Spin-Galvanic Effect in Quantum Wells

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It is shown that a homogeneous nonequlibrium spin polarization in semiconductor heterostructures results in an electric current. The microscopic origin of the effect is an inherent asymmetry of spin-flip scattering in systems with lifted spin degeneracy caused by $\boldsymbol{k}$-linear terms in the Hamiltonian.

1. INTRODUCTION

Much current interest of condensed matter physics is directed towards the understanding of various manifestations of spin-dependent phenomena. In particular, the spin of electrons and holes in solid-state systems is the decisive ingredient for active spintronic devices [1]. Here we report on a new property of the spin-polarized electron gas: its ability to drive an electric current [2]. While electric currents are usually generated by gradients of the potential, the carrier concentration or the temperature, it is shown that a uniform nonequilibrium spin orientation gives rise to an electric current. This new spin-related phenomenon named spin-galvanic effect has been observed recently in zinc-blende GaAs quantum well structures [2]. The microscopic origin of the effect observed in low-dimensional electron systems is an inherent asymmetry of the spin-flip scattering of electrons in systems with removed spin degeneracy of the band structure due to $\boldsymbol{k}$-linear terms in the Hamiltonian. Here we report on the investigation of spin-galvanic effect in InAs and GaAs QWs.

2. OVERVIEW

A basic symmetry property of low-dimensional zinc-blende-based structures is that they belong to gyrotropic crystal classes. This means that an axial vector of an average spin polarization $\boldsymbol{S}$ and a polar vector of an electric current $\boldsymbol{j}$ may be linked by a second rank pseudotensor $\boldsymbol{Q}$:

$$j_\alpha = \sum_\beta Q_{\alpha\beta} S_\beta. \tag{1}$$

Nonzero components of $Q_{\alpha\beta}$ can exist in QWs in contrast to the corresponding bulk crystals. In (001)-grown QWs of C_{2v} symmetry only two linearly independent components, Q_{xy} and Q_{yx}, are different from zero ($x\|[1\bar{1}0]$ and $y\|[110]$). Hence, to observe a spin-polarization-driven current a spin component lying in the plane of the QW is required (e.g., S_y in Fig. 1). Microscopically, the spin-galvanic effect is caused by the asymmetric spin-flip relaxation of spin-polarized electrons in systems with $\boldsymbol{k}$-linear contributions to the effective Hamiltonian. The lifting of spin degeneracy of a two dimensional electron gas (2DEG) depicted in Fig. 2 is a consequence of a contribution to the Hamiltonian of the form $\hat{H}_k = \sum_{\gamma\alpha} \beta_{\alpha\gamma} \sigma_\alpha k_\gamma$, where σ_α are the Pauli spin matrices and β is a pseudotensor subjected to the same symmetry restriction as $\boldsymbol{Q}$ used in Eq. (1). Figure 2 sketches the electron energy spectrum with the term $\beta_{yx}\sigma_y k_x$ included. This term leads to the splitting of the band into two branches with the spin states $|\pm 1/2\rangle_y$ relatively shifted along

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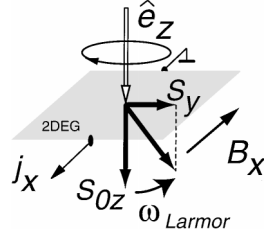
Fig. 1. Experimental procedure to obtain a uniform spin polarization in the plane of a QW. Electron spins are oriented normal to the plane by circularly polarized radiation and rotated into the plane by Larmor precession in a magnetic field.

the k_x-direction. Spin orientation in y-direction yields an unbalanced population in the spin-down and spin-up subbands. The current flow is caused by the ***k***-dependent spin-flip relaxation processes. Spins oriented in y-direction are scattered along k_x from the higher filled, e.g., spin-down subband, $|-1/2\rangle_y$, to the less filled spin-up subband, $|+1/2\rangle_y$. Four quantitatively different spin-flip scattering events exist and are sketched in Fig. 2 by bent arrows. The spin-flip scattering rate depends on the values of the wavevectors of the initial k_{xi}, and the final k_{xf} states, respectively [3]. Therefore spin-flip transitions, shown by solid arrows in Fig. 2, have the same rates. They preserve the symmetric distribution of carriers in the subbands and, thus, do not yield a current. However, the two scattering processes shown by broken arrows are inequivalent and generate an asymmetric carrier distribution around the subband minima in both subbands. This asymmetric population results in a current flow along the x-direction. Within our model of elastic scattering the current is not spin-polarized since the same numbers of spin-up and spin-down electrons move in the same direction with the same velocity. The uniformity of the spin polarization in space is preserved during the scattering processes.
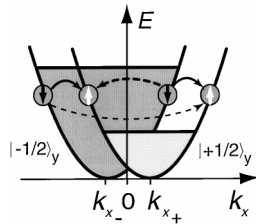
Fig. 2. Sketch of spin orientation (shading) at spin-split subbands and current due to wavevector-dependent asymmetric spin-flip scattering.

