Intersubband polaritonics with SOI

Oleksandr Kyriienko*, Ivan A. Shelykh

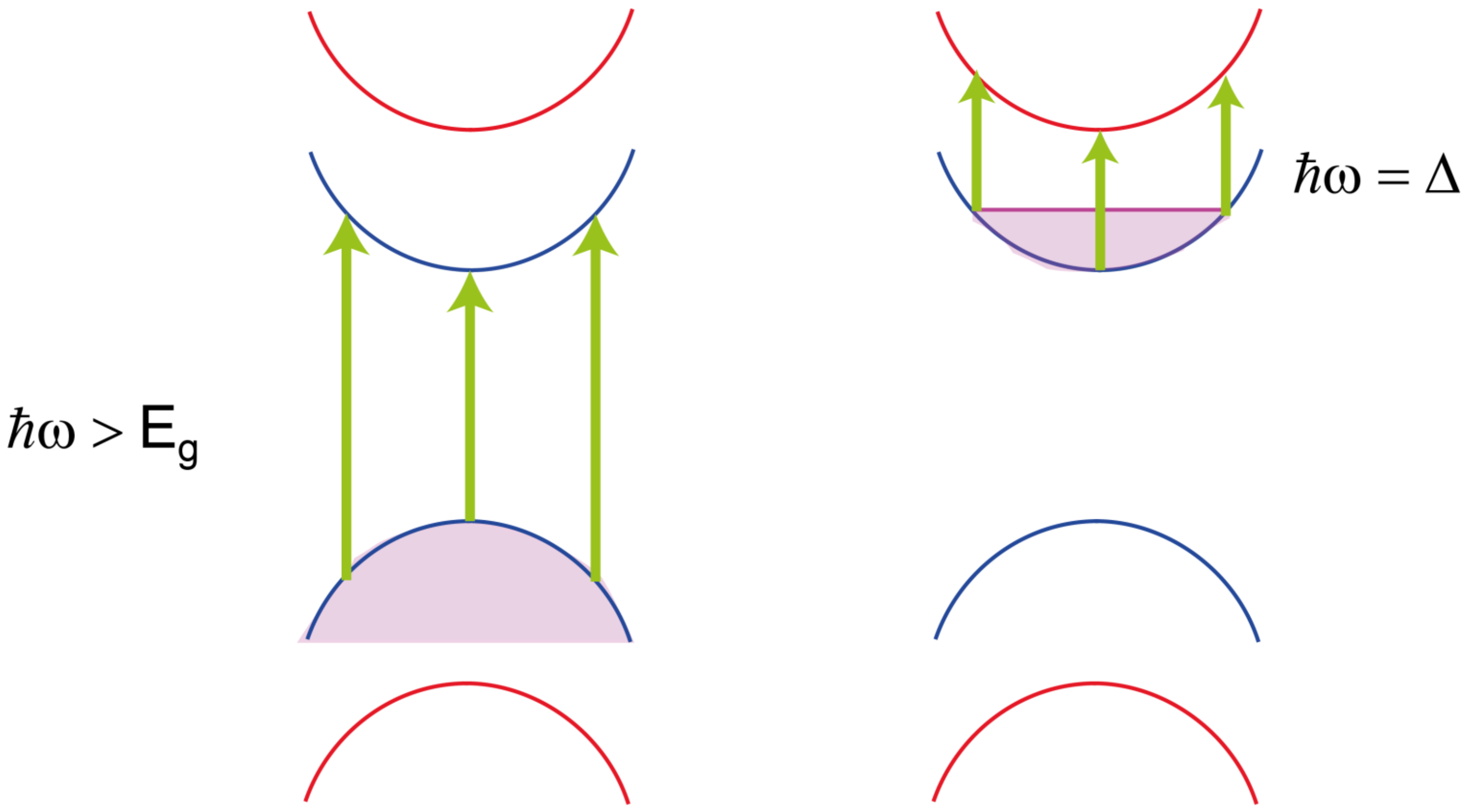
Science Institute, University of Iceland

Division of Physics and Applied Physics, Nanyang Technological University, Singapore

Outline

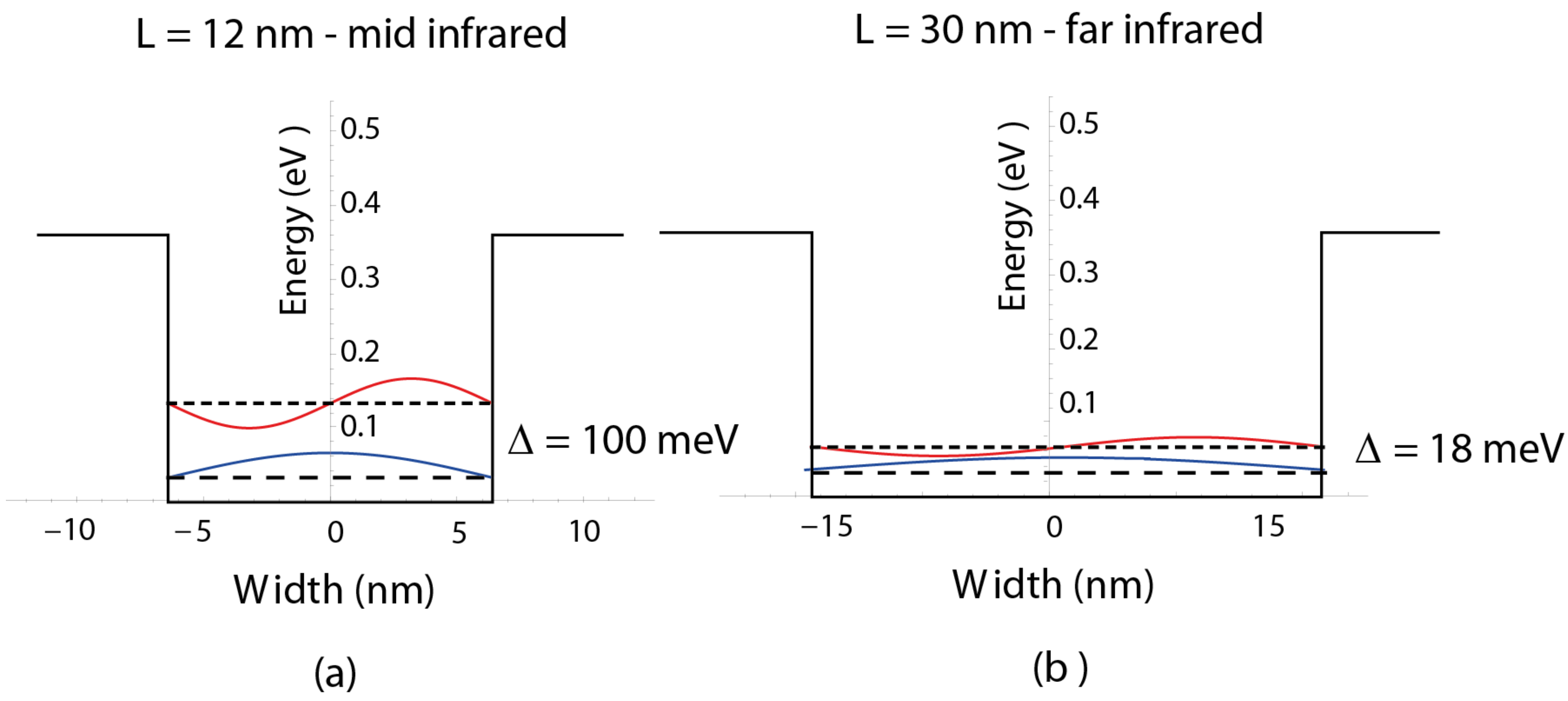
- Introduction
- Model
- Spin polarization
- Intersubband polaritons
- Conclusions

