Magnetism and Spin-Orbit Interaction:

Magnetism

Basic concepts

magnetic moments, susceptibility, paramagnetism, ferromagnetism
exchange interaction, domains, magnetic anisotropy,

Examples:

detection of (nanoscale) magnetization structure
using Hall-magnetometry, Lorentz microscopy and MFM

Spin-Orbit interaction

Some basics

Rashba- and Dresselhaus contribution, SO-interaction and effective magnetic field

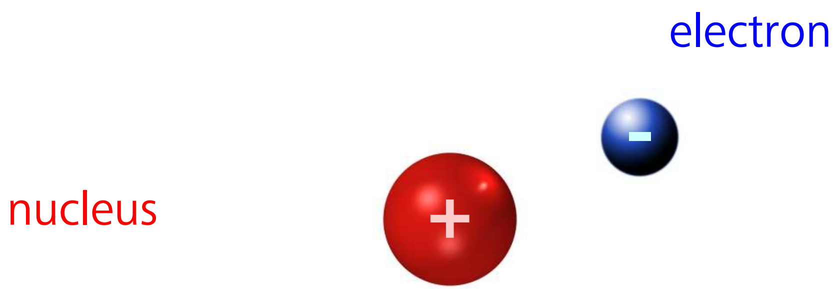
Example:

Ferromagnet-Semiconductor Hybrids: TAMR involving epitaxial Fe/GaAs interfaces

Origin of spin-orbit (SO) interaction

Spin-orbit interation $E = -\mu_B B_{eff}$ due to orbital motion

magnetic moment of electron



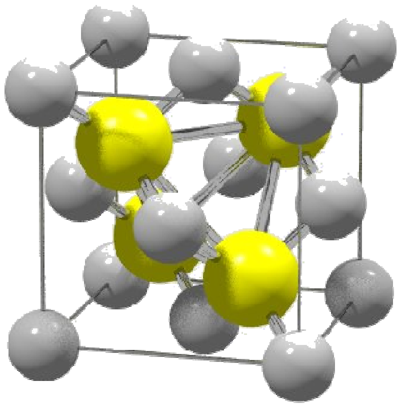
$$\hat{H}_{SO} = -\mu_B \hat{\boldsymbol{\sigma}} \cdot \left[\frac{\mathbf{E} \times \mathbf{p}}{2mc^2} \right]$$

vector of Pauli spin matrices

$$\mathbf{B}_{eff} = \frac{\mathbf{E} \times \mathbf{p}}{2mc^2}$$

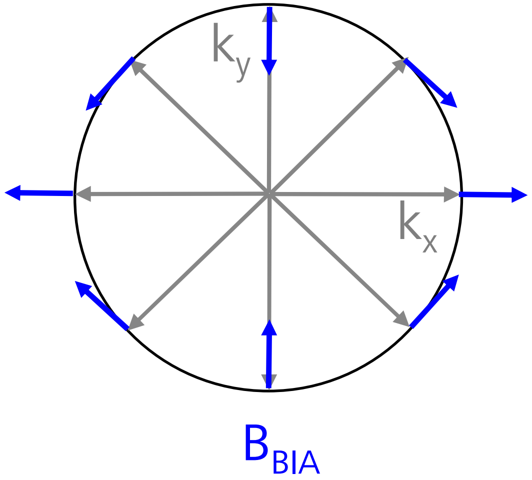
$$\hat{H}_{Zeeman} = -\mu_B \hat{\boldsymbol{\sigma}} \cdot \mathbf{B}$$

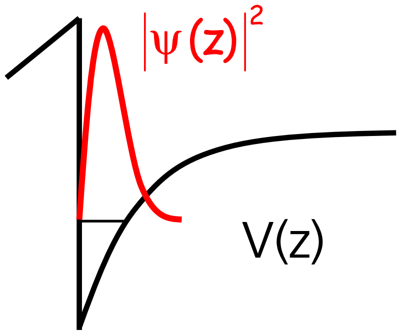
Electric field E in solids



Bulk inversion asymmetry (BIA)
Lack of inversion symmetry in III-V semiconductors
"Dresselhaus contribution γ"

