Available online at www.sciencedirect.com
SCIENCE DIRECT®
Physica E 20 (2004) 419–423
PHYSICA E
www.elsevier.com/locate/physe

The infrared spin-galvanic effect in semiconductor quantum wells

S.D. Ganichev

Fakultät für Physik, Universität Regensburg, 93040 Regensburg, Germany

Abstract

The spin-galvanic effect generated by homogeneous optical excitation with infrared circularly polarized radiation in quantum wells (QWs) is reviewed. The spin-galvanic current flow is driven by an asymmetric distribution of spin-polarized carriers in $\boldsymbol{k}$-space of systems with lifted spin degeneracy due to $\boldsymbol{k}$-linear terms in the Hamiltonian. Spin photocurrents provide methods to investigate the spin-splitting of the band structure and to make conclusion on the in-plane symmetry of QWs.

PACS: 72.40.+w; 72.25.Fe; 78.67.−n

Keywords: Spin-galvanic effect; Quantum well; Infrared; Spin orientation

1. Introduction

Spin photocurrents generated by excitation with circularly polarized radiation in quantum wells (QWs) have attracted considerable attention in the recent decade [1]. They demonstrate a new property of the electron spin in a homogeneous spin-polarized two-dimensional electron gas (2DEG): its ability to drive an electric current if some general symmetry requirements are met. Even a thermalized but spin-polarized electron gas can drive an electrical current [2]. A homogeneous spin polarization yields a current if the same symmetry requirements are met, which allow $\boldsymbol{k}$-linear terms in the Hamiltonian [3]. This phenomenon is referred to as the spin-galvanic effect [4]. The microscopic origin of the spin-galvanic effect is an inherent asymmetry of spin-flip scattering of electrons in systems with removed $\boldsymbol{k}$-space spin degeneracy of the band structure. This effect has been demonstrated by optical spin orientation [4,5] and therefore represents a spin photocurrent. Several aspects raised by the investigation of the spin-galvanic effect are directly connected with the rapidly developing field "spintronics" aimed to realize novel concepts of semiconductor devices [6]. Indeed, necessary conditions to create spintronic devices are high spin polarizations in QWs and a large spin-splitting of subbands in $\boldsymbol{k}$-space, which allows to manipulate spins with an external electric field by the Rashba effect [3]. The spin-galvanic effect offers a new experimental access to investigate these phenomena. While the spin-galvanic effect may occur at visible excitation there is a particular interest in its investigation applying infrared radiation. First of all, in the infrared range the spin-galvanic current is not masked by strong spurious photocurrents like the Dember effect, photovoltaic effects, etc. Furthermore, in contrast to optical spin orientation using inter-band transitions [8],

E-mail address: sergey.ganichev@physik.uni-regensburg.de (S.D. Ganichev).

1386-9477/$ - see front matter
doi:10.1016/j.physe.2003.08.049

infrared radiation excites only one type of charge carriers yielding a monopolar spin orientation [1]. Electrons remain close to the Fermi energy which corresponds to the conditions of electrical spin injection. Finally, spin relaxation may be investigated in the absence of electron–hole interaction and exciton formation.

2. Theoretical consideration

Phenomenologically, an electric current can be linked to the electron's averaged spin polarization $\boldsymbol{S}$ by

$$j_\alpha = \sum_\gamma Q_{\alpha\gamma} S_\gamma \ , \qquad (1)$$

where $Q_{\alpha\gamma}$ is a second-rank pseudo-tensor. For C_{2v} symmetry of (0 0 1)-grown QWs relevant to present experiments the spin-galvanic current is given by

