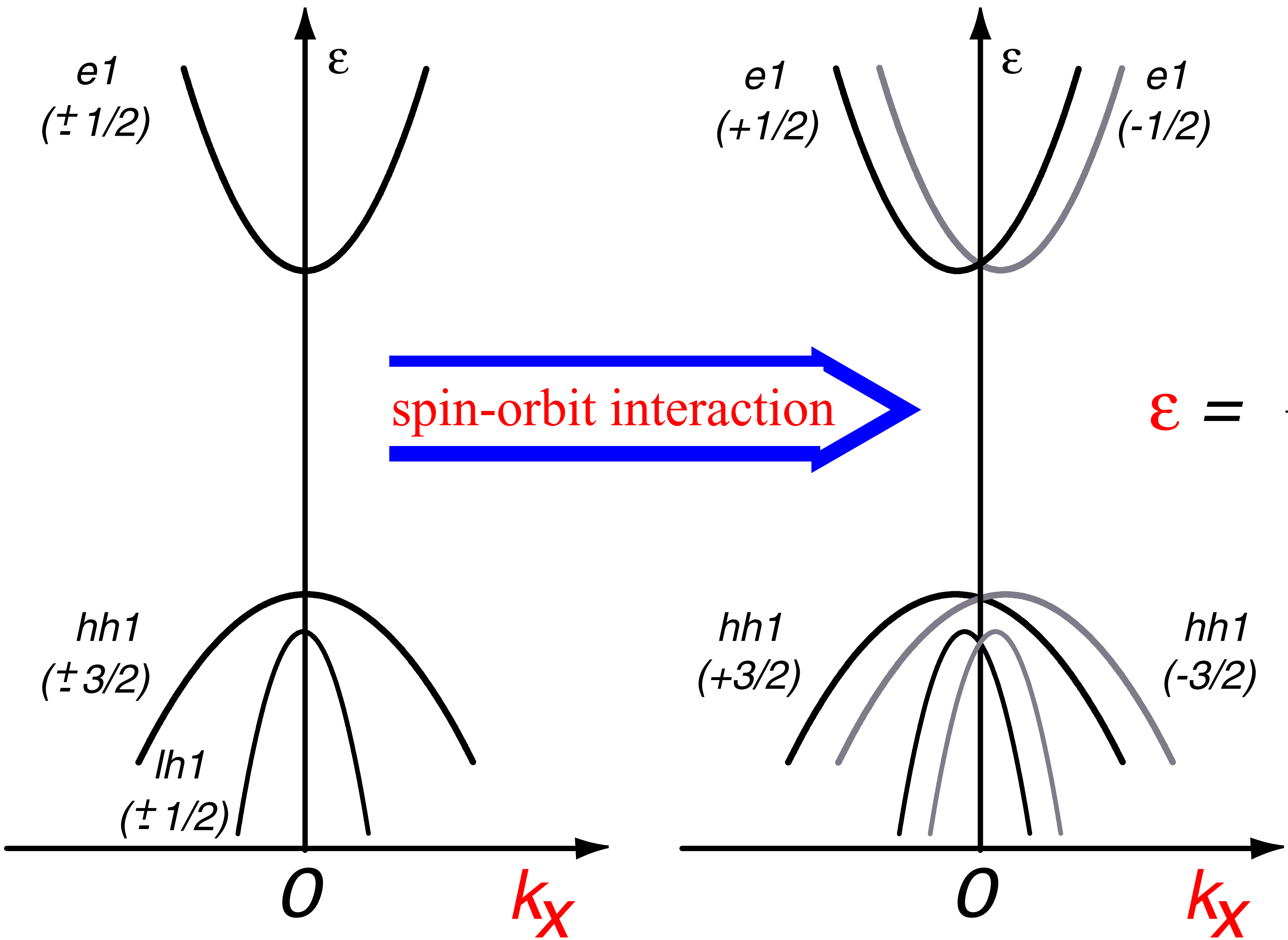
Microscopic model:
k-linear terms in the Hamiltonian



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

k-linear terms

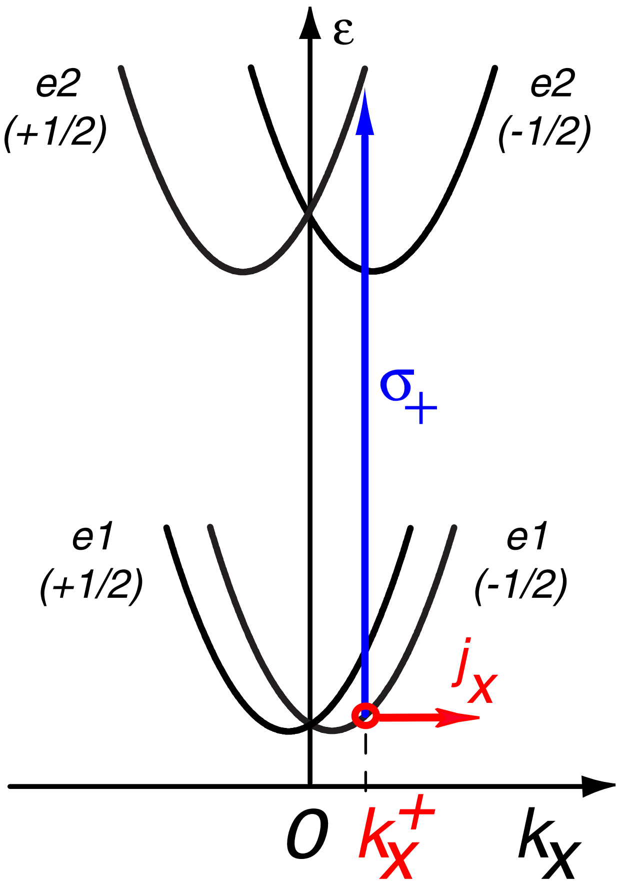
BIA (Dresselhauser)
IIA
SIA (Rashba)

PRL **86**, 4358 (2001)

Microscopic model: direct transitions

$$j \propto W(\varepsilon)\, \nu(k_x^-)\, (\tau_{pi} - \tau_{pf})$$

$$\hbar\omega > \hbar\omega_{LO} \rightarrow \tau_{pi} \gg \tau_{pf}$$



PRL **86**, 4358 (2001)

