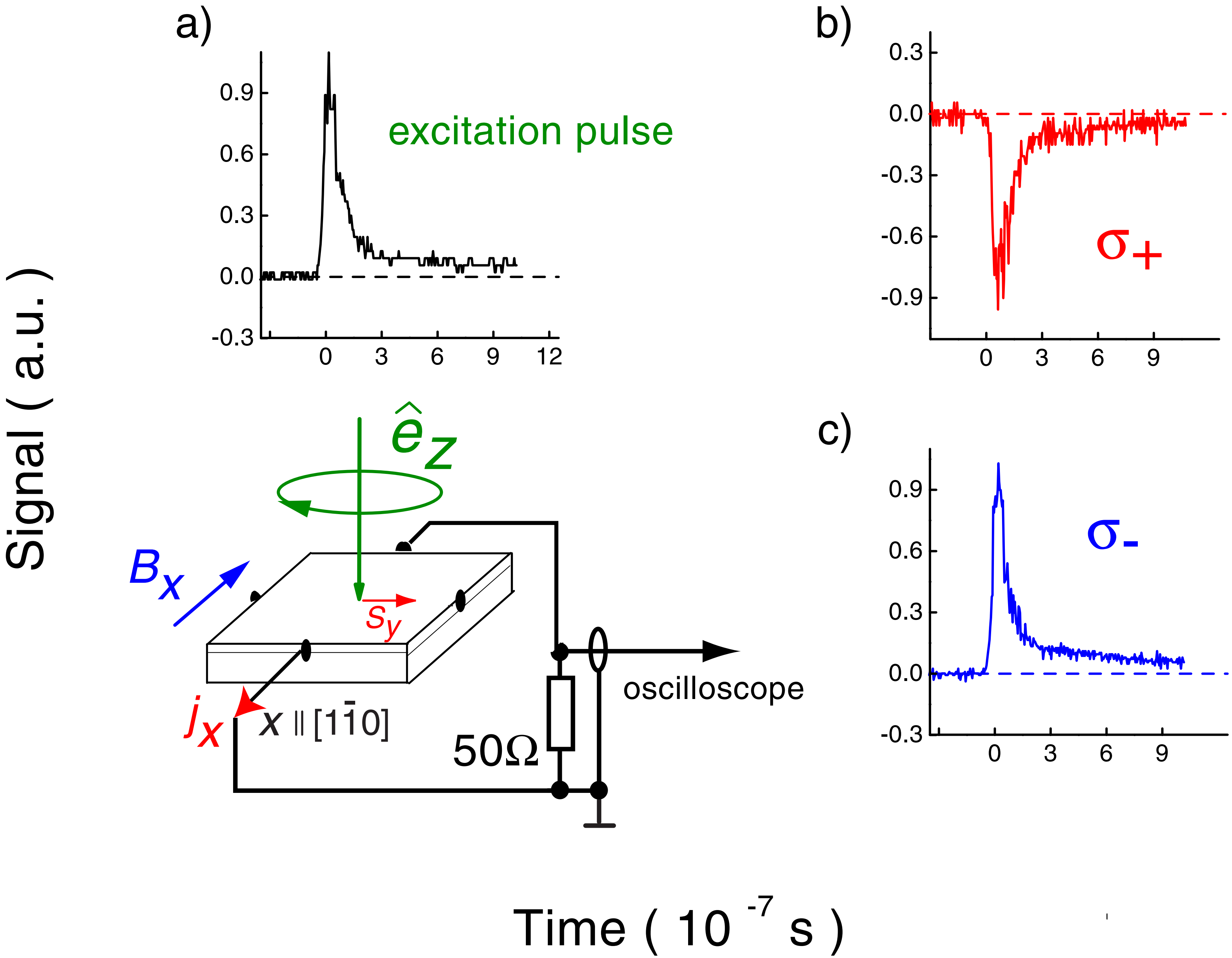
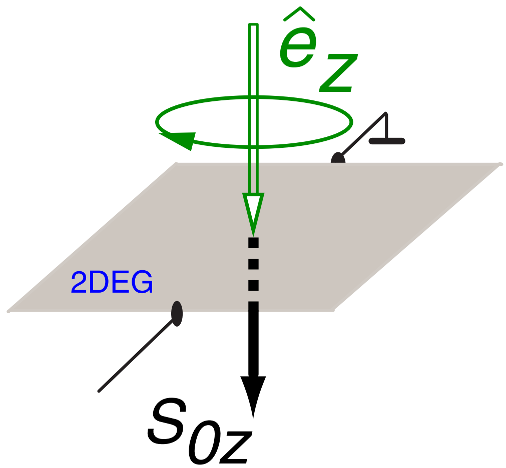
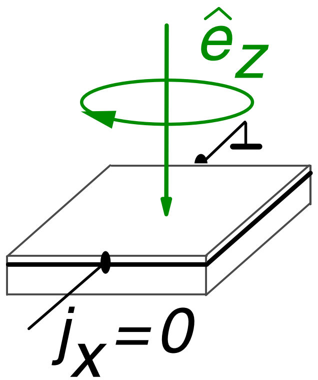
# Methods II



