# Terahertz Spin-Photocurrents and Rashba/Dresselhaus spin-orbit coupling

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# Spin-Photocurrents

Spin photocurrents are electric or spin currents which are driven by optically generated spin polarization. To the present time studied spin-photocurrents are:

- due to inhomogeneous spin orientation

  - *M.I. D'yakonov, V.I. Perel', JETP Lett. 13, 144 (1971).*
  - *N.S. Averkiev, and M.I. D'yakonov, Phys.Semicond. 17, 393 (1983).*
  - *A.A. Bakun, B.P. Zakharchenya, A.A. Rogachev, M.N. Tkachuk, and V.G. Fleisher, JETP Lett. 40, 1293 (1984).*
  - *I. Zutic, J. Fabian, and S. Das Sarma, Phys. Rev. Lett. 88, 066603 (2002).*

- due to homogeneous spin orientation (Rashba/Dresselhaus spin splitting)

  - *S.D. Ganichev, E. L. Ivchenko, S.N. Danilov, J. Eroms, W. Wegscheider, D. Weiss, and W. Prettl, Phys. Rev. Lett. 86, 4358 (2001).*
  - *S.D. Ganichev, E.L. Ivchenko, V.V. Bel'kov, S.A. Tarasenko, M. Sollinger, D. Weiss, W. Wegscheider, and W. Prettl, Nature (London) 417, 153 (2002).*

- due to quantum interference (simultaneous one- and two-photon coherent excitation)

  - *M.J. Stevens, A.L. Smirl, R.D.R. Bhat, J.E. Sipe, and H.M. van Driel, J. Appl. Phys. 91, 4382 (2002).*

# Spin photocurrents due to inhomogeneous spin polarization

- An inhomogeneity of the spin polarization of electrons results in a surface current due to spin-orbit interaction. A gradient of spin density was observed in a bulk AlGaAs by making use of the strong fundamental absorption of circularly polarized light at the band edge of the semiconductor.

  *- M.I. D'yakonov, V.I. Perel', JETP Lett. 13, 144 (1971).*
  *- N.S. Averkiev, and M.I. D'yakonov, Phys.Semicond. 17, 393 (1983).*
  *- A.A. Bakun, B.P. Zakharchenya, A.A. Rogachev, M.N. Tkachuk, and V.G. Fleisher, JETP Lett. 40, 1293 (1984).*

- Spin photocurrent due to the photo-voltaic effect in p-n junctions (solar cell). Circular polarizaed light generates spin polarized electrons and holes. Due to the fast relaxation of hole spin polarization in the bulk and the long spin lifetime of electrons, the photocurrent becomes spin polarized.

  *- I. Zutic, J. Fabian, and S. Das Sarma, Phys. Rev. Lett. 88, 066603 (2002).*

# Spin photocurrents due to quantum interference

- A pure spin current due to quantum interference has been demonstrated at simultaneous one- and two-photon coherent excitation of proper polarization.

  - *M.J. Stevens, A.L. Smirl, R.D.R. Bhat, J.E. Sipe, and H.M. van Driel, J. Appl. Phys. 91, 4382 (2002).*
  - *J. Hübner, W.W. Rühle, M. Klude, D. Hommel, R.D.R. Bhat, J.E. Sipe, and H.M. van Driel, Phys. Rev. Lett. 90, 216601 (2003).*

# Spin photocurrents due to homogeneous spin polarization

- Circularly photogalvanic effect: homogeneous irradiation of gyrotropic QWs with circularly polarized light results in a non-uniform distribution of spin oriented photoexcited carriers in k-space due to optical selection rules and energy and momentum conservation which leads to a spin current.

  *- S.D. Ganichev, E. L. Ivchenko, S.N. Danilov, J. Eroms, W. Wegscheider, D. Weiss, and W. Prettl, Phys. Rev. Lett. 86, 4358 (2001).*