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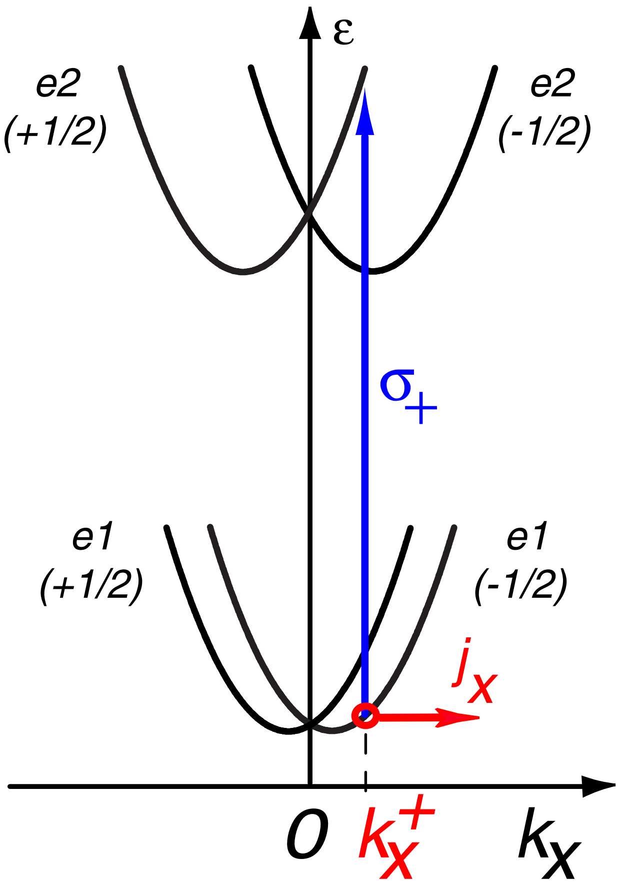
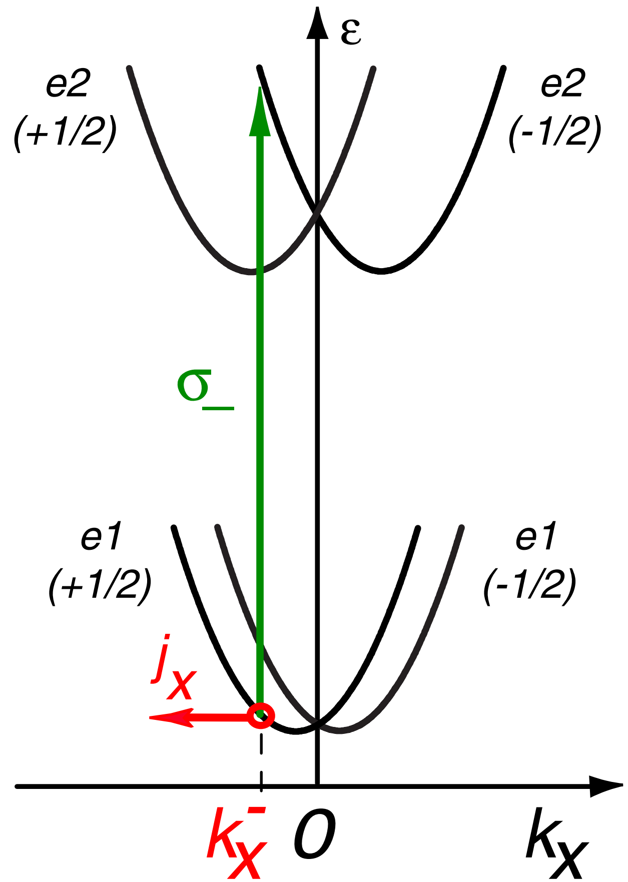
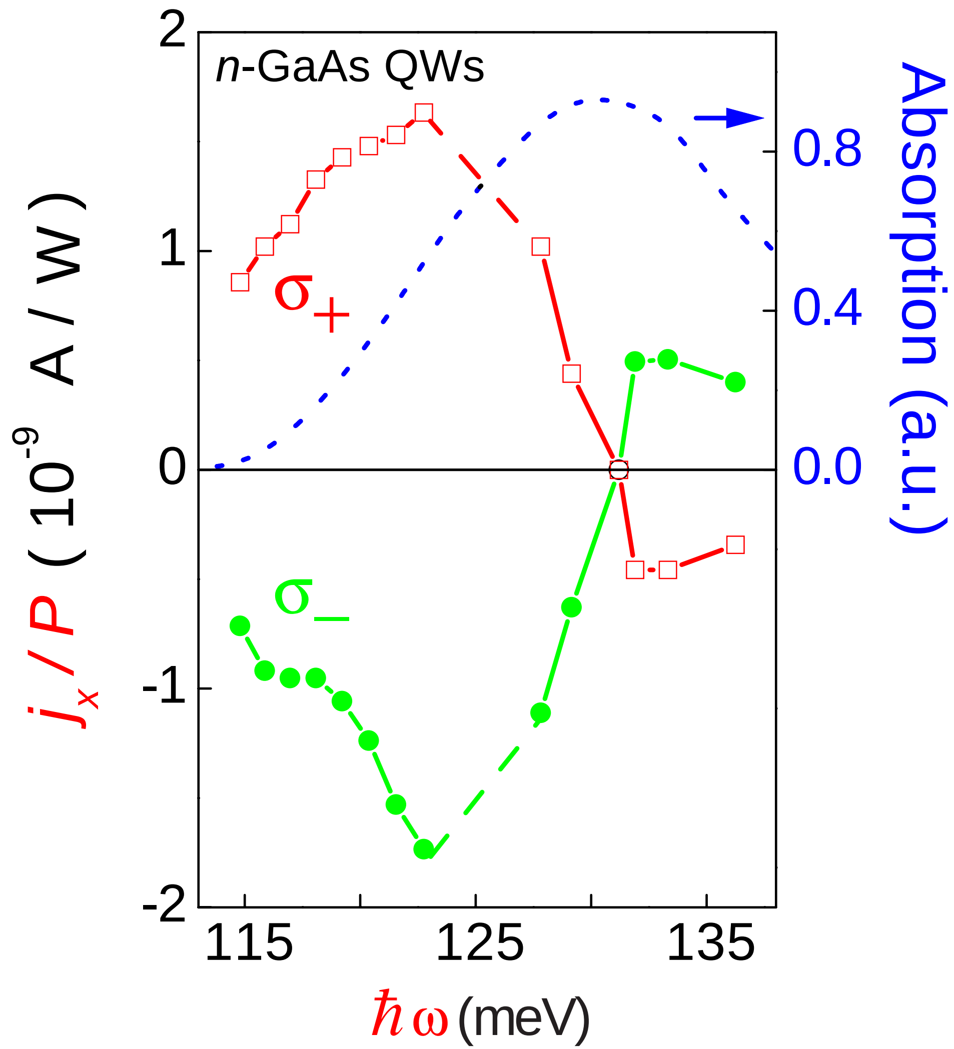


