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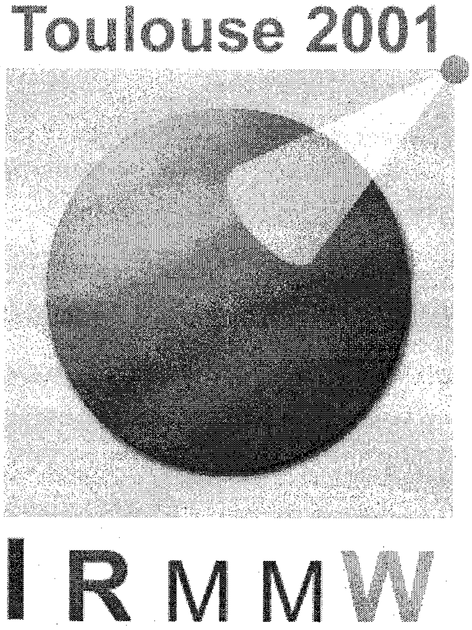

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Spin dependent photocurrents in quantum well structures induced by FIR radiation

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Abstract. A circular photogalvanic effect and a magnetic field induced circular photogalvanic effects caused by absorption of far infrared radiation have been observed in quantum well structures. Applying circularly polarized radiation a monopolar spin polarization has been achieved. The spin polarization results in a directed motion of free carriers in the plane of a quantum well perpendicular to the direction of the incident circularly polarized light. Due to spin selection rules the direction of the current is determined by the helicity of the light and can be reversed by switching the helicity from right- to left-handed

Introduction

A substantial portion of current research in condensed-matter physics is directed towards 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, 2]. Different polarization of circularly polarized light is frequently used to prepare an ensemble of spin polarized carriers [3]. The experiments described below show that in low-dimensional systems having a band splitting in k-space due to k-linear terms in the Hamiltonian, optical excitation leads not only to a spin polarized ensemble of electrons but also to a current whose direction depends solely on the predominant spin orientation. The observed spin photocurrent flows in the quantum well and reverses its direction by switching the helicity of the radiation and hence the spin orientation of free carriers. The effect is quite general and has been observed for all semiconductor systems investigated sofar.

Experimental technique and samples

The experiments were carried out on heterostructures of two different symmetry classes. Higher symmetric structures were (001)-grown n-InAs QWs of 15 nm width and (001)-grown n-GaAs/AlGaAs single heterojunctions. These structures can belong to two different point groups, either D_{2d} or C_{2v}. Our measurements showed that all samples investigated here belong to the group C_{2v}. Structures of the lower symmetry C_s were (113)A-MBE grown p-GaAs/AlGaAs single QWs and multiple QWs (MQW) containing 20 wells of 15 nm width. Samples with free-carrier densities about $10^{11}\,\mathrm{cm}^{-2}$ were studied in the range from liquid helium to room temperature. Two pairs of ohmic contacts have been centered along opposite sample edges. For optical excitation we used a high power far-infrared pulsed NH_3 laser optically pumped by a TEA-CO_2 laser which yields strong linearly polarized emission at wavelengths between 35 and

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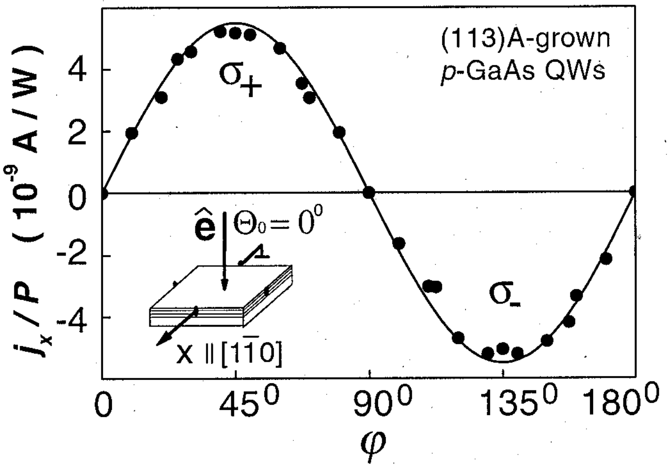

Figure 1. Photocurrent of (113)A-grown p-GaAs/AlGas MQWs at T = 300 K normalized by the light power P of $\lambda = 76\,\mu$m as a function of the phase angle φ defining helicity

280 μm [4]. The radiation induces indirect optical transitions in the lowest conduction subband of our n-type samples and direct optical transitions between heavy hole and light hole subbands in the p-type samples. The polarization of the laser light was modified from linear to circular using quartz $\lambda/4$ plates. The helicity P_{circ} of the incident light was varied from -1 (left handed circular, σ_-) to $+1$ (right handed circular, σ_+) according to $P_{circ} = \sin 2\varphi$ were φ is the angle between the initial plane of polarization and the optical axis of the $\lambda/4$ plate.

Experimental results and discussion

In samples of C$_s$-symmetry grown on a (113)-GaAs surface, the spin photocurrent can be observed under normal incidence of radiation. The reversal of the current direction when the polarization switches from left-handed to right-handed circular polarization is shown in Fig. 1 where the normalized current is plotted versus the phase angle φ. For this symmetry the direction of the current is determined by the symmetry of the quantum wells. The current flows always along the [1$\bar{1}$0]-direction perpendicular to the plane of the mirror reflection of the point group C$_s$, independent of the plane of incidence of the laser beam. In (001)-oriented samples of the higher symmetry class C$_{2v}$ a signal proportional to the helicity P_{circ} is only observed under oblique incidence and the photocurrent is perpendicular to the wavevector of the incident light.

