Microscopic model: 
\( k \)-linear terms in the Hamiltonian

\[ \varepsilon = \frac{\hbar^2 k^2}{2m} \pm \beta k_x \]

- \( k \)-linear terms
- Spin-orbit interaction

- BIA (Dresselhauser)
- IIA
- SIA (Rashba)
Microscopic model: direct transitions

\[ j \propto W(\varepsilon) \tilde{v}(k_x^-) (\tau_{pi} - \tau_{pf}) \]

\[ h\omega > h\omega_{LO} \rightarrow \tau_{pi} \gg \tau_{pf} \]
Microscopic model: direct transitions

\[ j \propto W(\varepsilon) \nu(k_x) (\tau_{pi} - \tau_{pf}) \]

\[ h\omega > h\omega_{LO} \rightarrow \tau_{pi} \gg \tau_{pf} \]
Experiment: *e1*-e2 direct transitions

![Graph showing absorption in n-GaAs QWs](image-url)
Resonant inversion of the CPGE

\[ j_x (\text{CPGE}) \propto (\tau_{p1} - \tau_{p2}) \frac{d \eta_{21}(\hbar \omega)}{d \hbar \omega} \frac{IP_c}{\hbar \omega} \]

\[ \hbar \omega_1 > \hbar \omega_2 \]

\[ \sigma_+, \hbar \omega_1 \]

\[ \sigma_+, \hbar \omega_2 \]

\[ e^2 \quad (+1/2) \]

\[ e^2 \quad (-1/2) \]
Microscopic model: direct transitions

\[ j \propto W(\varepsilon) \nu(k) \tau_p(\varepsilon) \]
Direct interband transitions

Regensburg group (S. Ganichev) & Hannover group (M. Oesstreich), solid state comm. (2003)

M. Sakaki, Y. Ohno, H. Ohno, ICPC-2004

Excitation energy, $\hbar \omega$ (eV)

Degree of polarization

Time (ps)

Degree of polarization
Phenomenological description of PGE I

Fourier amplitudes: $j_i(\omega)$, $E_j(\omega)$

\[ j(0) = \sigma_{ij} E_j(0) \quad \text{Ohm's law} \]

\[ + \alpha_{ijkl} E_j(0) E_k(\omega) E^*_l(\omega) \quad \text{Photoconductivity} \]

\[ + \lambda_{ijk} E_j(\omega) E^*_k(\omega) \quad \text{Photogalvanic effect (PGE)} \]

\[ E_j(0) = 0 \quad \Rightarrow \quad j(0) = \lambda_{ijk} E_j(\omega) E^*_k(\omega) \]

Phenomenological description of PGE II

Photogalvanic effect (PGE):

$$j_i \text{ (PGE)} = \alpha_{i jl} e_j e^*_l = \chi_{i jl} [e_j e^*_l + e_l e^*_j] / 2 + \gamma_{ij} i (e \times e^*)_j$$

**Linear PGE**
(symmetric part)

**Circular PGE**
(anti-symmetric part)

$\chi_{i jl}$ - third rank *piezoelectric* tensor

$\gamma_{ij}$ - second rank *gyration* pseudo-tensor

$$j_i \text{ (CPGE)} = \gamma_{ij} i (e \times e^*)_j \propto E_0^2 P_{circ} = E_0^2 \sin 2\varphi$$

at first theoretically considered by: Ivchenko & Pikus
and, independently, by Belinicher & Sturman
observed in a bulk tellurium by V.M. Asnin, A.A. Bakun, A.M. Danishevskii, and A.A. Rogachev,
**Symmetry:**

- **Bulk GaAs, InAs etc.:** point group $T_d$
  - inversion asymmetric, but *non-gyrotropic*
  - no CPGE (linear photogalvanic effect only)

- **(001) - oriented QWs:** point group $D_{2d}$ or $C_{2v}$
  - CPGE --- only at oblique incidence

- **(113) - oriented QWs:** point group $C_S$
  - CPGE at normal and at oblique incidence
Mechanical analogues of the CPGE

transversal -wheel
longitudinal - propeller

angular momentum of circ. pol. photons $\rightarrow$ directed motion of carriers

$\vec{j}_x$
Helicity dependent current

$C_S$ symmetry

(113)A or miscut - grown QWs

$$j_x = (\gamma_{xy}\hat{e}_y + \gamma_{xz}\hat{e}_z)E_0^2\sin 2\varphi$$

CPGE current occurs normal to the mirror reflection plane!