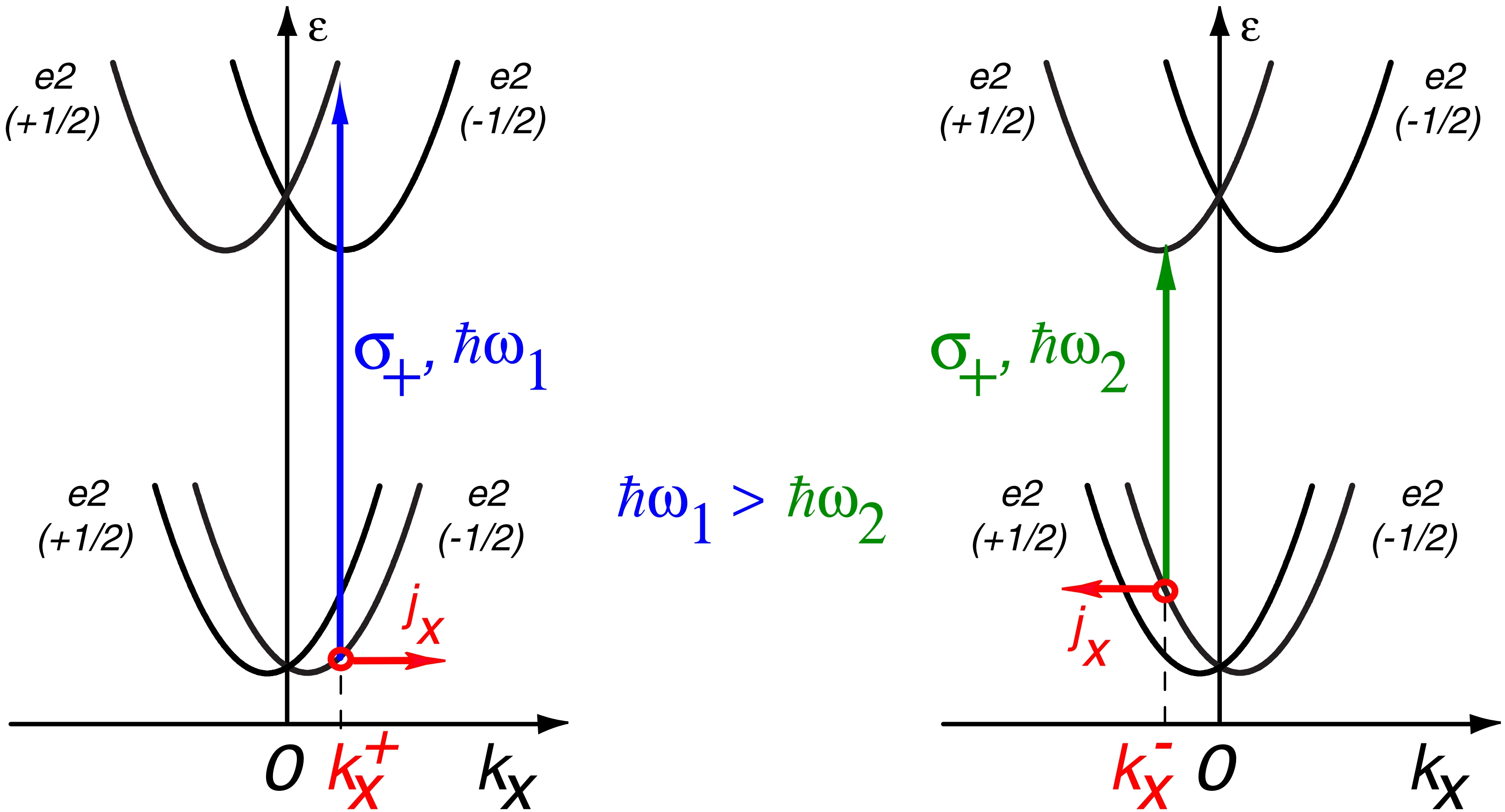


PRB (2003), cond-mat/0303054

Experiment: *e1-e2* direct transitions



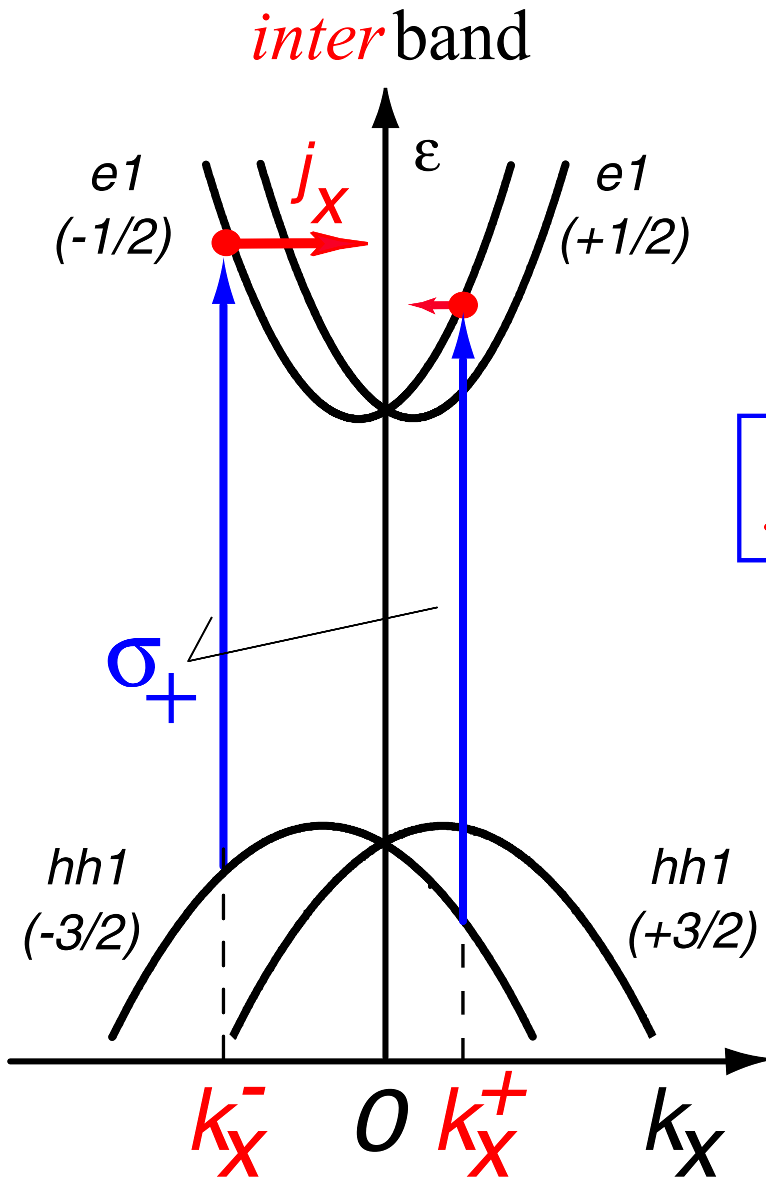
Resonant inversion of the CPGE



$$j_x(\mathrm{CPGE}) \propto (\tau_{p1} - \tau_{p2}) \frac{d\,\eta_{21}(\hbar\omega)}{d\,\hbar\omega} \frac{IP_c}{\hbar\omega}$$

