - W_{\boldsymbol{p}'\boldsymbol{p}}f(\boldsymbol{p})\right]$$

Expansion in the series of the electric field

$$f(\boldsymbol{p},t) = f_0(\boldsymbol{p}) + \left[\underbrace{f_1(\boldsymbol{p})e^{-i\omega t}}_{\sim E} + \mathrm{c.c.}\right] + \underbrace{f_2(\boldsymbol{p})}_{\sim EE^*}$$

DC electric current

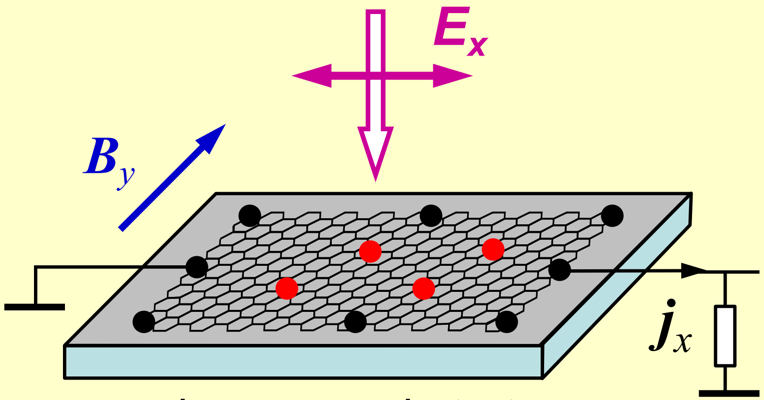
$$\boldsymbol{j} = ev\sum_{\boldsymbol{p}}\boldsymbol{v}f_2(\boldsymbol{p})$$

$$j_x = M_1(|E_x|^2 - |E_y|^2)B_y + M_2|\mathbf{E}|^2 B_y$$

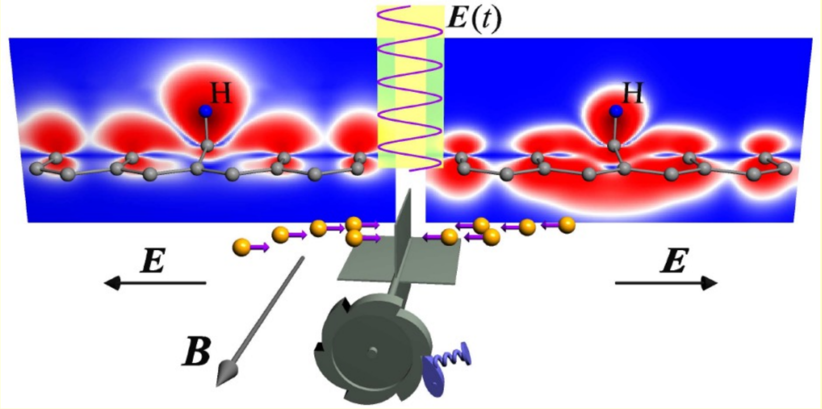
$$j_y = M_1(E_xE_y^* + E_yE_x^*)B_y + M_3\,\mathrm{i}[\mathbf{E}\times\mathbf{E}^*]_z B_y$$

V.I. Fal'ko, Phys. Solid State (1989)
S.A.T., Phys. Rev. B (2011)
G.V. Budkin, S.A.T., Phys. Rev. B (2016)

MAGNETIC QUANTUM RATCHET EFFECT IN GRAPHENE



graphene on substrate



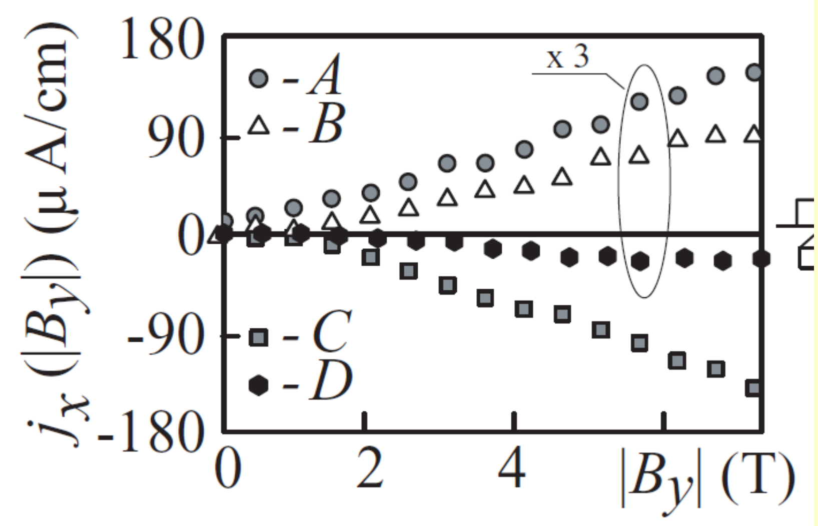
Lorentz force + scattering by adatoms

Samples

(A,B,C) MBE-grown n-type monolayers
on Si-terminated 4H-SiC(0001)
electron density 1.5÷7×10^{12} cm^{-2},
mobility 10^3 cm^2/Vs at T=300K
(D) CVD-grown monolayer

THz excitation

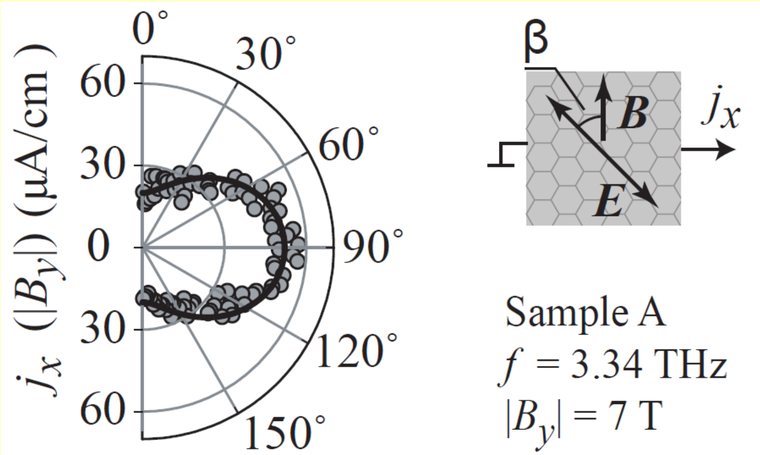
- cw laser CH_3OH (λ = 118 μm, P=0.5 mW)
- pulse laser NH_3 (λ = 90.5, 148, 280 μm, P=10 kW)