3. EXPERIMENTAL RESULTS AND DISCUSSION

To achieve a homogeneous nonequilibrium spin polarization in experiment, we used optical spin orientation. Figure 1 shows the geometry of the experiment. At normal incidence of circularly polarized radiation the optical excitation yields a steady-state spin orientation S_{0z} in the z-direction. To obtain an in-plane component of the spins, necessary for the novel effect described here, a magnetic field, B, was applied (Fig. 1). The field perpendicular to both the light propagation direction z and the optically oriented spins rotates the spins into the plane of the 2DEG due to Larmor precession. With the magnetic field oriented along the x-axis, we obtain a non-equilibrium spin polarization S_y which is

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

where $\tau_s = \sqrt{\tau_{s\parallel}\tau_{s\perp}}$ and $\tau_{s\parallel}\tau_{s\perp}$ are the longitudinal and transverse electron spin relaxation times, ω_L is the Larmor frequency. Utilizing the Larmor precession, we prepared the situation sketched in Fig. 1, where the spin polarization S_y lies in the plane. The denominator in Eq. (2) yielding the decay of S_y for ω_L exceeding the inverse spin relaxation time is well known from the Hanle effect [4].

The experiments were carried out at various temperatures from room temperatures down to 4.2 K on n-GaAs single QWs of 7- and 15-nm width, on n-GaAs single heterojunctions and on a single n-InAs QW of 15- or 7.6-nm width. These (001)-oriented samples grown by molecular-beam-epitaxy contain 2DEG systems with electron densities $n_s \cong 2 \cdot 10^{11}$ cm^{-2} and mobilities μ above 10^6 cm^2/Vs at $T = 4.2$ K. Two pairs of point contacts were centered on opposite sample edges along the direction $x \| [1\bar{1}0]$ and $y \| [110]$. Two additional pairs of ohmic contacts have been formed in the corners of the sample corresponding to the $\langle 100 \rangle$ crystallographic directions. The radiation of a cw Ti:Sapphire laser at the wavelength 0.77 μm was applied for interband excitation. As radiation source for intraband excitation a pulsed TEA-CO$_2$ laser and a TEA-CO$_2$ laser pumped molecular far-infrared (FIR) laser were used. Depending on the photon energy and quantum well band structure, the infrared and FIR radiation induce direct optical transitions between size-quantized subbands or, at longer wavelength, indirect optical transitions in the lowest subband. For both visible and infrared radiations a current has been observed for all (001)-oriented
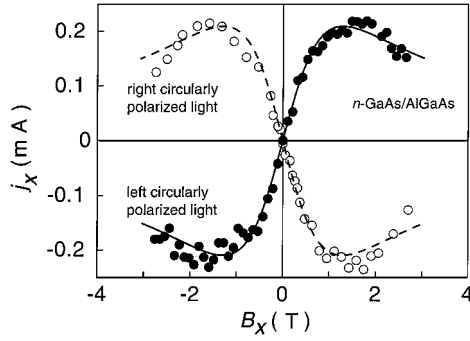
Fig. 3. Current versus magnetic field obtained for an *n*-GaAs/AlGaAs single heterojunction at $T = 4.2$ K and $\lambda = 148 \, \mu$m. Curves are after Eq.(2).

n-type GaAs and InAs samples after applying an in-plane magnetic field in the whole temperature range. In Fig. 3 the observed current as a function of the magnetic field is shown for right- and left-handed circular polarization of $\lambda = 148 \, \mu$m radiation. The polarity of the current depends on the initial orientation of the excited spins and on the direction of the applied magnetic field.

The current is parallel (antiparallel) to the magnetic field vector and follows the field as it is rotated around the growth axis which has been checked by using of different pairs of contacts. For higher magnetic fields the current assumes a maximum and decreases upon further increase of *B*. This is ascribed to the Hanle effect, Eq. (2). The observation of the Hanle effect demonstrates that free carrier intra-subband transitions can polarize the spins of electron systems. In a very direct way the measurements allow to obtain the spin relaxation time τ_s from the peak position of the photocurrent where $\omega_L \tau_s = 1$.

