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CIRCULAR PHOTON DRAG EFFECT IN QUANTUM WELLS

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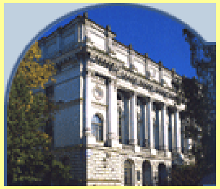

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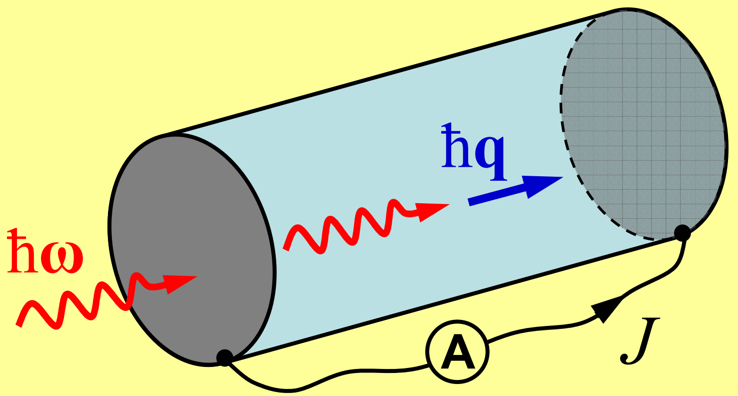
CIRCULAR PHOTON DRAG EFFECT IN QWS

Outline

- Introduction. Photon Drag in semiconductors
- Phenomenological analysis:
  Photogalvanic effect vs. Photon Drag effect
- Experiment. Intersubband transitions in (110)-QWs
  - normal incidence: Circular Photogalvanic effect
  - oblique incidence: Circular Photon Drag
- Microscopic model of the Circular Photon Drag