Introduction



interband transition **vs.** intersubband transition

Introduction



intersubband transition

Introduction

dipole matrix element

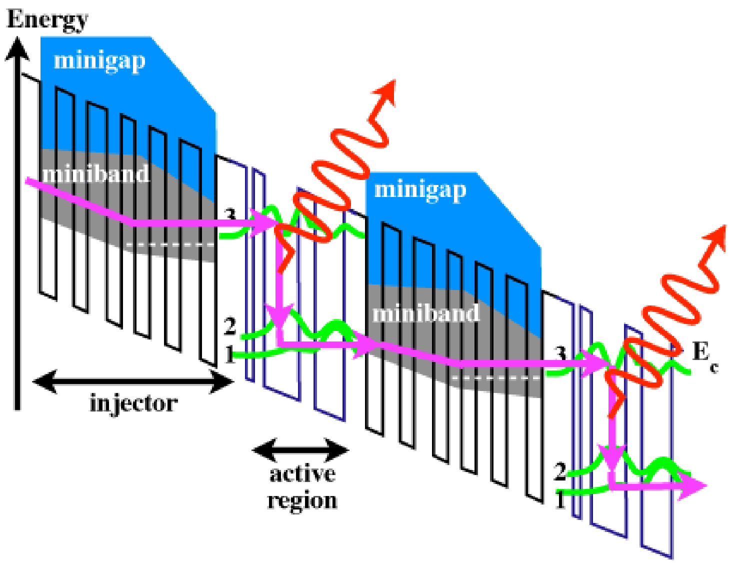
$$\langle\phi_{0,k}|e\cdot d|\phi_{1,k'}\rangle = \frac{1}{A}\int d^3r e^{-\mathrm{ik}_{\parallel}r}\phi_0{}^*(z)\cdot[e_x d_x + e_y d_y + e_z d_z]\cdot e^{\mathrm{ik}_{\parallel}r}\phi_1(z)$$

only TM polarization is absorbed

optical selection rules

Introduction

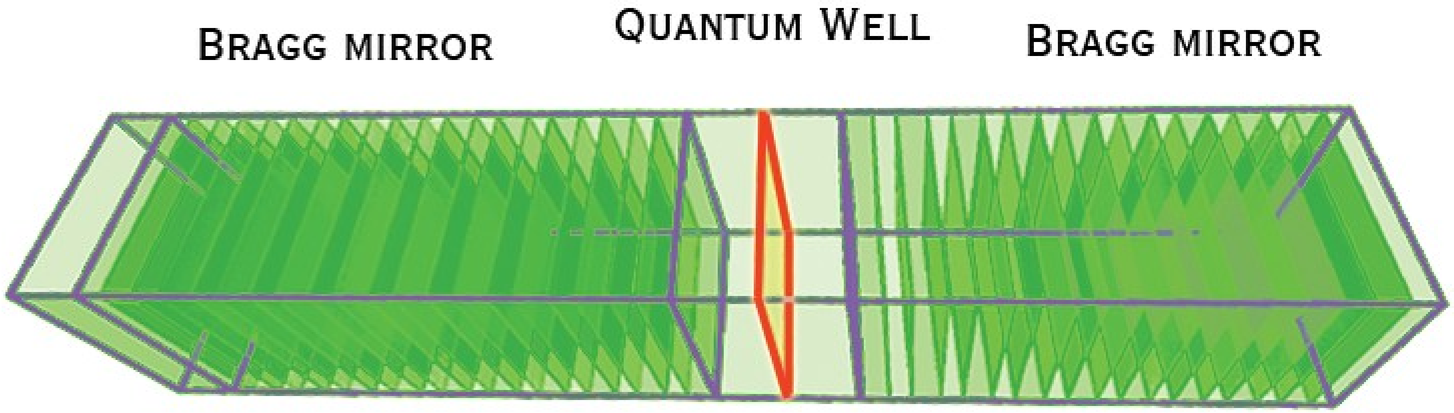
- Cascade lasers



- QW infrared photodetector

applications

Introduction

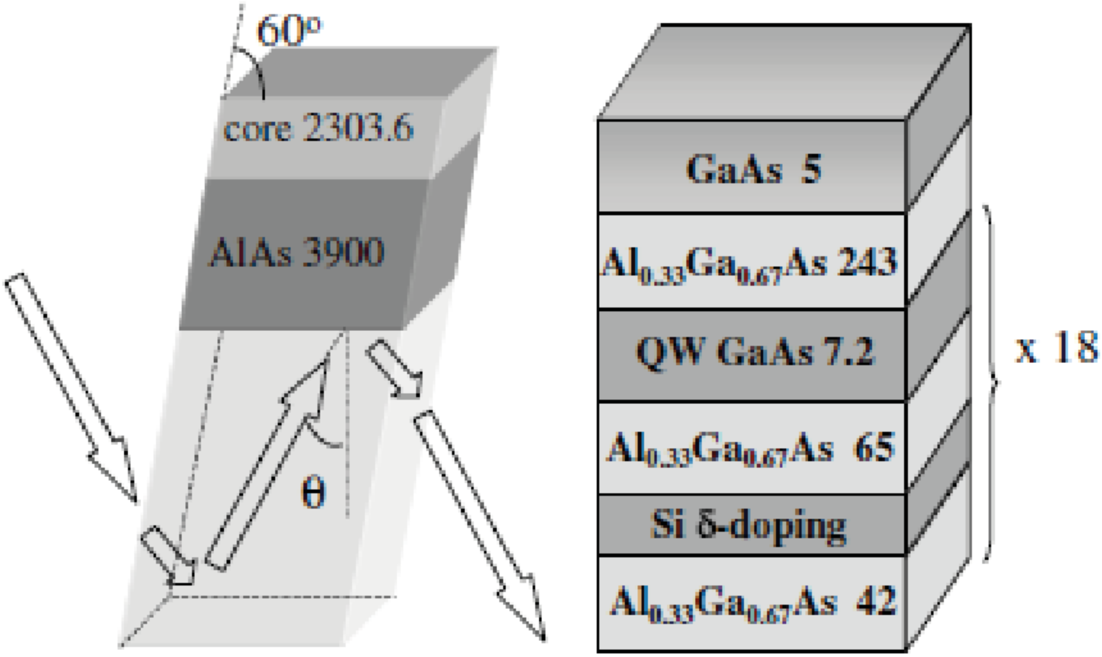


Cavity photon is confined between two Bragg reflectors and interacts with intersubband transition in QW.