$$j_x = Q_{xy} S_y, \quad j_y = Q_{yx} S_x \qquad (2)$$

with $x \| [1\,\bar{1}\,0]$ and $y \| [1\,1\,0]$. Hence, a spin-polarization-driven current needs a spin component lying in the plane of the QWs. There are two different microscopic mechanisms of the spin-galvanic effect, namely, kinetic and relaxational [2]. Fig. 1a illustrates the generation of a spin-galvanic current due to a kinetic mechanism relevant to experiments presented below. The current flow is caused by $\boldsymbol{k}$-dependent spin-flip relaxation processes. Spins oriented in the y-direction are scattered along k_x from the, e.g. higher-filled spin subband $|+1/2\rangle_y$ to the less-filled spin subband $|-1/2\rangle_y$. The spin-flip scattering rate depends on the values of the wave vectors of the initial and final states [9]. Two scattering processes shown by broken arrows in Fig. 1a are inequivalent and generate an asymmetric carrier distribution around the subband minima in both subbands which results in a current flow along the x-direction. The picture depicted in Fig. 1b also takes into account an elastic scattering with $k_y \neq 0$ (see Ref. [1]). The uniformity of spin polarization in space is preserved during the scattering processes. Therefore, the spin-galvanic effect differs from other experiments carried out in visible spectral range where the spin current is caused by inhomogeneities [12–14]. The reverse process to the spin-galvanic effect, i.e. a spin polarization induced by an electric current flow in gyrotropic media has been theoretically proposed in Refs. [10,11].

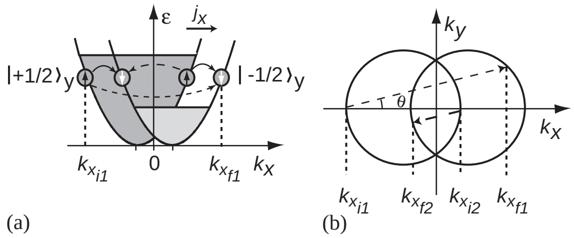

Fig. 1. Microscopic origin of the spin-galvanic current in presence of $\boldsymbol{k}$-linear terms in the electron Hamiltonian.

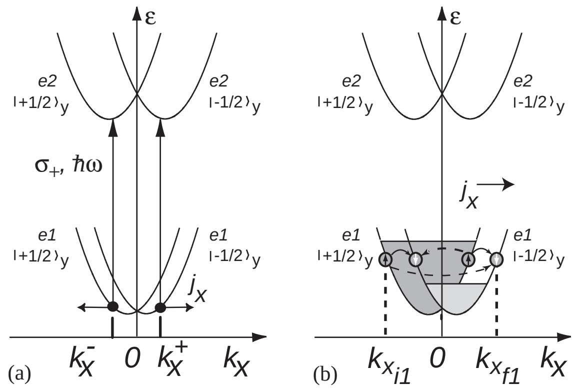

Fig. 2. Microscopic picture of (a) circular photogalvanic effect and (b) spin-galvanic effect at inter-subband excitation in C_{2v} point group samples.

The microscopic theory of the spin-galvanic effect for inter-subband transitions in n-type materials of C_{2v} symmetry has been developed in Ref. [5]. In this case, the spin orientation (see Fig. 2b) is generated by resonant spin-selective optical excitation (see Fig. 2a) followed by spin-non-specific thermalization. The spin-galvanic current, e.g. in x-direction, is given by

$$j_{\mathrm{SGE},x} = Q_{xy} S_y \sim e \, \frac{\beta_{yx}}{\hbar} \, \frac{\tau_p \tau_s}{\tau_s'} \, \frac{\eta_{21} I}{\hbar\omega} P_{\mathrm{circ}} \hat{\mathbf{e}}_y \ , \qquad (3)$$

where η_{21} is the absorbance at transitions between e1 and e2 subbands, β_{yx} is a pseudo-tensor describing the subband splitting and $\hat{\mathbf{e}}$ is the unit vector pointing in the direction of the light propagation. Since scattering is the origin of the spin-galvanic effect, the current j_{SGE} is determined by the Elliot–Yafet spin relaxation process [9] even if other spin relaxation mechanisms dominate. The Elliot–Yafet relaxation time τ_s' is proportional to the momentum relaxation time τ_p. Therefore, the ratio τ_p/τ_s' in Eq. (3) does not depend on the momentum relaxation time. The in-plane average spin, e.g. S_y, decays with the total spin relaxation time τ_s. Thus the time decay of the spin-galvanic current following pulsed photoexcitation is determined by τ_s. This time may have contributions from any spin relaxing process and in the present case of GaAs QWs is determined by D'yakonov–Perel' mechanism [9].