Magnetic field dependence

POLARIZATION DEPENDENCE

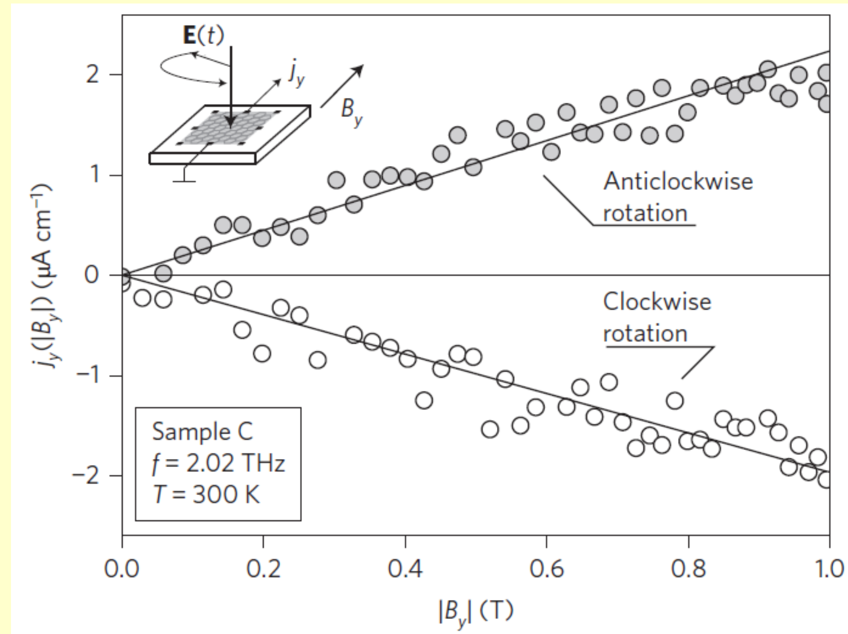
(i) Linear ratchet effect



Polarization dependence

$$j_x = j_0 \cos 2\beta + j_1$$

(ii) Circular ratchet effect



Polarization dependence

$$j_y \propto P_{circ}$$

C. Drexler, S.A.T., P. Olbrich et al., Nature Nanotech. (2013)

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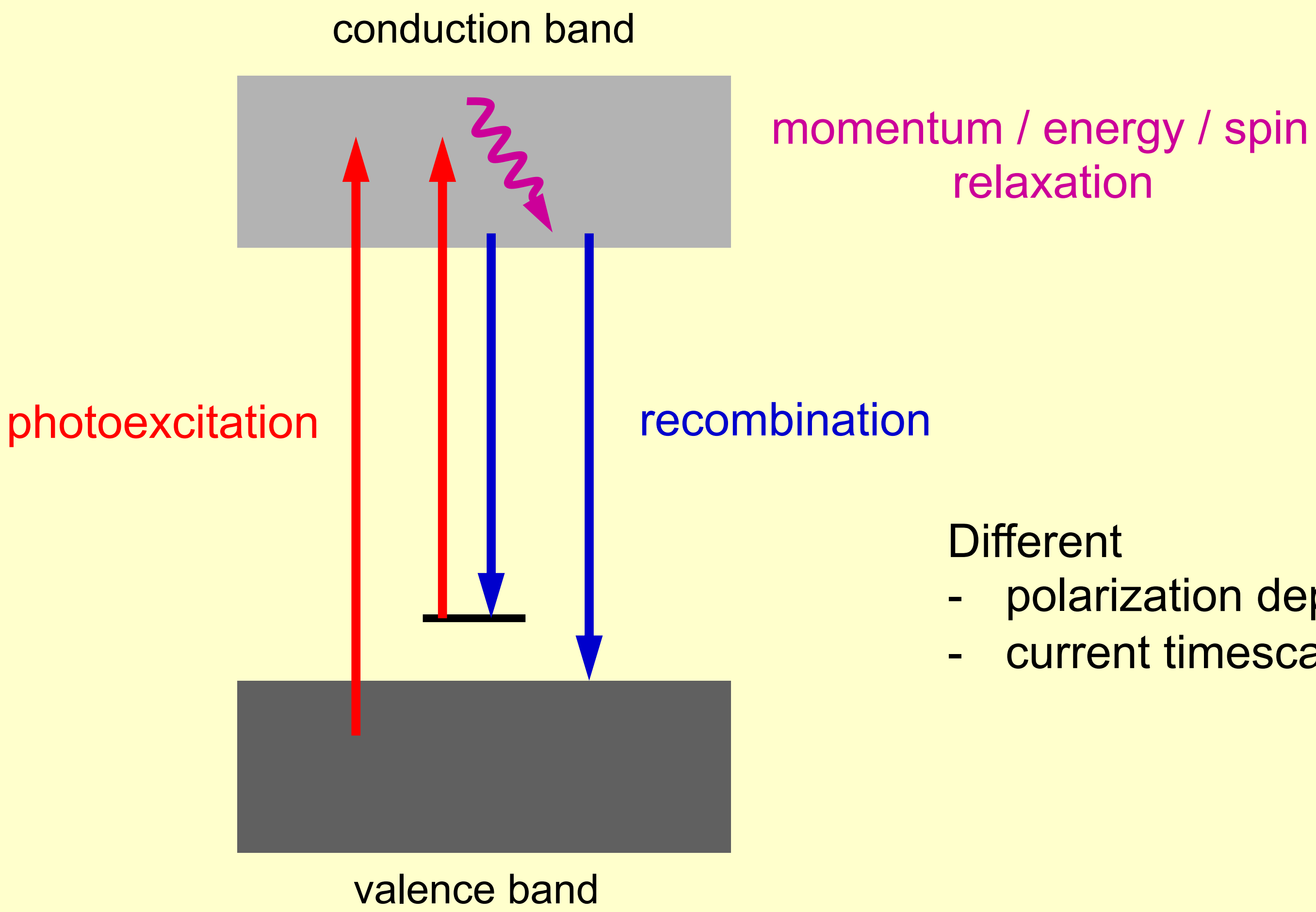
  - магнитоиндуцированные эффекты
  - общее описание
  - токи, обусловленные энергетической и спиновой релаксацией
- Спиновые и долинные фототоки
- Основные результаты

EXCITATION AND RELAXATION MECHANISMS



Different
- polarization dependence
- current timescales

BALLISTIC AND SHIFT CONTRIBUTIONS

Most general description by density matrix

$$\rho_{nk,\boldsymbol{n'k'}}$$

Bloch states

$$\psi_{n\mathbf{k}} = \exp(i\mathbf{k}\cdot\mathbf{r})\,u_{n\mathbf{k}}(\mathbf{r})$$

Electric current $\boldsymbol{j} = e\,\mathrm{Tr}(\boldsymbol{v}\rho) = e\,\mathrm{Tr}\left(\frac{d\boldsymbol{r}}{dt}\rho\right)$

(i) Dominant contribution (typically)

$$\boldsymbol{j}_\mathrm{b} = e\sum_{n\boldsymbol{k}} v_{n\boldsymbol{k}}\,f_{n\boldsymbol{k}}$$

$f_{n\boldsymbol{k}} = \rho_{n\boldsymbol{k},n\boldsymbol{k}}$ distribution function

(ii) Shift (side-jump) contribution

$$\boldsymbol{j}_\mathrm{s} = e\sum_{n\neq n',\boldsymbol{kk}'} \boldsymbol{R}_{n'\boldsymbol{k}',n\boldsymbol{k}}\,W_{n'\boldsymbol{k}',n\boldsymbol{k}}$$

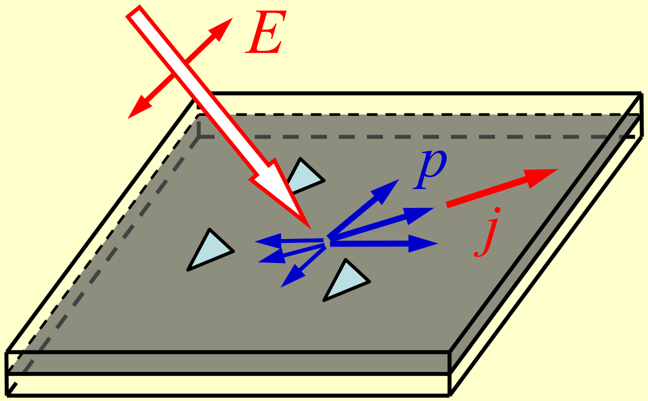
$\boldsymbol{R}_{n'\boldsymbol{k}',n\boldsymbol{k}}$ shift in real space

$W_{n'\boldsymbol{k}',n\boldsymbol{k}}$ transition probability

J.M. Luttinger, Phys. Rev. (1958)
V.I. Belinicher, E.L. Ivchenko, B.I. Sturman, Sov. Phys. JETP (1982)
N.A. Sinitsyn, J. Phys.: Condens. Matter (2007)
L.E. Golub, E.L. Ivchenko, JETP (2011)

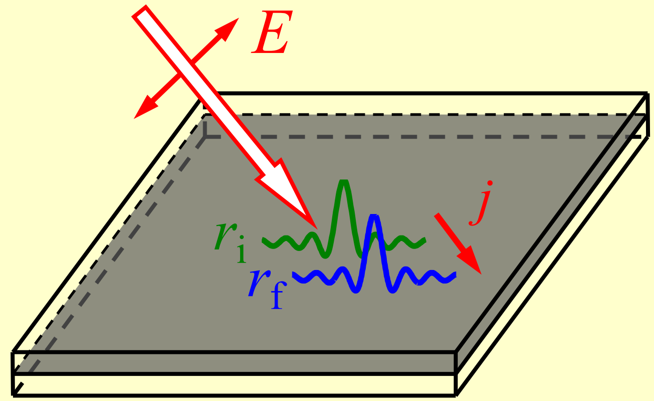
BALLISTIC AND SHIFT CONTRIBUTIONS

Ballistic current



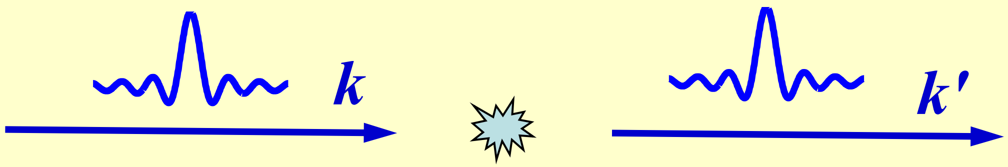
Asymmetry of distribution
function in ***p*** space

Shift current



Shift of electron wavepacket
in ***r*** space at quantum transition

SHIFT OF WAVEPACKET



$$\Psi_{\boldsymbol{k}} = \mathrm{e}^{i\boldsymbol{k}\cdot\boldsymbol{r}} \sum_{k} c_{\boldsymbol{q}} \mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{r}} \qquad \Psi_{\boldsymbol{k}'} = \mathrm{e}^{i\boldsymbol{k}'\cdot\boldsymbol{r}} \sum_{k} c_{\boldsymbol{q}} e^{i\Phi(\boldsymbol{q})} \mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{r}}$$

The phase acquired at transition

$$\Phi(\boldsymbol{q}) \approx \Phi(0) + \nabla_{\boldsymbol{q}}\Phi \cdot \boldsymbol{q}$$

$$\Psi_{\boldsymbol{k}'} = \mathrm{e}^{i\boldsymbol{k}'\cdot\boldsymbol{r}} e^{+i\Phi(0)} \sum_{k} c_{\boldsymbol{q}} \mathrm{e}^{i\boldsymbol{q}\cdot(\boldsymbol{r}+\nabla_{\boldsymbol{q}}\Phi)}$$

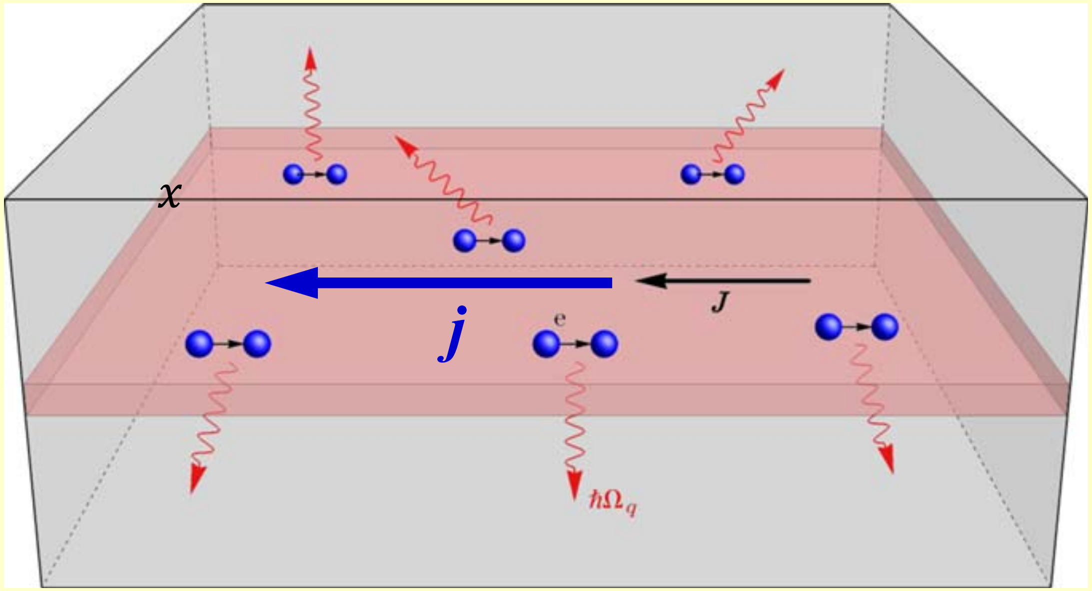
Shift of the Bloch electron

$$\boldsymbol{R}_{n'\boldsymbol{k}',n\boldsymbol{k}} = -(\boldsymbol{\nabla}_{\boldsymbol{k}} + \boldsymbol{\nabla}_{\boldsymbol{k}'})\Phi_{n'\boldsymbol{k}',n\boldsymbol{k}} + \boldsymbol{\Omega}_{n'\boldsymbol{k}'} - \boldsymbol{\Omega}_{n\boldsymbol{k}}$$