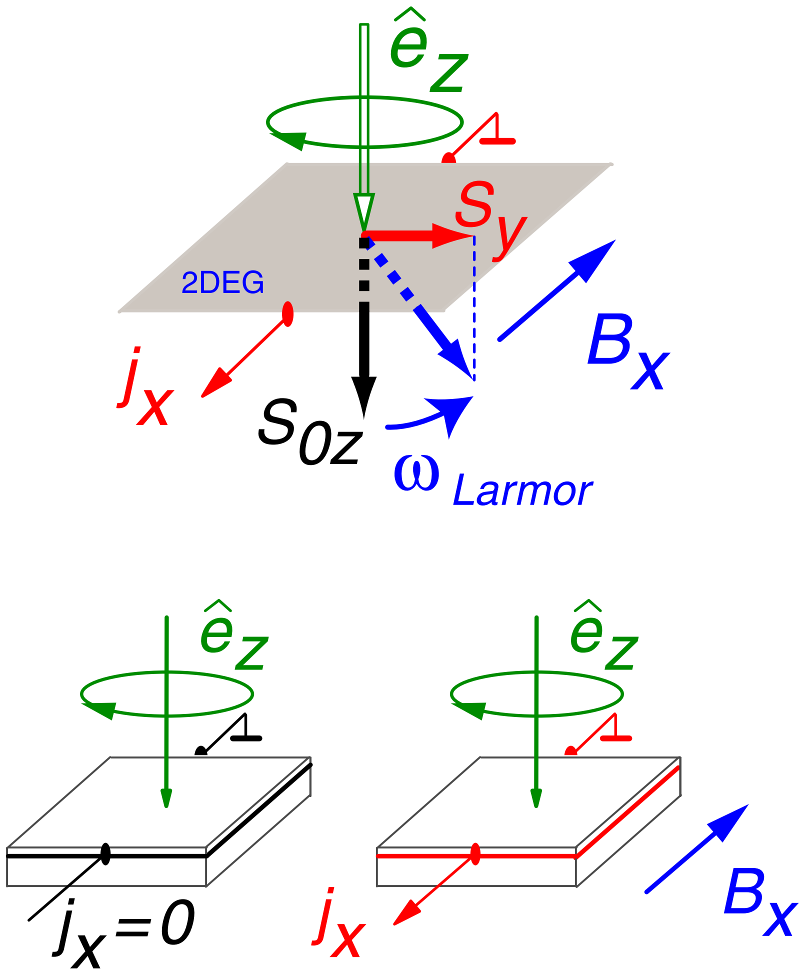
a)
excitation pulse
b)
σ+
c)
σ-
Signal ( a.u. )
Time ( 10 -7 s )
$\hat{e}_z$
$B_x$
$s_y$
$j_x$
x ∥ [1$\bar{1}$0]
50Ω
oscilloscope