strong coupling

Introduction

s
t
r
u
c
t
u
r
e

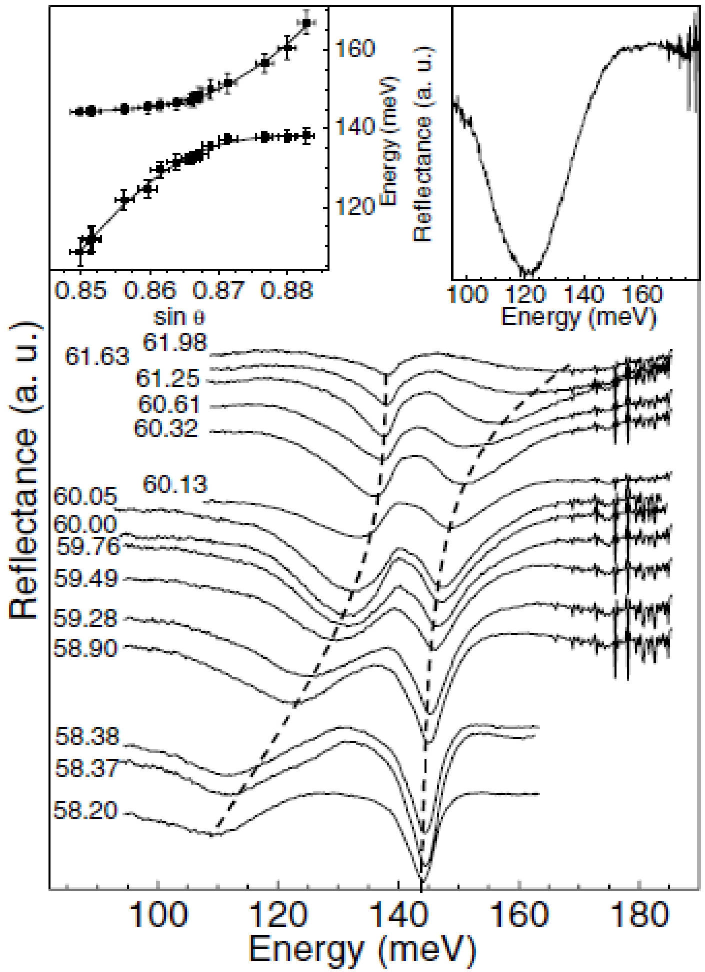


first experiment: **[Dini et al., PRL (2003)]**

intersubband polaritons

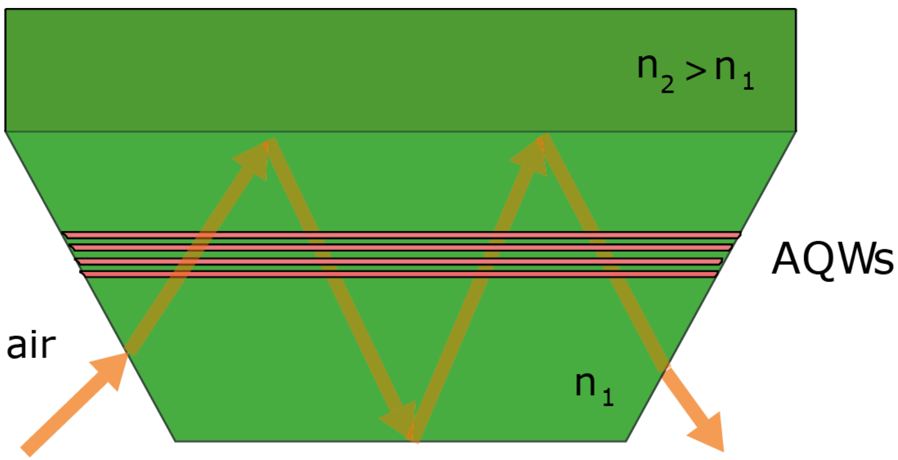
Introduction

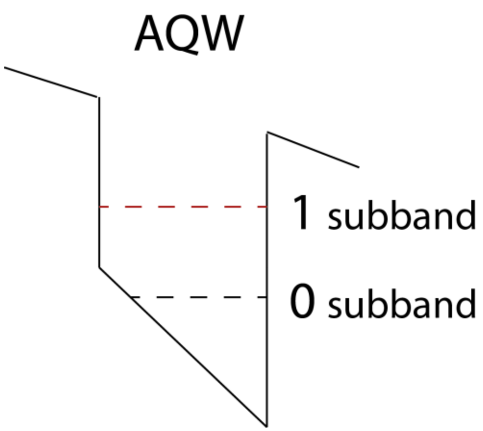
r
e
s
u
l
t
s



[Dini et al., PRL (2003)]

Model





photonic microcavity with embedded asymmetric quantum wells

geometry

Model

1. $$H = \sum_{k,j} E_{k,j} a^\dagger_{k,j} a_{k,j} + \sum_q E^{ph}_q b^\dagger_q b_q + \sum_{k,q,\sigma} (g^*_q a^\dagger_{k,1} a_{k+q,2,\sigma} b^\dagger_q + g_q a_{k,1,\sigma} a^\dagger_{k+q,2} b_q)$$

electrons photons coupling

2. Spin-orbit interaction (SOI):

$$H_{SIA} = \alpha(\sigma_x k_y - \sigma_y k_x) = \frac{\hbar}{2}(\mathbf{\Omega}_{eff} \cdot \sigma)$$ – **Rashba SOI**

$$H_{BIA} = \beta(\sigma_x k_x - \sigma_y k_y)$$ – **Dresselhaus SOI**

Hamiltonian

Model

add SOI (Rashba)

$$H = \sum_{k,j,\sigma} E_{k,j} a^{\dagger}_{k,j,\sigma} a_{k,j,\sigma} + \sum_{k,j} (\alpha^R_j (k_y + i k_x) a^{\dagger}_{k,j,\uparrow} a_{k,j,\downarrow} + + H.c.) + \sum_q E^{ph}_q b^{\dagger}_q b_q + \sum_{k,q,\sigma} (g_q a^{\dagger}_{k,1,\sigma} a_{k+q,2,\sigma} b^{\dagger}_q + H.c.)$$

and diagonalize using operators with new spin states $\widetilde{\sigma} = +, -$

$$c_{k,\pm} = \frac{1}{\sqrt{2}} \left[\pm i e^{-i\theta_k} a_{k,\uparrow} + a_{k,\downarrow} \right]$$

first two terms $\widetilde{H_0} = \sum_{k,j,\widetilde{\sigma}} \widetilde{E}_{k,j,\widetilde{\sigma}} c^{\dagger}_{k,j,\widetilde{\sigma}} c_{k,j,\widetilde{\sigma}}$, $\widetilde{E_j}(k) = E_j(k) \pm \alpha^R_j |k|$

Model

$$\widetilde{H} = \sum_{k,j,\widetilde{\sigma}} \widetilde{E}_{k,j,\widetilde{\sigma}} c^{\dagger}_{k,j,\widetilde{\sigma}} c_{k,j,\widetilde{\sigma}} + \sum_{q} E^{ph}_{q} b^{\dagger}_{q} b_{q} + \sum_{k,q} [g_{++}(k,q) \times$$

$$\times\, c^{\dagger}_{k,1,+} c_{k+q,2,+} + g_{--}(k,q) c^{\dagger}_{k,1,-} c_{k-q,2,-} + g_{+-}(k,q)$$

$$\times\, c^{\dagger}_{k,1,+} c_{k+q,2,-} + g_{-+}(k,q) c^{\dagger}_{k,1,-} c_{k+q,2,+}] b^{\dagger}_{q} + H.c.$$

rewritten fourth term using

$$g_{++}(k,q) = g(q) e^{-i\frac{\theta_k - \theta_{k+q}}{2}} \cos\left(\frac{\theta_k - \theta_{k+q}}{2}\right)$$

$$g_{+-}(k,q) = i g(q) e^{-i\frac{\theta_k - \theta_{k+q}}{2}} \sin\left(\frac{\theta_k - \theta_{k+q}}{2}\right)$$

$$g_{-+}(k,q) = i g(q) e^{-i\frac{\theta_k - \theta_{k+q}}{2}} \sin\left(\frac{\theta_k - \theta_{k+q}}{2}\right)$$

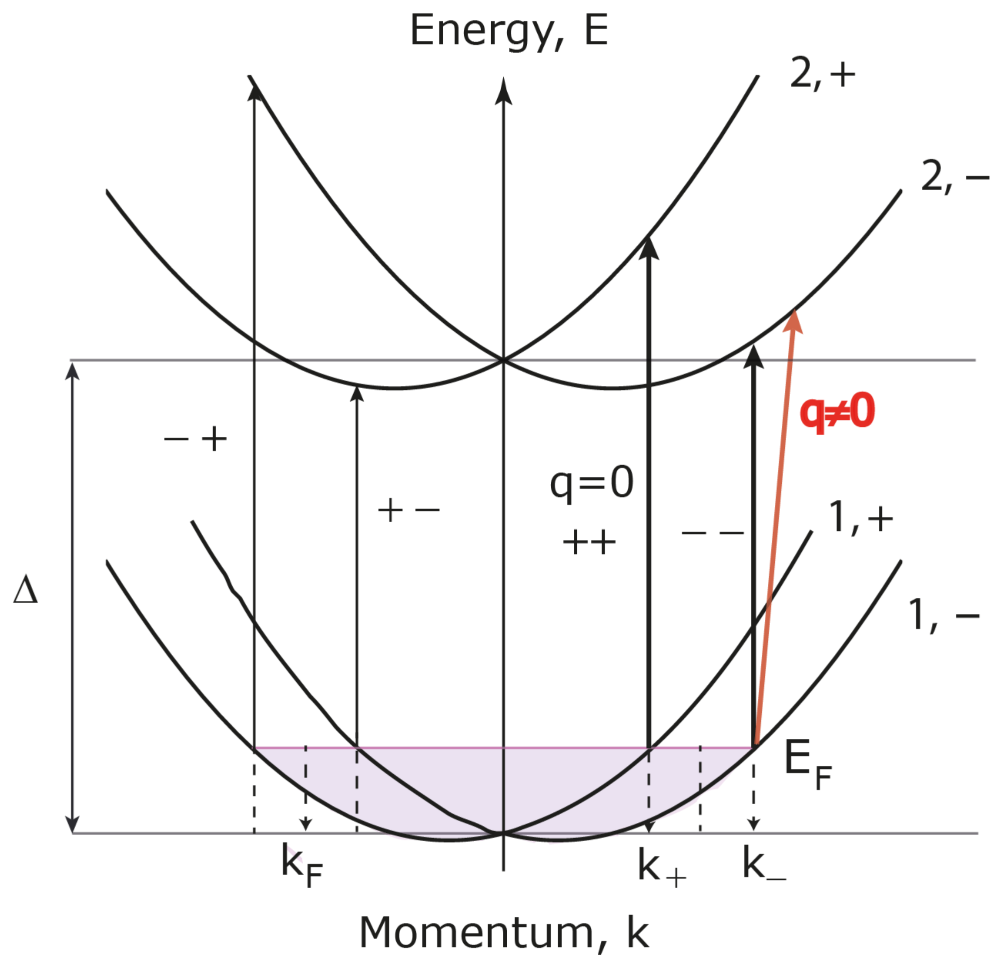
$$g_{--}(k,q) = g(q) e^{-i\frac{\theta_k - \theta_{k+q}}{2}} \cos\left(\frac{\theta_k - \theta_{k+q}}{2}\right)$$

$$\theta_k = \arctan(k_y/k_x)$$

$$\theta_k - \theta_{k+q} \approx \arcsin(q/k_F)$$

$$g_{-+}, g_{+-} \ll 0$$

Model



$$k_{\mp} = k_F(1 \pm \eta_R)$$

$$\eta_R = \frac{\alpha m}{\hbar^2 k_F}$$

transitions

Model

$$H = H_0 + H_{SIA} + H_{BIA}$$

diagonalize using operators

$$c_{k,\pm} = \frac{1}{\sqrt{2}} \left[\pm \frac{i\alpha e^{-i\theta_k} + \beta e^{i\theta_k}}{\sqrt{\alpha^2 + \beta^2 + 2\alpha\beta \sin\theta_k}} a_{k,\uparrow} + a_{k,\downarrow} \right]$$

$$\Rightarrow \quad \widetilde{E_j}(k) = E_j(k) \pm |k| \sqrt{\alpha_j^2 + \beta_j^2 + 2\alpha\beta \sin 2\theta_k}$$

