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Circular photogalvanic effect in $p-$GaAs/AlGaAs MQW

S.D. Ganichev[1,2], **E.L. Ivchenko**[2], **H. Ketterl**[1], **L.E. Vorobjev**[3], **M. Bichler**[4], **W. Wegscheider**[1], **W. Prettl**[1]

[1] Institut für Experimentelle und Angewandte Physik, Universität Regensburg 93040 Regensburg, Germany e:-mail sergey.ganichev@physik.uni-regensburg.de
[2] A.F. Ioffe Physico-Technical Institute, Russian Academy of Sci. 194021 St. Petersburg, Russia
[3] St. Petersburg State Technical University, 195251 St. Petersburg, Russia
[4] Walter Schottky Institut, TU München, 85748, Garching, Germany

Abstract The circular photogalvanic effect (CPGE) has been observed in (001)- and (311)A-oriented p-GaAs/AlGaAs quantum wells at normal incidence of far-infrared radiation. It is shown that monopolar optical spin orientation of free carriers causes an electric current which reverses its direction upon changing from left to right circularly polarized radiation. As proposed, CPGE can be utilized to investigate separately spin polarization of electrons and holes.

1 Introduction

Spin polarization and spin relaxation in semiconductors are the subject of intensive studies of spin-polarized electron transport aimed at the development of spinotronic devices like a spin transistor [1,2]. So far, photo-induced spin polarization has been achieved by *interband* optical absorption of circularly polarized light with the photogeneration of spin-polarized electrons and holes [3–5].

Here we report on the first observation of the circular photogalvanic effect (CPGE) at *intersubband* transitions in quantum-well (QW) structures. Phenomenologically, the effect is a transfer of angular momenta of circularly polarized photons to the directed movement of free carriers, electrons or holes, and therefore depends on the symmetry of the medium. Microscopically, it arises due to optical spin orientation of holes in QWs and asymmetric spin-dependent scattering of spin-polarized carriers followed by an appearance of an electric current. The two states of light circular polarization $\sigma_\pm$ result in different spin orientations and, thus, in electric photocurrents of opposite directions. In contrast to the case of *interband* optical excitation, under *intersubband* transitions only one kind of carriers is involved leading to a monopolar spin orientation. The observed effect can be utilized to investigate spin polarization of free carriers.

2 Experimental set up and samples

The experiments have been carried out on (001)-MOCVD grown p-GaAs/AlGaAs multi QW structures with 400 undoped wells of 20 nm width separated by 10 nm wide doped barriers and on a p-GaAs/AlGaAs (311)A-MBE grown single QW of 15 nm width. Samples of 5×5 mm^2 size with hole densities in the QWs varying from $2\cdot10^{11}$ cm^{-2} to $2\cdot10^{12}$ cm^{-2} have been investigated. Two pairs of ohmic contacts (see inset Fig. 1) have been prepared along [1$\bar{1}$0] and [110] for (001)-GaAs/AlGaAs and [0$\bar{1}$1] and [$\bar{2}$33] for (311)-GaAs/AlGaAs, respectively.

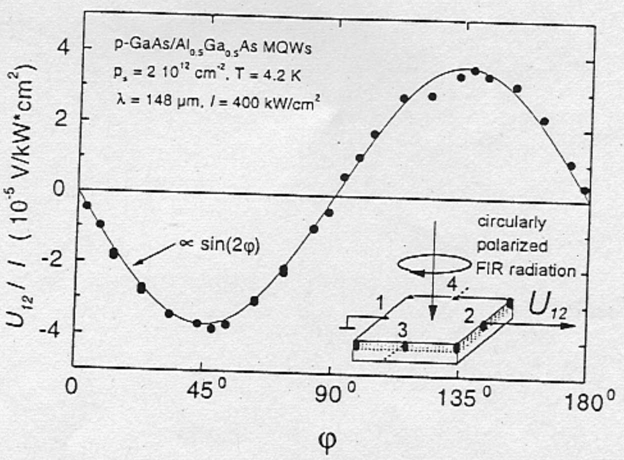

Fig. 1 Photogalvanic voltage signal U_{12} picked up across the contact pair 1-2 and normalized by the intensity I as a function of phase angle φ. The full line is fitted after Eq. 2 ($U_{12} \propto sin2\varphi$).

A high power far-infrared molecular laser pumped by a TEA-CO$_2$ laser has been used as a radiation source delivering 100 ns pulses with the intensity up to 1 MW/cm^2. NH$_3$ has been used as a FIR laser medium yielding strong linearly-polarized emissions at wavelengths $\lambda =$ 76 μm, 90 μm, and 148 μm [6,7]. The photon energies of the radiation correspond to transitions between heavy- and light- hole subbands of GaAs QWs. The linearly polarized laser light could be modified to a circularly polarized light by applying crystalline quartz $\lambda/4$–plates.

3 Experimental results and discussion

While irradiating the (001) GaAs QWs by normally incident circularly polarized radiation (see inset in Fig. 1) a fast photocurrent signal, U_{12}, has been observed in unbiased samples across one contact pair (contacts 1 & 2 in the inset). The photocurrent changes sign if the circular polarization is switched from σ_+ to σ_-. Measurements of U_{12} as a function of the angle φ between the optical axis of the $\lambda/4$-plate and the plane of polarization of the laser radiation, reveal that the photogalvanic current j is proportional to the degree of circular polarization $P_{circ} = \sin 2\varphi$ (Fig. 1). The magnitude and the