PHOTON DRAG OF CHARGE CARRIERS



Photocurrent caused by transfer of photon linear momenta to free carriers

Electric current density

$$j^{\text{Drag}} \propto e\tau_p K(\omega) I$$

e the electron charge

τ_p the momentum relaxation time

$K(\omega)$ the absorption coefficient

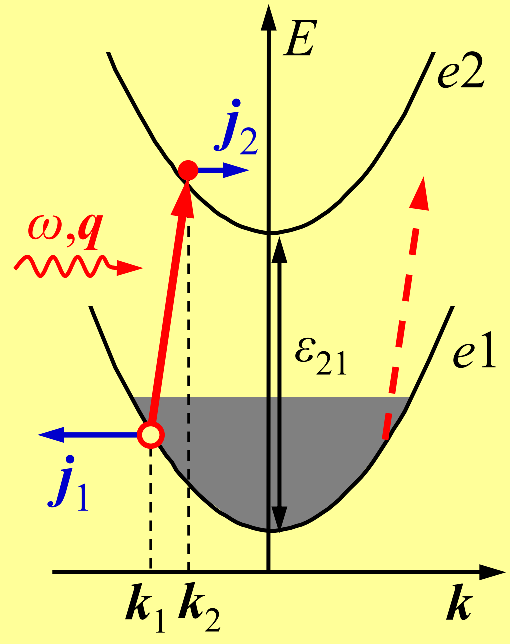
I the light intensity

First observation: Bulk *p*-Ge

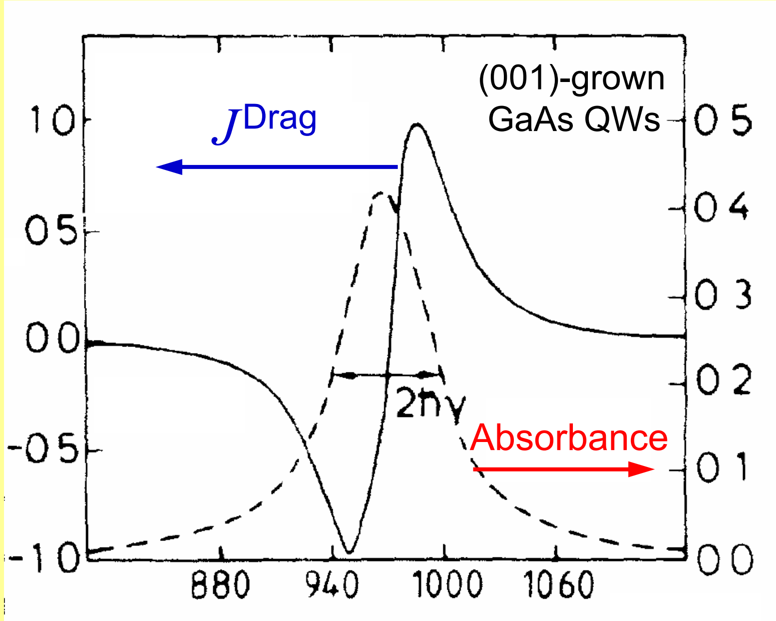
A.M. Danishevskii et al., Sov. Phys. JETP **31,** 292 (1970)

A.F. Gibson et al, Appl. Phys. Lett. **17**, 75 (1970)

INTERSUBBAND TRANSITIONS IN *N*-TYPE QWS



Spectral dependence



S. Luryi, PRL **58**, 2263 (1987)

A.D. Wieck, H. Sigg, K. Ploog, PRL **64**, 463 (1990)

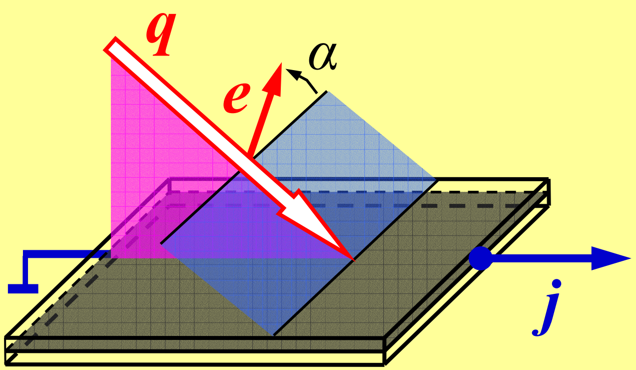
Momentum and energy conservation

$$\boldsymbol{k}_2 = \boldsymbol{k}_1 + \boldsymbol{q}\,, \quad \varepsilon_{e2,\boldsymbol{k}2} = \varepsilon_{e1,\boldsymbol{k}1} + \hbar\omega - \varepsilon_{21}$$

Electric current

$$\boldsymbol{j}^{\mathrm{Drag}} = \boldsymbol{j}_1 + \boldsymbol{j}_2 \propto e\left(\tau_2 \boldsymbol{k}_2 - \tau_1 \boldsymbol{k}_1\right)\eta(\omega) I$$

POLARIZATION DEPENDENCE



Selection rules for the intersubband optical transitions

s-polarization $(\alpha=0) \rightarrow \eta \neq 0$

p-polarization $(\alpha=90^{o}) \rightarrow \eta=0$

QW absorbance

$$\eta \propto |e_z|^2$$

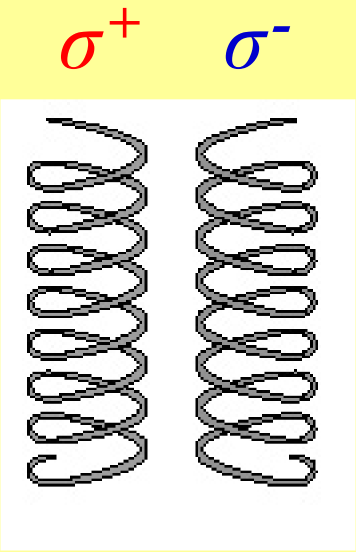
Polarization dependence of the Photon Drag current

$$j^{\text{Drag}} \propto \eta \propto \sin^2\alpha$$

This is <u>Linear</u> Photon Drag

CIRCULAR PHOTON DRAG ?

Does a Helicity-Dependent Photon Drag contribution exist?