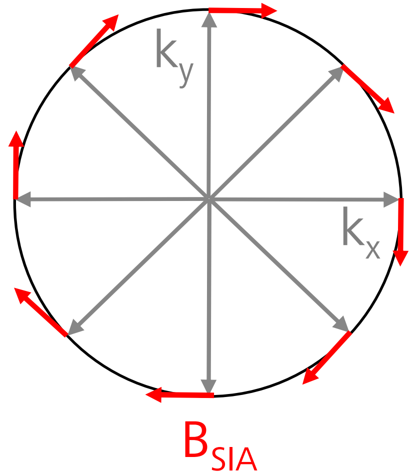
$$B_{BIA} \propto \gamma \begin{pmatrix} k_x \\ -k_y \end{pmatrix}$$





Structure inversion asymmetry (SIA) due to macroscopic confining potential: "Rashba contribution α". Tunable by external electric field!

$$B_{SIA} \propto \alpha \begin{pmatrix} k_y \\ -k_x \end{pmatrix}$$



SO interaction in 2DEG: Rashba & Dresselhaus terms

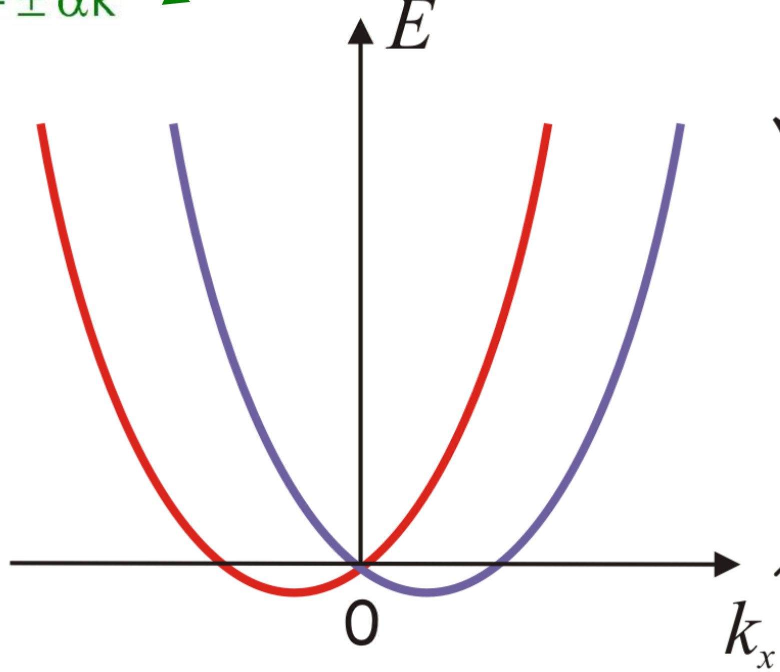
$$\hat{\mathbf{H}} = \frac{\hbar^2 k^2}{2m} + \hat{\mathbf{H}}_{SO} \quad \text{with}$$

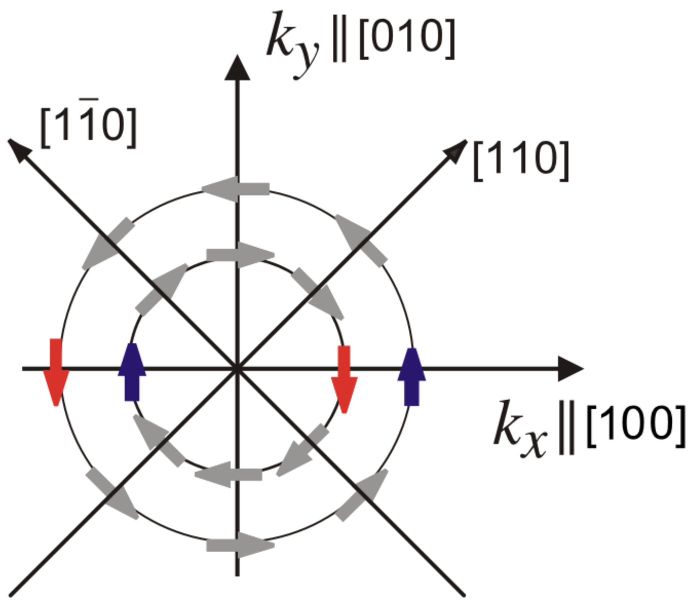
tunable by gate voltage

Pauli spin matrix

$$\hat{\mathbf{H}}_{SO} = \underbrace{\alpha(\boldsymbol{\sigma}_x k_y - \boldsymbol{\sigma}_y k_x)}_{\text{Rashba}} + \underbrace{\gamma(\boldsymbol{\sigma}_x k_x - \boldsymbol{\sigma}_y k_y)}_{\text{Dresselhaus}}$$