$\hat{e}_z$
2DEG
$S_{0z}$

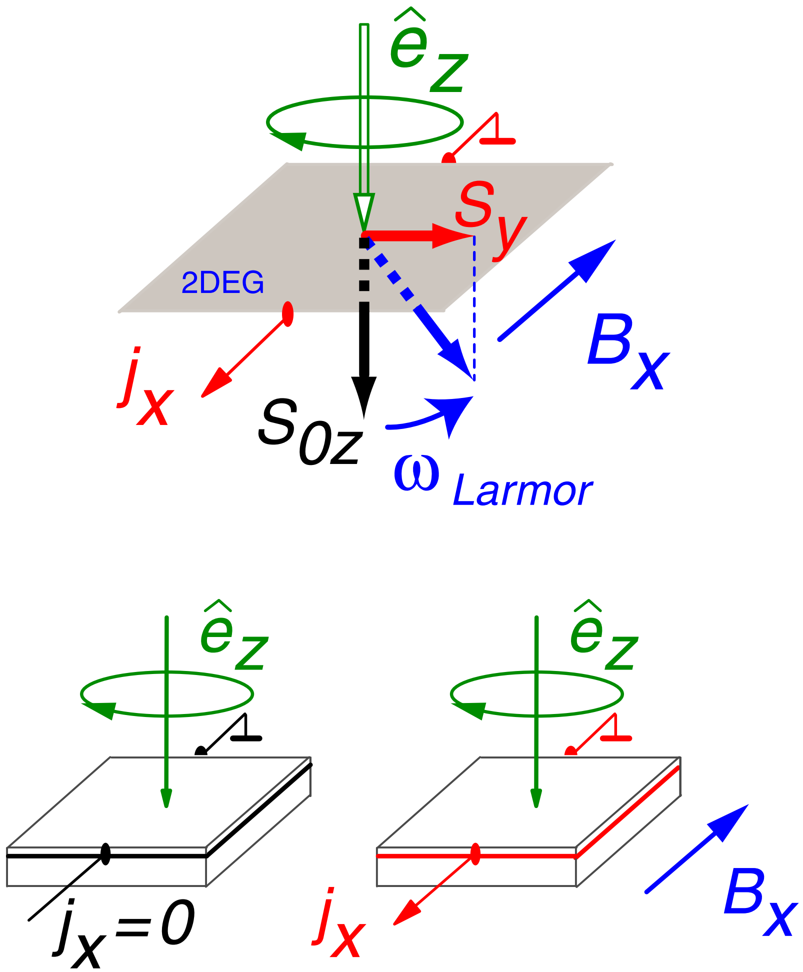
$\hat{e}_z$
$j_x = 0$

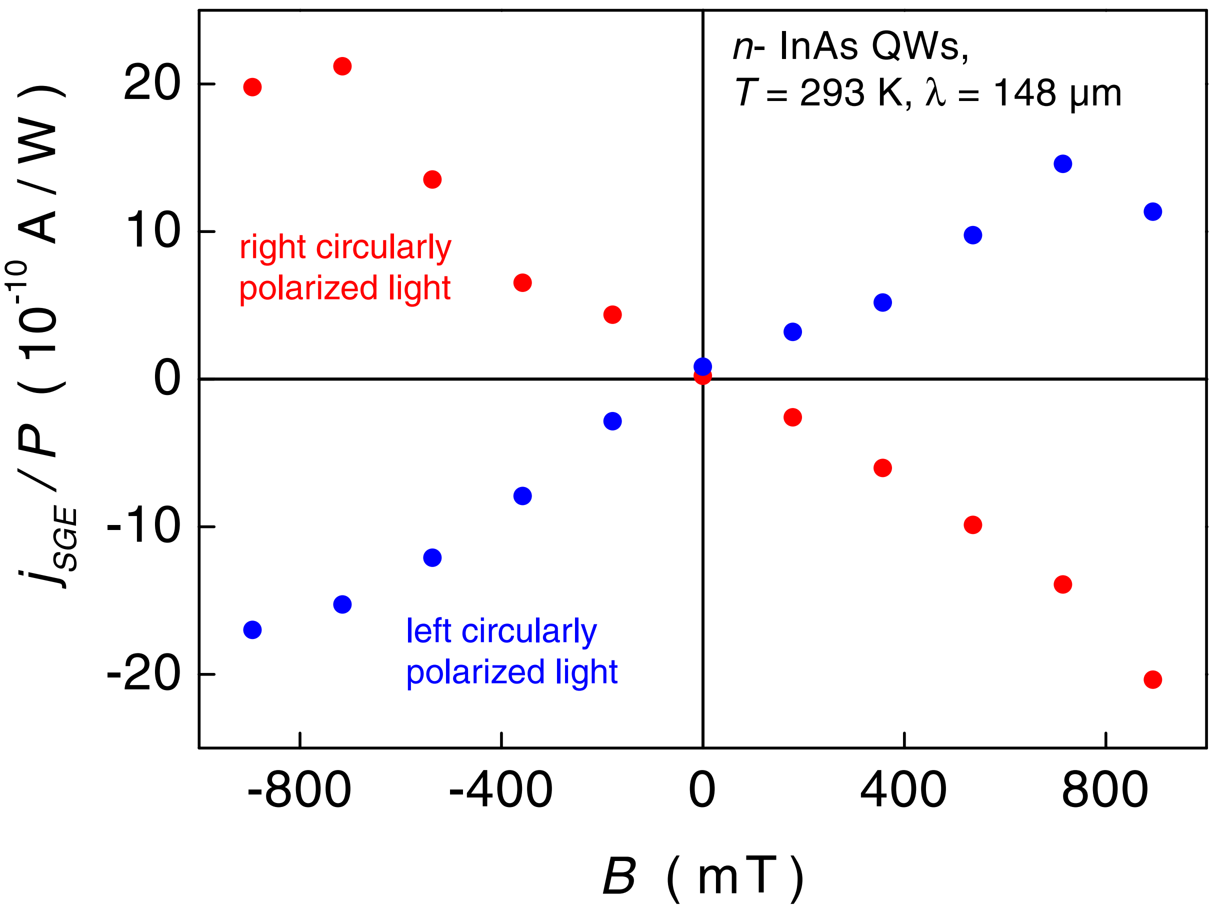


ê z
S y
2DEG
B x
j x
S 0z
ω Larmor
ê z
ê z
j x =0
j x
B x

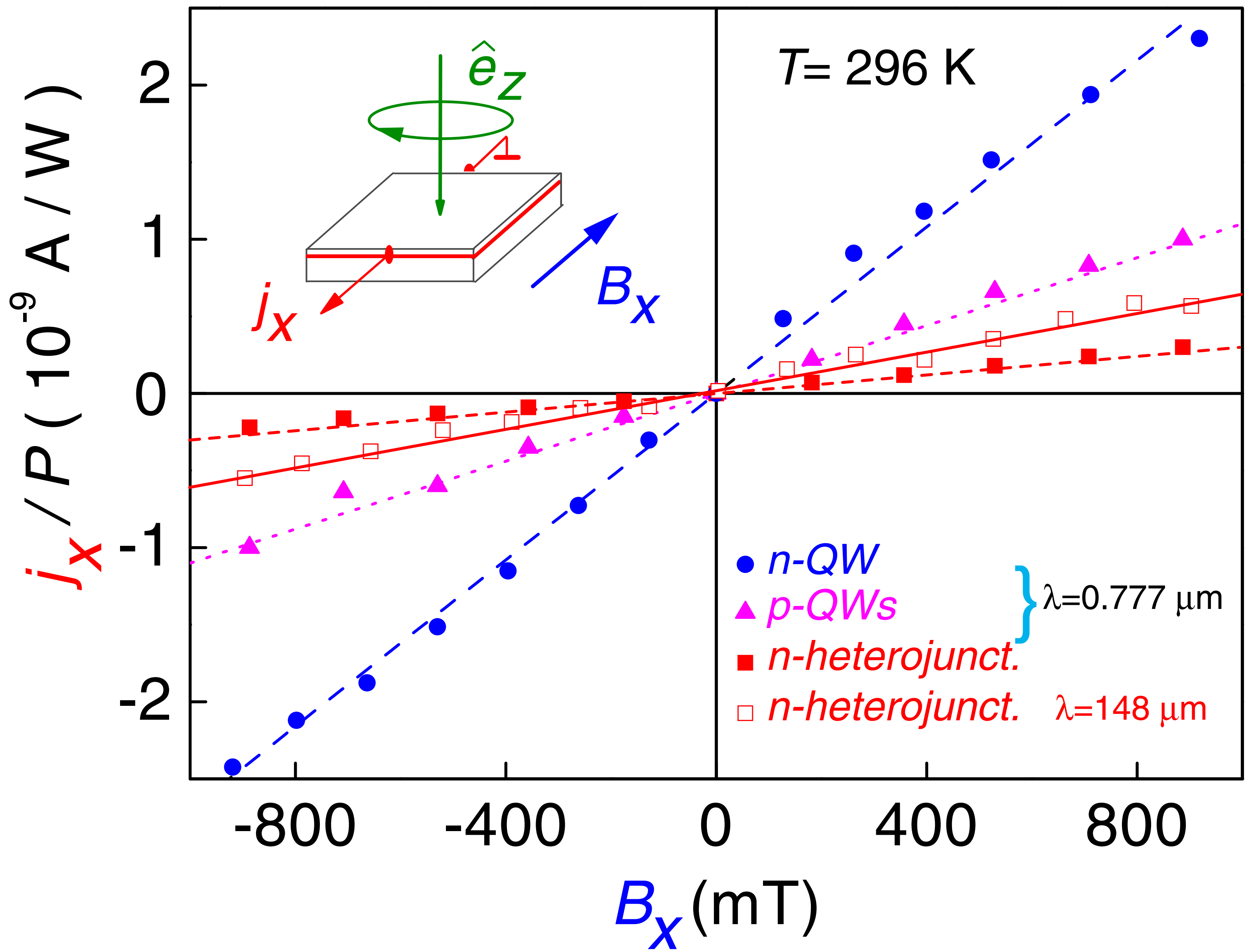