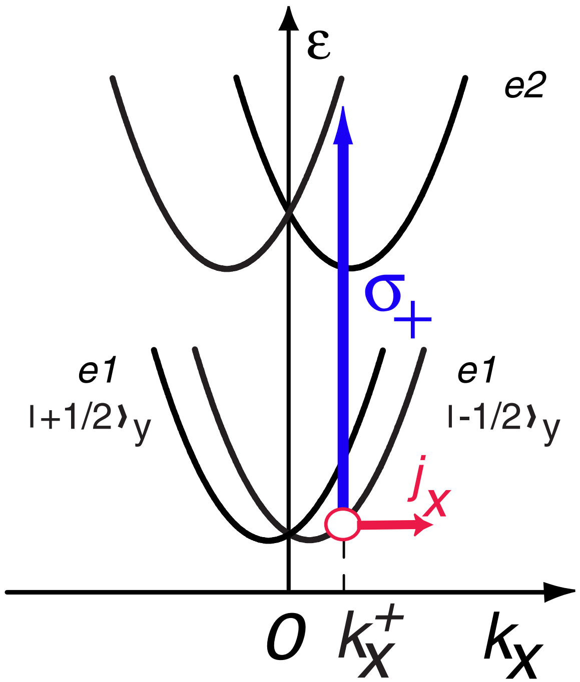
- Spin-galvanic effect: A homogeneous spin polarization obtained by any means, not necessarily optical, yields a current, if the same symmetry requirements, which allow k-linear terms in the Hamiltonian, are met. The microscopic origin of the spin-galvanic effect is an inherent asymmetry of spin-flip scattering of electrons in systems with removed k-space spin degeneracy of the band structure. This effect has been demonstrated by optical spin orientation and therefore also represents a spin photocurrent.

  *- S.D. Ganichev, E.L. Ivchenko, V.V. Bel'kov, S.A. Tarasenko, M. Sollinger, D. Weiss, W. Wegscheider, and W. Prettl, Nature (London) 417, 153 (2002).*

# In *GaAs, InAs* and other gyrotropic QWs a *uniform* *non*-equilibrium spin polarization results in a current flow.

## Circular Photogalvanic Effect

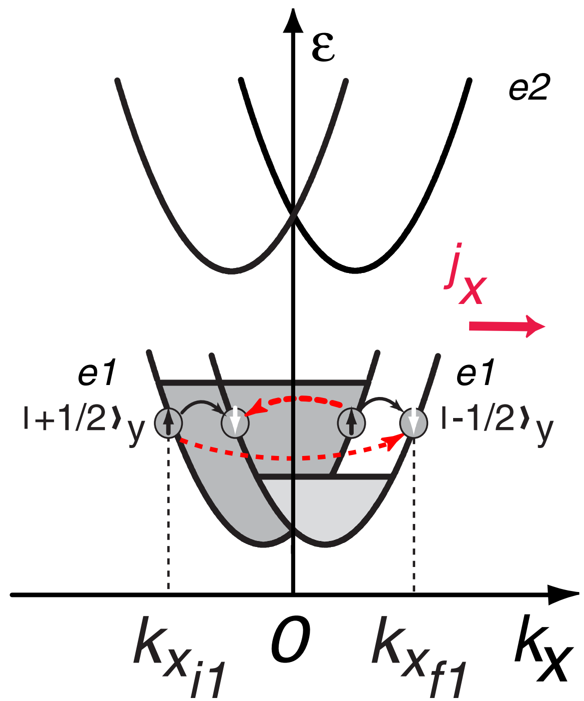
Phys. Rev. Lett. 86, 4358 (2001)




decays with a *momentum* relaxation time

## Spin-Galvanic Effect

*Nature* 417, 153 (2002)




decays with a *spin* relaxation time

# Why terahertz radiation?

Spin photocurrents at homogeneous excitation have been observed at very different types of optical excitation at wavelengths ranging from the visible to the far-infrared. However, most of the measurements were carried out in the far-infrared range (terahertz frequencies) with photon energies less than the energy gap of investigated semiconductors.

Terahertz excitation has several advantages like:

- in contrast to inter-band excitation, there are no spurious photocurents due to other mechanisms like the Dember effect, photovoltaic effects at contacts etc.

- only one type of carriers is excited yielding monopolar spin orientation **-->**
  **-->** Access to the spin-orbit coupling and spin relaxation processes within one band.