Bloch states $\psi_{n\boldsymbol{k}} = \mathrm{e}^{i\boldsymbol{k}\cdot\boldsymbol{r}} u_{n\boldsymbol{k}}(\boldsymbol{r})$ $\qquad \boldsymbol{\Omega}_{s\boldsymbol{k}} = i\langle u_{s\boldsymbol{k}}|\boldsymbol{\nabla}_{\boldsymbol{k}}|u_{s\boldsymbol{k}}\rangle$

Berry connection

CURRENT BY ENERGY RELAXATION



(011)-grown zinc-blende-type quantum wells

Electric current

$$j_x \propto W$$

$$x \parallel [100]$$

Estimations

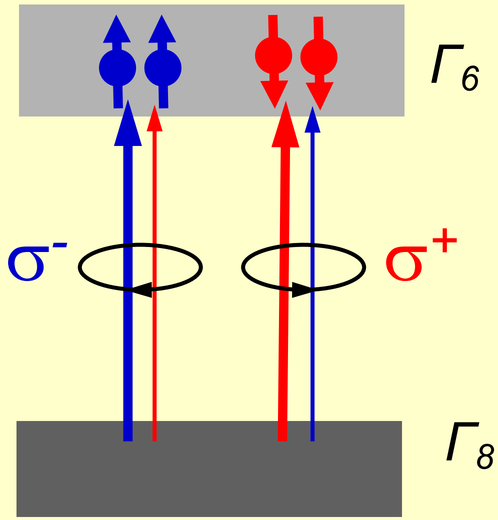
$$j_x \sim 3\mu\text{A/cm}$$

$$@\ W = 1\ \text{W/cm}^2$$

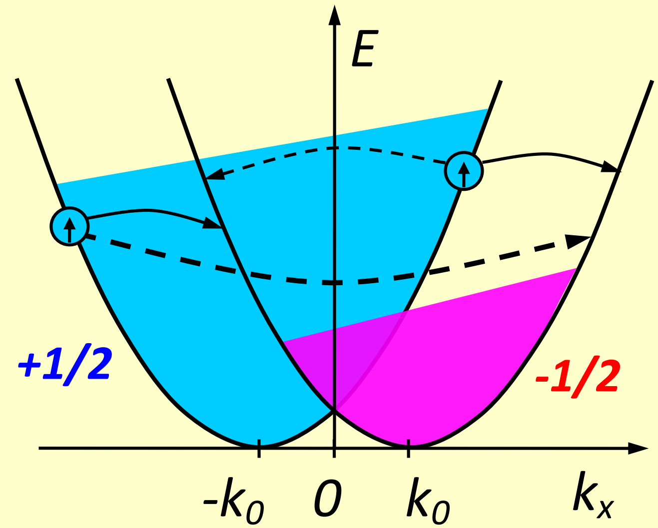
HgTe-based QWs

G.V. Budkin and S.A.T., New J. Phys. **22**, 013005 (2020)

OPTICAL ORIENTATION AND SPIN-GALVANIC EFFECT



Mechanisms based on ***k***-linear terms



Current

$$j_\alpha \propto \left(\frac{dS_\beta}{dt}\right)_{\mathrm{rel}}$$

Hamiltonian of ***k***-linear spin-orbit splitting

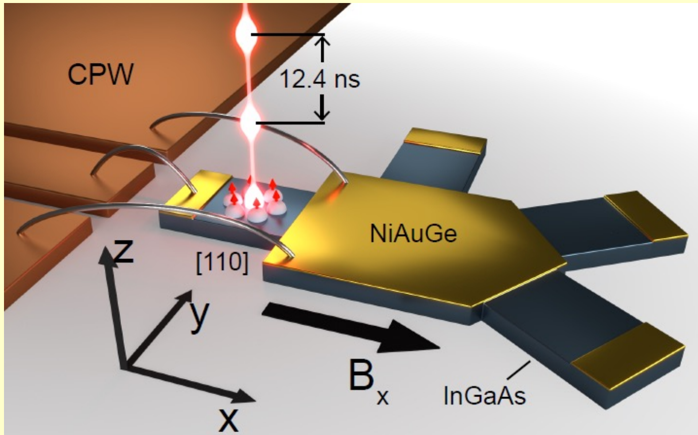
$$H_{so} = \beta_{xy}\sigma_x k_y + \beta_{yx}\sigma_y k_x$$

(001) QWs, Rashba + Dresselhaus terms, $x \parallel [1\bar{1}0], y \parallel [110]$

E.L. Ivchenko, Yu.B. Lyanda-Geller, G.E. Pikus, JETP (1990)
S.D. Ganichev, E.I. Ivchenko, V.V. Belkov, S.A.T. et al., Nature (2002)

CURRENT BY SPIN PRECESSION IN MAGNETIC FIELD

Experimental geometry



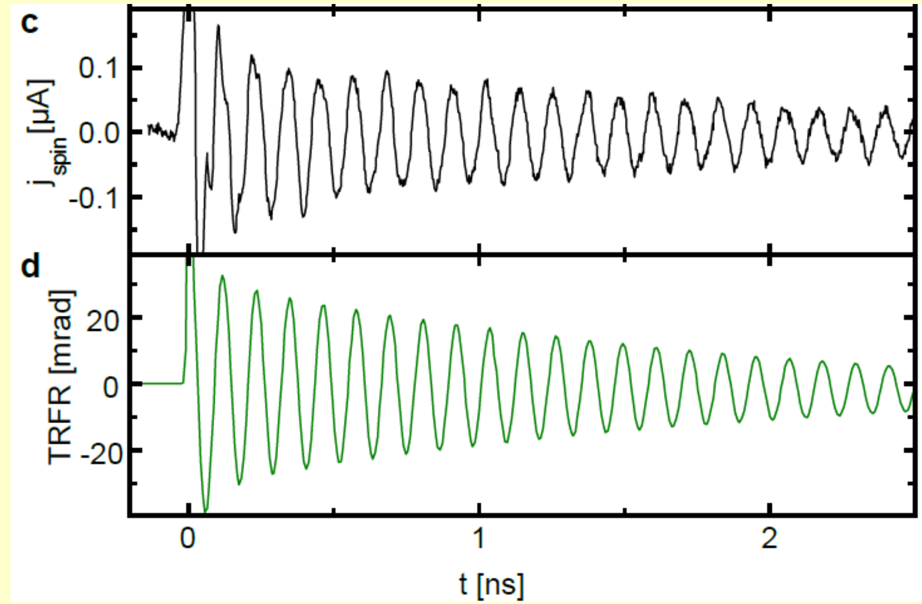
$In_{0.07}Ga_{0.93}As$ epilayers
thickness 500 nm, $n \sim 3\times10^{16}$ cm^{-2}

Experiment by

I. Stepanov, M. Ersfeld, B. Beschoten
RWTH Aachen University

M. Lepsa, *Forschungszentrum Jülich*

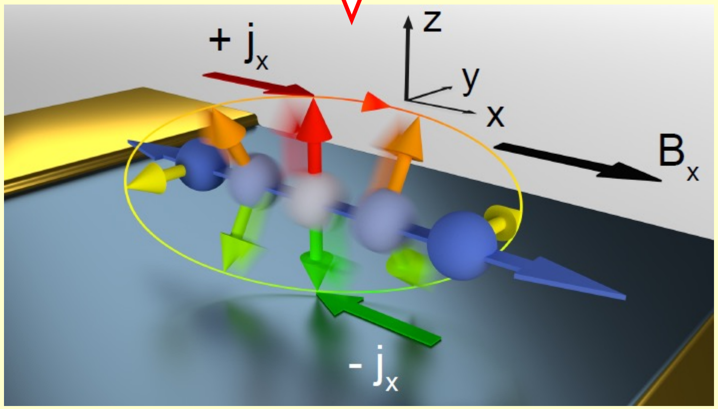
Time dependence of
(c) electric signal
(d) spin Faraday rotation angle



optical excitation by Ti:sapphire laser, 3 ps pulse
temperature 50 K, magnetic field B_x = 1 T

MICROSCOPIC CONSIDERATION

pulse σ^+



Hamiltonian

$$H = \frac{\hbar^2 k^2}{2m} + \beta_{yx}\sigma_y k_x + \frac{\hbar}{2}\Omega_L \sigma_x$$

k-linear SOI   Zeeman

Velocity operator

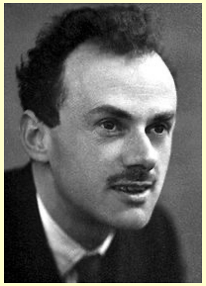
$$\hat{v}_x = \frac{i}{\hbar}[H, x] = \frac{\hbar k_x}{m} + \frac{\beta_{yx}}{\hbar}\sigma_y$$