PRL **86**, 4358 (2001)

Microscopic model: direct transitions

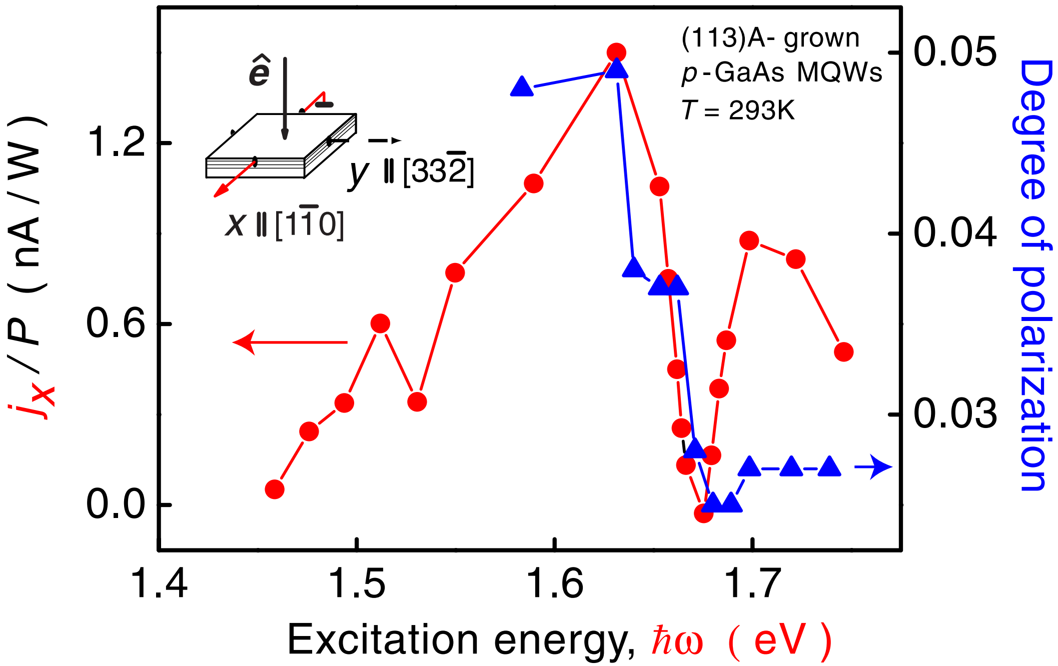


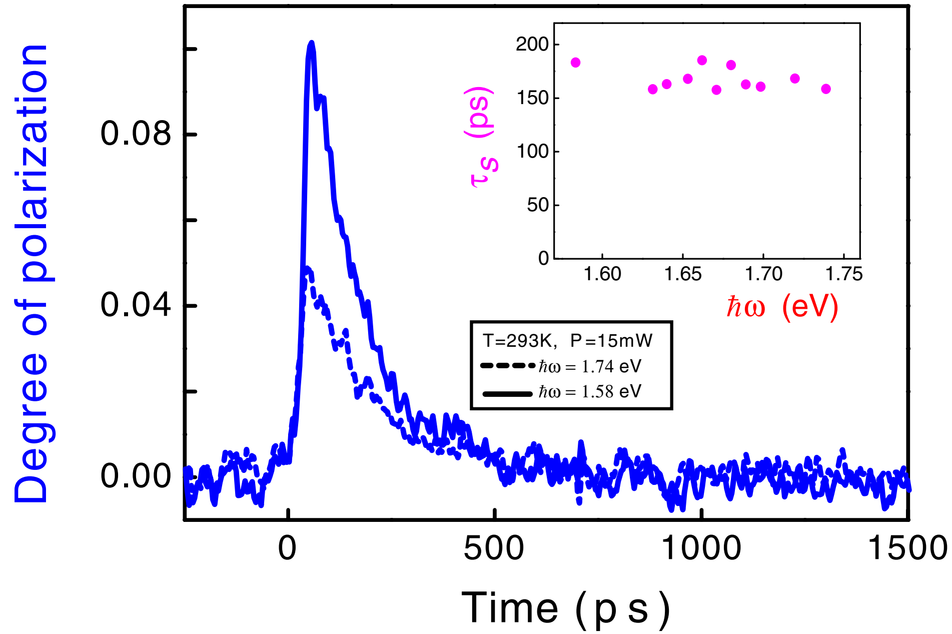
$$j \propto W(\varepsilon)\, \nu(k)\, \tau_p(\varepsilon)$$

Direct interband transitions

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

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





Phenomenological description of PGE I

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

$$j(0) = \sigma_{ij} E_j(0)$$ Ohm's law

$$+ \alpha_{ijkl} E_j(0) E_k(\omega) E_l^*(\omega)$$ Photoconductivity

$$+ \lambda_{ijk} E_j(\omega) E_k^*(\omega)$$ Photogalvanic effect (PGE)

$$E_j(0) = 0 \Longrightarrow j(0) = \lambda_{ijk} E_j(\omega) E_k^*(\omega)$$

see for review:

E.L. Ivchenko, G.E. Pikus, *Superlattices and Other Heterostructures. Symmetry and Optical Phenomena,* (second edition, Springer, Berlin 1999)

B.I. Sturman, V.M. Fridkin, *The Photovoltaic and Photorefractive Effects in Non-Centrosymmetric Materials*, Gordon and Breach Science Publishers, New York, 1992.