3. Samples and experimental technique

The experiments were carried out on n-type (0 0 1)-oriented GaAs and InAs QWs belonging to C_{2v} symmetry. Samples of QWs with widths of 7–20 nm and free-carrier densities of about 10^{11} cm^{-2} were studied in a temperature range from 4.2 to 293 K. For optical excitation in the mid-infrared (MIR) range a high power pulsed TEA-CO_2 laser and the free electron laser "FELIX" at FOM-Rijnhuizen in The Netherlands [15] have been used. In the FIR range, a molecular FIR laser [1] has been used. The radiation pulses of the CO_2 and the molecular laser with pulse duration of $\simeq$ 100 ns and a radiation power P up to 100 kW were focused to a spot of about 1 mm^2. The output pulses of light from FELIX were chosen to be 3 ps long, separated by 40 ns, in a train (or "macropulse") of 5 μs duration. Typically, these lasers emit linearly polarized radiation. The polarization was modified from linear to circular using a Fresnel rhomb and $\lambda/4$ plates for MIR and FIR radiation. Depending on the photon energy and QW band structure MIR and FIR radiation induce direct optical transitions between size quantized subbands or, at longer wavelengths, indirect optical transitions in the lowest subband. The photocurrent j_x was measured in unbiased structures via the voltage drop across a 50 Ω load resistor in a closed-circuit configuration.

4. Spin-galvanic effect at optical orientation

A spin-galvanic effect at optical excitation in (0 0 1)-grown QWs may be observed if an in-plane component of the spin polarization is present due to oblique incidence of the exciting circularly polarized radiation. In this case, however, a circular photogalvanic effect (CPGE) [7] may also occur interfering with the spin-galvanic effect. Both effects are described by pseudo-tensors subjected to the same symmetry restrictions which make them phenomenologically inseparable. Nevertheless, a pure spin-galvanic current has been obtained at inter-subband transitions in n-type GaAs QWs [5]. Two effects were distinguished using their different microscopic origin which results in a qualitatively different spectral behavior. Indeed the spectrum of CPGE changes sign and vanishes in the center of the resonance [16]. In contrast, the optically induced spin-galvanic current is proportional to the absorbance (Eq. (3)) and, hence, assumes a maximum at the center of the resonance [5]. Thus, if a measurable helicity dependent current is present in the center of the resonance it must be attributed to the spin-galvanic effect.

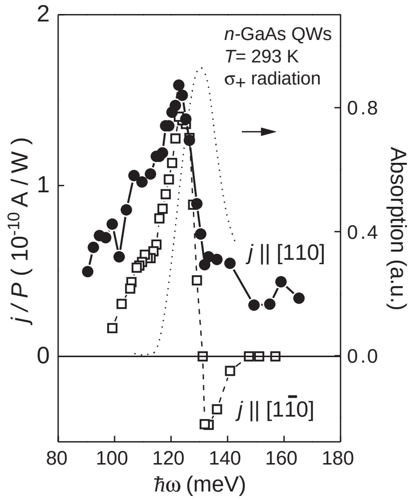

Fig. 3. Photocurrent n-type GaAs QWs of 8.2 nm width as a function of the photon energy $\hbar\omega$. The dotted line shows the absorption spectra.

Fig. 3 shows the photon energy dependence of the current measured for incidence of σ_+ radiation in two different planes with components of propagation along the x- and y-directions. It can be seen that for a current along $x \| [1\,\bar{1}\,0]$ the spectral shape is similar to the derivative of the absorption spectrum, as it is expected for CPGE [16]. When the sample was rotated by 90° around z the sign change in the current, now along $y \| [1\,1\,0]$, disappears and its spectral shape follows more closely the absorption spectrum indicating the spin-galvanic effect.

The fact that the current in x-direction is dominated by CPGE and in y-direction by the spin-galvanic effect is caused by the crystallographic non-equivalence of the two axes $[1\,1\,0]$ and $[1\,\bar{1}\,0]$ in C_{2v} symmetry. Both currents, CPGE and spin-galvanic, are caused by spin splitting of subbands in $\boldsymbol{k}$-space. This spin splitting is strongly different for x- and y-directions due to an interplay of Rashba (SIA) and Dresselhaus (BIA) terms in the Hamiltonian when rotating the wave vector in the QW plane [6]. For the data of Fig. 3, it appears so that due to this interplay the spin-galvanic effect dominates over CPGE for the current along y-direction [5].