PHENOMENOLOGICAL DESCRIPTION

Electric current induced by light

$$j_\lambda = I\left\{\sum_{\mu\nu}\alpha_{\lambda\mu\nu}e_\mu e_\nu^* + \sum_{\mu\nu\delta}\beta_{\lambda\mu\nu\delta}\,q_\mu e_\nu e_\delta^*\right\}$$

PhotoGalvanic Effect

Photon Drag

$$\sum_{\mu\nu}L_{\lambda\mu\nu}(e_\mu e_\nu^* + e_\nu e_\mu^*)/2$$

Linear PGE

$$\sum_{\mu\nu\delta}T_{\lambda\mu\nu\delta}\,q_\mu(e_\nu e_\delta^* + e_\delta e_\nu^*)/2$$

Linear Photon Drag

$$\sum_{\mu\nu\delta}C_{\lambda\mu}\,i[\boldsymbol{e}\times\boldsymbol{e}^*]_\mu \quad \propto P_{circ}$$

Circular PGE

$$\sum_{\mu\nu}D_{\lambda\mu\nu}\,q_\mu\,i[\boldsymbol{e}\times\boldsymbol{e}^*]_\nu \quad \propto P_{circ}$$

Circular Photon Drag

I the light intensity, $\boldsymbol{q}$ the photon wavevector,
e the (unit) light polarization vector,

E.L. Ivchenko & G.E. Pikus, 1980

SYMMETRY ANALYSIS

✓ Bulk zinc-blende-type compounds (GaAs etc.)

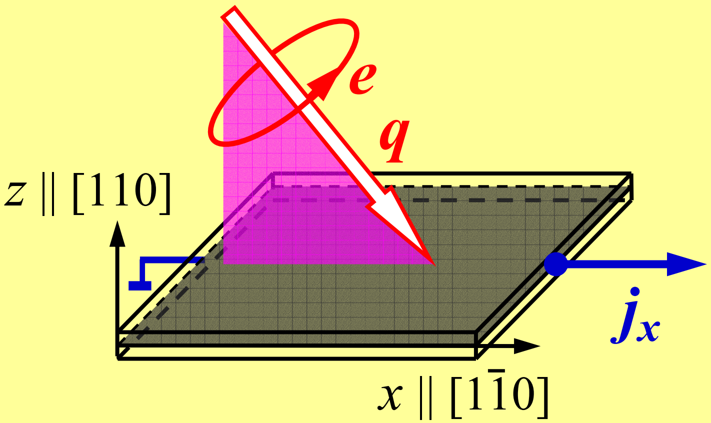
Circular PGE: $C_{\lambda\mu} = 0$, Circular Photon Drag: $D_{\lambda\mu\nu} = 0$

Helicity-dependent photocurrents are forbidden

✓ Low-dimensional zinc-blende-type structures

Both Circular PGE and Circular Photon Drag are allowed

ASYMMETRICAL (110)-GROWN QUANTUM WELLS



C_s point-group symmetry

Helicity-dependent photocurrent

$$j_x \propto \left(C[\boldsymbol{e}\times\boldsymbol{e}^*]_z + D\, q_x\, i[\boldsymbol{e}\times\boldsymbol{e}^*]_x \right) I$$