Phenomenological description of PGE II

Photogalvanic effect (PGE):

$$j_i\,(PGE) = \alpha_{ijl}\, e_j\, e_l^* = \chi_{ijl}\left[e_j\, e_l^* + e_l\, e_j^*\right]/2 + \gamma_{ij}\, i\,(\mathbf{e}\times\mathbf{e}^*)_j$$

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

χ_{ijl} - third rank *piezoelectric* tensor

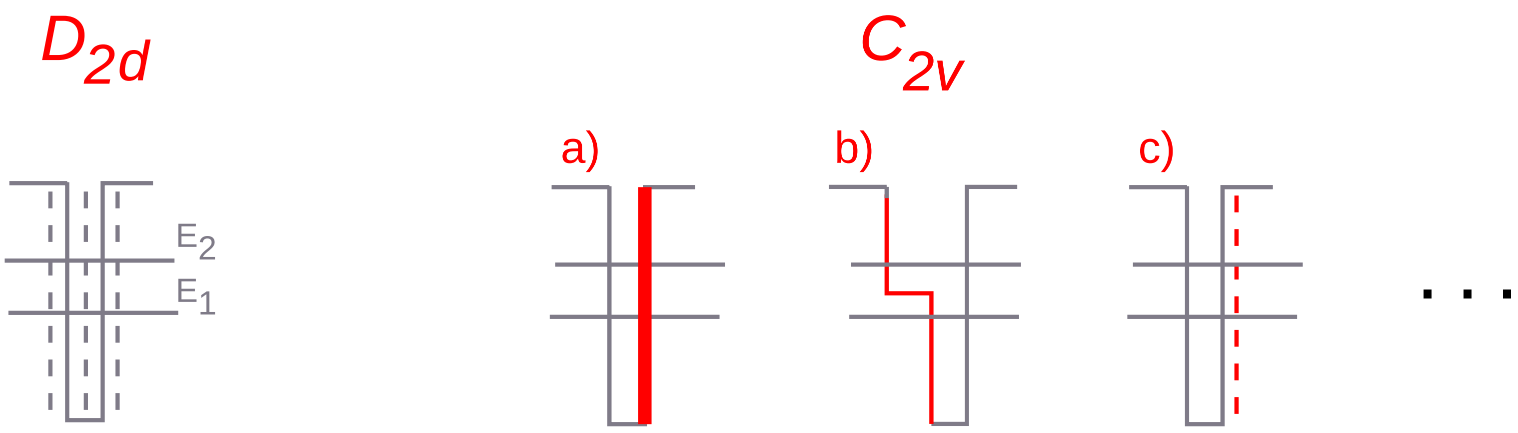
γ_{ij} - second rank *gyration* pseudo-tensor

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

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:

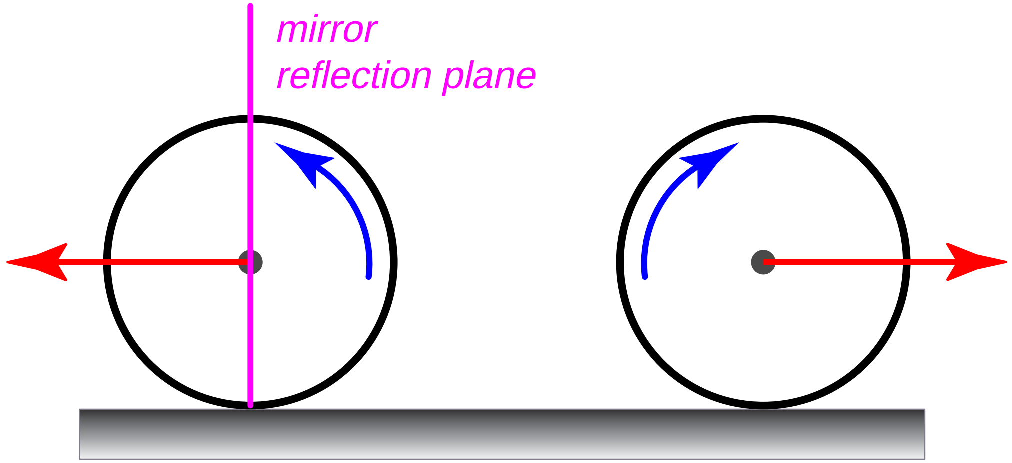
- Bulk GaAs, InAs etc.: point group T_d
  - inversion asymmetric, but *non-gyrotropic*
  - no CPGE (linear photogalvanic effect only)
- (001) - oriented QWs: point group D_{2d} or C_{2v}
  - CPGE -- only at oblique incidence



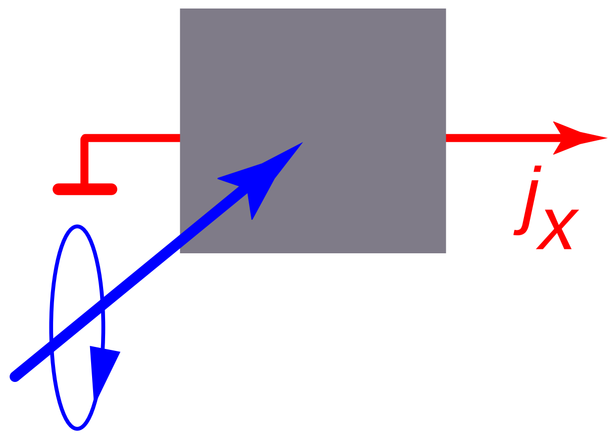
- (113) - oriented QWs: point group C_s
  - CPGE at normal and at oblique incidence

Mechanical analogues of the CPGE

transversal -wheel
longitudinal - propeller



angular momentum of circ. pol. photons ⟹ directed motion of carriers



Physica E **14**, 166 (2002)

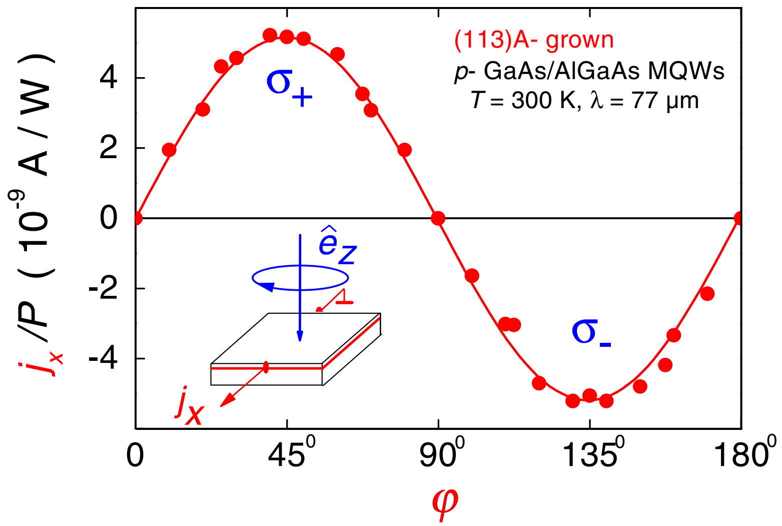
Helicity dependent current

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!