Rashba and Dresselhaus

Spin polarization

$$\langle \hat{S} \rangle = \sum_{k\sigma k'\sigma'} \langle k'\sigma' | \hat{S} | k\sigma \rangle c^{\dagger}_{k',\sigma'} c_{k,\sigma}$$ – average spin, $\hat{S} = \frac{\hbar}{2}(\sigma_x, \sigma_y, \sigma_z)$

$$\langle + | S_x | + \rangle = \sum_{\mathbf{k}} \sin\theta_k = \int_0^{k_+} \frac{kdk}{(2\pi)^2} \int_0^{2\pi} d\theta_k \sin\theta_k$$

$$\langle + | S_y | + \rangle = \sum_{\mathbf{k}} (-\cos\theta_k) = \int_0^{k_+} \frac{kdk}{(2\pi)^2} \int_0^{2\pi} d\theta_k (-\cos\theta_k)$$

$$\langle - | S_x | - \rangle = \sum_{\mathbf{k}} (-\sin\theta_k) = \int_0^{k_-} \frac{kdk}{(2\pi)^2} \int_0^{2\pi} d\theta_k (-\sin\theta_k)$$

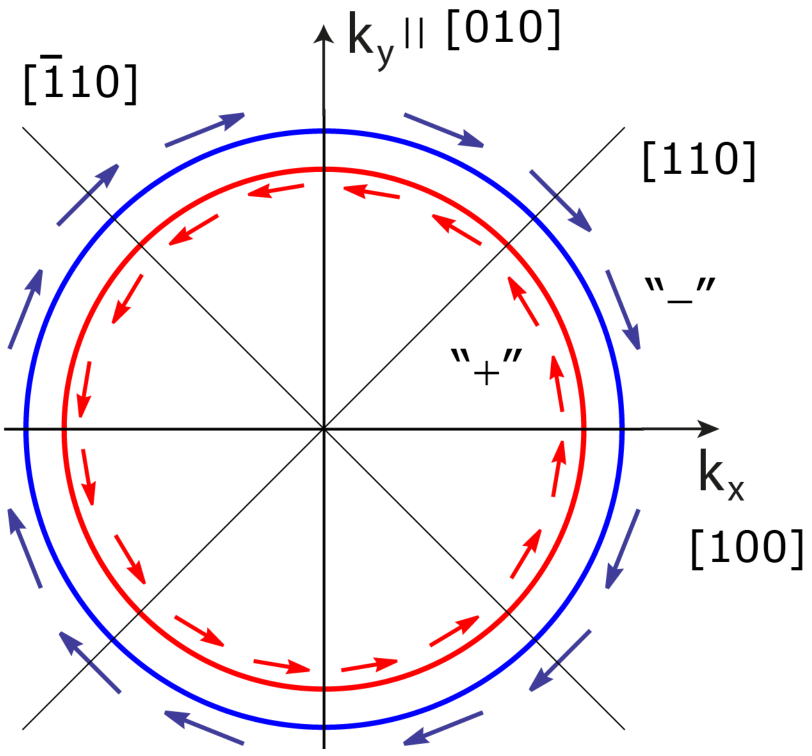
$$\langle - | S_y | - \rangle = \sum_{\mathbf{k}} \cos\theta_k = \int_0^{k_-} \frac{kdk}{(2\pi)^2} \int_0^{2\pi} d\theta_k \cos\theta_k$$

Rashba only

Spin polarization

q = 0

$\tilde{\alpha}=1$
$\tilde{\beta}=0$

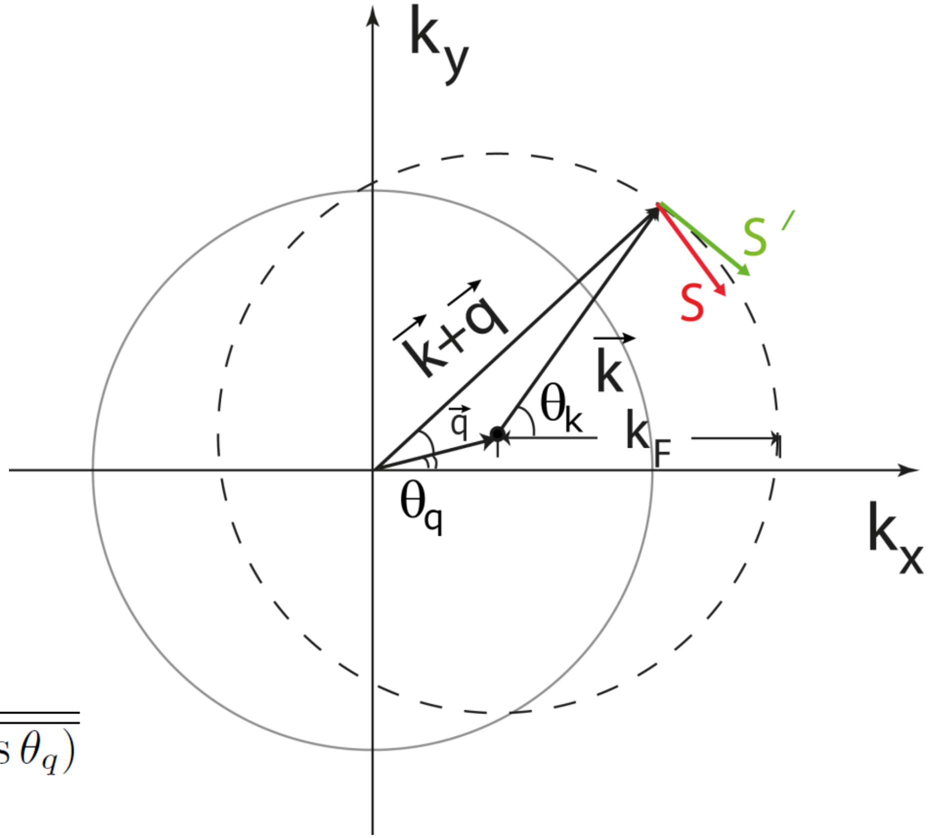


$$S_+ = (\sin\theta_k, -\cos\theta_k, 0) \qquad S_- = (-\sin\theta_k, \cos\theta_k, 0)$$

$$\langle S_+ \rangle = 0, \ \langle S_- \rangle = 0$$

Spin polarization

q ≠ 0



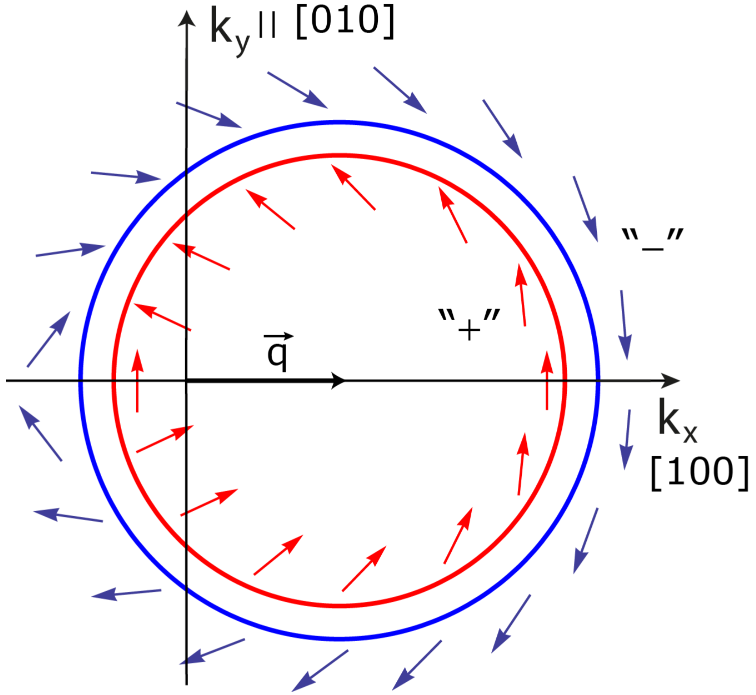
$$\theta_k \to \theta_{k+q},\; k_\pm \to k'_\pm$$

$$\cos\theta_{k+q} = \frac{k\cos\theta_k + q\cos\theta_q}{\sqrt{k^2+q^2+2kq\cos(\theta_k - \cos\theta_q)}}$$

$$\sin\theta_{k+q} = \frac{k\sin\theta_k + q\sin\theta_q}{\sqrt{k^2+q^2+2kq\cos(\theta_k - \theta_q)}},$$