Упражнение

$$[H, \hat{v}_x] = \beta_{yx}\Omega_L \sigma_z$$

velocity is not conserved

ZITTERBEWEGUNG OF DIRAC PARTICLES

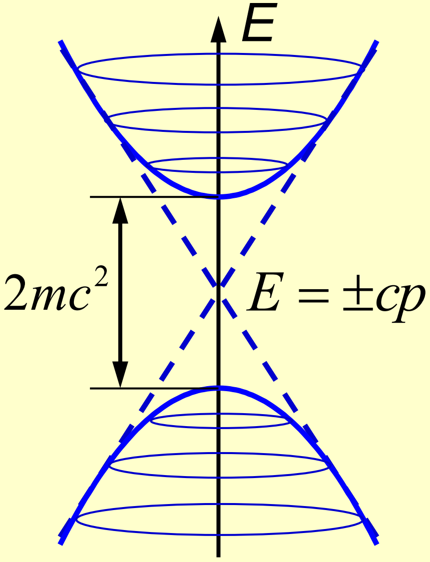


P. Dirac

E. Schrödinger

Relativistic wave equation
for spin-1/2 particle, 1928

$$i\hbar\frac{\partial\Psi}{\partial t} = H\Psi, \;\; H = \begin{pmatrix} mc^2 & c\boldsymbol{\sigma}\cdot\boldsymbol{p} \\ c\boldsymbol{\sigma}\cdot\boldsymbol{p} & -mc^2 \end{pmatrix}$$

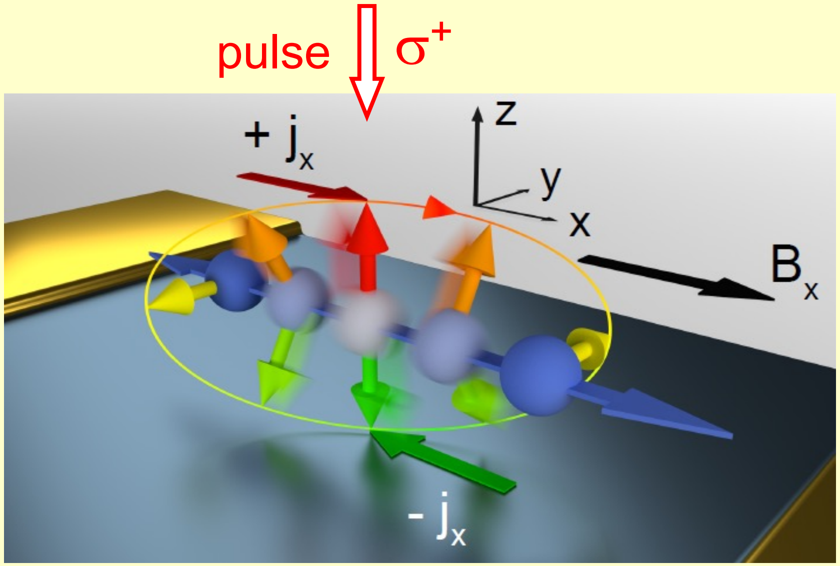


Velocity operator

$$\boldsymbol{v} = \frac{d\boldsymbol{r}}{dt} = \frac{i}{\hbar}[H, \boldsymbol{r}] = c\begin{pmatrix} 0 & \boldsymbol{\sigma} \\ \boldsymbol{\sigma} & 0 \end{pmatrix}$$

$[H, \boldsymbol{v}] \neq 0$ velocity is not conserved

COHERENT ELECTRON ZITTERBEWEGUNG



AC electric current as coherent Zitterbewegung

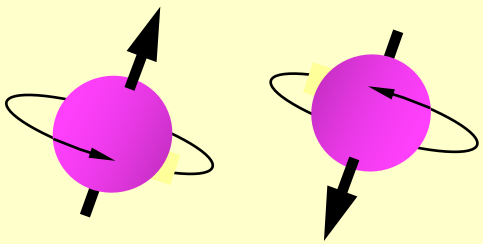
$$j_x(t) = 2n\tau_p \frac{\beta_{yx}}{\hbar} \frac{ds_y(t)}{dt}$$

S.A.T., A.V. Poshakinskiy, E.L. Ivchenko, I. Stepanov, M. Ersfeld, M. Lepsa, and B.Beschoten, JETP Letters (2018)

ПЛАН ЛЕКЦИИ

- Линейный отклик на электромагнитное поле
- Фотогальванические эффекты. Симметрийный анализ
- Линейный и циркулярный ФГЭ в 2D структурах
  - микроскопические механизмы, эксперимент
  - магнитоиндуцированные эффекты
  - токи, обусловленные энергетической и спиновой релаксацией
- Спиновые и долинные фототоки
- Основные результаты

SPIN AND VALLEY DEGREES OF FREEDOM



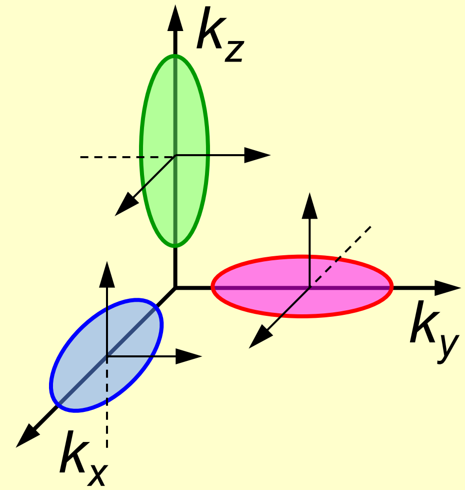
Selective population of spin subbands
by circularly polarized light
(optical orientation of electron spins)

G. Lampel, Phys. Rev. Lett. (1968)

Optical injection of spin currents

R.D.R. Bhat et al., Phys. Rev. Lett. (2005)
S.A.T. and E.L. Ivchenko, JETP Lett. (2005)

H. Zhao et al., Phys. Rev. B (2005)
S.D. Ganichev et al., Nature Phys. (2006)



Selective population of valleys
by linearly polarized light

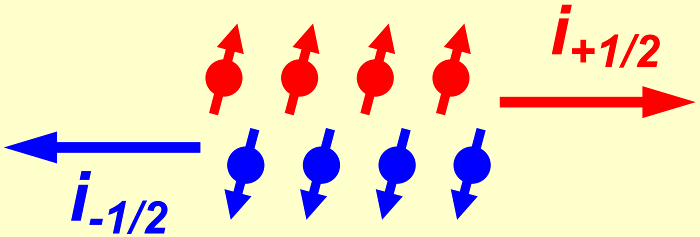
A.A. Kaplyanskii et al., Solid State Comm. (1976)

Optical injection of valley currents

S.A.T. and E.L. Ivchenko, JETP Lett. (2005)
J. Karch et al., Phys. Rev. B (2011)

PURE SPIN CURRENTS

Pure spin current



Second-rank tensor

$$J_{\beta}^{\alpha}$$

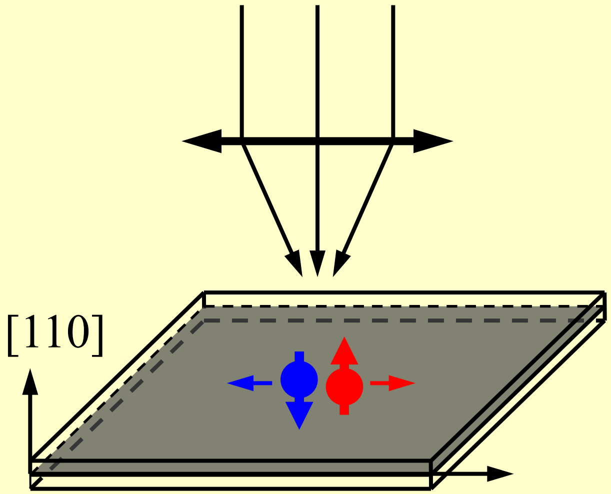
spin orientation (α)

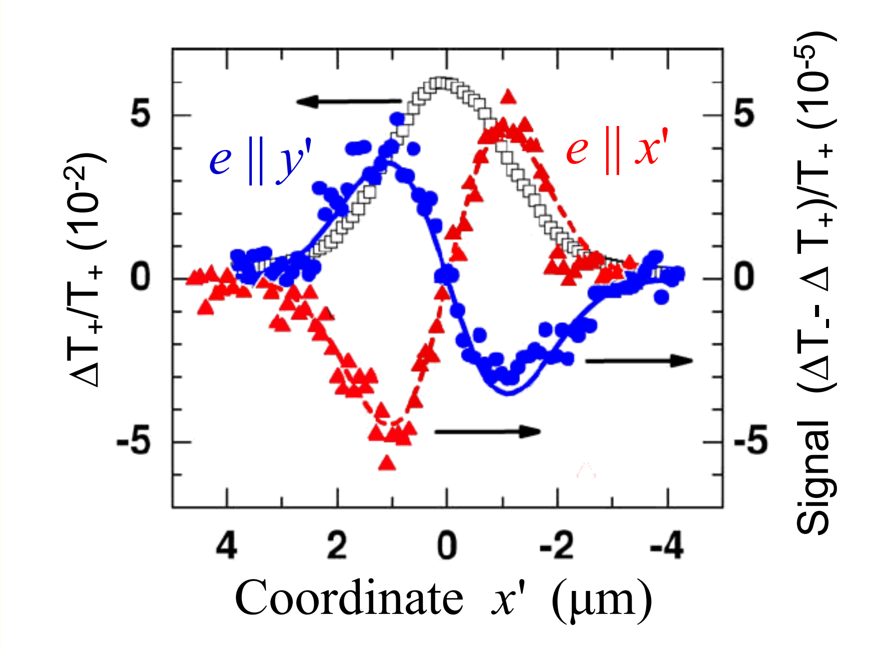
flow direction (β)