Physica E **14**, 166 (2002)

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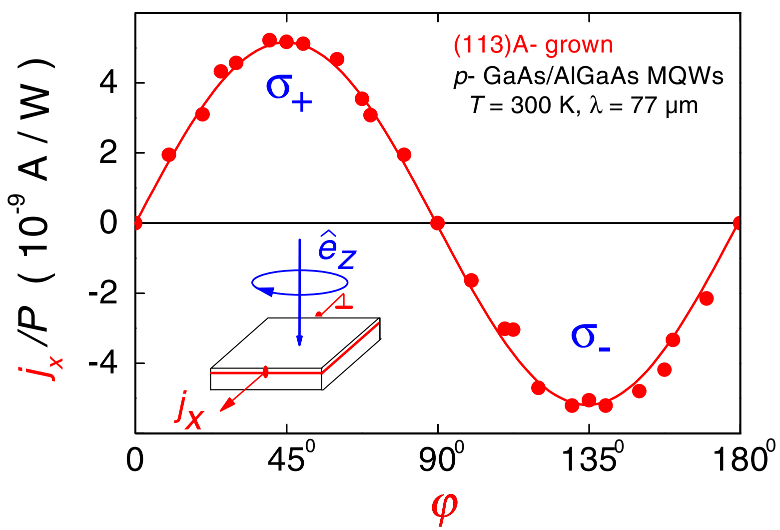
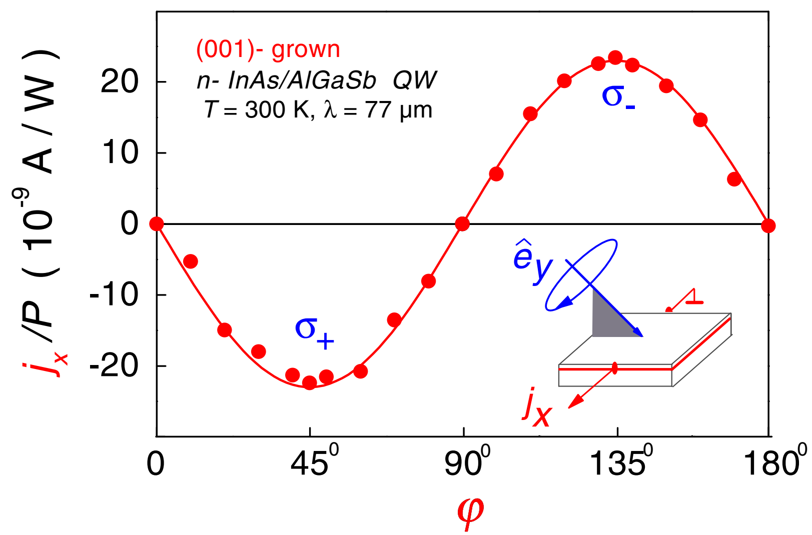


D_{2d} or C_{2v} symmetry

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

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

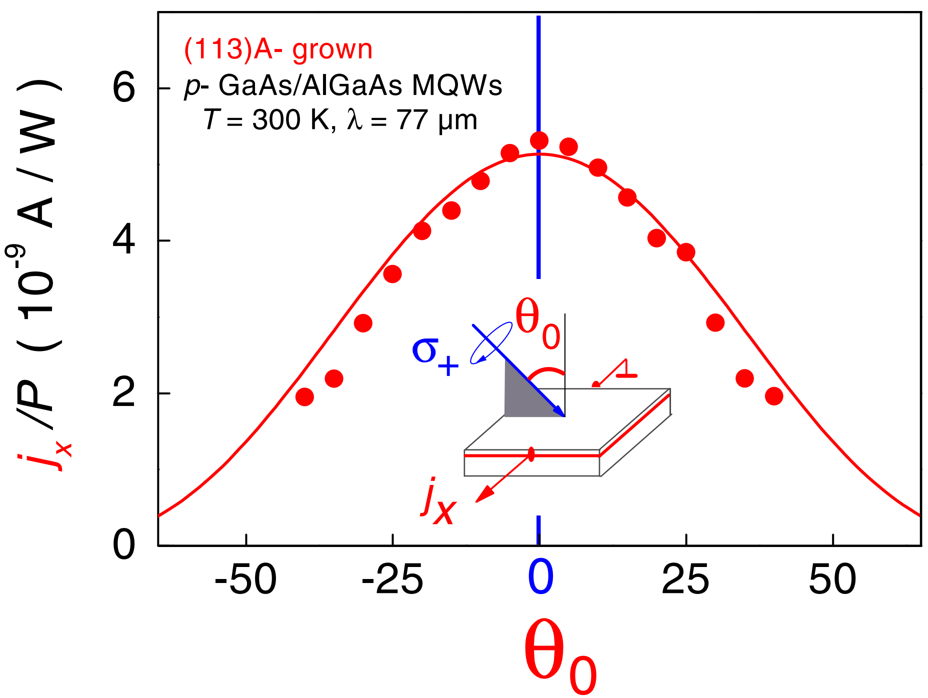
CPGE current occurs under oblique excitation only!



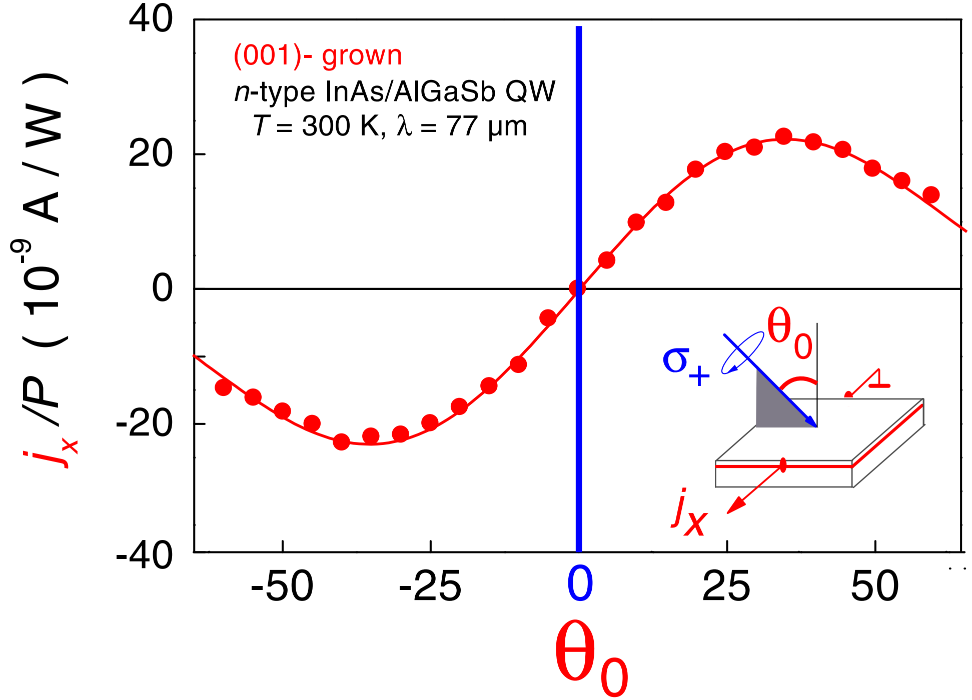
Physica E **14**, 166 (2002)