Spin polarization

q ≠ 0



$$\langle S_+ \rangle \neq 0,\ \langle S_- \rangle \neq 0$$

$$k'_{\mp} = k_{\mp}\left[\sqrt{1 - \frac{q^2}{k_{\mp}^2}\sin^2(\theta_k - \theta_q)} + \frac{q}{k_{\mp}\cos(\theta_k - \theta_q)}\right]$$

Spin polarization

$$\langle + | S_x | + \rangle = \sum_{\mathbf{k}} \frac{\widetilde{\alpha} \sin\theta_k + \widetilde{\beta} \cos\theta_k}{\sqrt{\widetilde{\alpha}^2 + \widetilde{\beta}^2 + 2\widetilde{\alpha}\widetilde{\beta} \sin 2\theta_k}}$$

$$\langle + | S_y | + \rangle = \sum_{\mathbf{k}} \frac{-\widetilde{\alpha} \cos\theta_k - \widetilde{\beta} \sin\theta_k}{\sqrt{\widetilde{\alpha}^2 + \widetilde{\beta}^2 + 2\widetilde{\alpha}\widetilde{\beta} \sin 2\theta_k}}$$

$$\langle - | S_x | - \rangle = \sum_{\mathbf{k}} \frac{-\widetilde{\alpha} \sin\theta_k - \widetilde{\beta} \cos\theta_k}{\sqrt{\widetilde{\alpha}^2 + \widetilde{\beta}^2 + 2\widetilde{\alpha}\widetilde{\beta} \sin 2\theta_k}}$$

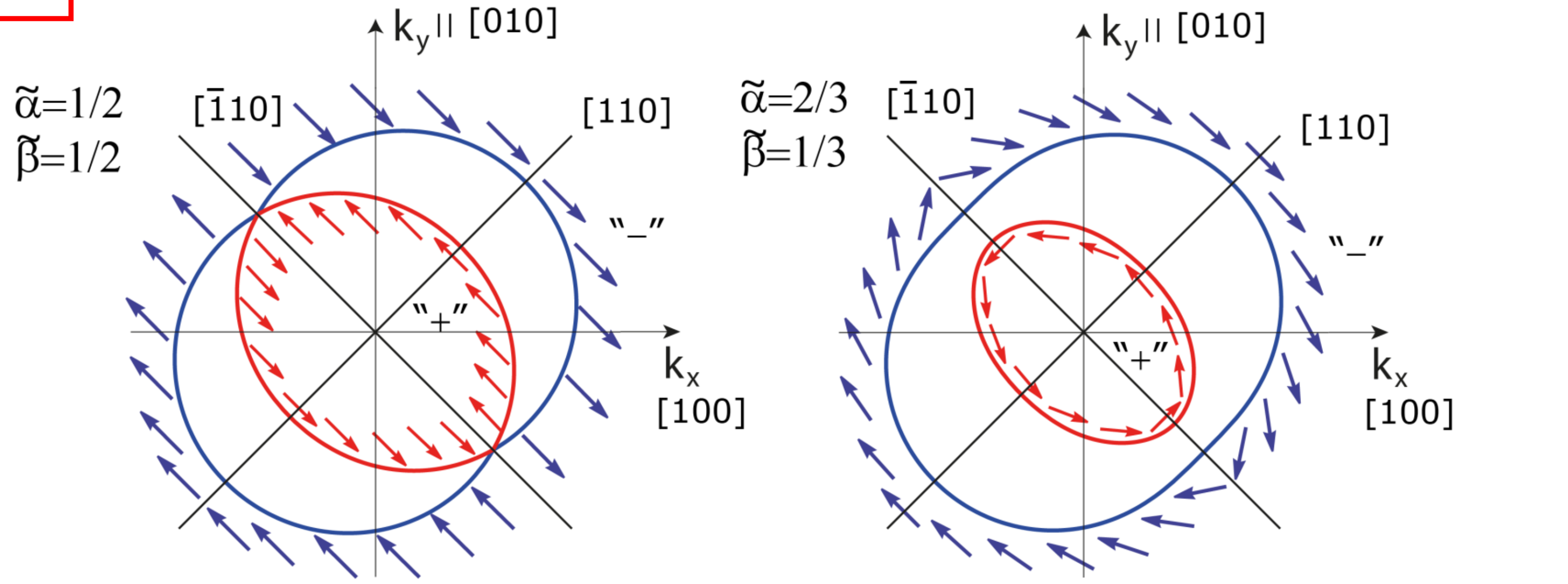
$$\langle - | S_y | - \rangle = \sum_{\mathbf{k}} \frac{\widetilde{\alpha} \cos\theta_k + \widetilde{\beta} \sin\theta_k}{\sqrt{\widetilde{\alpha}^2 + \widetilde{\beta}^2 + 2\widetilde{\alpha}\widetilde{\beta} \sin 2\theta_k}}$$

$$\widetilde{\alpha} = \frac{\alpha}{\alpha+\beta} \text{ and } \widetilde{\beta} = \frac{\beta}{\alpha+\beta}$$

Rashba and Dresselhaus

Spin polarization

q = 0



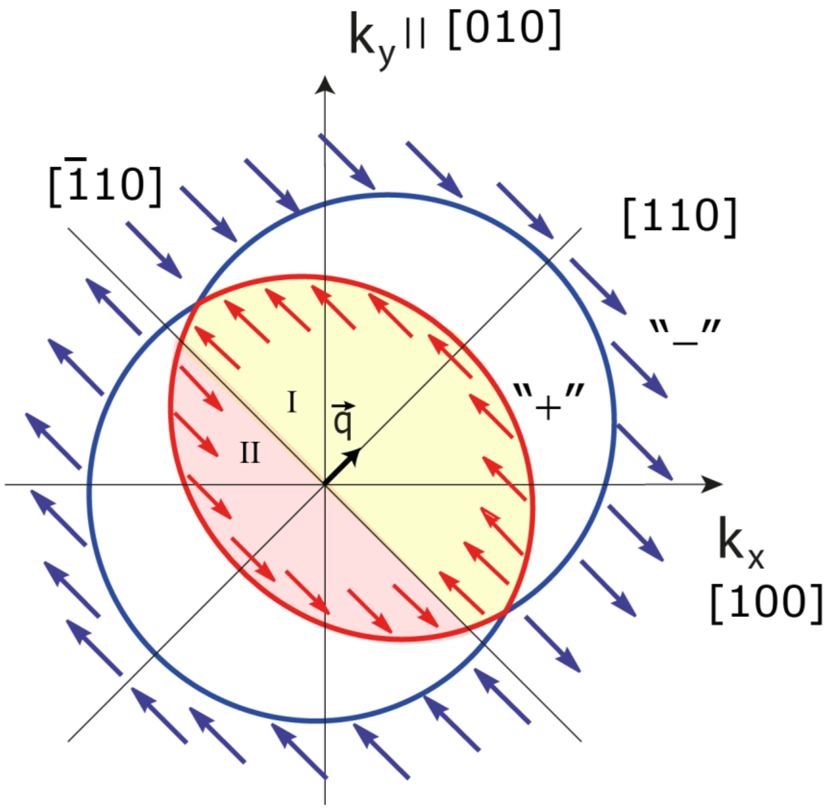
(a) (b)