$\propto P_{circ}$ $\propto P_{circ}$

Circular PGE

Circular Photon Drag $\propto q_x$

e the polarization vector
q the photon wavevector
I the light intensity

inside the sample

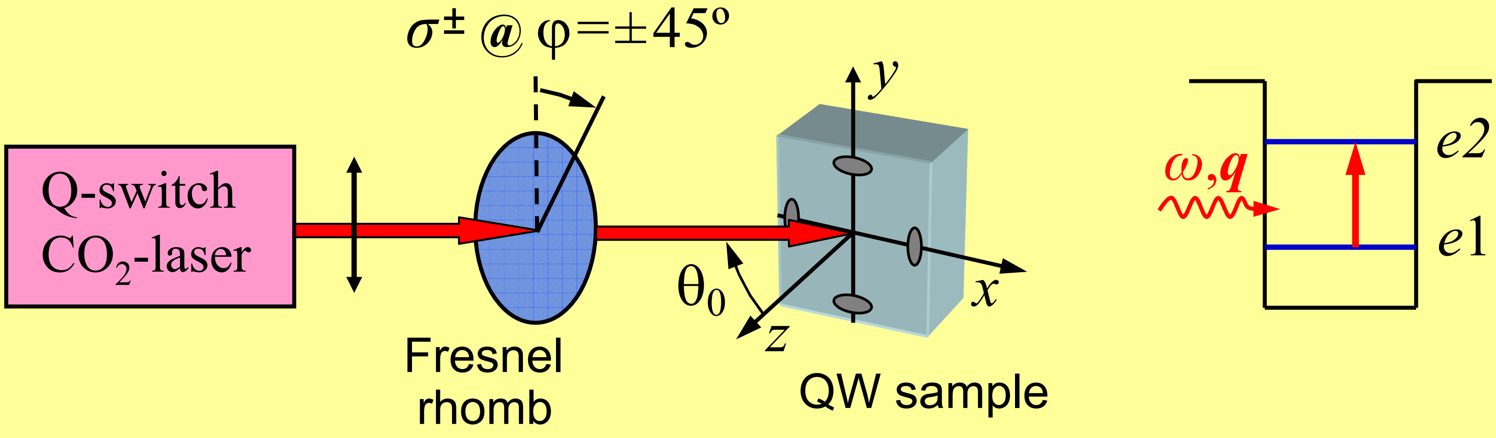
EXPERIMENT: SAMPLES AND TECHNIQUE

Samples: (110)-grown *n*-type GaAs/AlGaAs QWs

- QW width = 8.2 nm
- Barrier width = 40 nm
- Si-doped layers (10 nm) in barriers
- Electron density = $7{\cdot}10^{11}$ cm^{-2} per QW