# *Intra*-band Excitation

$$\boxed{j_x \propto \omega_L \tau_s}$$



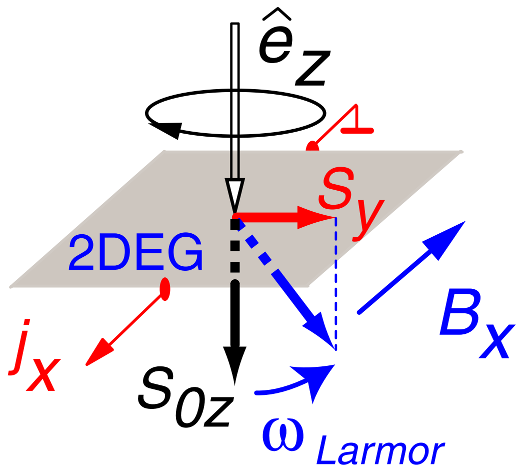



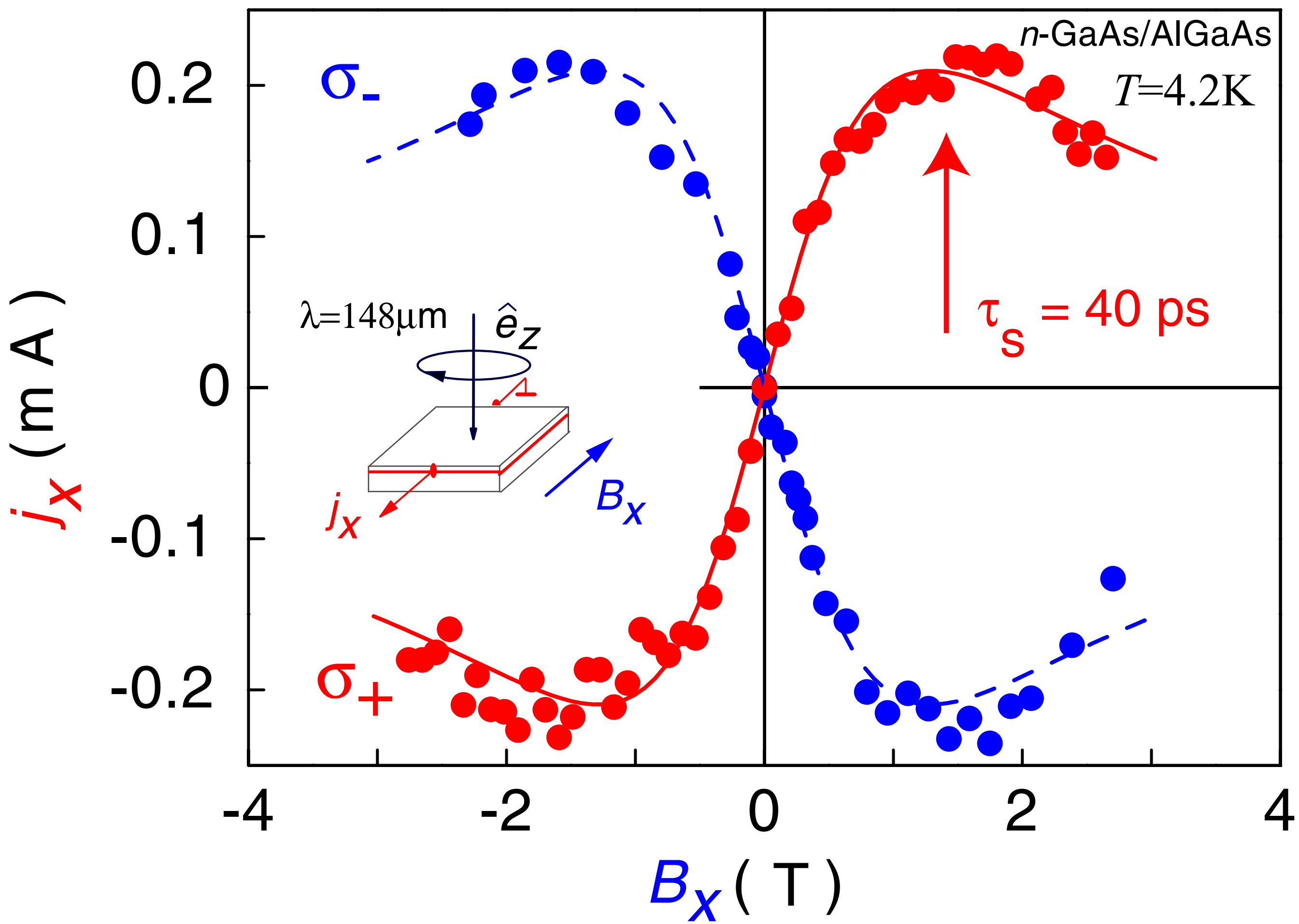
# *Intra*-band and *Inter*-band Excitation