$$\langle S_+ \rangle = 0, \ \langle S_- \rangle = 0$$

Spin polarization

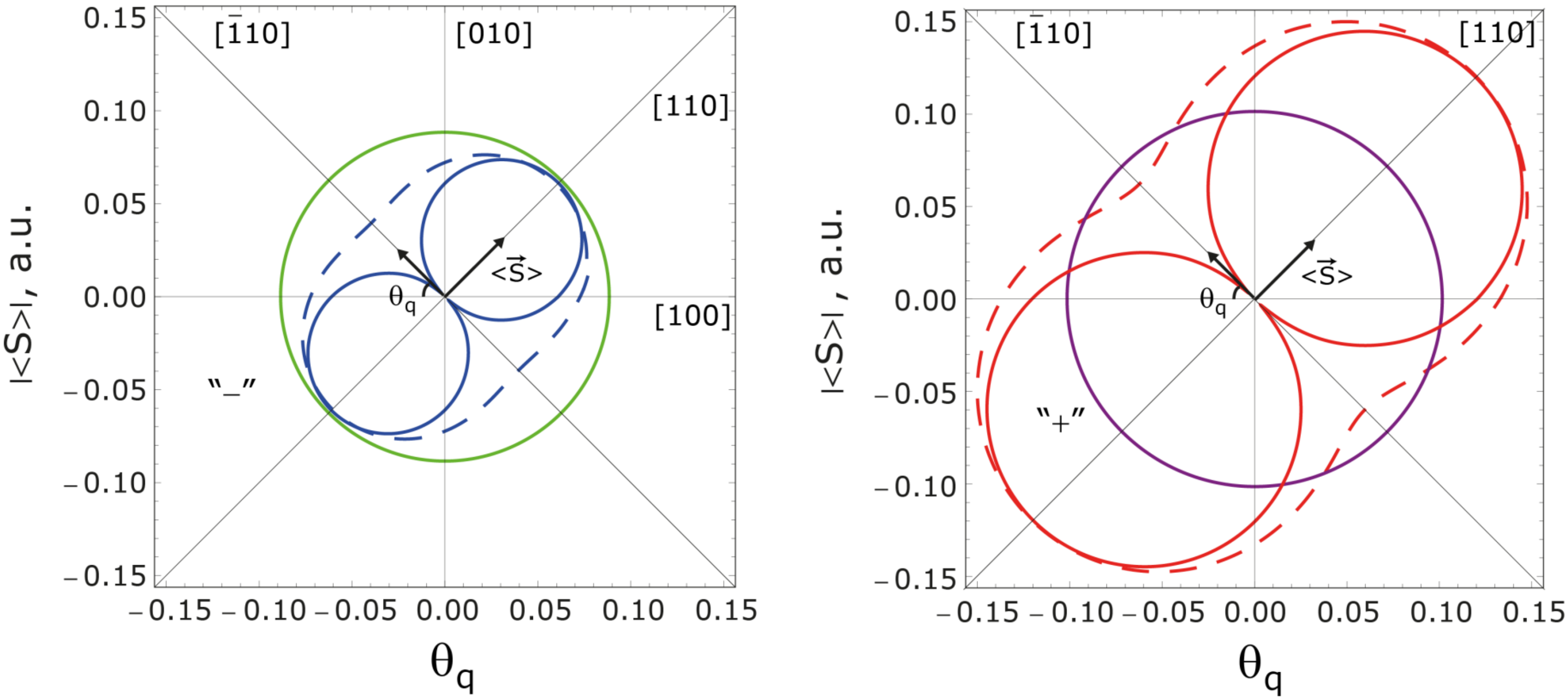
q ≠ 0

$\tilde{\alpha}=1/2$
$\tilde{\beta}=1/2$



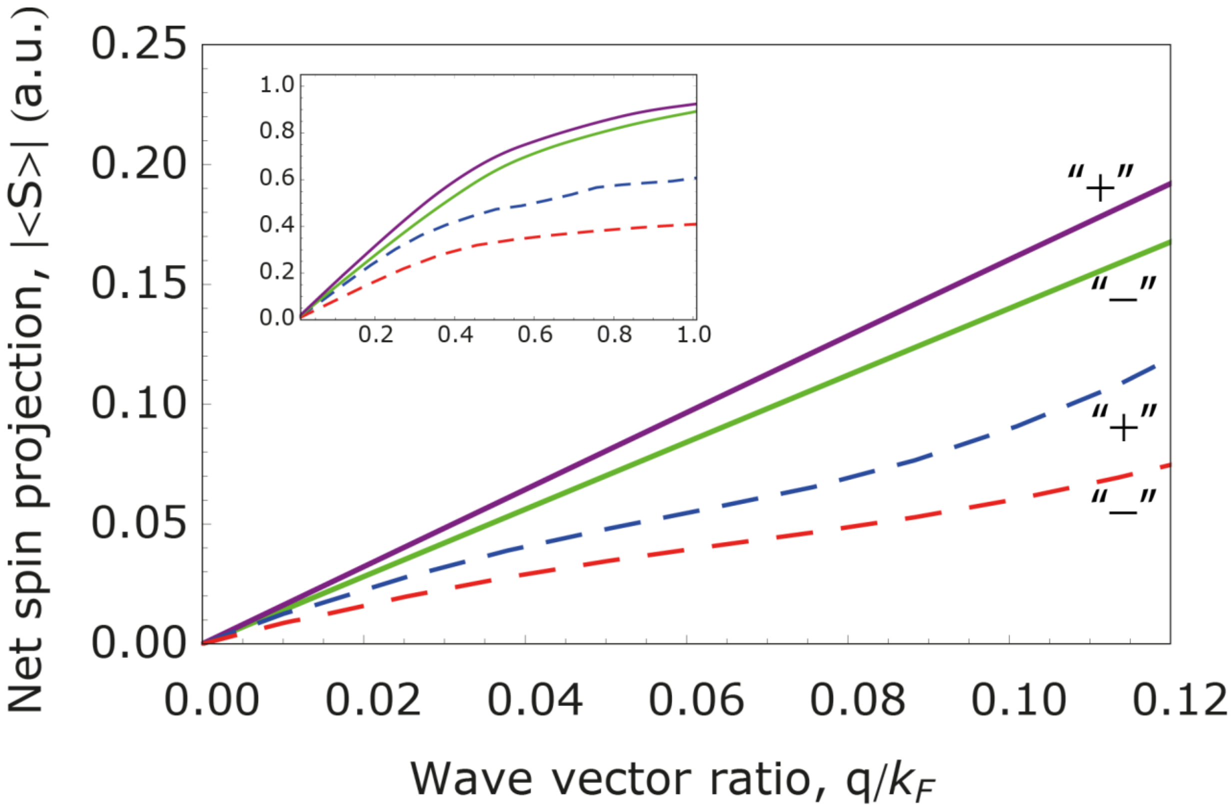
$$\langle S_+\rangle \neq 0,\ \langle S_-\rangle \neq 0$$