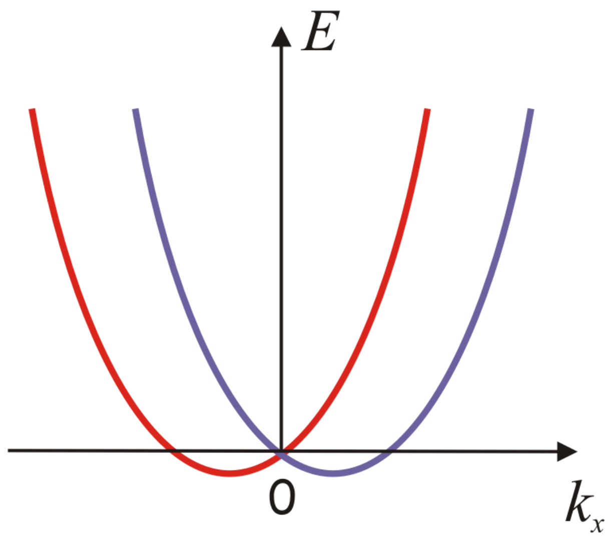
$$E = \frac{\hbar^2 k^2}{2m} \pm \alpha k$$





Calculation of Eigenvalue

$$E = \frac{\hbar^2 k^2}{2m} \pm \alpha k$$



$$\hat{\mathbf{H}}_{SO}^{Rashba} = \alpha(\boldsymbol{\sigma}_x k_y - \boldsymbol{\sigma}_y k_x)$$

$$\hat{\boldsymbol{\sigma}}_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}; \quad \hat{\boldsymbol{\sigma}}_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}; \quad \hat{\boldsymbol{\sigma}}_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Pauli Spin matrices

$$\hat{\mathbf{H}}_{SO}^{Rashba} = \alpha(\boldsymbol{\sigma}_x k_y - \boldsymbol{\sigma}_y k_x) =$$

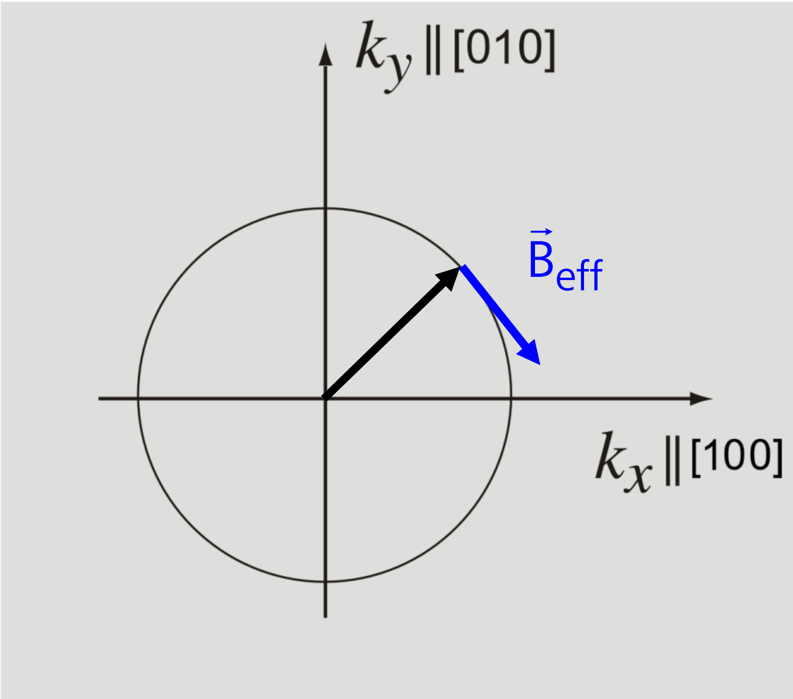
$$= \begin{pmatrix} 0 & \alpha k_y \\ \alpha k_y & 0 \end{pmatrix} - \begin{pmatrix} 0 & -i\alpha k_x \\ i\alpha k_x & 0 \end{pmatrix} = \begin{pmatrix} 0 & \alpha(k_y + ik_x) \\ \alpha(k_y - ik_x) & 0 \end{pmatrix}$$