SPIN CURRENT: INTERBAND EXCITATION

H. Zhao, X. Pan, A.L. Smirl et al., Phys. Rev. B 2005

Pump-probe technique with high spatial resolution





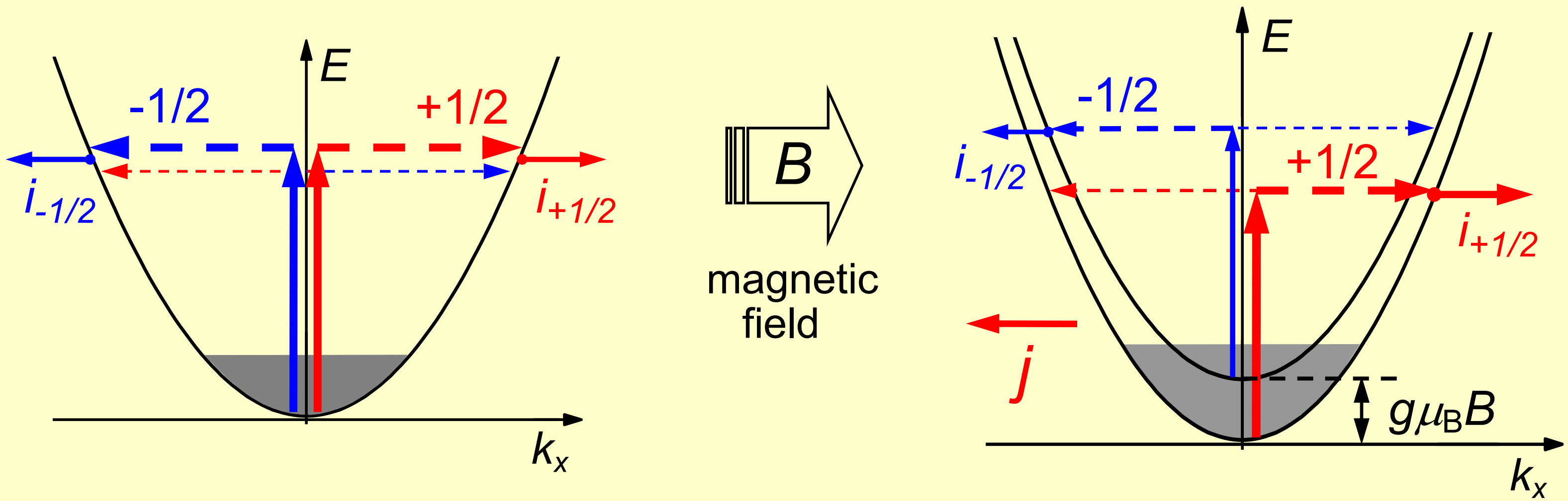
GaAs/AlGaAs (110)-grown quantum wells, temperature T=300K

See also

Y. Han, S. Xiao, H. Zhao et al., Appl. Phys. Lett. 2007 (detection by 2nd harmonic generation)

X.-D. Cui, Sh.-Q. Shen, J. Li et al., Appl. Phys. Lett. 2007 (electric measurements)

SPIN CURRENTS: FREE-CARRIER ABSORPTION



Pure spin current J_β^α

$$\boldsymbol{j} = e(\boldsymbol{i}_{+1/2} + \boldsymbol{i}_{-1/2}) = 0$$

Electric current

$$j_\beta = 4e\sum_\alpha J_\beta^\alpha s_\alpha$$

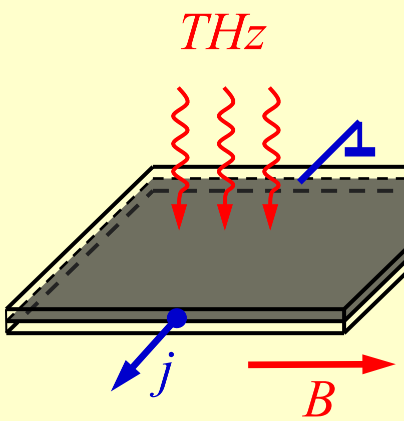
Spin-dependent electron scattering

$$V_{\mathbf{k'k}} = V_0 + \sum_{\alpha\beta} V_{\alpha\beta}\hat{\sigma}_\alpha (k_\beta + k'_\beta)$$

S.D. Ganichev, V.V. Bel’kov, S.A.T. et al., Nature Phys. 2006

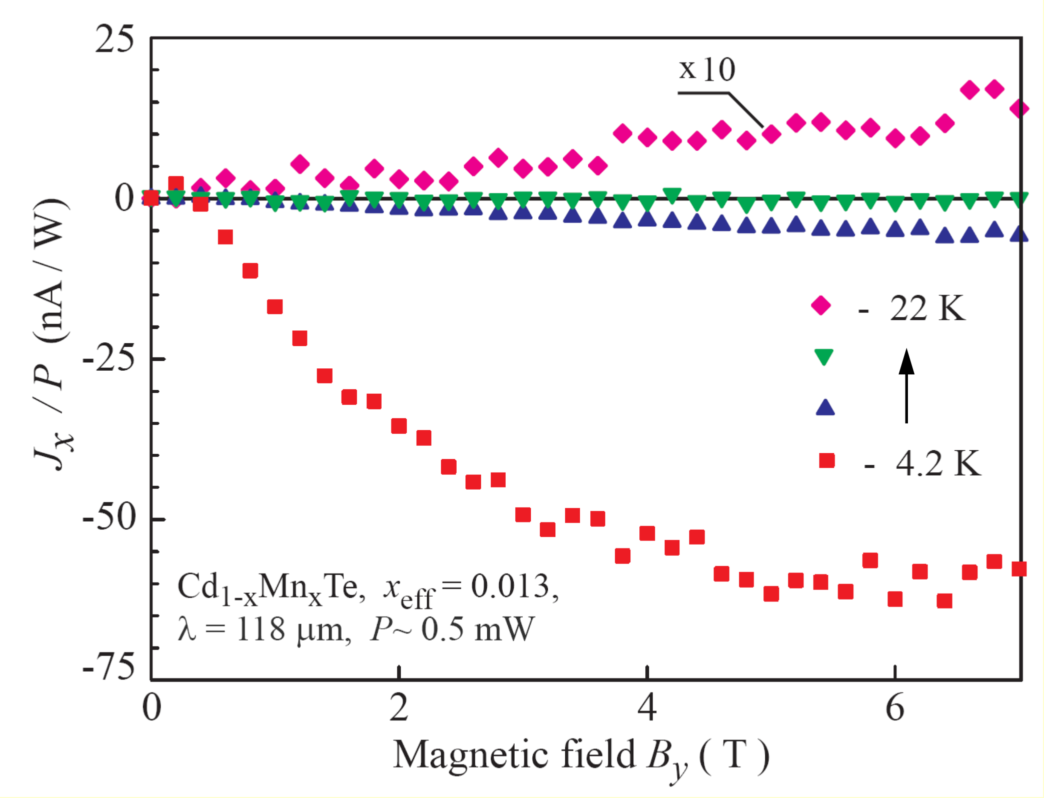
EXPERIMENT: MAGNETIC-FIELD-INDUCED CURRENT

Geometry of experiment



Electric current
at low temperatures

$$j \propto S^{\mathrm{Mn}}$$

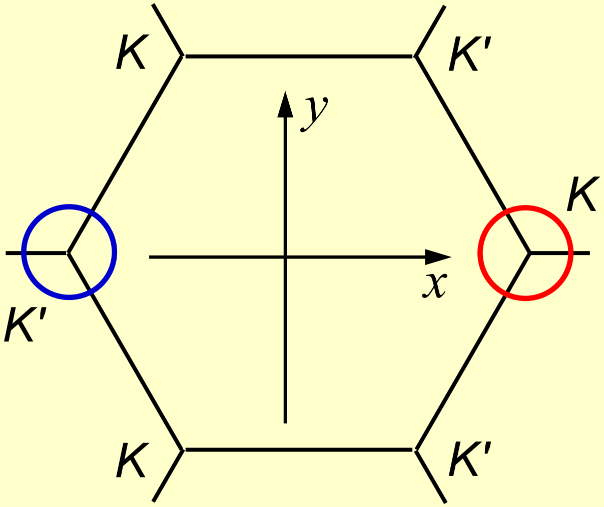


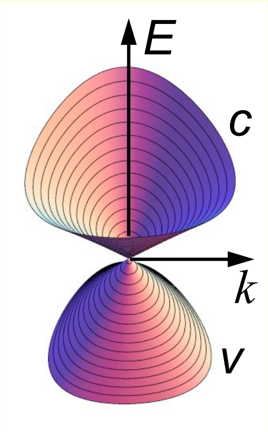
CdMnTe/CdMgTe (001) quantum wells

S.D. Ganichev, S.A.T., V.V. Bel'kov et al., PRL 102, 156602 (2009)
P. Olbrich, C. Zoth, P. Lutz et al., PRB 86, 085310 (2012)

BAND STRUCTURE OF GRAPHENE

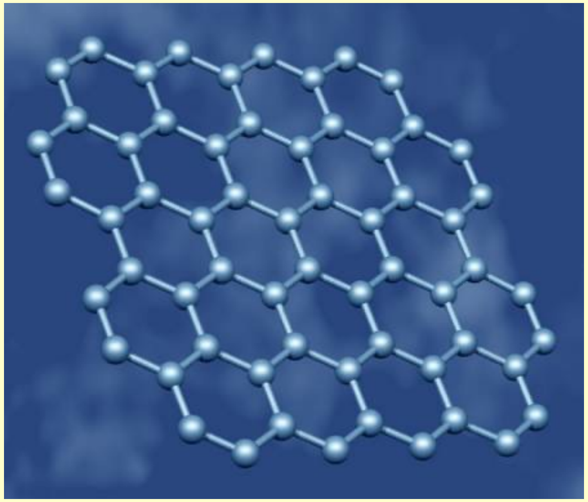
Brillouin zone of graphene





close to K-point
(D_{3h} group)