Normal and Oblique Incidence

C_s symmetry



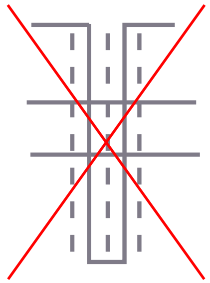
C_{2v} symmetry



Θ_0 - angle of incidence

PRB, (2002)

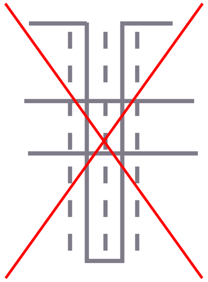
Si:Ge quantum wells

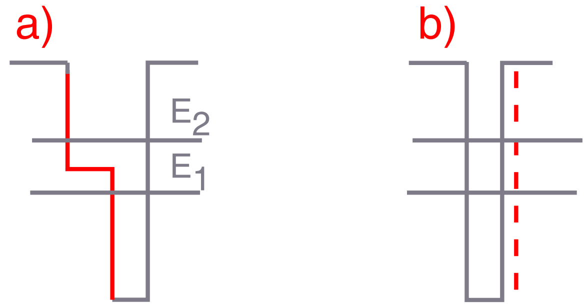


symmetric Si:Ge QWs
do not show CPGE.

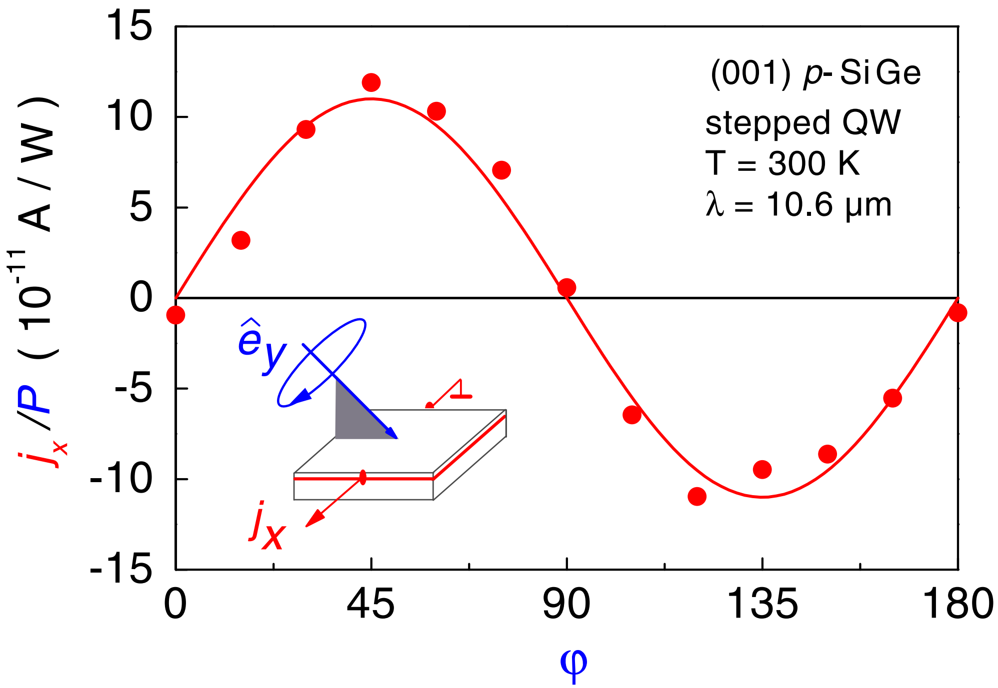
PRB, (2002)

Si:Ge quantum wells





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



Nature **417**, 153 (2002)

Spin-galvanic effect

$$j_\alpha = \sum_\beta Q_{\alpha\beta} S_\beta$$

current *averaged spin*

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

$$\boxed{j_x = Q_{xy} S_y}$$

Nature **417**, 153 (2002)

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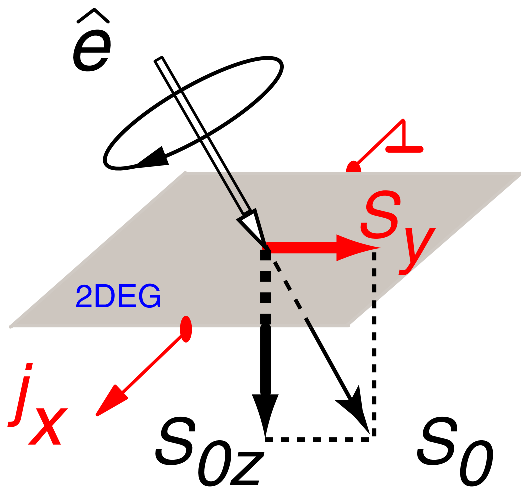

Nature **417**, 153 (2002)

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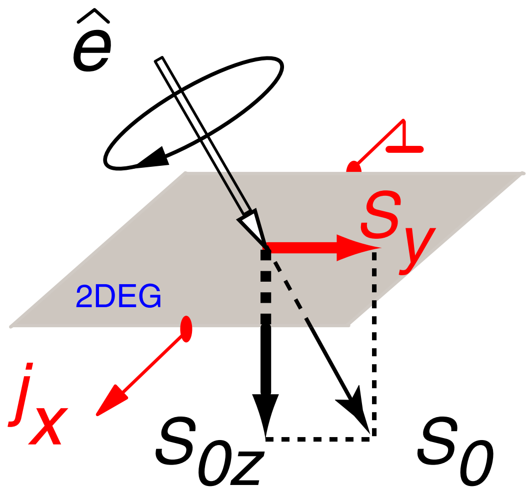
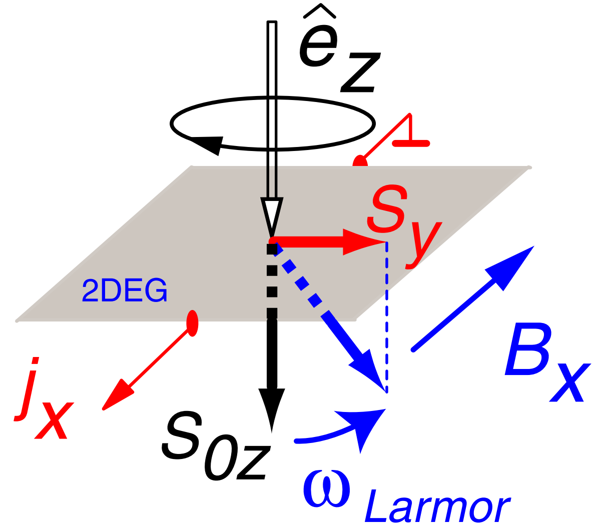
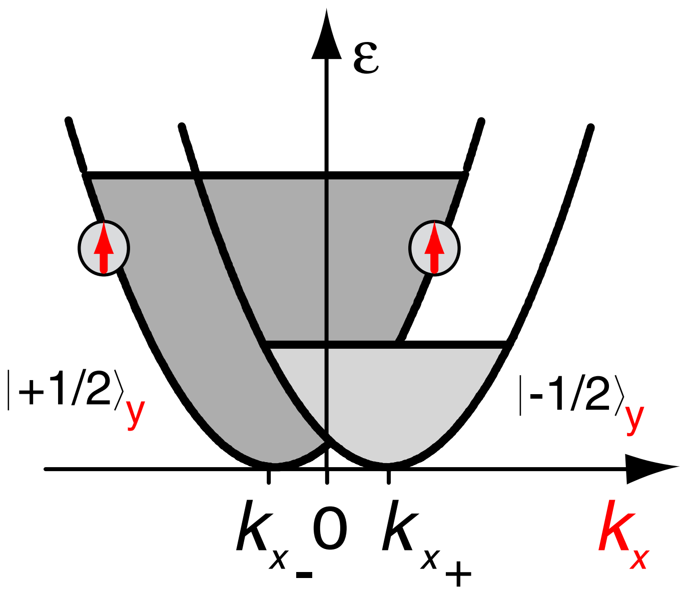




