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Spin-Photocurrent in *p*-SiGe Quantum Wells under Terahertz Laser Irradiation

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A detailed study of the circular photogalvanic effect (CPGE) in SiGe structures is presented. It is shown that the CPGE becomes possible because of the built-in asymmetry of quantum wells (QWs) in compositionally stepped samples and in asymmetrically doped structures. The photocurrent arises due to optical spin orientation of free carriers in QWs with spin splitting in $\boldsymbol{k}$-space. It is shown that the effect can be applied to probe the macroscopic in-plane symmetry of low dimensional structures and allowing to conclude on Rashba or Dresselhaus terms in the Hamiltonian.

KEY WORDS: SiGe-QWs; photogalvanic effect; Rashba term.

1. INTRODUCTION

Recently it has been demonstrated that in quantum well (QW) structures based on III–V compounds an electric current linked to spin-polarized carriers can be generated by circularly polarized light. Two such effects were observed: the circular photogalvanic effect [1] and the spin-galvanic effect [2]. Microscopically both effects are based on $\boldsymbol{k}$-linear terms in the electron Hamiltonian known as Rashba and Dresselhaus terms [3,4] which lift the spin degeneracy of electron subbands. The current flow is driven by an asymmetric distribution of carriers in the spin-split subbands.

On a phenomenological level a current due to a spin polarization as well as $\boldsymbol{k}$-linear terms in the band structure become possible in systems belonging to one of the gyrotropic crystal classes [5]. This condition is met by zinc blende structure based QWs. In materials of T_d-symmetry which lack a center of inversion, gyrotropy is obtained because of the reduction of the dimensionality alone. In contrast, in low dimensional structures based on Si and Ge (SiGe QW) which have inversion symmetry both effects are forbidden by symmetry. Recently we have shown that even in such structures spin photocurrents may be obtained if the inversion symmetry is broken by preparation of compositionally stepped quantum wells or asymmetric doping of compositionally symmetric quantum wells [6]. Here we present a detailed study of the CPGE and demonstrate that investigation of the photogalvanic current with respect to the crystallographic directions allows to determine the macroscopic in-plane symmetry of QW structures.

2. THEORETICAL CONSIDERATION

The principal microscopic aspect of a photon helicity driven spin photocurrent like CPGE is a removal of spin-degeneracy in the subband states due to the reduced symmetry of the quantum well structure [1,2]. It is related to the appearance of $\boldsymbol{k}$-linear terms in the Hamiltonian,

$$H^{(1)}(\boldsymbol{k}) = \sum_{lm} \beta_{lm}\sigma_l k_m \qquad (1)$$

where β is a pseudotensor and the σ are the Pauli spin matrices. As discussed in [1] the coupling between the carrier spin (σ_l) and momentum (k_m) together with the

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spin-controlled dipole selection rules yields a net current under circularly polarized excitation. Depending on the photon energy this spin photocurrent can be either due to direct or indirect intraband transitions. Spin degeneracy results from the simultaneous presence of time-reversal and spatial inversion symmetry. If one of these symmetries is broken the spin degeneracy is lifted. In our SiGe QW systems the spatial inversion symmetry is broken and, as a consequence, spin-dependent $\boldsymbol{k}$-linear terms appearing in the electron Hamiltonian lead to a splitting of the electronic subbands at nonzero in-plane wavevector. In the context of spin related phenomena in QW structures most frequently the Rashba term of the the form $\sigma_x k_y - \sigma_y k_x$ is taken into account being caused by a structural inversion asymmetry (SIA) [7].

In zinc blende structure based QWs a $\boldsymbol{k}$-linear term proportional to $\sigma_x k_x - \sigma_y k_y$ (Dresselhaus term) is also present because of the bulk inversion asymmetry (BIA). We have shown in [6] that a term of this form can also be obtained in (001)-grown SiGe structures of C_{2v} symmetry, which does not have bulk inversion asymmetry. In this case the tetrahedral orientation of chemical bonds at interfaces gives rise to a coupling between heavy and light hole states [8]. We would like to emphasize that Dresselhaus terms of this type may also be present in zinc blend structure based QWs that have not yet been considered. Several microscopically different mechanisms leading to $\boldsymbol{k}$-linear terms of both types were discussed in [6].