Crystal lattice of graphene



Point group D_{6h}

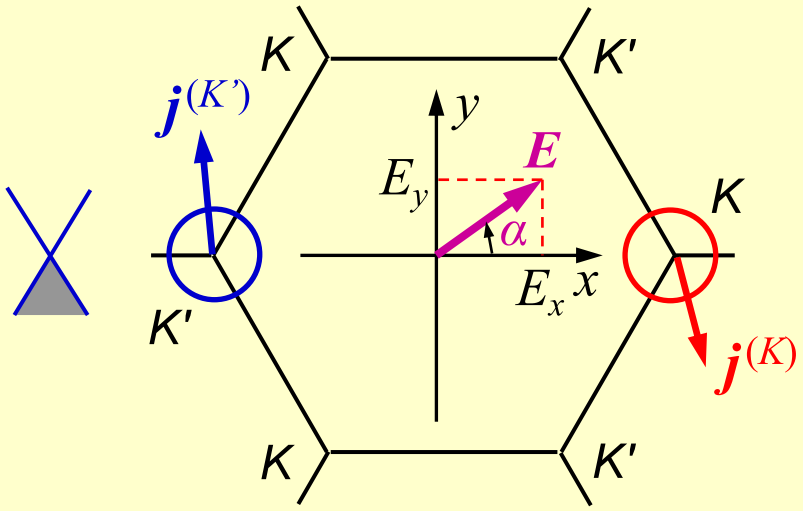
Effective Hamiltonian at the *K* point of the Brillouin zone

$$\hat{H} = \begin{pmatrix} 0 & \Omega_{\boldsymbol{p}} \\ \Omega_{\boldsymbol{p}}^{*} & 0 \end{pmatrix}, \quad \Omega_{\boldsymbol{p}} = v_0(p_x - ip_y) - \mu(p_x + ip_y)^2$$

trigonal warping

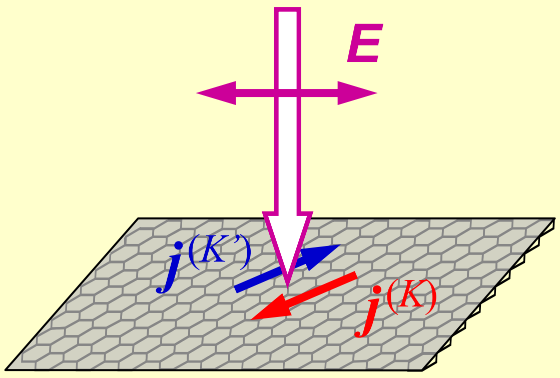
Review: A.H. Castro Neto, F. Guinea, N.M.R. Peres,
K.S. Novoselov, and A.K. Geim, Rev. Mod. Phys. **81**, 109 (2009)

PURE VALLEY PHOTOCURRENTS



D_{3h} group
(no center of inversion)

Experimental geometry



D_{6h} point-group symmetry
(center of inversion)

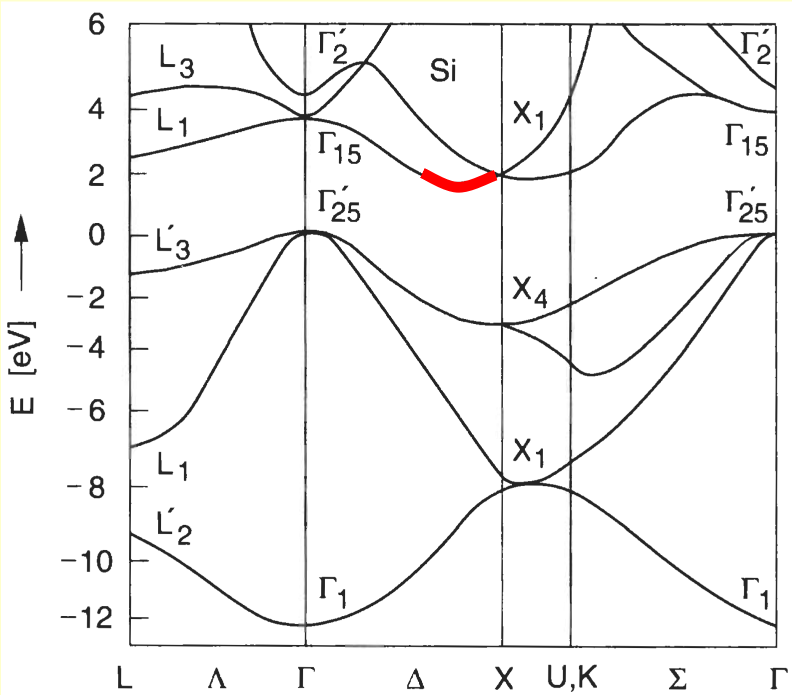
Photocurrents in the *K* и *K'* valleys: $\boldsymbol{j}^{(K')} = -\boldsymbol{j}^{(K)}$

$$j_x^{(K)} = \chi(|E_x|^2 - |E_y|^2) \propto |E|^2 \cos 2\alpha$$

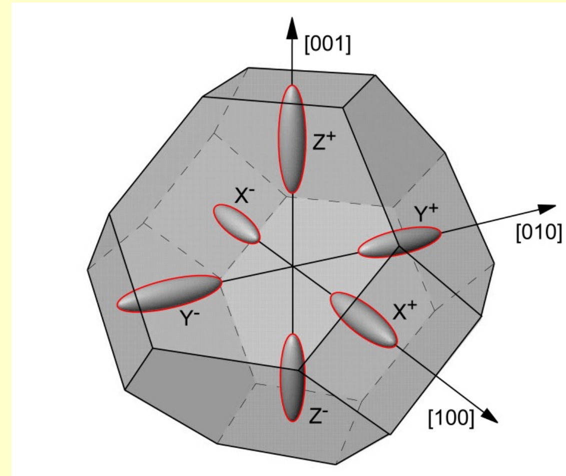
$$j_y^{(K)} = -\chi(E_x E_y^* + E_y E_x^*) \propto |E|^2 \sin 2\alpha$$

L.E. Golub, S.A.T., M.V. Entin, and L.I. Magarill, Phys. Rev. B (2011)
R.R. Hartmann and M.E. Portnoi, LAP LAMBERT Academic Publishing (2011)

BAND STRUCTURE OF SILICON



Brillouin zone of silicon

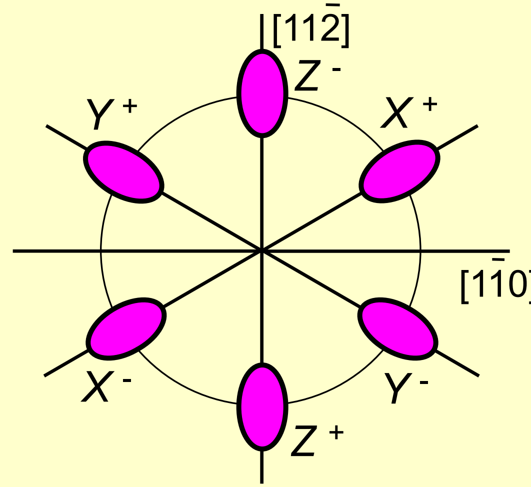


Electron dispersion in valleys

$$E_{\boldsymbol{k}} = \frac{\hbar^2 k_{\parallel}^2}{2m_{\parallel}} + \frac{\hbar^2 k_{\perp}^2}{2m_{\perp}}$$