# Hanle Effect in Spin-Galvanic Effect

$$j_x \propto S_y = S_{oz} \frac{\omega_L \tau_s}{1 + (\omega_L \tau_s)^2}$$

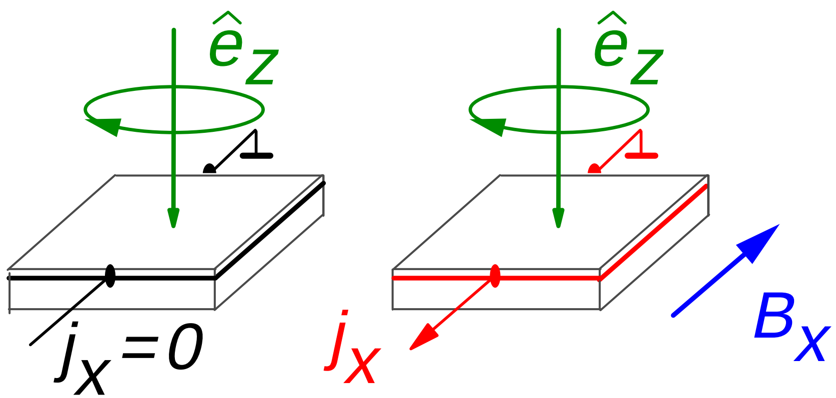


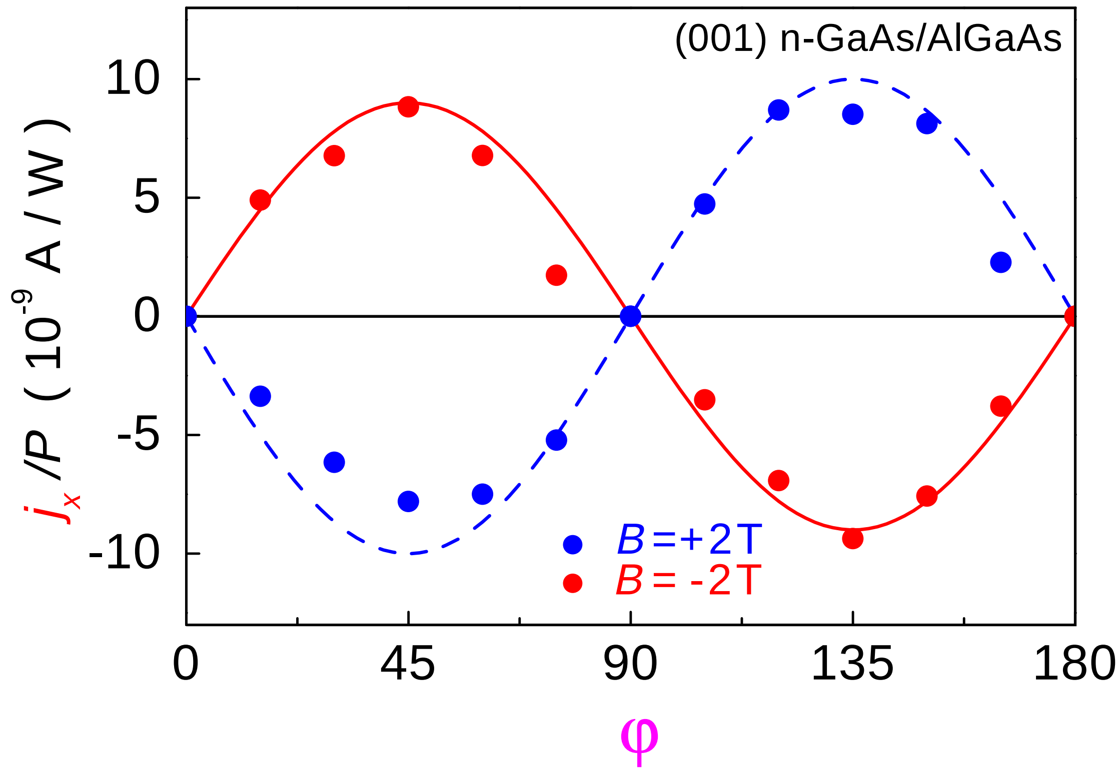



# Magnetic field induced circular photogalvanic effect

$$j_x = -\mu B_x E_0^2 P_{circ} \propto B_x \sin 2\varphi$$

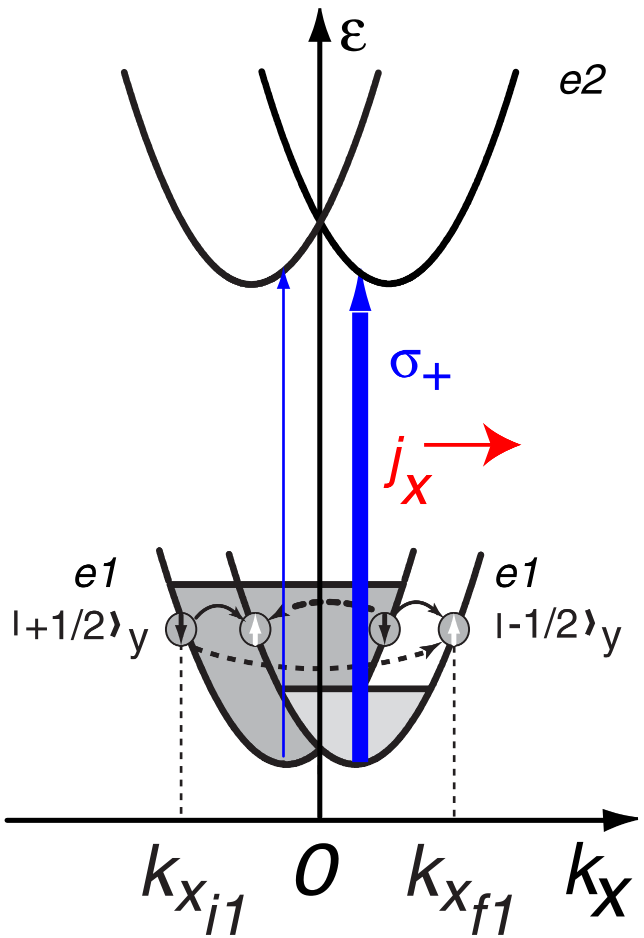
(001)-grown GaAs QW:

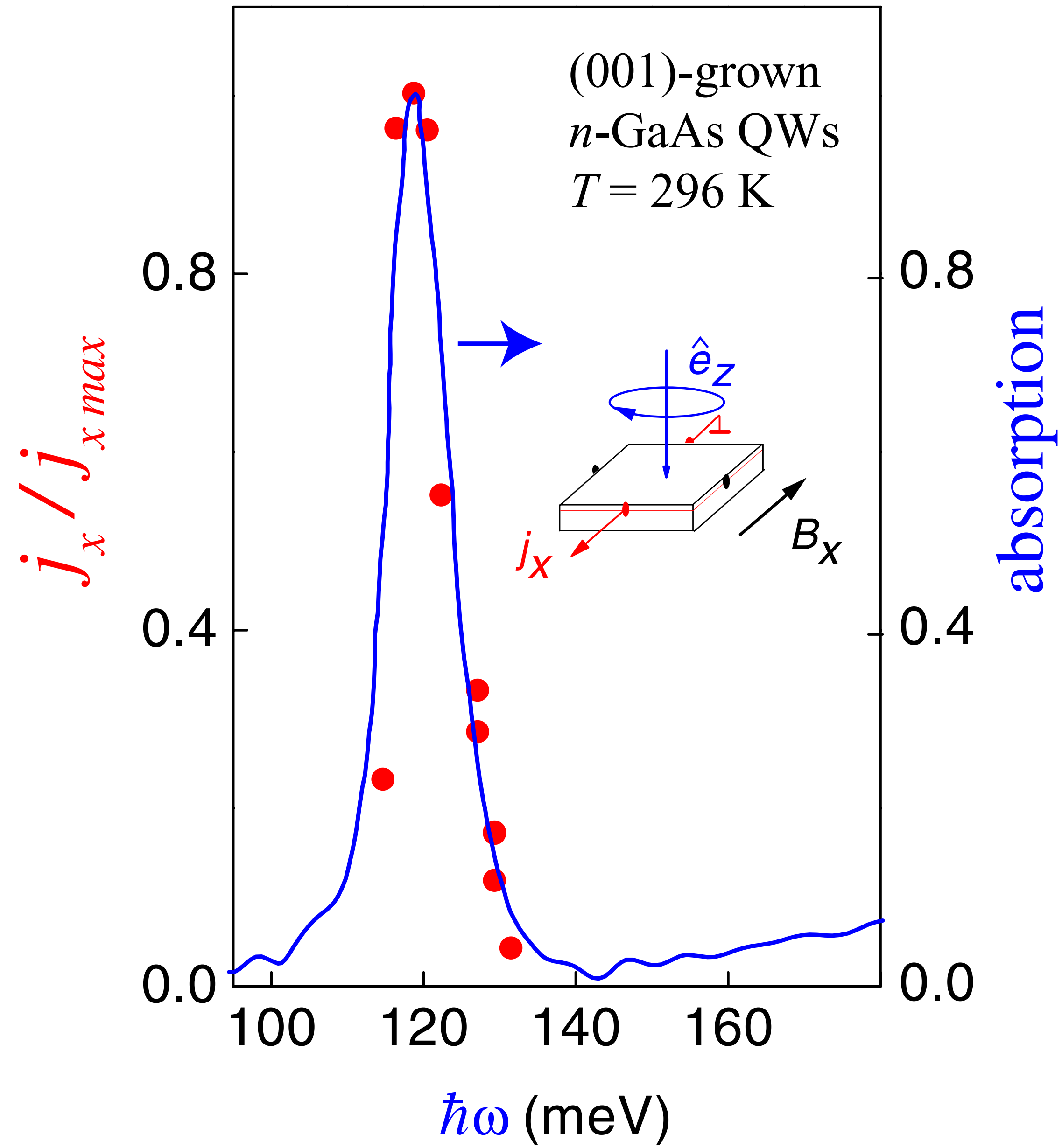



in the case of QW ⇒ Spin-galvanic effect

# *Inter-sub*band Excitation



# Removal of space inversion

In noncentrosymmetrical materials space symmetry is absent: $\varepsilon_{\uparrow}(k) = \varepsilon_{\uparrow}(-k)$
(Without magnetic field Kramers doublets are present (time symmetry: $\varepsilon_{\uparrow}(k) = \varepsilon_{\downarrow}(-k)$ )

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

**Bulk Inversion Asymmetry**

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

**In the coordinate system** x ‖ [100], y ‖ [010], z ‖ [001] :

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

**(G.Dresselhaus, Phys. Rev. 1955)**

k-cubic terms in the effective Hamiltonian

# Removal of space inversion in zink-blende structure based symmetrical QWs

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

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

**For QWs system grown in z || [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.**

**BIA + IIA → 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: $\varepsilon_{\uparrow}(k) = \varepsilon_{\downarrow}(-k)$ )

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

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

**SIA → Rashba term**

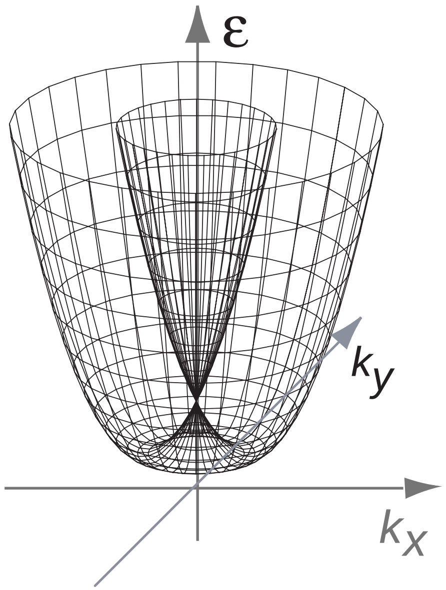
TOTAL: $\hat{H}_{SO} = \alpha(\sigma_x k_y - \sigma_y k_x) + \beta(\sigma_x k_x - \sigma_y k_y)$

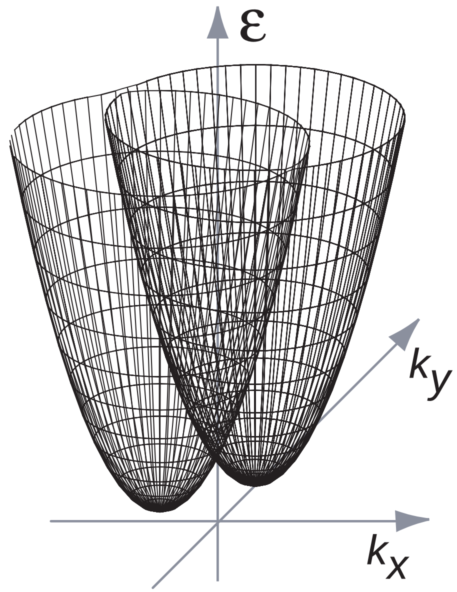
In the coordinate system $1 \parallel [1\bar{1}0],\ 2 \parallel [110],\ z \parallel [001]$ :