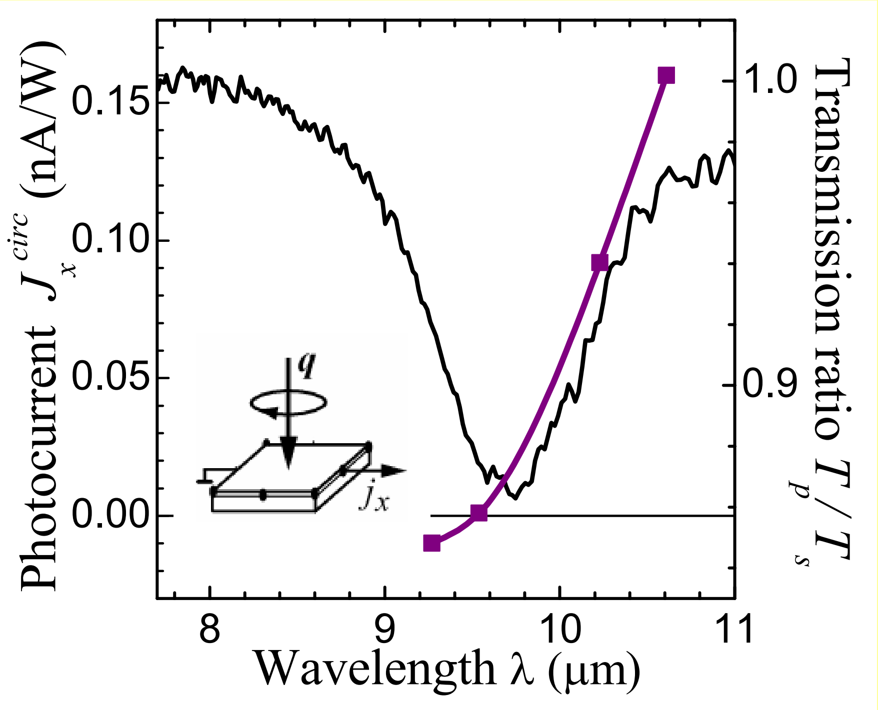
100 periods

Experimental technique

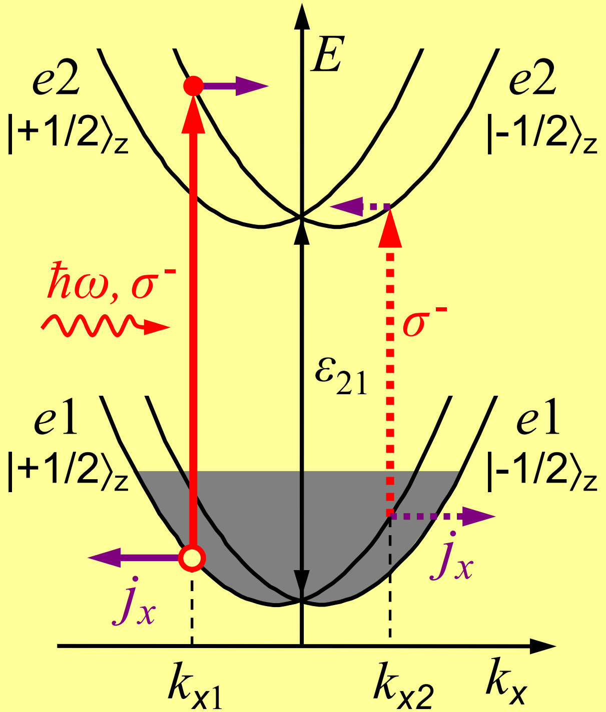


Circular photocurrent $J^{circ} = [J(\sigma^{+}) - J(\sigma^{-})]/2$

EXPERIMENT: NORMAL INCIDENCE



Mechanism of Circular PGE



Circular Photocurrent

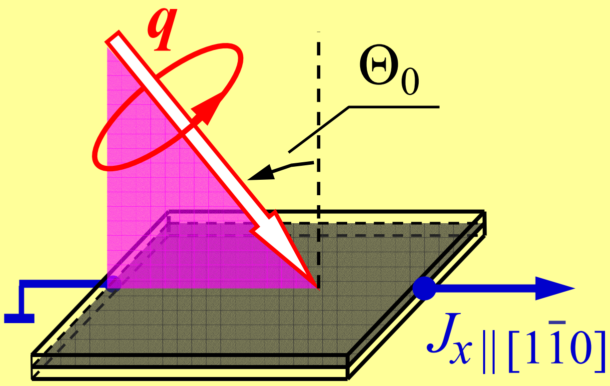
$$j_x \propto t_p t_s \left(C[\boldsymbol{e}\times\boldsymbol{e}^*]_z + D q_x i[\boldsymbol{e}\times\boldsymbol{e}^*]_x \right) I$$