strong mass anisotropy $m_{\parallel}/m_{\perp} \approx 5$

2D structure on the (111) surface

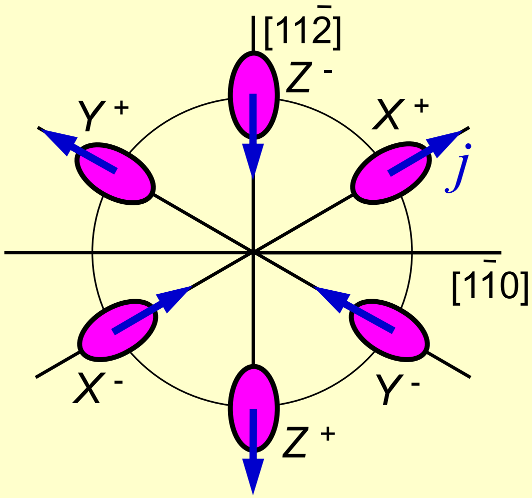


C_{3v} overall point group

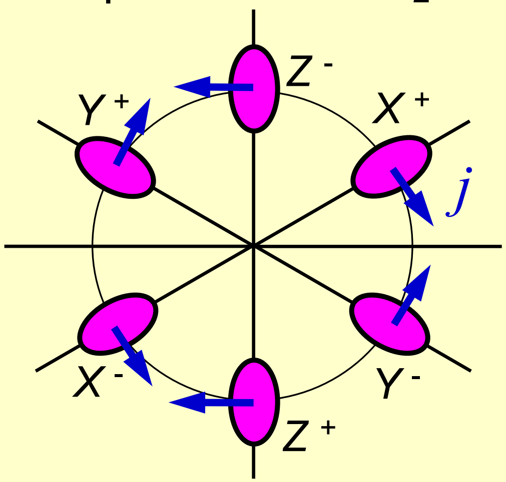
C_S group of a valley

CLASSIFICATION OF VALLEY CURRENTS

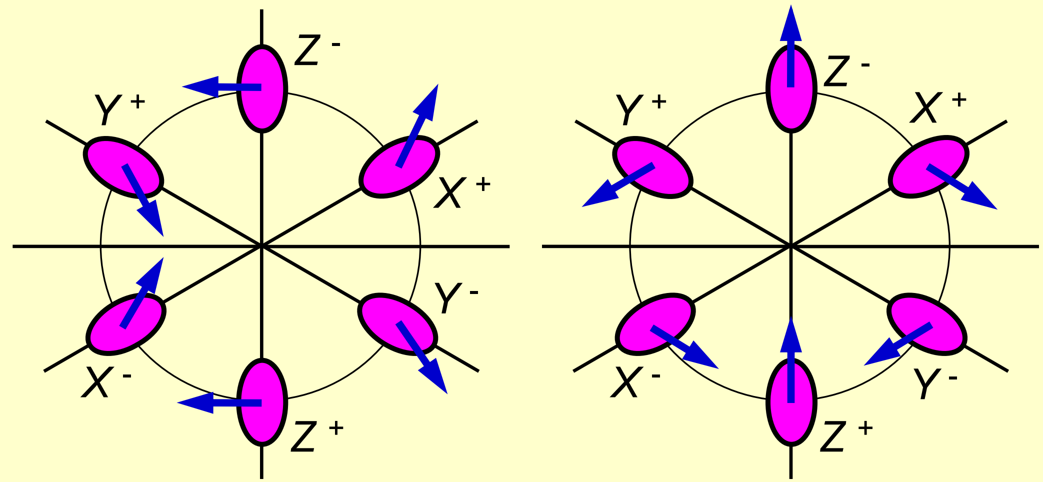
Representation A_1



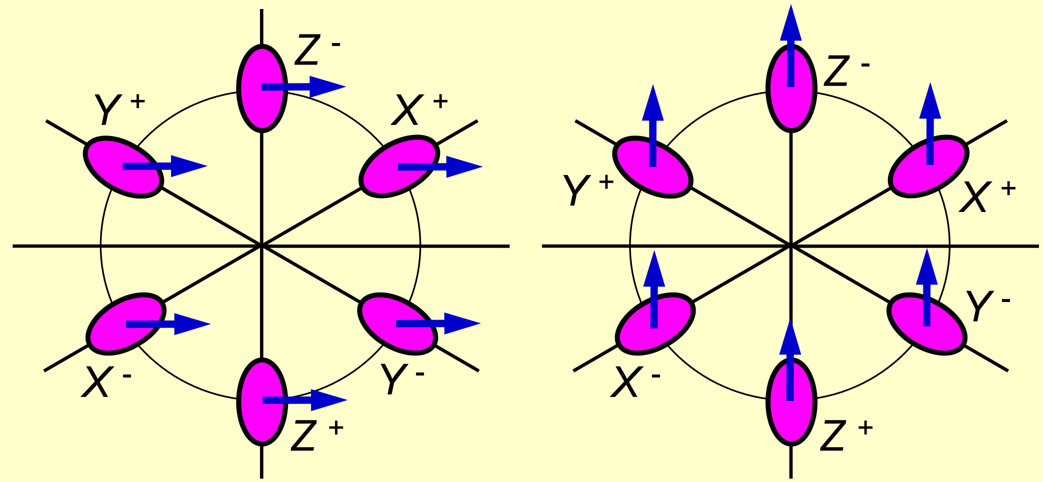
Representation A_2



Representation E

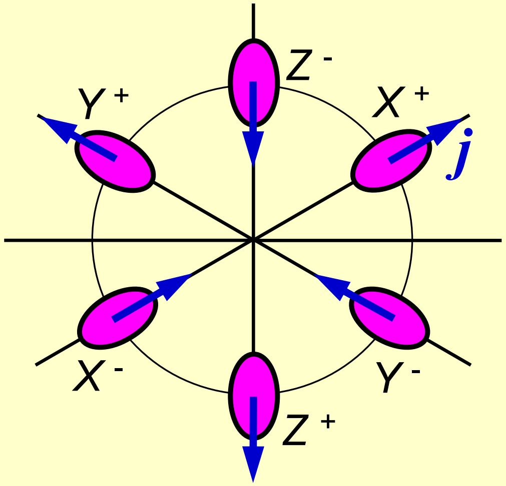


Representation E (electric current)

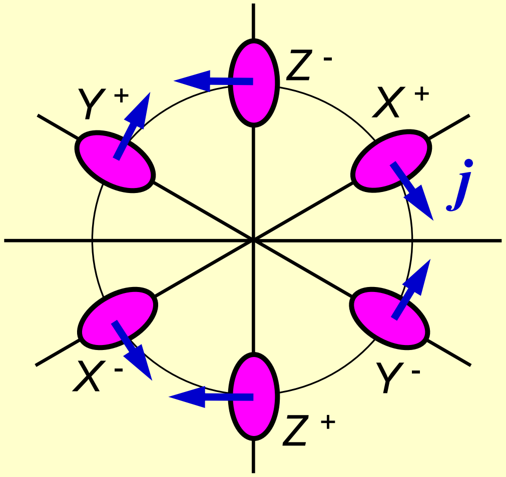


VALLEY CURRENTS IN (111) SILICON STRUCTURES

Excitation with unpolarized radiation



Circularly polarized radiation

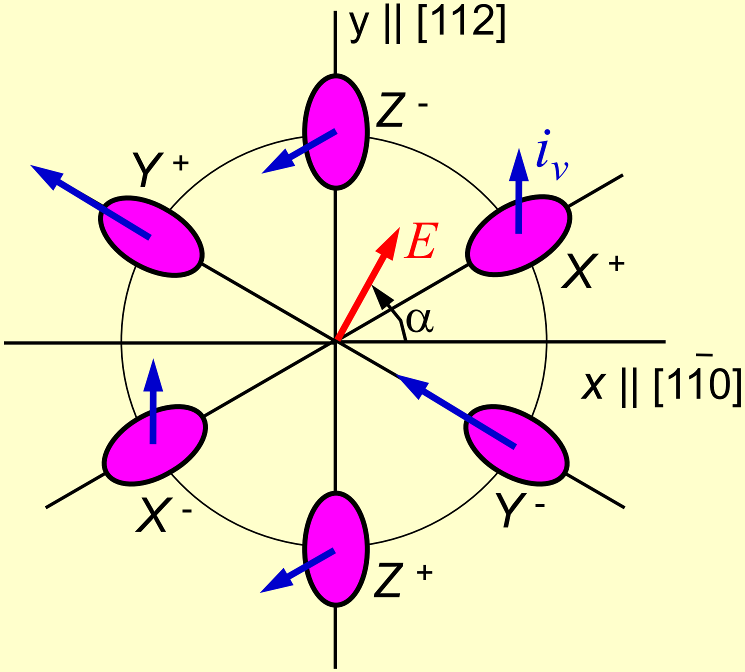


$$\boldsymbol{j}_{\Sigma} = \sum_{\nu} \boldsymbol{j}_{\nu}$$

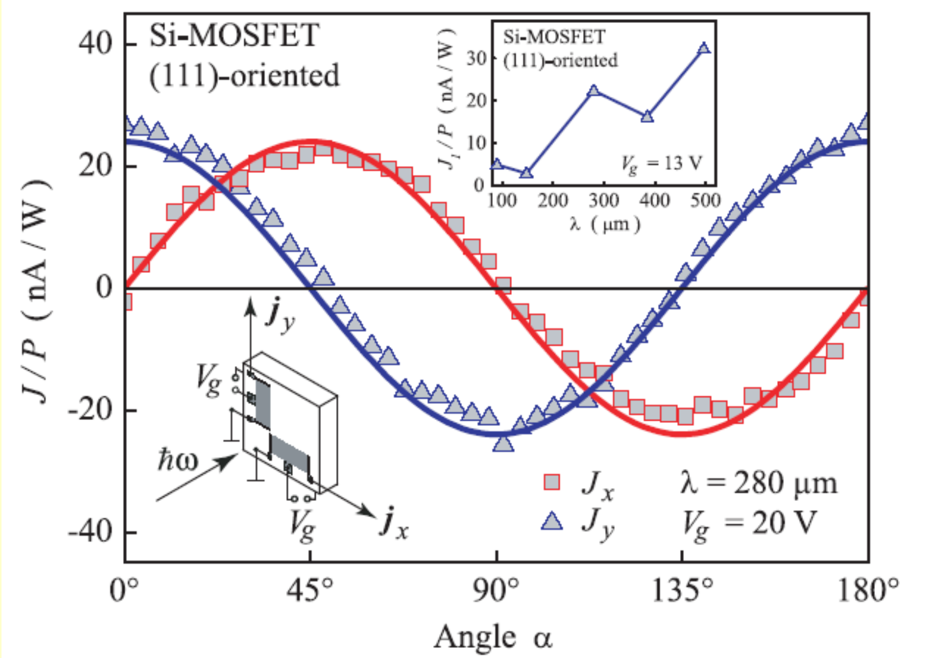
net electric current

EXCITATION WITH LINEARLY POLARIZED RADIATION

Photocurrent distribution



Polarization dependence of current



(111) Si-MOS structure, room temperature

Total electric current

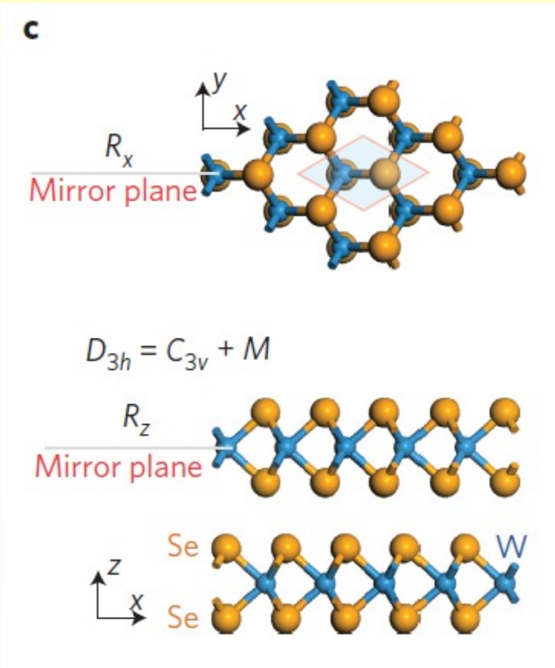
$$J_x / I = \sum_\nu j_{\nu,x} / I = -3(B+D)(e_x e_y^* + e_y e_x^*) \propto \sin 2\alpha$$