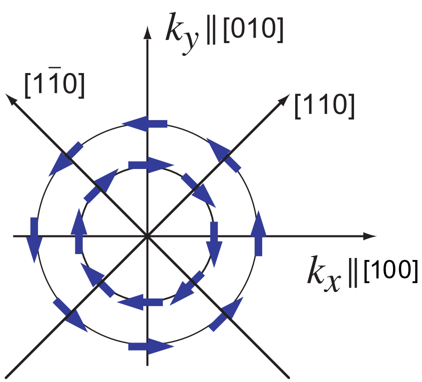
$$\hat{H}_{SO} = \alpha(\sigma_1 k_2 - \sigma_2 k_1) + \beta(\sigma_1 k_2 + \sigma_2 k_1)$$

k-linear terms in the effective Hamiltonian

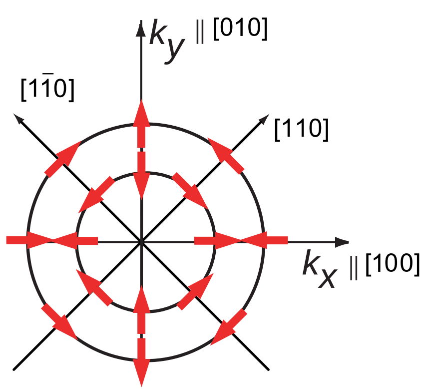
# 2D band structure



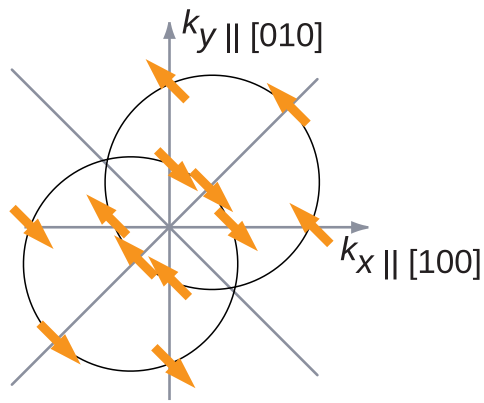



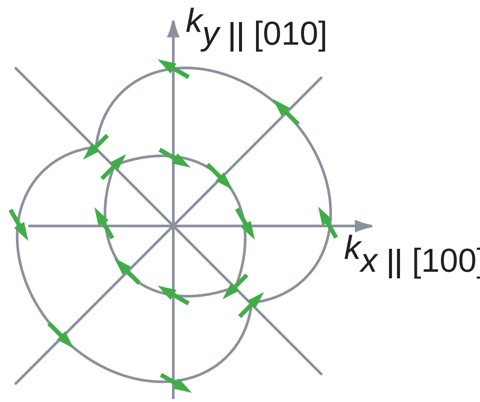

BIA=0
SIA≠0




BIA≠0
SIA=0




BIA = SIA




BIA ≠ SIA

# Experiments on the details of the band structure

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

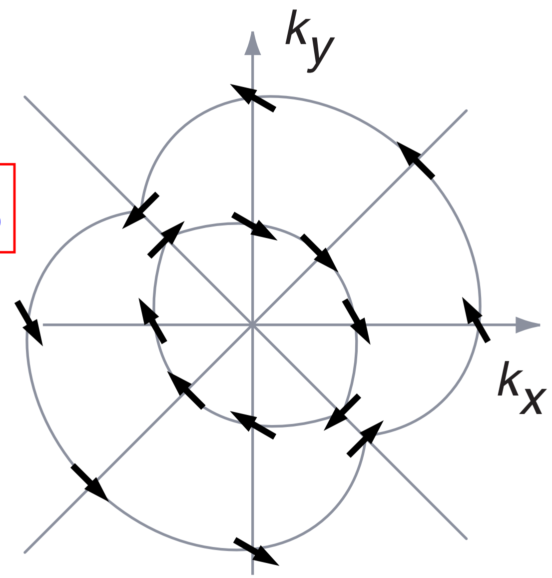
*Cubic axes: $x,y$*

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

$\alpha$ - *Rashba term*

$\beta$ - *Dresselhaus term*

$\alpha \neq \beta$



# Experiments on the details of the band structure

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

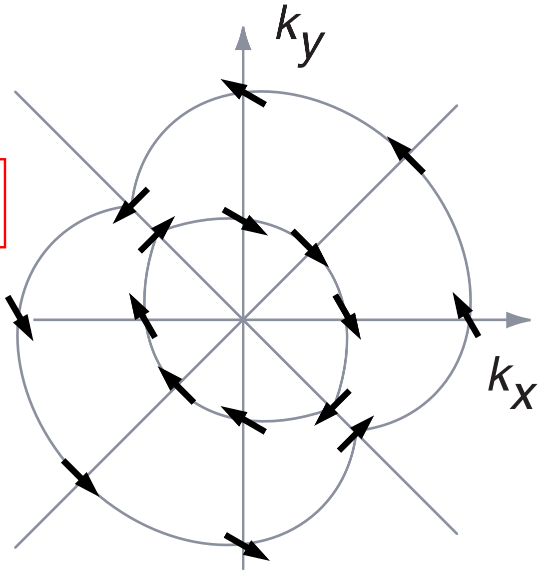
*Cubic axes: x,y*

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

$\alpha$ - *Rashba term*

$\beta$ - *Dresselhaus term*

$\alpha \neq \beta$




## Spin-galvanic current:

$$\vec{j}_{SGE} \propto \begin{pmatrix} \beta & -\alpha \\ \alpha & -\beta \end{pmatrix} \vec{S} \longrightarrow$$