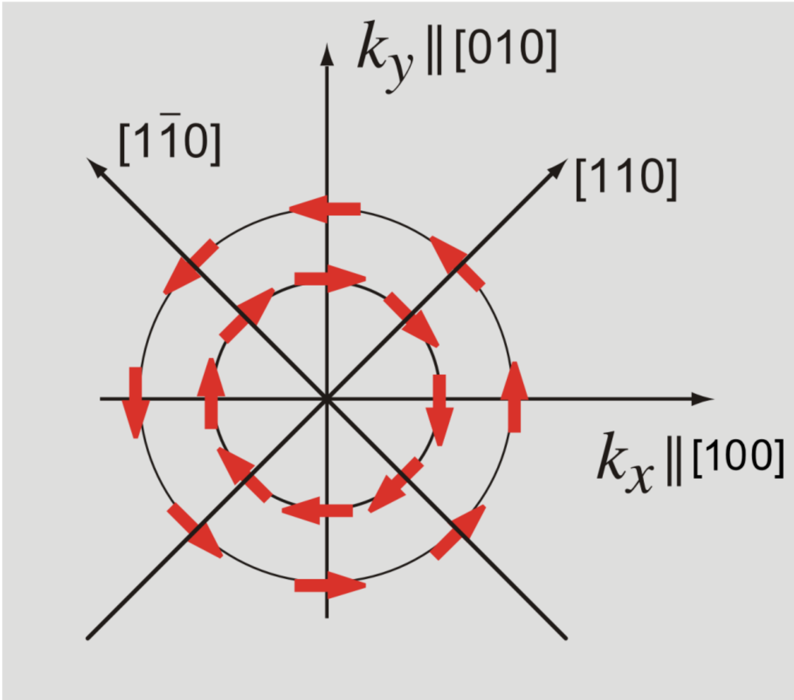
Eigenvalues of the matrix: $\pm\alpha\sqrt{k_x^2 + k_y^2} = \pm\alpha k_{||}$

Description of zero-field spin splitting by B_{eff}

$$\hat{H}_{SO} = \underbrace{\alpha(\sigma_x k_y - \sigma_y k_x)}_{\text{Rashba}} + \underbrace{\gamma(\sigma_x k_x - \sigma_y k_y)}_{\text{Dresselhaus}} \sim \hat{\sigma} \cdot \vec{B}_{eff}; \quad \hat{\sigma} \cdot \vec{B}_{eff} = \sigma_x B_x + \sigma_y B_y + \sigma_z B_z$$

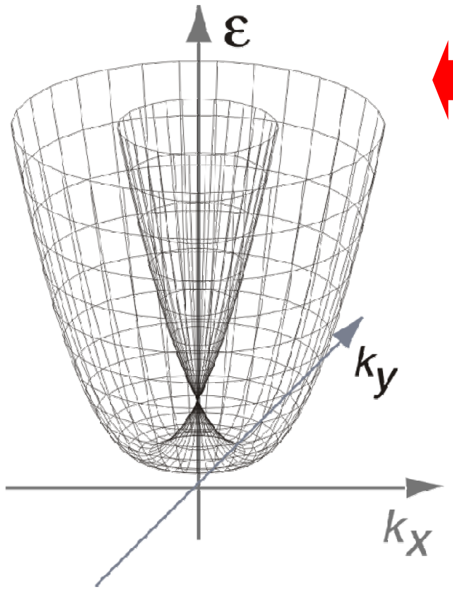
Comparison of coefficients. E.g. only Rashba contribution: $\vec{B}_{eff} \propto \alpha \begin{pmatrix} k_y \\ -k_x \end{pmatrix}$





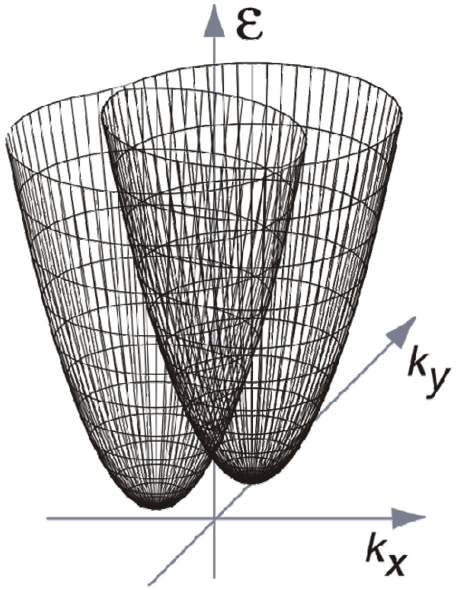
E.A. de Andrada e Silva PRB **46**, 1921 (1992)