(113)A- grown p-GaAs/AlGaAs MQWs
$T = 300$ K, $\lambda = 77$ µm

$\sigma_+$

$\sigma_-$

Physica E 14, 166 (2002)
Helicity dependent current

**C\textsubscript{S} symmetry**

(113)A or miscut - grown QWs

\[ j_x = (\gamma_{xy}\hat{e}_y + \gamma_{xz}\hat{e}_z)E_0^2\sin 2\varphi \]

CPGE current occurs normal to the mirror reflection plane!

**D\textsubscript{2d} or C\textsubscript{2v} symmetry**

in (001) - grown QWs, \( \hat{e}_y \parallel [110] \)

\[ j_x = \gamma_{xy}\hat{e}_y E_0^2\sin 2\varphi \]

CPGE current occurs under oblique excitation only!

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(113)A- grown
p- GaAs/AlGaAs MQWs
\( T = 300 \text{ K}, \lambda = 77 \text{ µm} \)

(001)- grown
n- InAs/AlGaSb QW
\( T = 300 \text{ K}, \lambda = 77 \text{ µm} \)
Normal and Oblique Incidence

$C_S$ symmetry

- (113)-grown $p$-GaAs/AlGaAs MQWs
  - $T = 300\ K$, $\lambda = 77\ \mu m$

$C_{2v}$ symmetry

- (001)-grown $n$-type InAs/AlGaSb QW
  - $T = 300\ K$, $\lambda = 77\ \mu m$

$\Theta_0$ - angle of incidence
Si:Ge quantum wells

[Diagram: cross symbol over a symmetric Si:Ge QW structure]

symmetric Si:Ge QWs do not show CPGE.
Si:Ge quantum wells

symmetric Si:Ge QWs do not show CPGE. ↔ asymmetric Si:Ge QWs!

PRB, (2002)

(001) p-SiGe stepped QW
T = 300 K
λ = 10.6 µm
Spin-galvanic effect

\[ j_\alpha = \sum_\beta Q_{\alpha\beta} S_\beta \]

current \hspace{1cm} averaged spin

e.g. for C_{2v}-symmetry and \( x \parallel [1\bar{1}0] \): \( Q_{xy}, Q_{yx} \) are non-zero:

\[ j_x = Q_{xy} S_y \]
Spin-galvanic effect

\[ j_\alpha = \sum_\beta Q_{\alpha\beta} S_\beta \]

current \hfill averaged spin

e.g. for $C_{2v}$-symmetry and $x \parallel [\bar{1}10]$: $Q_{xy}, Q_{yx}$ are non-zero:

\[ j_x = Q_{xy} S_y \]
Spin-galvanic effect

\[ j_\alpha = \sum_{\beta} Q_{\alpha\beta} S_\beta \]

current \quad \text{averaged spin}

e.g. for \( C_{2v} \)-symmetry and \( x \parallel [\bar{1}10] \): \( Q_{xy}, Q_{yx} \) are non-zero:

\[ j_x = Q_{xy} S_y \]
Microscopic model

\[ j_x = Q_{xy} S_y \]
Microscopic model

\[ j_x = Q_{xy} S_y \]

spin orientation

\[ k \text{-dependent spin-flip scattering} \]

\[ [v (k_{xf} - k_{xi})]^2 (k_{xf} + k_{xi})^2 \]
Microscopic model

\[ j_x = Q_{xy} S_y \]

spin orientation

k-dependent spin-flip scattering

\[ [v (k_{xf} - k_{xi})]^2 (k_{xf} + k_{xi})^2 \]

equilibrium