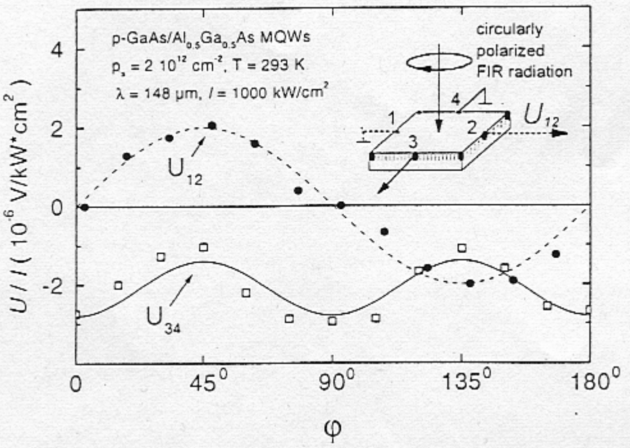

Fig. 2 Photogalvanic voltage signal U normalized by the intensity I for the two different contact pairs as a function of phase angle φ. Lines are fitted after Eq. 2 as $U_{12} \propto \sin 2\varphi$ and $U_{34} \propto (\chi_+ + \chi_- \cos^2 2\varphi)$, respectively.

sign of the CPGE are practically unchanged with variation of the angle of incidence in the range of -40° to +40°. The photogalvanic signal picked up at the other pair of contacts (contacts 3 & 4 in the inset of Fig. 2) does not change sign by switching of the circular polarization from σ_+ to σ_-. This is demonstrated in Fig. 2 where the voltage U_{34} is plotted as a function of the phase angle φ together with U_{12}. The signal U_{34} is periodic in φ with the period being one half of that of U_{12}. The photogalvanic current under study can be described by the following phenomenological expression

$$j_\lambda = \chi_{\lambda\mu\nu}(E_\mu E_\nu^* + E_\nu E_\mu^*)/2 + \gamma_{\lambda\mu}\, i(\mathbf{E} \times \mathbf{E}^*)_\mu \,, \qquad (1)$$

where $\mathbf{E}$ is the complex amplitude of the electric field of the electromagnetic wave and

$$i\,(\mathbf{E} \times \mathbf{E}^*) = P_{circ}\, E_0^2\, \frac{\mathbf{q}}{q} \,,$$

$E_0 = |\mathbf{E}|$, $\mathbf{q}$ is the light wavevector. In a bulk crystal, $\lambda = x, y, z$, while in a QW structure grown along the z direction, say $z \parallel [001]$, the index λ runs only over the in-plane axes $x \parallel [100], y \parallel [010]$ because the barriers prevent carriers from moving along the z axis and, definitely, $j_z = 0$. The photocurrent given by the tensor χ describes the so-called linear photogalvanic effect (LPGE) 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.

In an (001)-grown QW structure with D$_{2d}$ or C$_{2v}$ point symmetry a generation of the circular photocurrent *under normal incidence* is forbidden. Thus in order to explain the experimental data the next possible subgroup C$_s$ is needed, which contains only two elements: the identity and one mirror reflection. In this case under normal incidence and for light initially polarized along x' and transmitted through the $\lambda/4$ plate we have

$$j_{x'} = \gamma E_0^2 \sin 2\varphi = \gamma E_0^2 P_{circ} \,, \qquad (2)$$
$$j_{y'} = E_0^2(\chi_+ + \chi_- \cos^2 2\varphi) = E_0^2(\chi_2 - \chi_- P_{circ}^2) \,,$$

where $\chi_\pm = (\chi_{y'x'x'} \pm \chi_{y'y'y'})/2, \chi_2 \equiv \chi_{y'x'x'}$. Instead of x and y we use here the axes $x' \parallel [1\bar{1}0], y' \parallel [110]$. It follows then that a circular photocurrent is induced only along x', while the current induced along y' is a result of the linear photogalvanic effect described by the χ tensor components $\chi_{y'x'x'}$ and $\chi_{y'y'y'}$. by the projection of the circularly polarized radiation on x'. The CPGE described by γ can be related to an electric current in a system of free carriers with nonequilibrium spin-polarization [8]. The possible microscopic mechanism is the spin-dependent scattering of optically oriented holes.

Comparison of Eq. (2) and Figs. 1,2 demonstrates a good agreement between the theory and the experimental data. In order to prove that $j_{y'}$ is caused by the linear photogalvanic effect, we excited the sample by linearly polarized light and measured the voltage U_{34} as a function of the angle α between the plane of linear polarization and the axis x'. This signal is well described by $U_{34} \propto [\chi_+ + \chi_- \cos(2\alpha)]$ which follows from Eq. (1).

The low symmetry C$_s$ gives an evidence for the in-plane anisotropy showing that in the investigated QWs (i) the [110] and [1$\bar{1}$0] crystallographic directions are different, and (ii) one of the reflection planes is removed as a symmetry element. This symmetry reduction is attributed to a tilt angle of 5° between the crystallographic [001] direction and the sample surface normal as has been verified by x-ray diffraction. In order to prove this assumption one sample grown on a (311)A-plane has been investigated. The CPGE has been observed with a magnitude comparable to the signal of the (001) sample. Since in the case of the (311)- sample only one QW has been grown in contrast to the (001) samples which consisted of 400 QWs, we conclude that the magnitude of the signal from a single (311)A-grown QW is several tens of times larger than that of tilted (001) samples.

To summarize, it is shown that the optical orientation of free carriers can be accompanied by their drift. The symmetry considerations show that the CPGE can be observed also in an ideal QW of the symmetry D$_{2d}$ if the incident radiation is obliquely incident. The experiments presented here have been carried out in p-doped QWs but similar results are expected also for n-QWs.

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Professor Dr. Noboru Miura
Professor Tsuneya Ando
Institute for Solid State Physics
Roppongi, Minato-ku
106-8666 Tokyo, Japan

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