# Methods

## *Inter- and intra*-subband excitation: Infrared and far infrared range

- molecular optically pumped laser (Regensburg): $\lambda$ = 9-1000 μm, P < 40 kW, 100 ns pulses
- free-electron-laser FELIX (Holland): $\lambda$ = 6-150 μm, P < 10 kW, ~10 ps pulses

*Methods:* $\lambda/4$ - plates, digital oscilloscope

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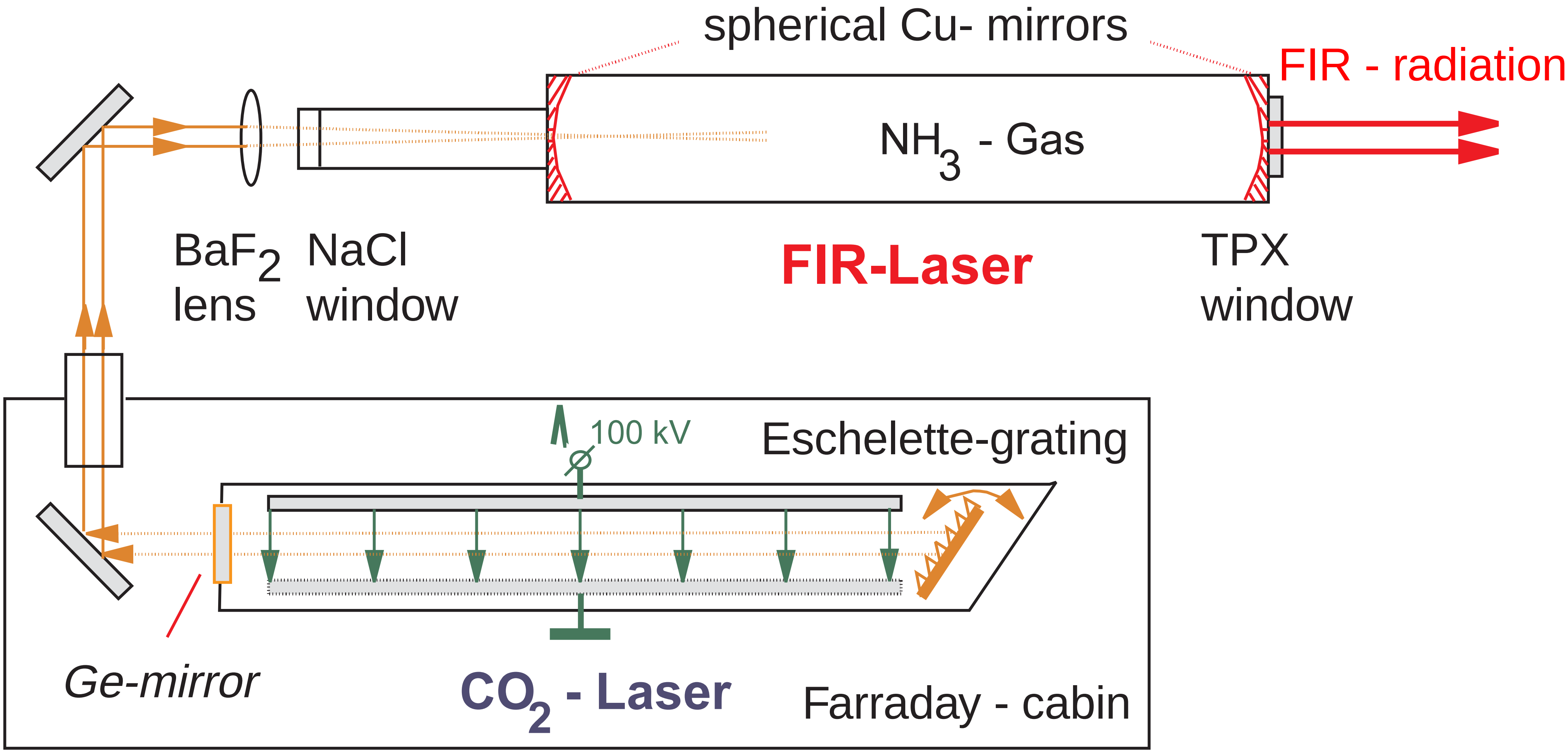
*Methods:* $\lambda/4$ - plates, digital oscilloscope

## *Inter*-band excitation:

- cw and pulsed Ti:sapphire laser : $\lambda$ = 0.7-0.85 μm, $P_{cw}$ = 20 mW,
  (Hannover, gr. M. Oestreich and Regensburg, gr C. Back and W. Wegscheider):