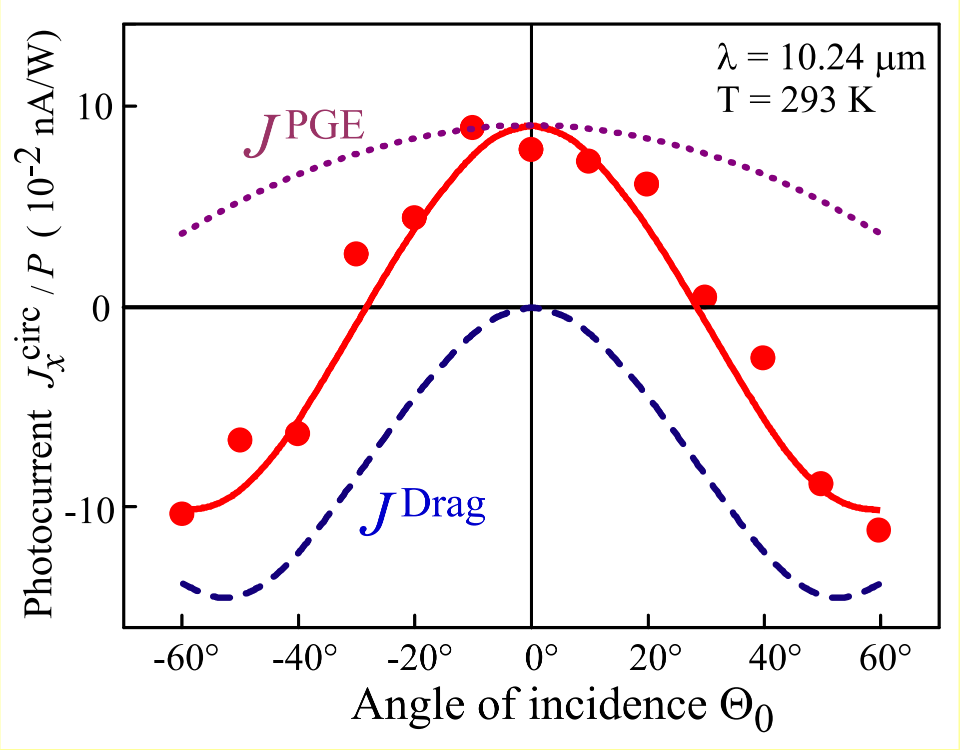
Circular PGE

- spin-orbit splitting
- spin-sensitive transitions

PRB **68,** 035319 (2003)

EXPERIMENT: OBLIQUE INCIDENCE





Circular Photocurrent

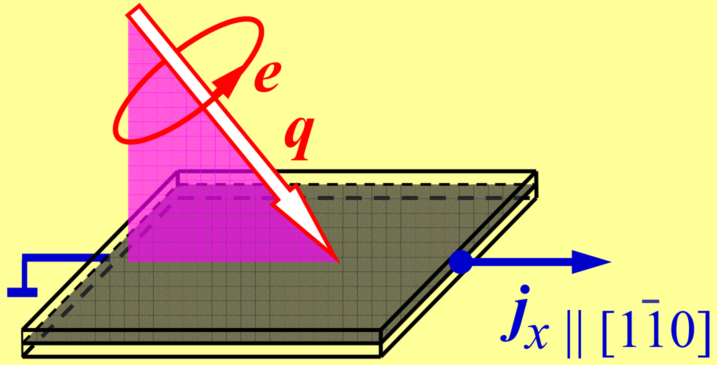
$$j_x \propto t_p t_s \left(C[\boldsymbol{e}\times\boldsymbol{e}^*]_z + D q_x i [\boldsymbol{e}\times\boldsymbol{e}^*]_x \right) I$$

$\propto \cos\Theta_0$ $\propto q \sin^2\Theta_0$

Circular PGE Circular Photon Drag

JETP Lett. **84**, 570 (2006)

MICROSCOPIC MODEL OF CIRCULAR PHOTON DRAG



Photocurrent

$$j_x \propto q_x i[\boldsymbol{e} \times \boldsymbol{e}^*]_x I \propto q_x P_{circ} I$$