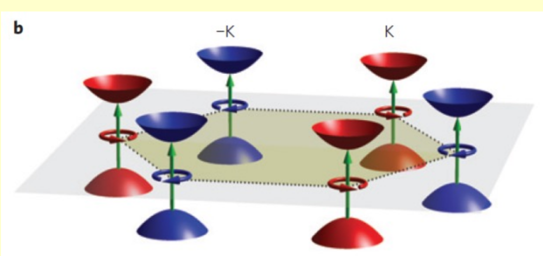
$$J_y / I = \sum_\nu j_{\nu,y} / I = -3(B+D)(|e_x|^2 - |e_y|^2) \propto \cos 2\alpha$$

J. Karch et al., Phys. Rev. B **83**, 121312R (2011)

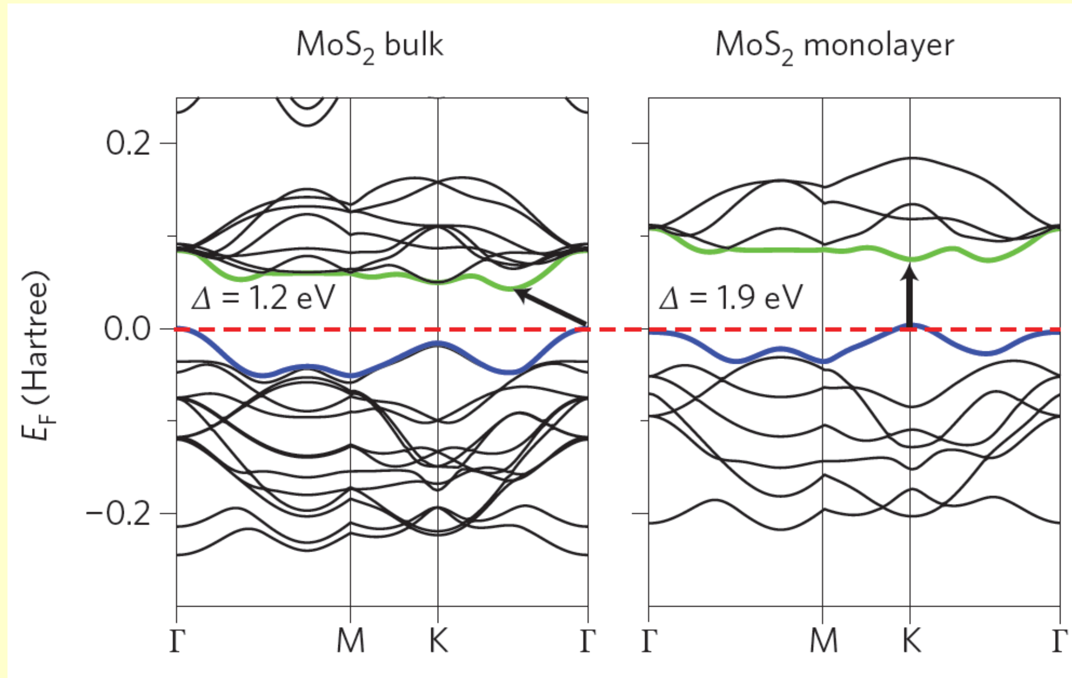
TRANSITION METAL DICHALCOGENIDES
MX_2 (M = Mo, W; X = S, Se)

Crystal structure





Band structure of bulk material and monolayers

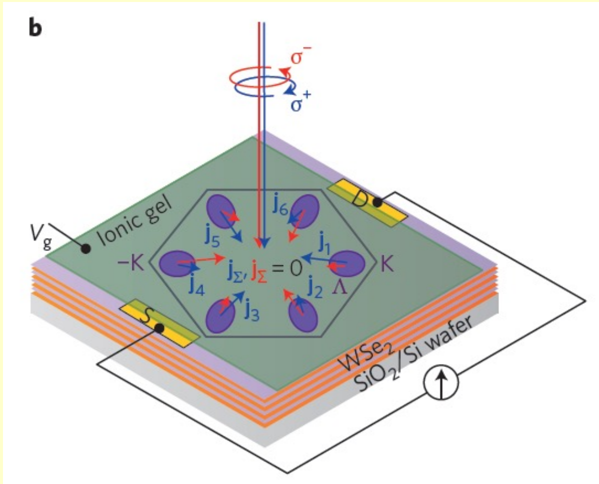


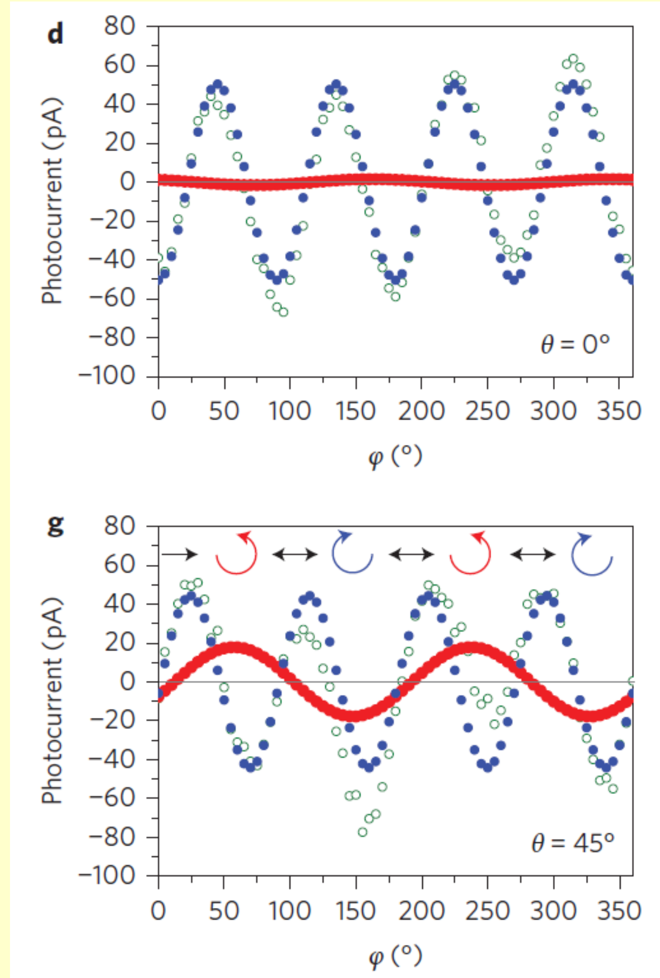
Q. H. Wang et al., Nature Nanotech. **7**, 699 (2012)
X. Xu et al., Nature Phys. **10**, 343 (2014)

Excitons: G. Wang, A. Chernikov, M.M. Glazov et al., Rev. Mod. Phys. **90**, 021001 (2018)

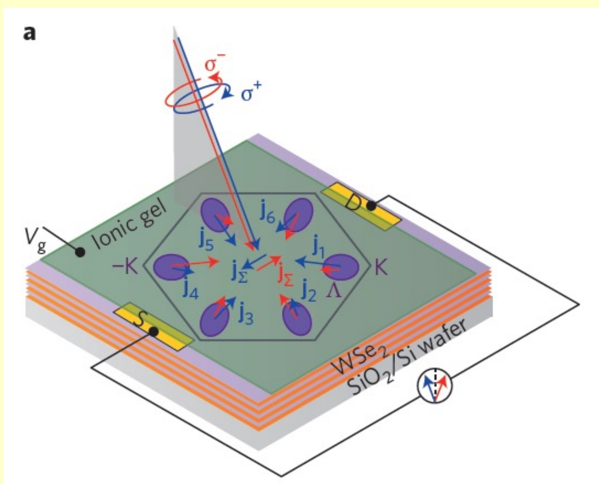
VALLEY PHOTOCURRENTS IN WSe_2 LAYERS

Normal incidence of circularly polarized light





Oblique incidence of circularly polarized light



C_{3v} overall point group

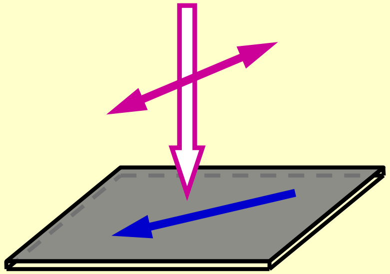
C_1 group of a valley

H. Yuan et al., Nature Nanotech. **9**, 851 (2014)
S.A.T., Nature Nanotech. **9**, 752 (2014)

Valley photocurrents in TMDC, Weyl semimetals, etc.

ФОТОГАЛЬВАНИЧЕСКИЕ ЭФФЕКТЫ

- Фотогальванические эффекты и эффекты храповика в двумерных системах без центра инверсии. Инструмент изучения симметрии системы, электрон-фотонного взаимодействия, процессов релаксации



- Спиновые и долинные фототоки (в графене, TMDC слоях, Si, полуметаллах Вейля и др.). Электрический ток определяется суммой парциальных вкладов и отсутствует для чисто спиновых/долинных токов