The phenomenological theory of the CPGE allows us to probe the macroscopic in-plane symmetry of QW structures. The CPGE is described by

$$j_\lambda = \sum_\mu \gamma_{\lambda\mu}\, i(\boldsymbol{E}\times\boldsymbol{E}^*)_\mu, \qquad (2)$$

where j is the photocurrent density, γ is a second rank pseudotensor, $\boldsymbol{E}$ is the complex amplitude of the electric field of the electromagnetic wave, and $i(\boldsymbol{E}\times\boldsymbol{E}^*)_\mu = \hat{e}_\mu P_{\mathrm{circ}} E_0^2$, with E_0, P_{circ}, $\hat{e} = \boldsymbol{q}/q$ and $\boldsymbol{q}$ being the electric field amplitude, the degree of light circular polarization, the unit vector pointing in the direction of light propagation, and the light wavevector inside the medium, respectively. The second rank pseudotensors γ, $\boldsymbol{\beta}$, and the tensor of gyrotropy are isomorphic. Nonzero components of these tensors may exist if at least one component of a polar and an axial vector transforms according to the identity representation of the corresponding point group.

Nonzero components of γ for (001)- or (113)-grown SiGe QWs can be obtained by preparation of compositionally stepped QWs and asymmetric doping of compositionally symmetric QWs. Several point groups are relevant in connection with the photogalvanic experiments described later. For asymmetric QWs (because of doping or different profiles of the left and right interfaces) the macroscopic symmetry is reduced to C_{2v}. If QWs are grown along the low-symmetry axis $z \parallel [hhl]$ with $[hhl] \neq [001]$ or [111] the point group becomes C_s and thus CPGE is also allowed as it is the case for zinc blende structure based QWs grown on (113)-oriented substrates.

Making use of the sample symmetry we derive the photocurrent $\boldsymbol{j}$ of Eq. (2) as a function of the light helicity. First we use cartesian coordinates x, y, z along the directions $[1\bar{1}0]$, $[ll(\overline{2h})]$, and $[hhl]$, respectively, where $[hhl]$ ([001], or [113] in our case) is the growth axis of the QW structure. Because of carrier confinement in z direction the photocurrent in QWs has nonvanishing components only in x and y. Then, in a system of C_{2v} symmetry, the tensor $\boldsymbol{\gamma}$ describing the CPGE has two linearly independent components γ_{xy} and γ_{yx} and Eq. (2) reduces to

$$j_x = \gamma_{xy}\hat{e}_y P_{\mathrm{circ}} E_0^2, \qquad j_y = \gamma_{yx}\hat{e}_x P_{\mathrm{circ}} E_0^2. \qquad (3)$$

The same equations are also valid for the point group D_{2d} but this higher symmetry imposes the condition $\gamma_{xy} = \gamma_{yx}$ on the γ tensor components.

For both symmetries, D_{2d} and C_{2v}, a circular photocurrent can be induced only under oblique incidence of radiation because for normal incidence, $\hat{\mathbf{e}}\|[001]$ and hence $\hat{e}_x = \hat{e}_y = 0$. Thus rewriting the components $\gamma_{\lambda\mu}$ in the form $\gamma_{xy} = \gamma_1 + \gamma_2$, $\gamma_{yx} = \gamma_1 - \gamma_2$ and substituting this into Eq. (3) we can consider the coefficient γ_2 as a signature of the symmetry reduction from D_{2d} to C_{2v}. Choosing an other coordinate system (x', y', z) with the directions parallel to [100], [010] and [001], respectively, we obtain for the circular photogalvanic current

$$\begin{aligned} j_{x'} &= E_0^2 P_{\mathrm{circ}}(\gamma_1\hat{e}_{x'} + \gamma_2\hat{e}_{y'}),\\ J_{y'} &= E_0^2 P_{\mathrm{circ}}(-\gamma_2\hat{e}_{x'} - \gamma_1\hat{e}_{y'}). \end{aligned} \qquad (4)$$