5. Spin-galvanic effect in the presence of a magnetic field

A more general possibility to investigate the spin-galvanic effect without contributions of the CPGE has been introduced in Ref. [4]. The spin polarization was obtained by the absorption of circularly polarized radiation at normal incidence on (0 0 1)-grown QWs as depicted in Fig. 4. For normal incidence both the CPGE as well as the spin-galvanic effect vanish [1]. Thus, a steady-state spin polarization S_{0z} along z-axis is achieved, but no spin photocurrent is obtained. An in-plane component of the spins, necessary for the spin-galvanic effect, is generated by applying a magnetic field $\boldsymbol{B} \| x$. Due to Larmor precession a non-equilibrium spin polarization S_y is induced being

$$S_y = -\frac{\omega_L \tau_{s\perp}}{1 + (\omega_L \tau_s)^2} S_{0z} , \tag{4}$$

where $\tau_s = \sqrt{\tau_{s\|} \tau_{s\perp}}$, $\tau_{s\|}$, $\tau_{s\perp}$ are the longitudinal and transverse electron spin relaxation times and ω_L is the Larmor frequency. The denominator in Eq. (4) which yields a decay of S_y for ω_L exceeding the inverse spin relaxation time is well known from the Hanle effect [8].

With using this method the spin-galvanic effect has been detected in n-type GaAs and InAs samples. Fig. 4 shows the spin-galvanic current as a function of the external magnetic field. For low magnetic field strengths B, where $\omega_L \tau_s < 1$ holds, the photocurrent increases linearly as given in Eqs. (2) and (4). This is seen in Fig. 4a as well as in Fig. 4b for $B \leqslant 1$ T. The polarity of the current depends on the direction of the excited spins and on the direction of the applied magnetic field. For magnetic field pointing along $\langle 1\,1\,0 \rangle$ the current is parallel (anti-parallel) to the magnetic field vector. For $B \| \langle 1\,0\,0 \rangle$ both transverse and longitudinal effects are observed [1]. For higher magnetic fields the current assumes a maximum and decreases upon further increase of B, as shown in Fig. 4b. This drop of the current is ascribed to the Hanle effect.

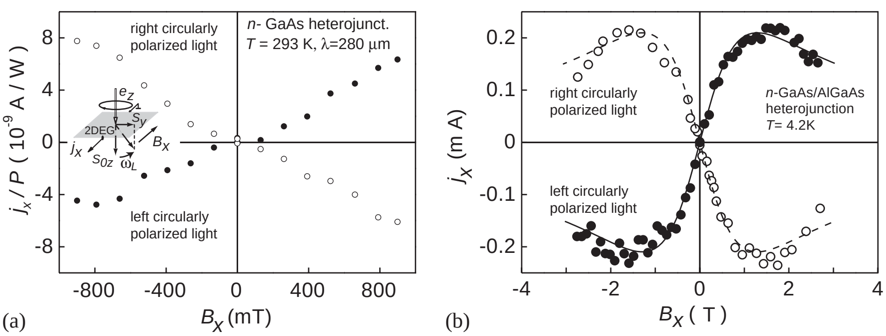

Fig. 4. Magnetic field dependence of spin-galvanic current achieved by intra-subband transitions within e1 subband: (a) excited by radiation at $\lambda = 280$ µm and for $T = 293$ K (b) excited by radiation at $\lambda = 148$ µm ($P = 20$ kW) and for $T = 4.2$ K. Curves in (b) are fitted after Eqs. (2) and (4). The inset shows the geometry of the experiment.

The experimental data are well described by Eqs. (2) and (4). The measurements allow to obtain the spin relaxation time τ_s from the peak position of the photocurrent where $\omega_L\tau_s = 1$ holds [4].

In the infrared range, spin-galvanic currents have been recorded for inter-subband as well as for intra-subband transitions [1,4,5]. Direct inter-subband transitions have been achieved in GaAs QWs. Applying MIR radiation of the CO_2 laser the spin-galvanic current at normal incidence of radiation has been observed [17]. The current repeats the spectral behaviour of direct inter-subband absorption as expected from Eq. (3). At indirect transitions the spin-galvanic effect, as in the case of CPGE, has been obtained in n-type GaAs and InAs QWs using FIR radiation (Fig. 4). The observation of the spin-galvanic effect gives clear evidence that direct inter-subband and Drude absorption of circularly polarized radiation results in a monopolar spin orientation considered in Ref. [17].

