Spin-Galvanic Effect and Spin Orientation Induced Circular Photogalvanic Effect in Quantum Well Structures

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Abstract. The spin-galvanic effect and the spin polarization induced circular photogalvanic effect generated by homogeneous optical excitation with circularly polarized radiation in quantum wells (QWs) are reviewed. In both effects the 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 spin relaxation in the condition of monopolar spin orientation and to conclude on the in-plane symmetry of QWs.

1 Introduction

he spin-degree of freedom of charge carriers and its manipulation has become a hot topic in material science under the perspective of spin-based electronic devices (for a review see [1]). One of the most frequently used and powerful methods of generation and investigation of spin polarization is optical orientation [2]. Optical generation of an unbalanced spin distribution in a semiconductor may lead to electrical currents driven by optically generated spin polarization. Spin photocurrents may be caused by an inhomogeneous spin distribution obtained due to inhomogeneous optical excitation [3,4] or inhomogeneities of materials like $p-n$ junctions [5] as well as at simultaneous one- and two-photon coherent excitation of proper polarization [6].

Here we review a new property of the electron spin in a homogeneous spin-polarized two-dimensional electron gas: its ability to drive an electric current if QWs belongs to one of the gyrotropic classes. Recently it was demonstrated that an excitation of QWs with circularly polarized radiation leads to a current whose direction depends on helicity of the incident light [7]. This effect belongs to the class of photogalvanic effects which were intensively studied in bulk semiconductors (for review see [8,9]) and represents a circular photogalvanic effect (CPGE). It was shown in [10] that in gyrotropic QW structures CPGE is caused by spin orientation of carriers in systems with band splitting in $\boldsymbol{k}$-space due to $\boldsymbol{k}$-linear terms in the Hamiltonian [11,12]. A homogeneous irradiation of QWs with circularly polarized light results in a non-uniform distribution of photoexcited carriers in $\boldsymbol{k}$-space due to optical selection rules and conservation laws which leads to a current [13].

Furthermore, a thermalized but spin-polarized electron gas can drive an electrical current [14]. Recently it was demonstrated that in a gyrotropic QWs a homogeneous spin polarization obtained by any means yields a current [15]. This phenomenon is referred to as spin-galvanic effect (SGE). While electrical currents are usually generated by electric fields or gradients, in this case a uniform non-equilibrium population of electron spins gives rise to an electric current. The microscopic origin of the SGE 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 orientation [15,16] and therefore also represents a spin photocurrent.

The CPGE and the SGE have in common that the current flow is driven by an asymmetric distribution of carriers in $\boldsymbol{k}$-space in systems with lifted spin degeneracy. The crucial difference between both effects is, that the spin-galvanic effect may be caused by any means of spin injection, while the spin orientation induced CPGE needs optical excitation. Even if the spin-galvanic effect is achieved by optical spin orientation the microscopic mechanisms are different. 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 spin-galvanic current vanishes. In contrast, the CPGE is the result of selective photoexcitation of carriers in $\boldsymbol{k}$-space and depends on momentum relaxation. Both spin photocurrents have been observed in n- and p-type QWs based on various semiconductor materials at very different types of optical excitation by application of several lasers at wavelengths ranging from the visible to the far-infrared.

2 Samples and Experimental Technique

The experiments were carried out on GaAs [13,17], InAs [10,15], asymmetric SiGe QWs [18], and BeZnMnSe [19] QW structures in belonging to two different classes of symmetry. Higher symmetric structures were (001)-oriented QWs which, as our measurements showed, corresponded to the point group C_{2v} [13]. Structures of the lower symmetry class C_s were (113)-oriented QWs. Samples of n- and p-type QWs with width L_w from 7 nm to 20 nm and free-carrier densities from $10^{11}\,\mathrm{cm}^{-2}$ to $2 \cdot 10^{12}\,\mathrm{cm}^{-2}$ were studied.

For optical excitation mid-infrared (MIR), far-infrared (FIR) and visible laser radiation was used. Most of the measurements were carried out in the infrared with photon energies less than the energy gap ε_g. Depending on the photon energy and QW band structure the MIR and FIR radiation induce direct transitions between size quantized subbands or, at longer wavelength, Drude absorption. A pulsed TEA-CO_2 laser and a molecular FIR laser [20] have been used as radiation sources in the spectral range between 9.2 μm and 496 μm. Some experiments in the MIR have been carried out making use of the tunability of the free-electron laser "FELIX" [21]. For optical inter-

band excitation a cw-Ti:sapphire laser was used providing radiation with λ=0.777 μm and radiation power $P \simeq 100$ mW.

The circular polarization has been obtained using a Fresnel rhomb, $\lambda/4$ plates, and a photoelastic modulator for MIR, FIR and visible radiation, respectively. The helicity P_{circ} of the incident light was varied from -1 (left-handed circular, σ_-) to $+1$ (right-handed circular, σ_+) according to $P_{circ} = \sin 2\varphi$, where the phase angle φ is the angle between the initial plane of polarization and the optical axis of the polarizer. Samples were studied in the temperature range of 4.2 K to 300 K. The photocurrent j_x was measured