Spin polarization

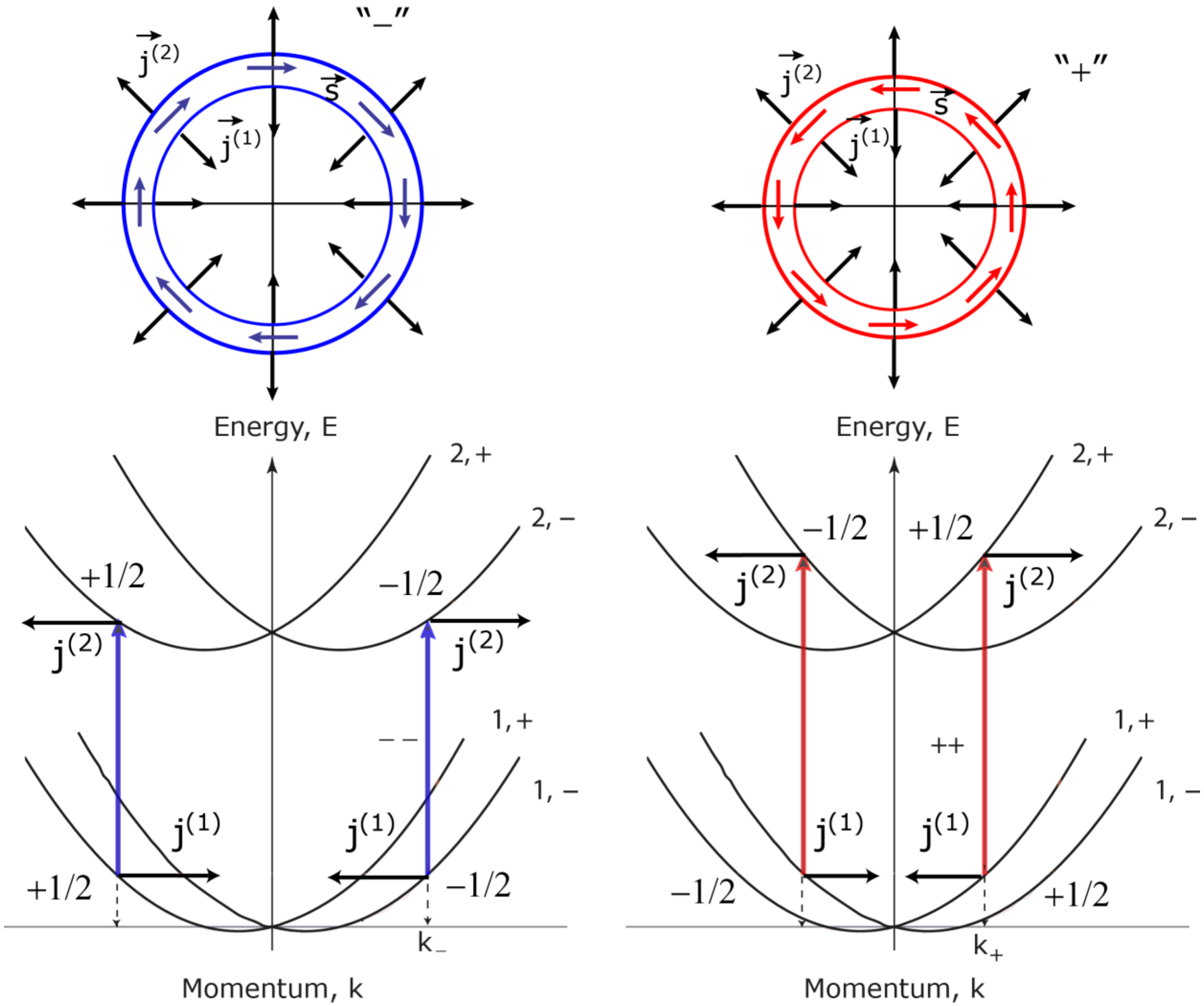


absolute value of average spin as a function of photon incident angle

Spin polarization

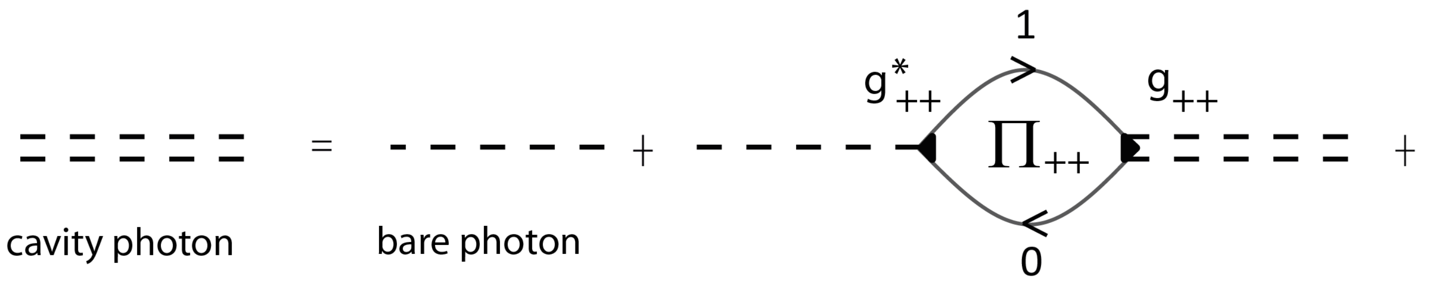


Spin currents

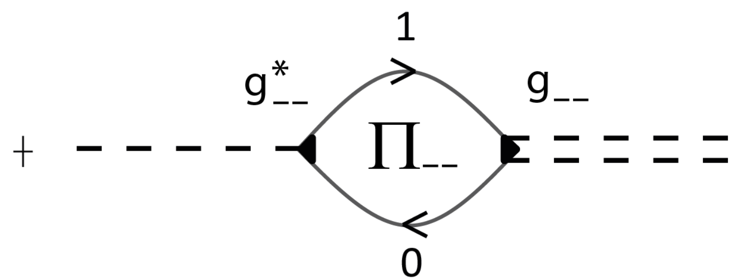


[E. L. Ivchenko and S. A. Tarasenko, Sem. Sci. Tech. 23, 114007 (2008)]