The experiments demonstrate that in zinc-blende QWs a spin polarization uniform in space results in an electric current. Therefore the spin-galvanic effect differs from other experiments where the spin current is caused by gradients of potentials, concentrations, etc. like the spin-voltaic effect [5,6], which, as the photovoltaic effect, occurs in inhomogeneous samples, as well as from surface currents induced by inhomogeneous spin orientation [7].

4. SPIN-GALVANIC VERSUS PHOTOGALVANIC EFFECT

In this section we would like to point out the difference between the spin-galvanic effect and another spin-related effect occurring in zinc-blende-structure-based QWs: the circular photogalvanic effect [8]. The crucial difference between both effects is that, while the spin-galvanic effect may be caused by any means of spin injection, the circular photogalvanic effect needs optical excitation with circularly polarized radiation. Even when the spin-galvanic effect is achieved by optical spin orientation, the microscopic mechanisms of both effects are different. The current flow in both the circular photogalvanic effect and the spin-galvanic effect is driven by an asymmetric distribution of carriers in *k*-space in systems with lifted spin degeneracy due to *k*-linear terms in the Hamiltonian. However, the spin-galvanic effect is caused by asymmetric spin-flip scattering of spin-polarized carriers and it is determined by the process of spin relaxation. If spin relaxation is absent, the effect vanishes. In contrast, the circular photogalvanic effect is the result of selective photoexcitation of carriers in *k*-space with circularly polarized light due to optical selection rules. In some optical experiments the photocurrent may represent a sum of both effects. For example, if we irradiate an (001)-oriented QW by oblique incidence of circularly polarized radiation, we obtain both selective photoexcitation of carriers in *k*-space and an in-plane component of nonequilibrium spin polarization. Thus both effects contribute to the current occurring in the plane of the QW. In the experiment presented earlier we used circularly polarized radiation at normal incidence where the circular photogalvanic effect is absent [8] and, hence, the current is purely due to the spin-galvanic effect.

The spin-galvanic effect reported here has been obtained making use of optical orientation of electron spins perpendicular to a QW and rotation of the spin polarization into the QW plane by Larmor precession in an external magnetic field. At low magnetic fields this current phenomenologically can be also described by a third rank tensor $\mu_{\alpha\beta\gamma}$ as

$$j_\alpha = \mu_{\alpha\beta\gamma} B_\beta i (\mathbf{E} \times \mathbf{E}^*)_\gamma = \mu_{\alpha\beta\gamma} E^2 B_\beta \hat{e}_\gamma P_{\text{circ}} \quad (3)$$

and might also be denoted as a magnetic-field-induced circular photogalvanic effect. In this equation **E** is the amplitude of the electric field of the radiation, $E = |\mathbf{E}|$, $i(\mathbf{E} \times \mathbf{E}^*)_\gamma = E^2 \hat{e}_\gamma P_{\text{circ}}$ and $\hat{\mathbf{e}}$ is a unit vector pointing in the direction of the radiation propagation. For C_{2v} symmetry of our samples the current is described by two independent constants and can be presented as

$$j_x = (\mu' + \mu) E^2 B_x \hat{e}_z P_{\text{circ}};$$
$$j_y = (\mu' - \mu) E^2 B_x \hat{e}_z P_{\text{circ}}. \quad (4)$$
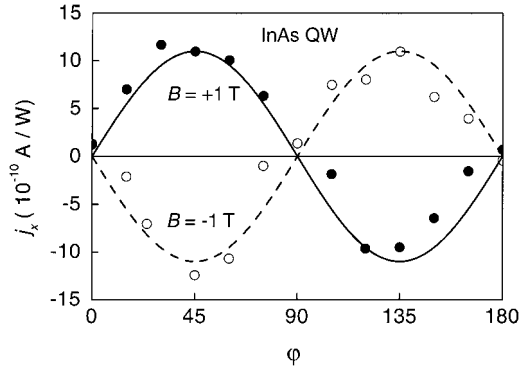
Fig. 4. Magnetic field induced photocurrent in QWs normalized by the light power P as a function of the phase angle φ defining the helicity for magnetic fields of two directions. The photocurrent excited by normal incident radiation of $\lambda = 148\ \mu$m is measured in an (001)-grown *n*-InAs QW of 15 nm at $T = 4.2$ K for magnetic fields along x.

The measured spin-galvanic current indeed follows the helicity of the radiation which is clearly seen in Fig. 4.

5. SUMMARY

In conclusion, our experimental results demonstrate that in gyrotropic quantum wells a current occurs if electrons are injected with an in-plane component of spin polarization. Therefore the effect allows to detect spin injection into quantum wells by measuring an electric current. Thinking on spintronic devices with quantum wells like spin transistors, this current must be taken into account.

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