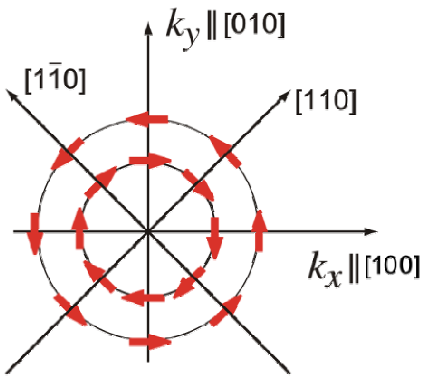
Presence of Rashba & Dresselhaus contributions



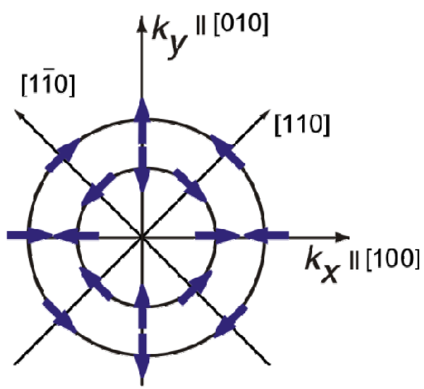
Rashba or Dresselhaus

Rashba and Dresselhaus

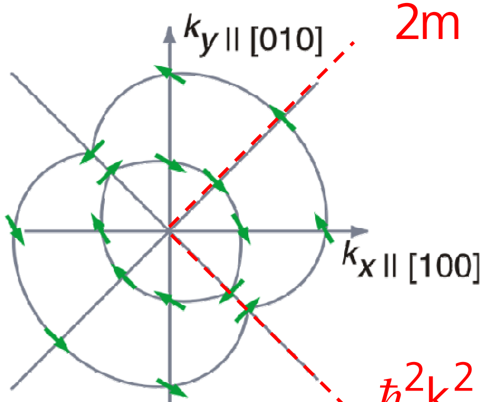




BIA=0
SIA≠0



