Methods II

**a)**
- Label: Signal (a.u.)
- Diagram: Excitation pulse
- Equations: $\hat{\theta}_z$, $B_x$, $j_x$, $\mathbf{x}_{\parallel}[1\bar{1}0]$, $S_y$
- Oscilloscope: $50\,\Omega$

**b)**
- Graphs: $\sigma_+$, $\sigma_-$
- Time (10\textsuperscript{−7}s)

**c)**
The diagram illustrates the behavior of a 2DEG (Two-Dimensional Electron Gas) under the influence of an external magnetic field $B_x$ and a current $j_x$. The vectors $\hat{e}_z$, $S_0z$, and $\omega_{\text{Larmor}}$ are also depicted, indicating the orientation and rotation angles. The notation $j_x = 0$ applies to a scenario where there is no current in the $x$ direction, while $j_x$ indicates a current flowing in the $x$ direction.
Intra-band Excitation

\[ j_x \propto \omega_L \tau_s \]

\[ j_x \sim \omega \tau_s \]

\[ j_x = 0 \quad j_x \neq 0 \]

2DEG

\[ \hat{e}_z \]

\[ S_0, S_y \]

\[ \omega_{\text{Larmor}} \]

\[ B_x \]

\[ j_{SGE} / P (10^{-10} A/W) \]

\[ n-\text{InAs QWs, } T = 293 K, \lambda = 148 \mu m \]

\[ \text{right circularly polarized light} \]

\[ \text{left circularly polarized light} \]

\[ B (\text{mT}) \]

\[ -800 \quad -400 \quad 0 \quad 400 \quad 800 \]
Intra-band and Inter-band Excitation

\[ \frac{j}{P} (10^{-9} \text{ A/W}) \]

\[ B_x (\text{mT}) \]

\[ T = 296 \text{ K} \]

\[ \lambda = 0.777 \mu \text{m} \]

\[ \lambda = 148 \mu \text{m} \]
Hanle Effect in Spin-Galvanic Effect

\[ j_x \propto S_y = S_{oz} \frac{\omega_L \tau_S}{1 + (\omega_L \tau_S)^2} \]

\[ j_x \propto S_y = S_{oz} \frac{\omega_L \tau_S}{1 + (\omega_L \tau_S)^2} \]

- n-GaAs/AlGaAs
- \( \lambda = 148 \mu m \)
- \( \tau_S = 40 \text{ ps} \)
- \( T = 4.2 \text{ K} \)
Magnetic field induced circular photogalvanic effect

\[ j_x = -\mu B_x E_0^2 P_{\text{circ}} \propto B_x \sin 2\phi \]

(001)-grown GaAs QW:

\[ j_x = 0 \]

\[ j_x \]

\[ B = \pm 2 \text{T} \]

(001) n-GaAs/AlGaAs

in the case of QW \(\Rightarrow\) Spin-galvanic effect
Inter-subband Excitation

(001)-grown $n$-GaAs QWs
$T = 296$ K
Removal of space inversion

In noncentrosymmetrical materials space symmetry is absent: $\varepsilon(k) = \varepsilon(-k)$

(Without magnetic field Kramers doublets are present (time symmetry: $\varepsilon(k) = \varepsilon(-k)$)

Bulk $A^3B^5$ (Noncentrosymmetric) semiconductors: Bulk Inversion Asymmetry

$$\hat{H}_{SO}^D = \hbar \Omega \cdot \sigma / 2.$$  

In the coordinate system $x \parallel [100]$, $y \parallel [010]$, $z \parallel [001]$:

$$\Omega \propto [k_x(k_y^2 - k_z^2)x + k_y(k_z^2 - k_x^2)y + k_z(k_x^2 - k_y^2)z$$

(G. Dresselhaus, Phys. Rev. 1955)

$k$-cubic terms in the effective Hamiltonian
Removal of space inversion in zinc-blende structure based symmetrical QWs