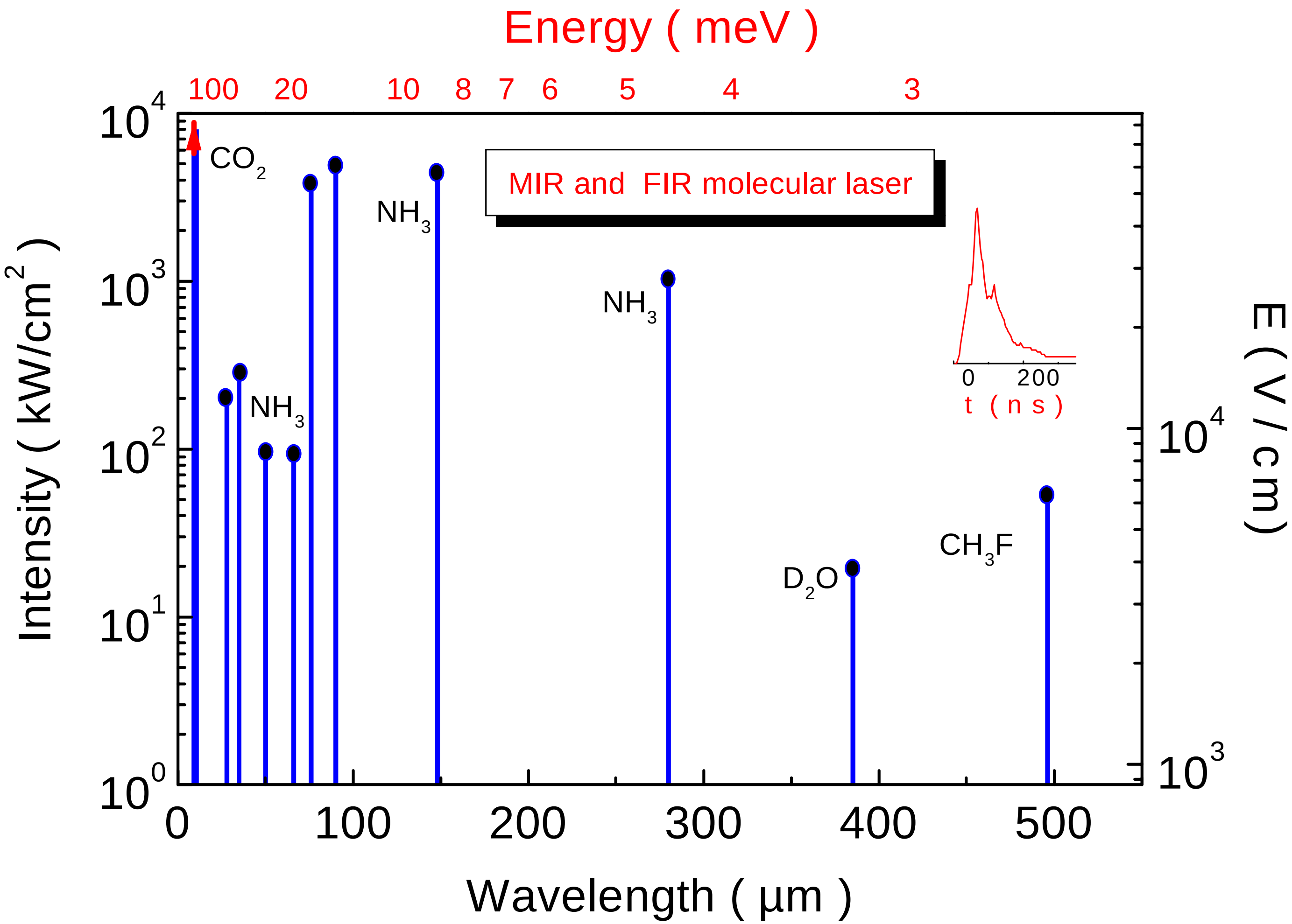
*Methods:* polarisation modulated by photoelastic modulator, lock-in amplifier


spherical Cu- mirrors
FIR - radiation
NH3 - Gas
BaF2 lens
NaCl window
FIR-Laser
TPX window
100 kV
Eschelette-grating
Ge-mirror
CO2 - Laser
Farraday - cabin

Physica B, **273-274,** 737 (1999)