6. Summary

A non-equilibrium uniform spin polarization obtained by optical orientation drives an electric current in QWs if they belong to a gyrotropic crystal class. The spin-galvanic current is driven by an asymmetric spin relaxation of a homogeneous non-equilibrium spin polarization. The current is present even if the initial electron distribution in each spin-split subband is uniform. The experimental results on spin photocurrents due to homogeneous spin polarization are in good agreement with phenomenological theory. Both, spin-galvanic currents and the removal of spin degeneracy in $\boldsymbol{k}$-space are described by second rank pseudo-tensors. Because of tensor equivalence in each symmetry the irreducible components of these tensors differ by scalar factors only. Therefore, macroscopic measurements of photocurrents in different geometric configurations of experiments allow to determine the different contributions to spin–orbit coupling and to conclude on the macroscopic symmetry of QWs [1].

Acknowledgements

The authors thank W. Prettl and Petra Schneider for helpful comments on the present manuscript. Financial support by the DFG is gratefully acknowledged.

References

[1] S.D. Ganichev, W. Prettl, J. Phys.: Condens. Matter 15 (2003) R935.
[2] E.L. Ivchenko, Yu.B. Lyanda-Geller, G.E. Pikus, JETP Lett. 50 (1989) 175.
[3] Y.A. Bychkov, E.I. Rashba, JETP Lett. 39 (1984) 78.
[4] S.D. Ganichev, E.L. Ivchenko, V.V. Bel'kov, S.A. Tarasenko, M. Sollinger, D. Weiss, W. Wegscheider, W. Prettl, Nature (London) 417 (2002) 153.
[5] S.D. Ganichev, Petra Schneider, V.V. Bel'kov, E.L. Ivchenko, S.A. Tarasenko, W. Wegscheider, D. Weiss, D. Schuh, D.G. Clarke, M. Merrick, B.N. Murdin, P. Murzyn, P.J. Phillips, C.R. Pidgeon, E.V. Beregulin, W. Prettl, Phys. Rev. B. (cond-mat/0303193), submitted for publication.
[6] D.D. Awschalom, D. Loss, N. Samarth (Eds.), Semiconductor Spintronics and Quantum Computation, in: K. von Klitzing, H. Sakaki, R. Wiesendanger (Eds.), Series Nanoscience and Technology, Springer, Berlin, 2002.
[7] S.D. Ganichev, E.L. Ivchenko, S.N. Danilov, J. Eroms, W. Wegscheider, D. Weiss, W. Prettl, Phys. Rev. Lett. 86 (2001) 4358.
[8] F. Meier, B.P. Zakharchenya (Eds.), Optical Orientation, Elsevier Science, Amsterdam, 1984.
[9] N.S. Averkiev, L.E. Golub, M. Willander, J. Phys.: Condens. Matter 14 (2002) R271.
[10] A.G. Aronov, Yu.B. Lyanda-Geller, JETP Lett. 50 (1990) 431.
[11] V.M. Edelstein, Solid State Commun. 73 (1990) 233.
[12] N.S. Averkiev, M.I. D'yakonov, Sov. Phys. Semicond. 17 (1983) 393.
[13] A.A.Bakun,B.P.Zakharchenya,A.A.Rogachev,M.N.Tkachuk, V.G. Fleisher, JETP Lett. 40 (1984) 1293.
[14] I. Žutić, J. Fabian, S. Das Sarma, Phys. Rev. Lett. 88 (2002) 066603.
[15] G.M.H. Knippels, X. Yan, A.M. MacLeod, W.A. Gillespie, M. Yasumoto, D. Oepts, A.F.G. van der Meer, Phys. Rev. Lett. 83 (1999) 1578.
[16] S.D. Ganichev, V.V. Bel'kov, Petra Schneider, E.L. Ivchenko, S.A. Tarasenko, D. Schuh, W. Wegscheider, D. Weiss, W. Prettl, Phys. Rev. B. (cond-mat/0303054), submitted for publication.
[17] S.A. Tarasenko, E.L. Ivchenko, V.V. Bel'kov, S.D. Ganichev, D. Schowalter, Petra Schneider, M. Sollinger, W. Prettl, V.M. Ustinov, A.E. Zhukov, L.E. Vorobjev, J. Supercond.: Incorporating Novel Magn. 16 (2003) 419.