BIA≠0
SIA=0

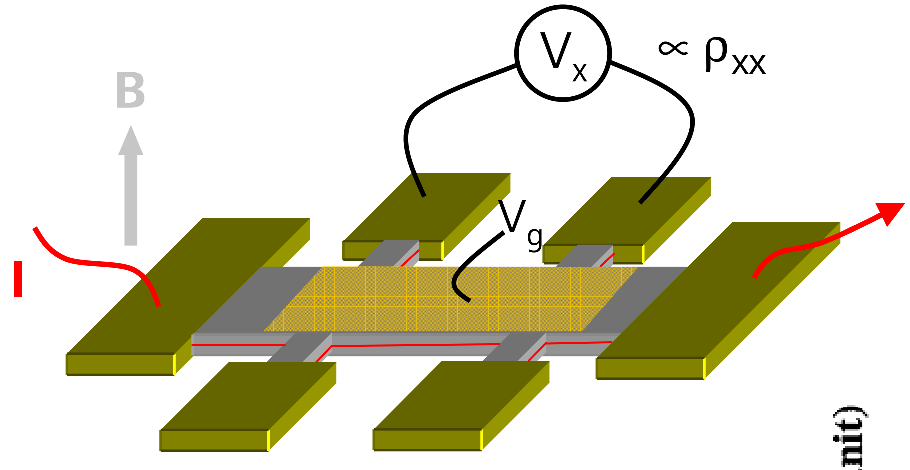


$$E = \frac{\hbar^2 k^2}{2m} \pm (\alpha + \gamma)\left|\vec{k}\right|$$

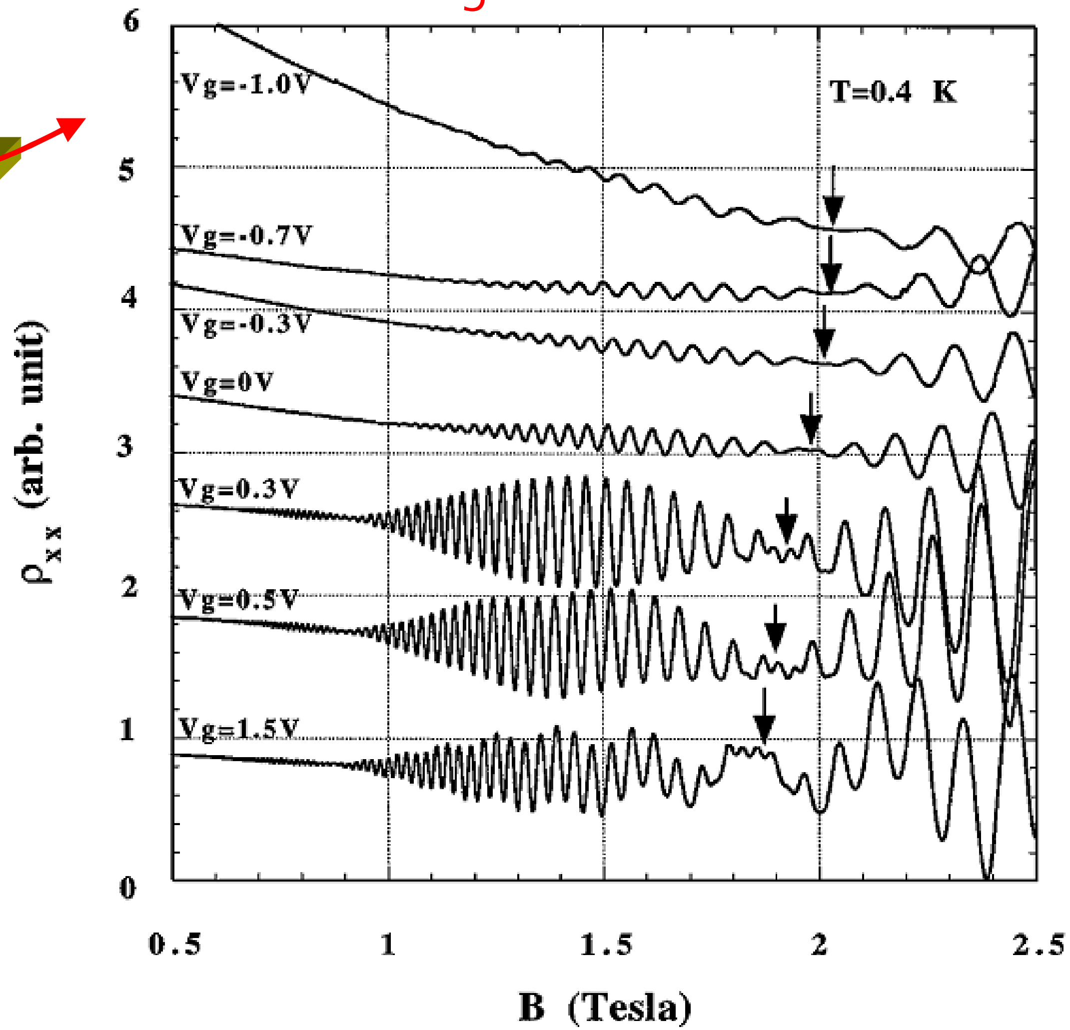
$$E = \frac{\hbar^2 k^2}{2m} \pm (\alpha - \gamma)\left|\vec{k}\right|$$