Intersubband polaritons



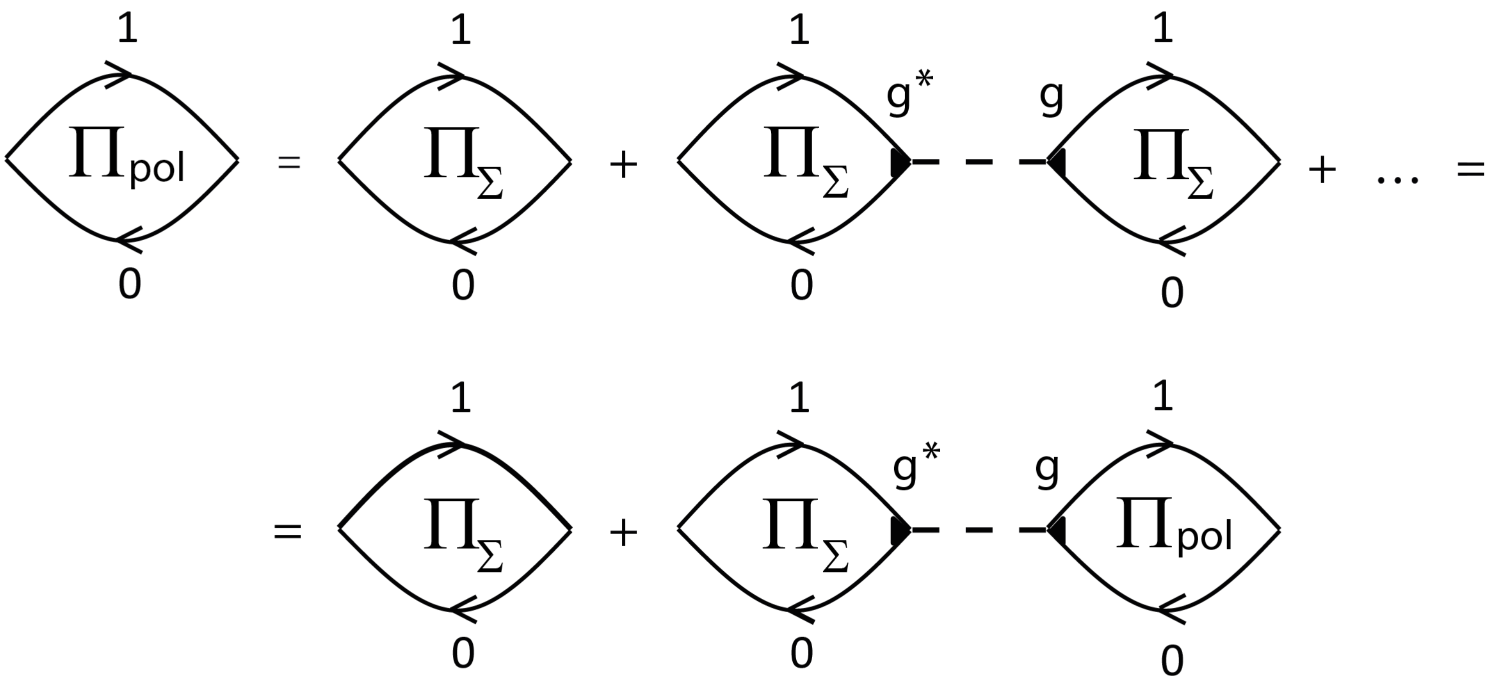
++ intersubband excitation



−− intersubband excitation

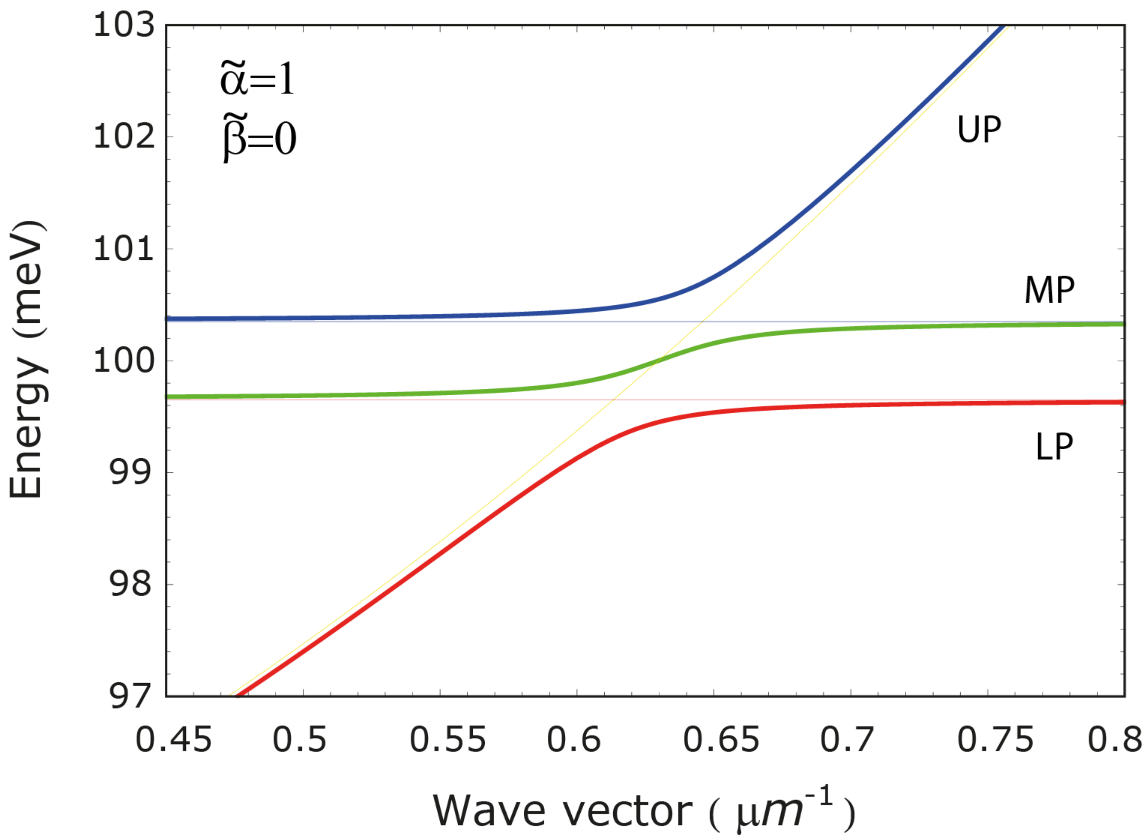
$$D = \frac{D_0}{1 - (g_{++}^2 \Pi_{++} + g_{--}^2 \Pi_{--}) D_0}$$

Intersubband polaritons



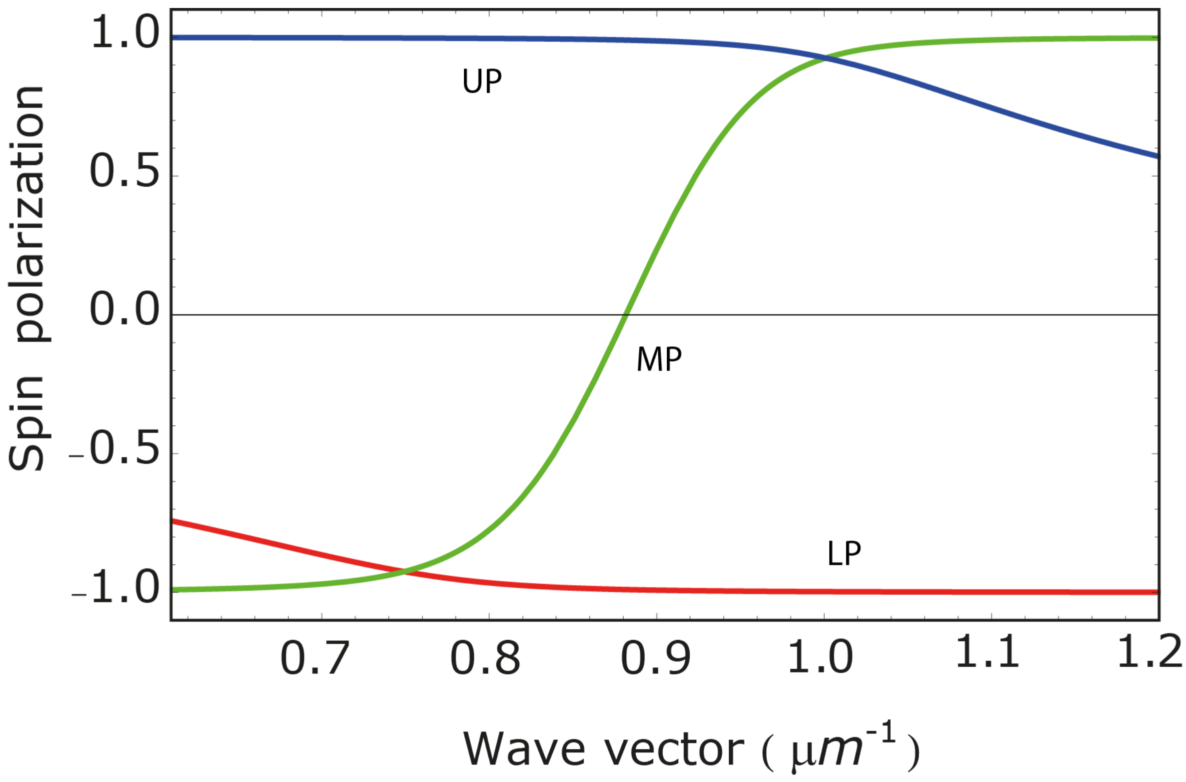
intersubband polariton absorption

Intersubband polaritons



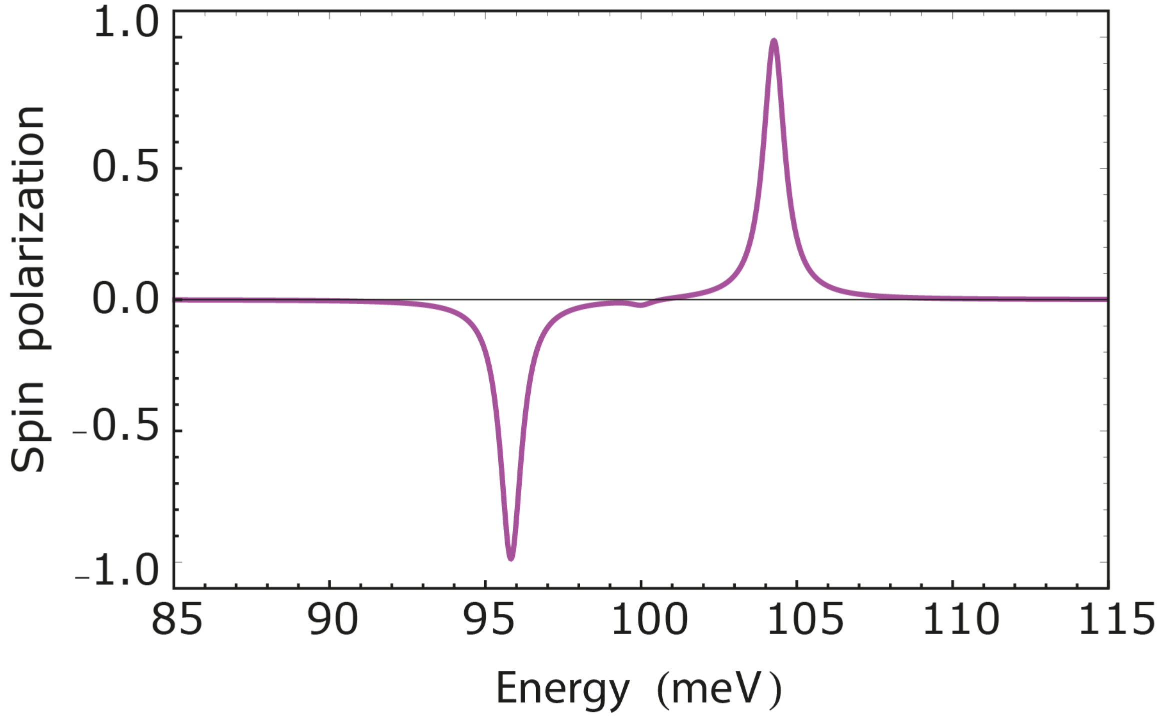
intersubband polariton dispersion

Intersubband polaritons



spin polarization for different polaritonic modes (normalized)

Intersubband polaritons



spin polarization for fixed *q* as a function of frequency

Conclusions

- SOI leads to formation of 3 polaritonic modes
- non-zero and tunable spin polarization of ISB polariton
- improved coherence due to cavity mode

This work is **[in progress]**

Thank you for attention!