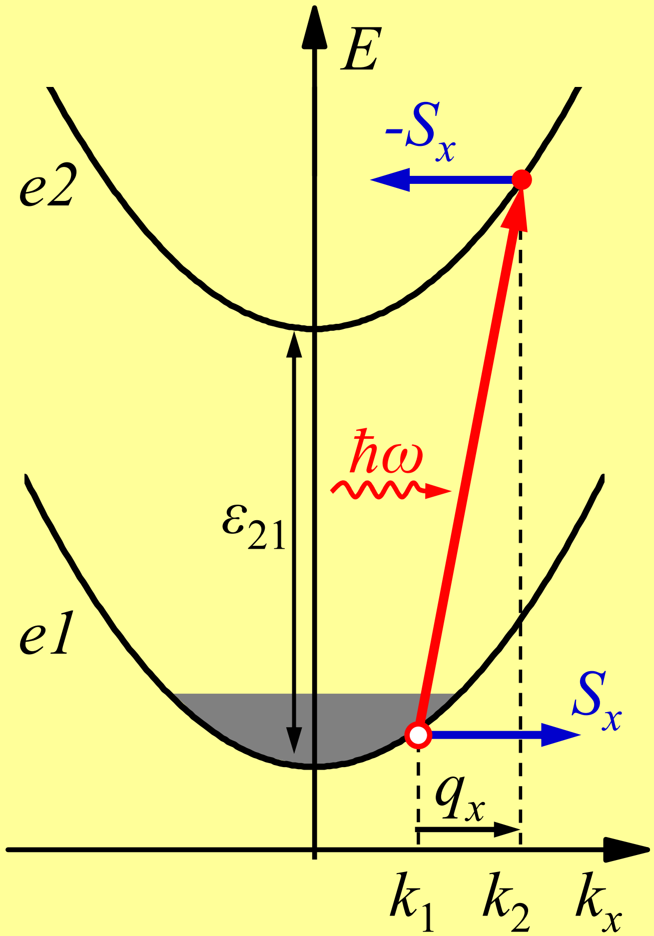
Three-stage process:

I. Helicity (P_{circ}) and wavevector ($\boldsymbol{q}$) dependent optical orientation

II. Spin rotation in an effective magnetic field

III. Electric current caused by asymmetry of spin relaxation

I. OPTICAL ORIENTATION OF ELECTRON SPINS



Energy and momentum conservation

$$\varepsilon_{e2,\boldsymbol{k}2} = \varepsilon_{e1,\boldsymbol{k}1} + \hbar\omega - \varepsilon_{21}$$

$$k_2 = k_1 + q_x$$

Spin-dependent selection rules for σ+ circularly polarized light

$|\mathbf{e1,\text{-}1/2}_x\rangle \rightarrow |\mathbf{e2,\text{-}1/2}_x\rangle$ high rate

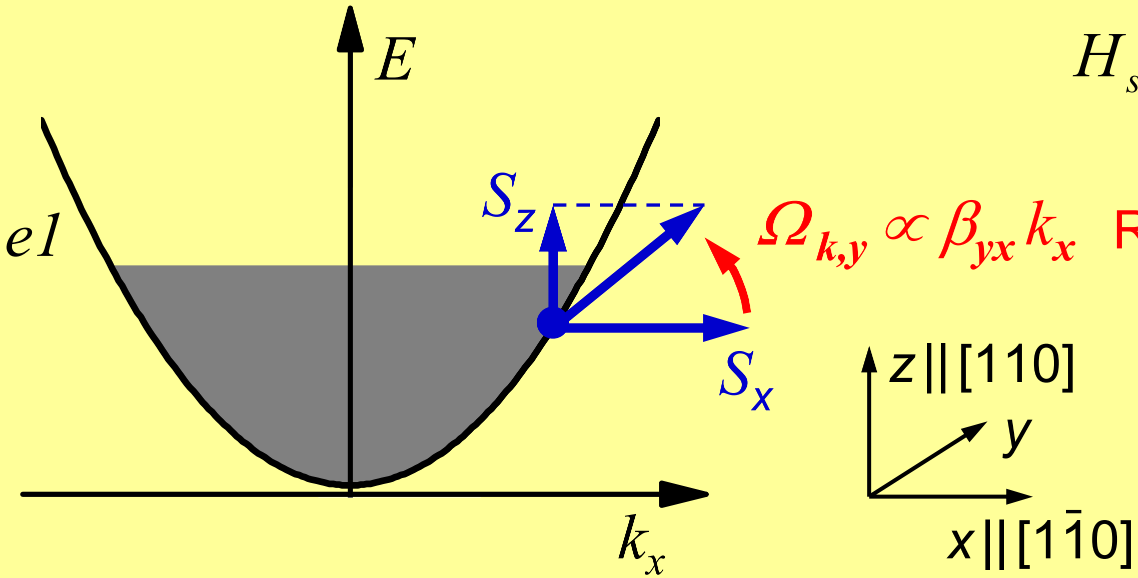
$|\mathrm{e1,+1/2}_x\rangle \rightarrow |\mathrm{e2,+1/2}_x\rangle$ low rate