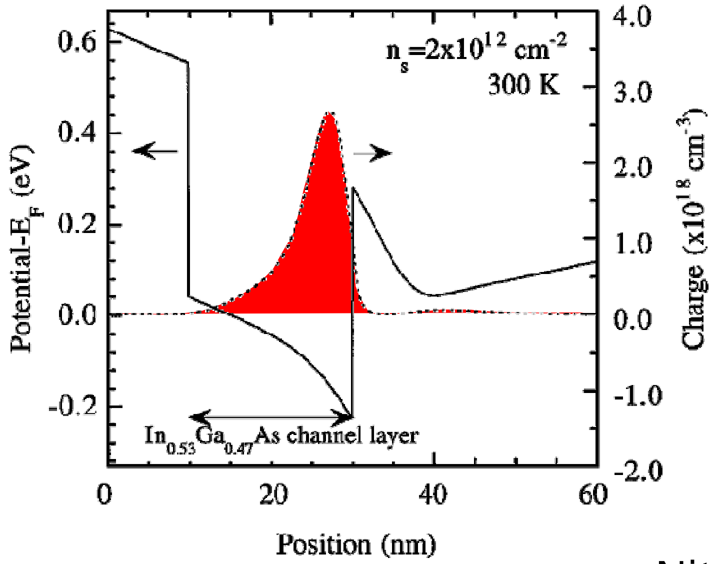
BIA ≠ SIA

SO-interaction in a InGaAs quantum well



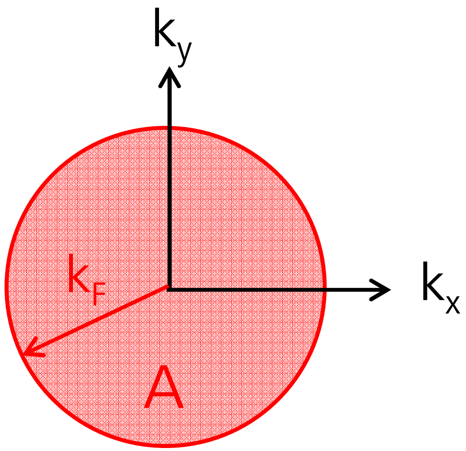
Beating of SdH-oscillations





Nitta et al., Phys. Rev. Lett **78**, 1335 (1997)

Quantum oscillations (SdH) reflect k-space area

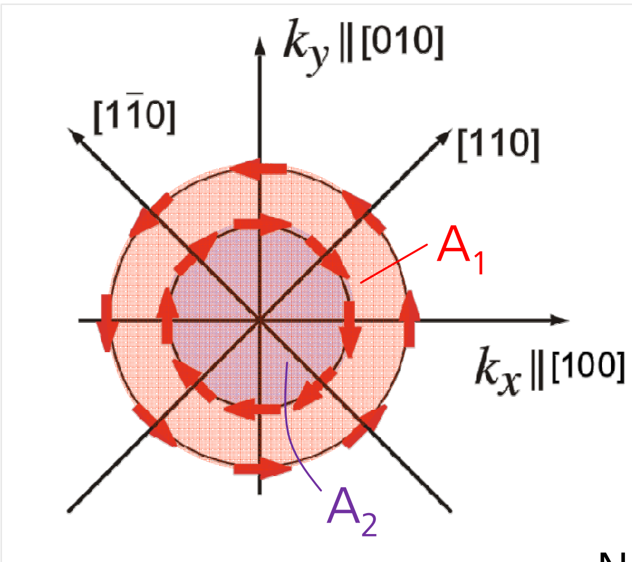


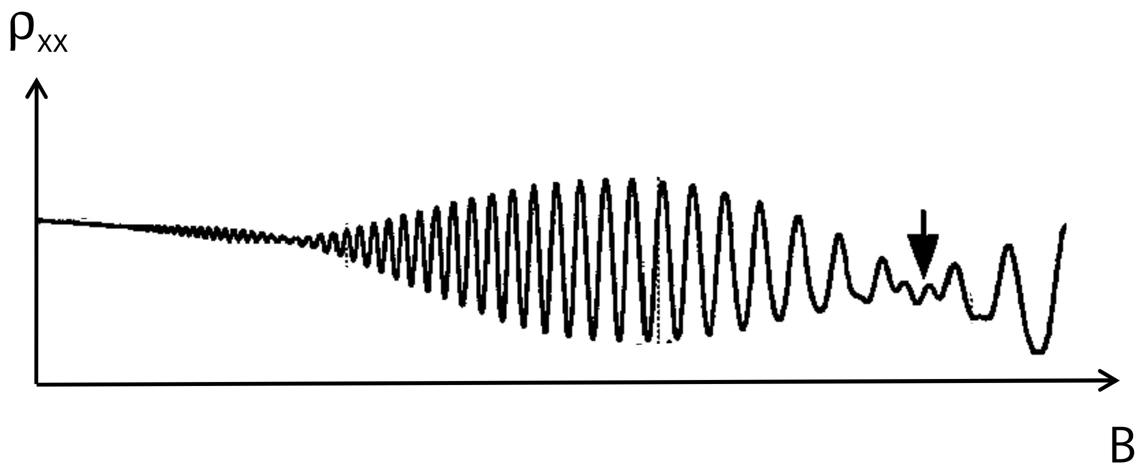
Periodicity of Shubnikov-de Haas (SdH) oscillations