Microscopic model

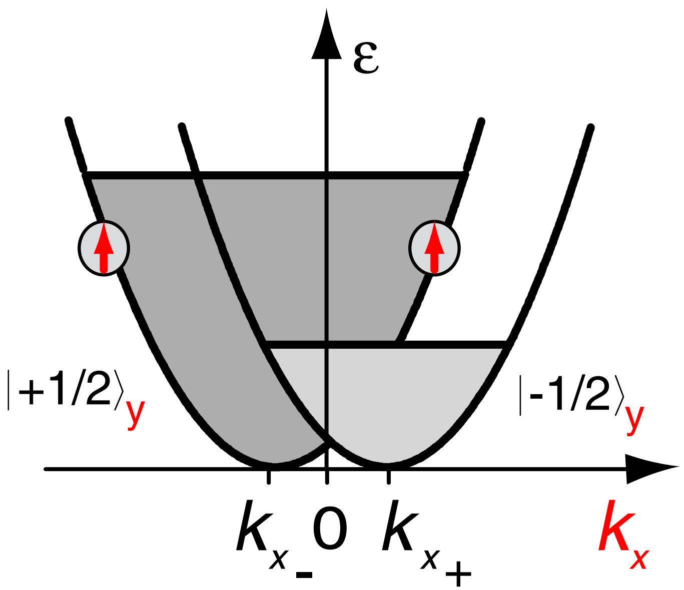
$$j_x = Q_{xy} S_y$$

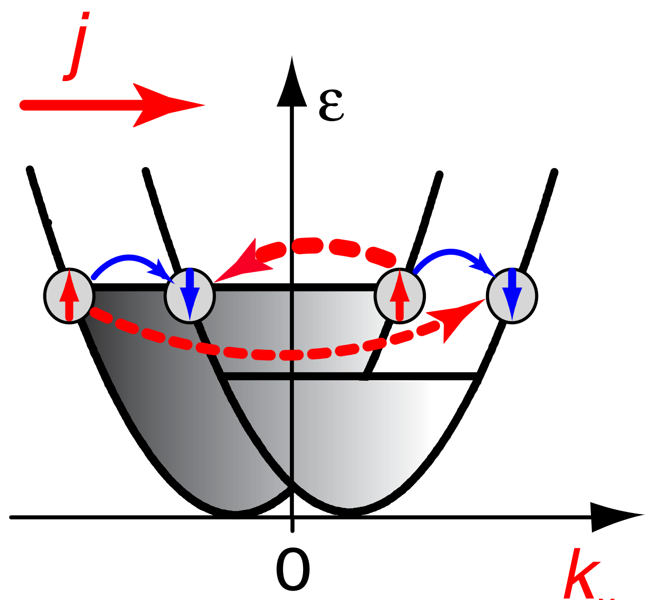


spin orientation

Microscopic model

$$j_x = Q_{xy} S_y$$





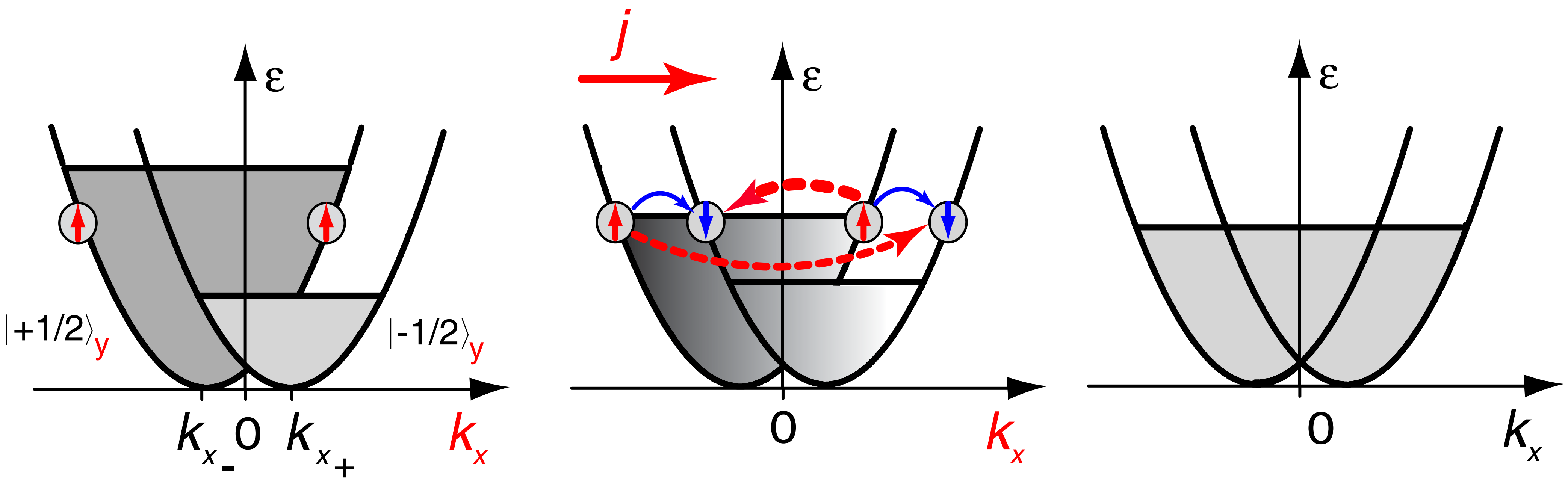
spin orientation

k-dependent
spin-flip scattering

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

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