# Source of radiation:

- Intensity: up to 5 MW/cm$^2$
- Pulse duration: ~ 100 ns
- Wavelength: 9-500 μm



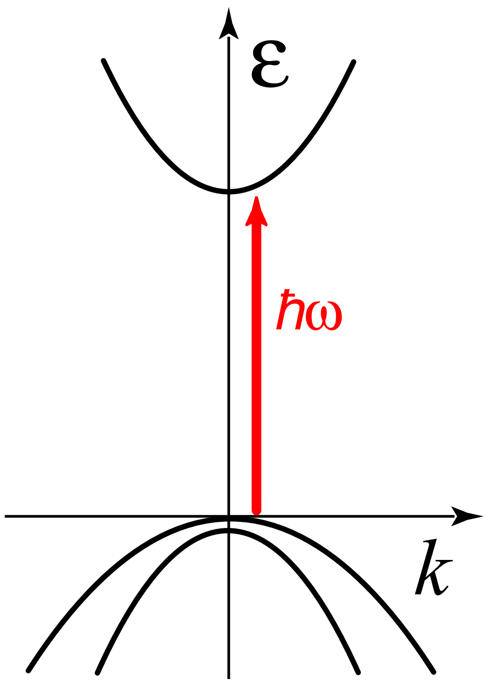
# Samples and Excitation Mechanisms

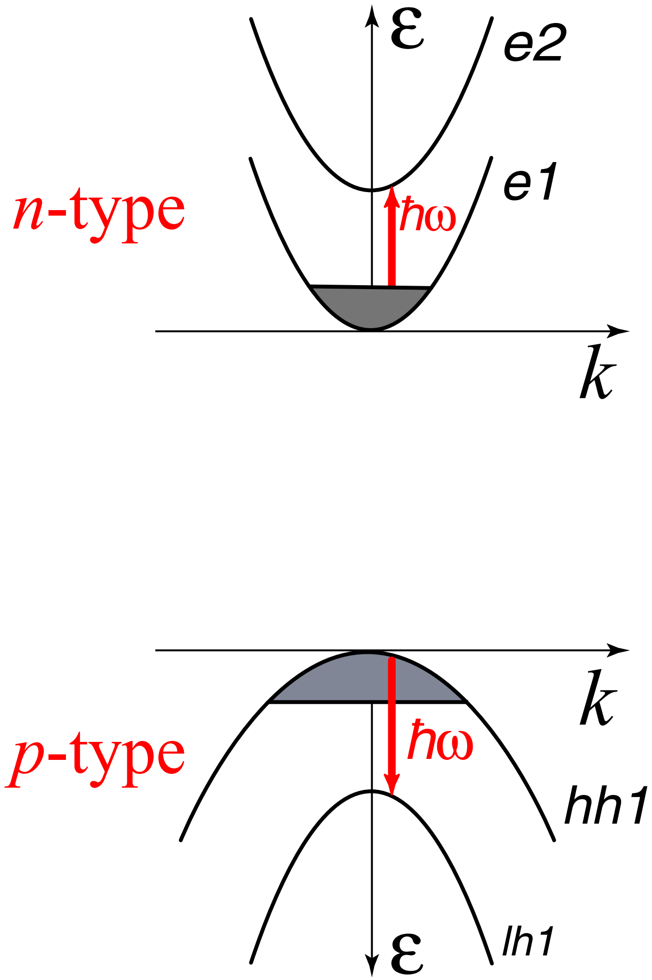
## Samples:

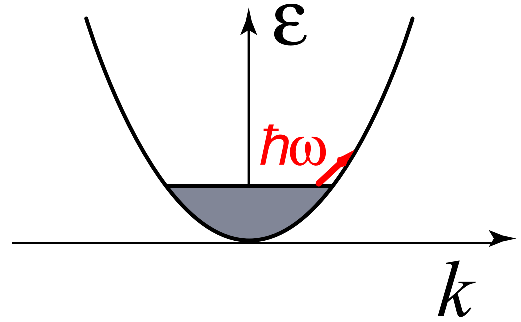
(001) and (113) MBE grown *n*- and *p*- type:

*GaAs*, *InAs*, *SiGe*, *BeZnMnSe* - QW structures ( $L_w$ = 7-20 nm )