JETP **99**, 379 (2004)

II. SPIN ROTATION IN EFFECTIVE MAGNETIC FIELD

Effective magnetic field caused by spin-orbit coupling

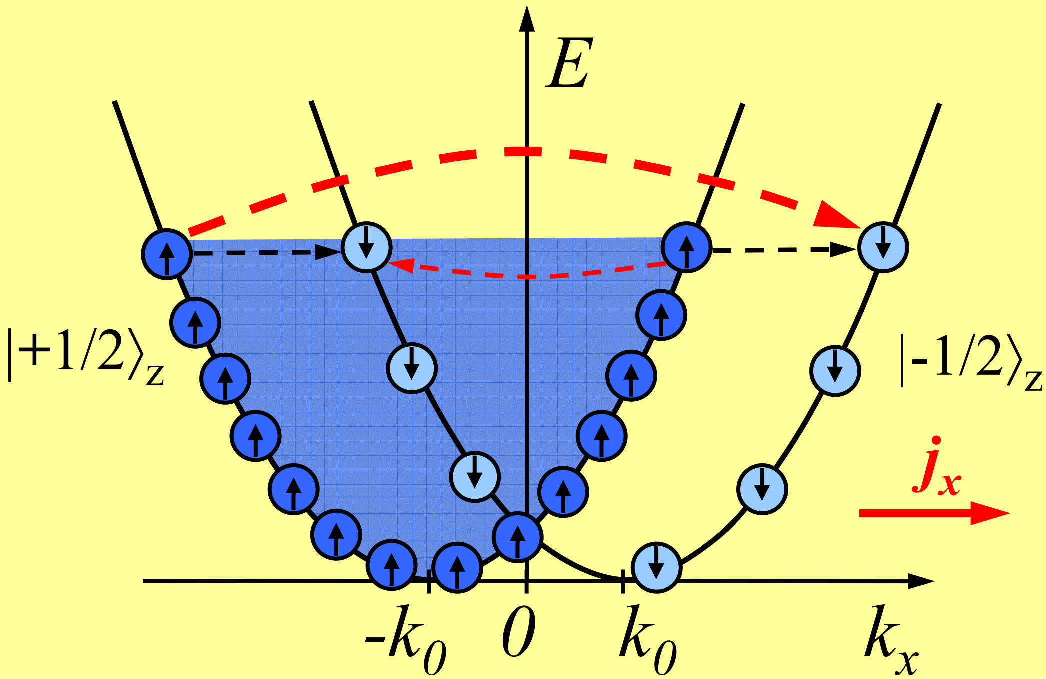
$$H_{so} = \frac{\hbar}{2}(\boldsymbol{\sigma} \cdot \boldsymbol{\Omega}_{\boldsymbol{k}})$$



Generation of the spin component S_z

$$\dot{S}_z = \Omega_{\boldsymbol{k},y} \tau_p \, \dot{S}_x \propto q_x P_{circ} I$$

III. SPIN-GALVANIC EFFECT



Asymmetry of spin relaxation processes

Conversion of spin into electric current

$\boldsymbol{S} \rightarrow \boldsymbol{j}$

(110)-grown QWs

$S_z \rightarrow j_x$

$S_x \not\rightarrow j_x$

Electric current

$j_x \propto S_z \propto q_x P_{circ} I$

Nature **417**, 153 (2002)

CIRCULAR PHOTON DRAG EFFECT IN QWS

Summary

- ✓ Circular Photon Drag has been observed in QW structures
- ✓ Experimental results are well described by the developed phenomenological theory
- ✓ Microscopic model of the Circular Photon Drag is proposed. It is a three-stage process that involves
  - light wavevector and helicity dependent optical orientation
  - spin rotation in an effective magnetic field
  - spin-galvanic effect caused by spin-relaxation asymmetry