Phenomenologically the photogalvanic current under study can be described by the following expression [5, 6]:

$$j_\lambda = \chi_{\lambda\mu\nu}(E_\mu E_\nu^* + E_\nu E_\mu^*)/2 + \gamma_{\lambda\mu}\, i(\mathbf{E} \times \mathbf{E}^*)_\mu \,, \tag{4.1}$$

where $\mathbf{E}$ is the complex amplitude of the electric field of the electromagnetic wave and i $(\mathbf{E} \times \mathbf{E}^*) = \hat{\mathrm{e}} P_{circ} E_0^2$ with the electric field amplitude $E_0 = |\mathbf{E}|$ and the unit vector ê pointing in the direction of light propagation. The photocurrent given by the tensor χ describes the so-called linear photogalvanic effect (LPGE) [6] because it is usually observed under linearly polarized optical excitation. The circular photogalvanic effect (CPGE) described by the pseudotensor γ can be observed only under circularly polarized excitation. The pseudotensor γ can have nonzero components which depend on the symmetry of the system. The phenomenological expressions Eq. 1 perfectly describes experimentally obtained dependencies of the current on

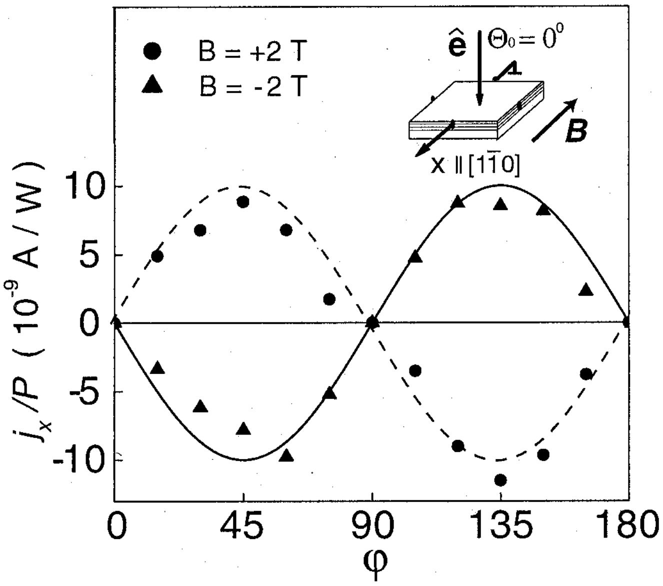

Figure 2. Magnetic field induced photocurrent in QWs normalized by the light power P as a function of the phase angle φ definding helicity for magnetic field $B = \pm 2$T of two directions. Photocurrent exited by normal incident radiation of $\lambda = 148$ μm is measured in (001)-grown n-GaAs/AlGaAs for magnetic field applied parallel to the direction x

the phase angle φ (Fig. 1) and the angle of incidence Θ_0 for samples of the symmetry C_{2v} and C_s [5, 6].

Microscopically a conversion of photon helicity into a spin photocurrent arises due to k-linear terms in the effective Hamiltonian $H^{(1)} = \beta_{lm}\sigma_l k_m$ where **k** is the electron wavevector, σ_l are the Pauli spin matrices and β_{lm} are real coefficients. The coefficients β_{lm} form a pseudotensor subject to the same symmetry restriction as the pseudotensor γ. These k-linear terms lift the spin degeneracy of the energy bands in k-space. The coupling between σ_l and the wavevector of the carriers k_m as well as spin controlled selection rules yield a net current dependent on the circularly polarized optical excitation [5]. Thus our experiments on quantum wells demonstrate a novel property of an unbalanced spin polarization: its ability to generate a directed current where the current's direction depends solely on the predominant spin orientation. This effect may be illustrated as an electron analog of mechanical systems where a rotational motion ('spin') is transmitted into a linear one ('current') like a rotating wheel on a hard surface.

In order to prove additionally that the current is caused by the spin orientation we investigated the influence of the magnetic field on the photocurrent. As it was shown above in samples grown on a (001) plane a spin photocurrent is absent at normally incident radiation. Here we demonstrate that the application of an external magnetic field, **B**, in the interface plane induces a helicity-dependent current even at normal incidence. The dependence of the magnetic field induced photocurrent on the phase angle φ for (001)-grown GaAs Qws is shown in Fig. 2. The current is proportional to P_{circ} and inverts its direction with the reversal of the magnetic field. The occurence of the current in the presence of a magnetic field is caused by the Larmor precession of the optically induced magnetic momentum yielding an in-plane component of that which as in the case of oblique incidence yields the current. Phenomenologically, the magneto-CPGE is described by a third-rank tensor as $j_\alpha = \mu_{\alpha\beta\gamma} B_\beta\, i\,(\mathbf{E} \times \mathbf{E}^*)_\gamma = \mu_{\alpha\beta\gamma} E_0^2 B_\beta \hat{e}_\gamma P_{circ}$.

In summary, the experiments carried out on different types of quantum wells have shown that circularly polarized far infrared radiation can generate a directed electric current at room temperature. The microscopic picture given above requires that the current is spin polarized and suggests that the system can be considered as a source for spin polarized currents. The effect, being sensitive to the degree of spin orientation, provides an easy access to spin dynamics in semiconductor structures [7]. We emphasize that in gyrotropic media with **k**-linear terms in the Hamiltonian, spin injection yielding an imbalance of spin orientations leads always to a current. Since quantum wells based on III-V compounds are gyrotropic, spin polarization causes in any case a current flow.

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