## Excitation:



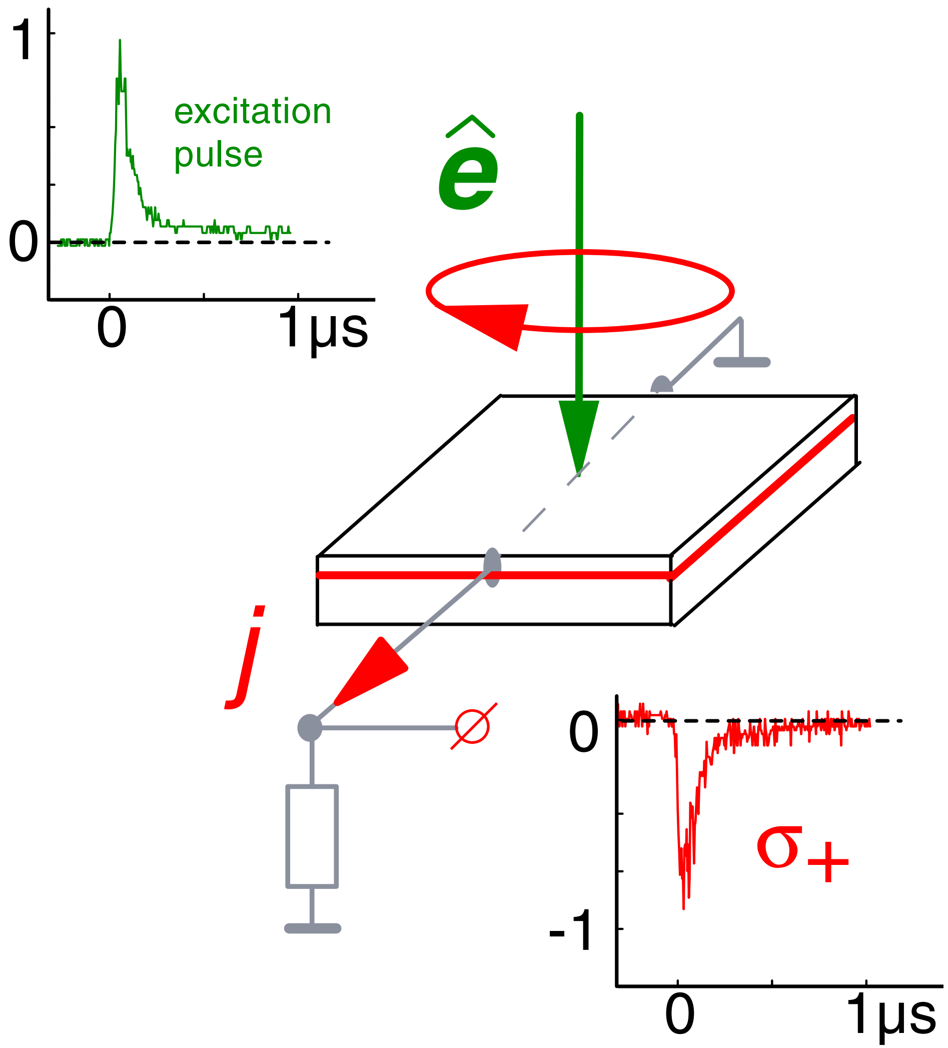




*n*- and *p*- type
(small ħω)