In two dimensional structures $k_z = 0$ (but not the average $k_z^2$ !!) (Without magnetic field Kramers doublets are present (time symmetry: $\varepsilon(k) = \varepsilon(-k)$)

$$\Omega \propto \left[ k_x (k_y^2 - k_z^2) x + k_y (k_z^2 - k_x^2) y + k_z (k_x^2 - k_y^2) z \right]$$

For QWs system grown in $z \parallel [001]$ direction by setting $k_z \to \langle k_z \rangle = 0$ and $k_z^2 \to \langle k_z^2 \rangle \approx (\pi/L_z)^2$ :

$$\hat{H}_{SO}^D = \beta (\sigma_x k_x - \sigma_y k_y) .$$

**Interface Inversion Asymmetry**:
no-common-atom system (InAs/GaSb). IIA vanishes for (110)–grown structures.

$$\text{BIA} + \text{IIA} \rightarrow \text{Dresselhaus term}$$

$k$-linear terms in the effective Hamiltonian
Removal of space inversion in asymmetrical QWs
(Without magnetic field Kramers doublets are stil present (time symmetry: $\varepsilon (k) = \varepsilon (-k)$)

**Structure Inversion Asymmetry**
(absence of inversion in the growth direction):
$z$ is non-equal to $-z$

$$\hat{H}_{SO}^R = \alpha [\sigma \times k]_z = \alpha (\sigma_x k_y - \sigma_y k_x).$$

**SIA $\rightarrow$ Rashba term**

**TOTAL:**

$$\hat{H}_{SO} = \alpha (\sigma_x k_y - \sigma_y k_x) + \beta (\sigma_x k_x - \sigma_y k_y)$$

In the coordinate system $1 \parallel [\overline{1}0], 2 \parallel [110], z \parallel [001]:$

$$\hat{H}_{SO} = \alpha (\sigma_1 k_2 - \sigma_2 k_1) + \beta (\sigma_1 k_2 + \sigma_2 k_1)$$

$k$-linear terms in the effective Hamiltonian
2D band structure

$\varepsilon_{kx} \parallel [100]$
$\varepsilon_{ky} \parallel [010]$

$|k_y| = |k_x|$

BIA=0
SIA≠0

BIA≠0
SIA=0

BIA = SIA

BIA ≠ SIA
Experiments on the details of the band structure

\[ H = \hbar^2 k^2 / 2m^* + \hat{H}_{SO} \]

Cubic axes: \(x, y\)

\[ \hat{H}_{SO} = \alpha(\sigma_x k_y - \sigma_y k_x) + \beta(\sigma_x k_x - \sigma_y k_y) \]

\(\alpha\) - Rashba term

\(\beta\) - Dresselhaus term

\[ \alpha \neq \beta \]
Experiments on the details of the band structure

\[ \hat{H} = \hbar^2 k^2 / 2m^* + \hat{H}_{SO} \]

Cubic axes: \( x, y \)

\[ \hat{H}_{SO} = \alpha (\sigma_x k_y - \sigma_y k_x) + \beta (\sigma_x k_x - \sigma_y k_y) \]

\( \alpha \) - Rashba term

\( \beta \) - Dresselhaus term

Spin-galvanic current:

\[ \vec{j}_{SGE} \propto \begin{pmatrix} \beta & -\alpha \\ \alpha & -\beta \end{pmatrix} \hat{S} \]

Direct measurement of the ratio \( \alpha / \beta \)

(\( \alpha \) - Rashba term, \( \beta \) - Dresselhaus term)
Experiments on the details of the band structure

Spin-galvanic current:

\[
\mathbf{j}_{SGE} \propto \begin{pmatrix} \beta & -\alpha \\ \alpha & -\beta \end{pmatrix} \mathbf{S}
\]

\[
j_R/j_D = \frac{\alpha}{\beta}
\]

\[
j(\Theta) = j_D \cos(\Theta + \phi) + j_R \sin(\Theta - \phi)
\]
Experiments on the details of the band structure

Spin-galvanic current: \[ j_{SGE} \propto (\beta - \alpha) \vec{S}, \quad j_R/j_D = \alpha / \beta \]

InAs: \[ \frac{\alpha}{\beta} = 2.15 \]