$$\Delta\left(\frac{1}{B}\right) = \frac{2\pi e}{\hbar A}$$

Note that $A = \pi k_F^2 = 2\pi^2 n_s$

Origin of beating: two periodicities due to two k-space areas A_1 and A_2

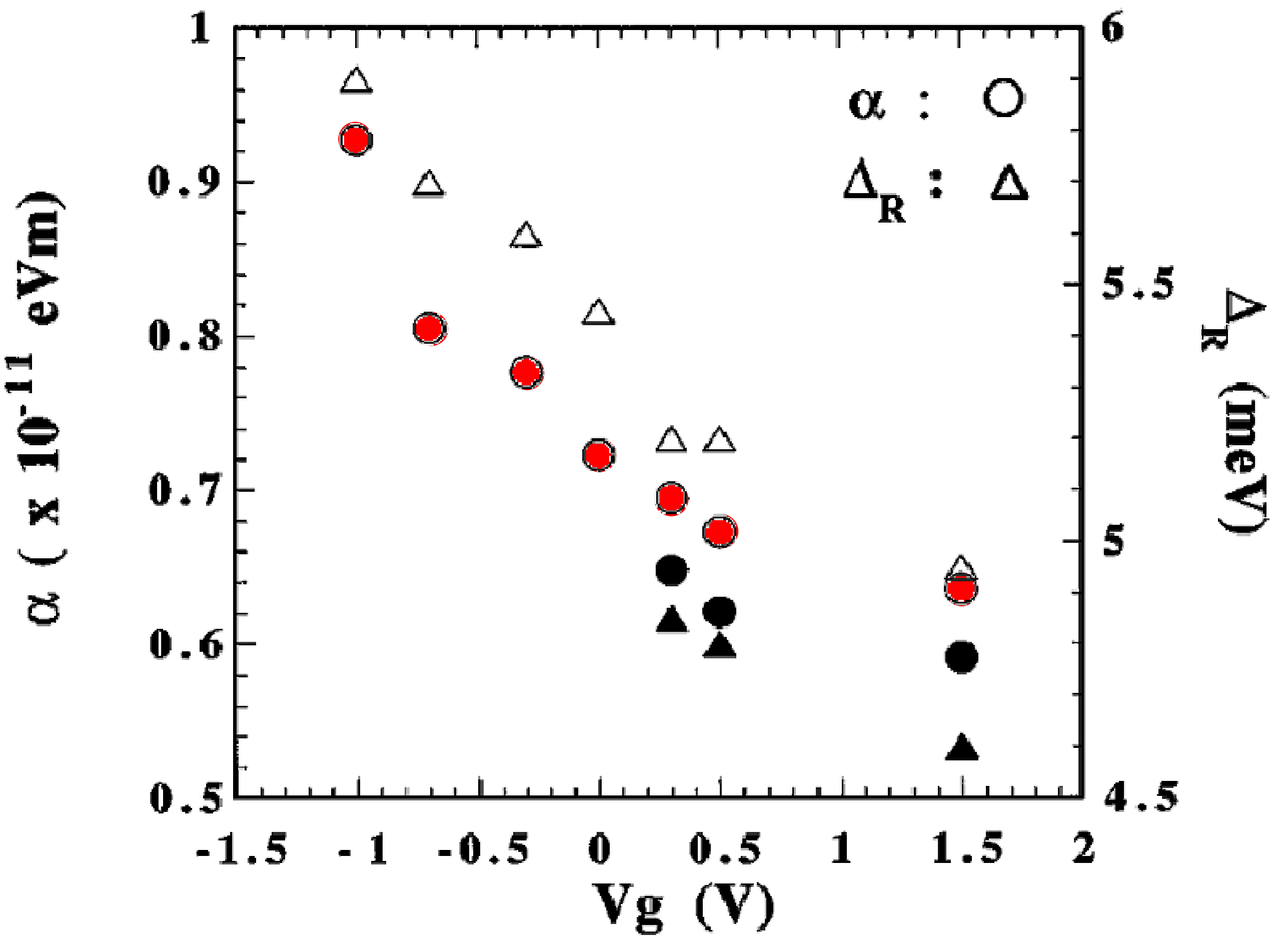




Nitta et al., Phys. Rev. Lett **78**, 1335 (1997)

Tuning of Rashba coefficient a by gate voltage V_g

Corresponds to tuning of spin orbit field, i.e., $\vec{B}_{eff} = \alpha \begin{pmatrix} k_y \\ -k_x \end{pmatrix}$



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