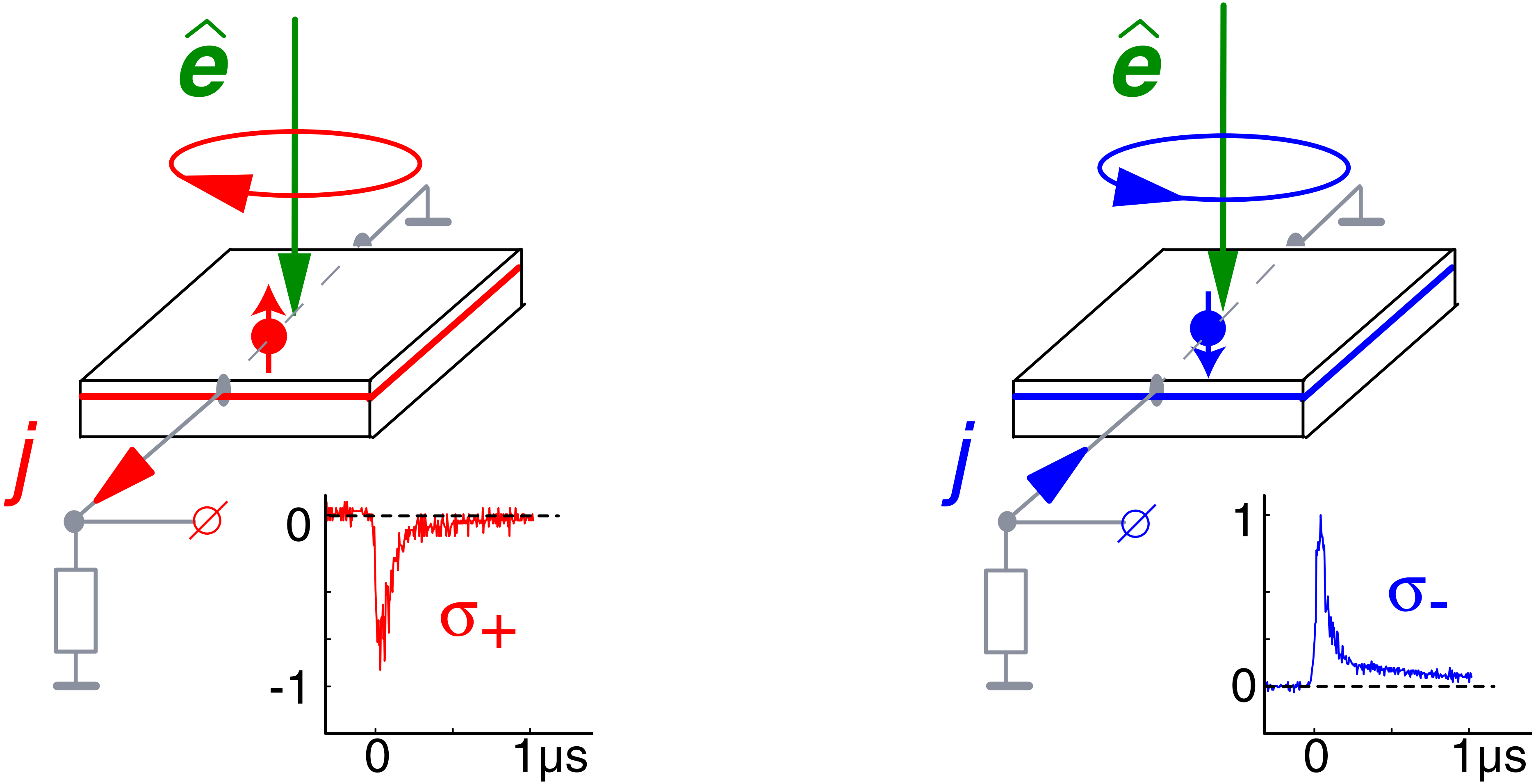
APL **77**, 3146 (2000)

# Circular photogalvanic effect in QW



APL **77**, 3146 (2000)

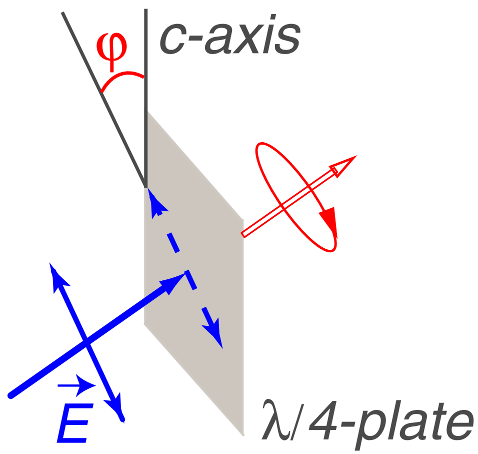
# Circular photogalvanic effect in QW




**Helicity of radiation ⇒ Spin ⇒ Current**

# Helicity dependence

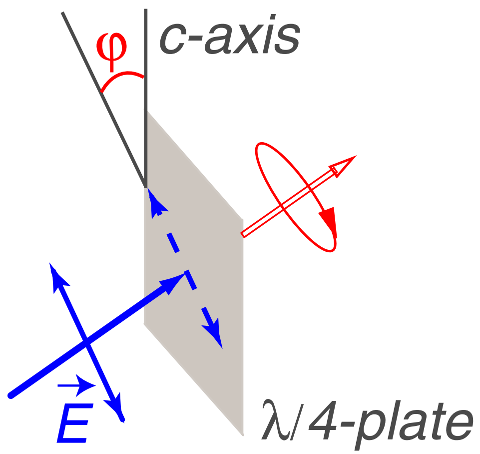
$$P_{circ} = \frac{I_{\sigma+} - I_{\sigma-}}{I_{\sigma+} + I_{\sigma-}} = \sin 2\varphi$$




$$E(\varphi) = E_x + e^{i\varphi} E_y$$

# Helicity dependence

$$j_x \propto P_{circ} = \frac{I_{\sigma+} - I_{\sigma-}}{I_{\sigma+} + I_{\sigma-}} = \sin 2\varphi$$




$$E(\varphi) = E_x + e^{i\varphi} E_y$$