Direct measurement of the ratio $\alpha / \beta$

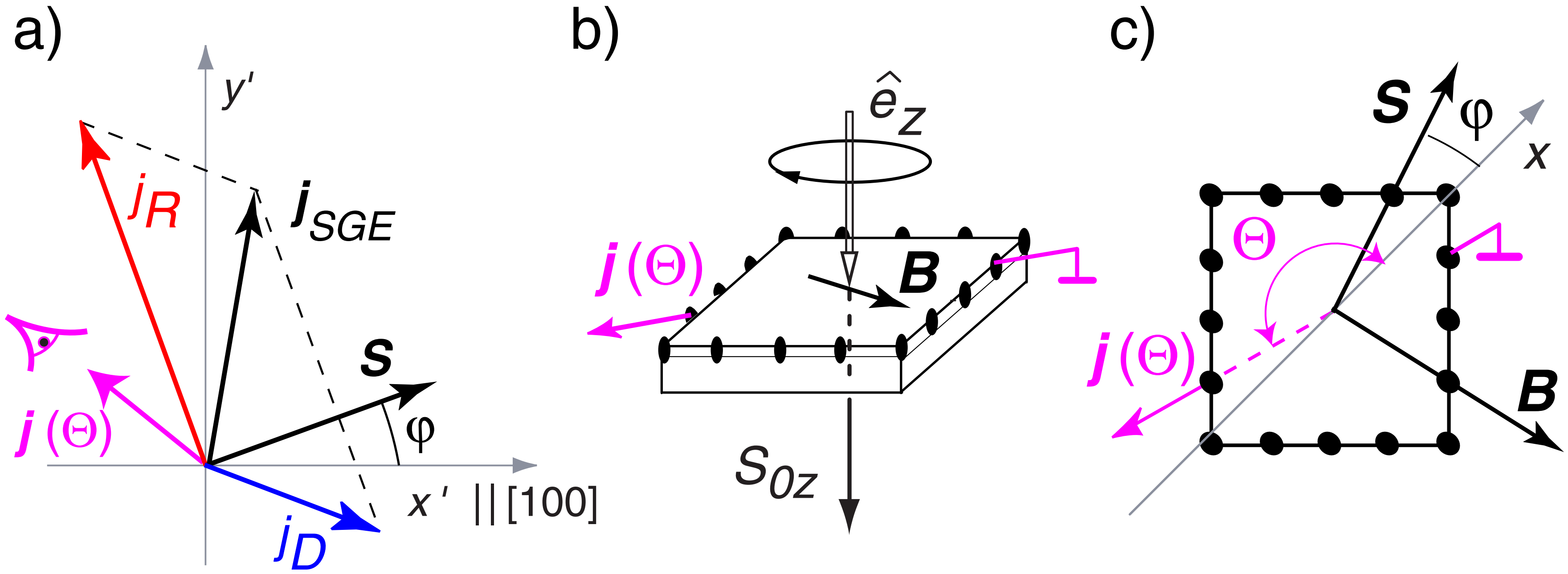
($\alpha$ - *Rashba term*, $\beta$ - *Dresselhaus term*)

# Experiments on the details of the band structure

Phy.Rev.Lett. 2004

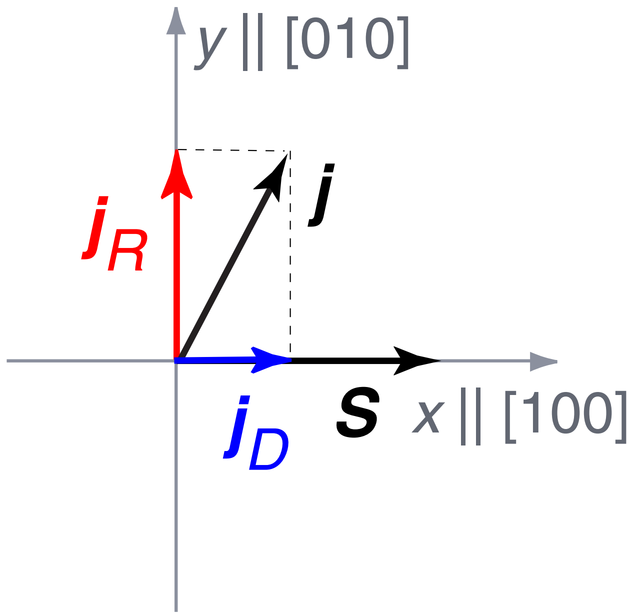
Spin-galvanic current: $\vec{j}_{SGE} \propto \begin{pmatrix} \beta & -\alpha \\ \alpha & -\beta \end{pmatrix} \vec{S}$ $\quad j_R / j_D = \alpha / \beta$

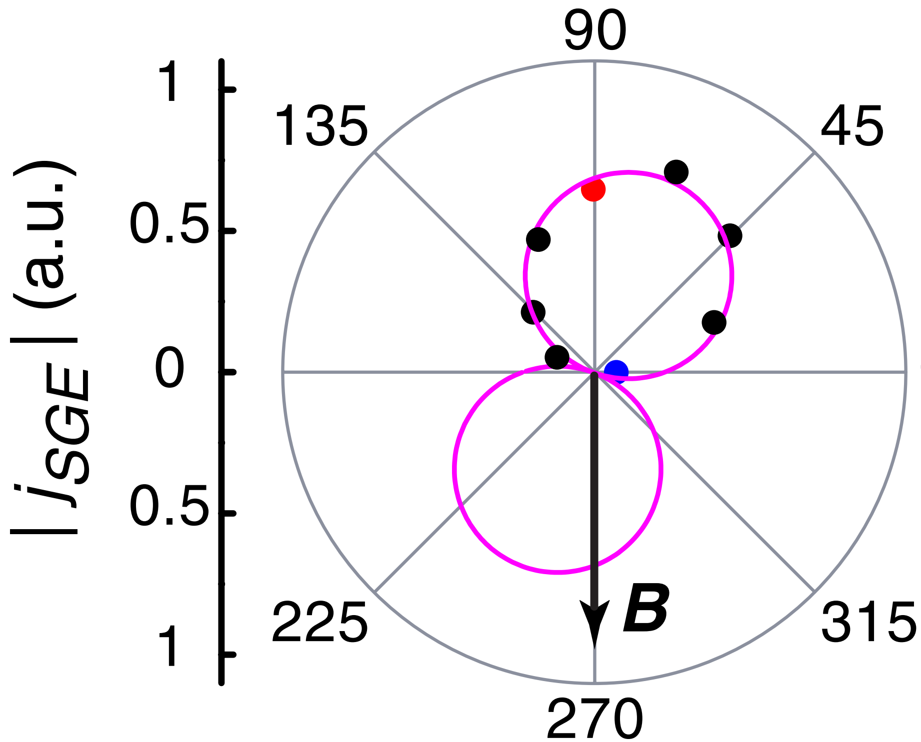
$$j(\Theta) = j_D \cos(\Theta + \varphi) + j_R \sin(\Theta - \varphi)$$



# Experiments on the details of the band structure

Spin-galvanic current: $\vec{j}_{SGE} \propto \begin{pmatrix} \beta & -\alpha \\ \alpha & -\beta \end{pmatrix} \vec{S}$ $\qquad j_R / j_D = \alpha / \beta$




InAs: $\alpha / \beta = 2.15$