While for x, y coordinates only a transverse effect occurs, see Eq. (3), for x', y' directions, both longitudinal and transverse effects may be present, see Eq. (4). This fact allows to make use of the CPGE for investigation of the macroscopic in-plane symmetry of QWs. Indeed, as it has been shown in [9] for the D_{2d} symmetry group γ_2 is equal to zero and, therefore, no transverse photogalvanic current can be generated at the excitation by light along x' or y' directions.

In contrast to structures of C_{2v} symmetry in structures of C_s symmetry the CPGE is allowed for normal incidence $\hat{\mathbf{e}} \parallel [hhl]$ because in this case the tensor γ has the additional nonzero component γ_{xz}. The current flows along $[1\bar{1}0]$ direction, perpendicular to the mirror reflection plane, and is described by

$$j_x = \gamma_{xz}\hat{e}_z P_{\mathrm{circ}} E_0^2 \qquad (5)$$

Thus the presence of the CPGE at normal incidence allows to conclude that the symmetry of the QW is not higher than C_s.

3. EXPERIMENT

The measurements were carried out on p-type SiGe quantum well structures MBE-grown on (001)- and (113)-oriented substrates. Two groups of (001)-grown samples were fabricated in the following manner. One of the groups of samples had a single quantum well of $Si_{0.75}Ge_{0.25}$ which was doped with boron from one side only. The second group comprised ten stepped quantum wells ($Si_{0.75}Ge_{0.25}$(4 nm)/ $Si_{0.55}$ $Ge_{0.45}$(2.4 nm)), separated by 6 nm Si barriers. These structures are of C_{2v} point group symmetry which is also confirmed by the present experiment. Structures of the lower symmetry C_s were (113)-grown with a Si/$Si_{0.75}Ge_{0.25}$(5 nm)/Si single QW one-side boron doped. As a reference sample, a (001)-grown compositionally symmetric (no step) and symmetrically boron doped multiple quantum well structure of sixty $Si_{0.7}Ge_{0.3}$(3 nm) QWs has been used.

All these samples have free carrier densities of about 8×10^{11} cm^{-2} and were studied at room temperature. For (001)-oriented samples two pairs of ohmic point contacts were prepared corresponding to x', y' parallel to $\langle 110\rangle$ and $\langle 100\rangle$-directions, respectively (see inset Fig. 1). Two additional pairs of contacts were formed in the center of the sample edges with connecting lines along $x \parallel [1\bar{1}0]$ and $y \parallel [110]$. For (113)-oriented samples two pairs of contacts were centered along opposite sample edges pointing in the directions $x \parallel [1\bar{1}0]$ and $y \parallel [33\bar{2}]$.

A high power pulsed mid-infrared (MIR) TEA-CO_2 laser and a far-infrared (FIR) NH_3-laser have been used as radiation sources delivering 100 ns pulses with radiation power P up to 100 kW. Several lines of the CO_2 laser between 9.2 and 10.6 μm and of the NH_3-laser [10] between $\lambda = 76$ and 280 μm have been used for excitation in the MIR and FIR range, respectively. The MIR radiation induces direct optical transitions between heavy hole and light hole subbands while the FIR radiation causes indirect optical transitions in the lowest heavy hole subband. The laser light polarization was modified from linear to circular using for MIR a Fresnel rhombus and for FIR quartz $\lambda/4$ plates. The helicity of the incident light was varied according to $P_{\mathrm{circ}} = \sin 2\varphi$ where φ is the angle between the initial plane of linear polarization and the optical axis of the $\lambda/4$ plate.

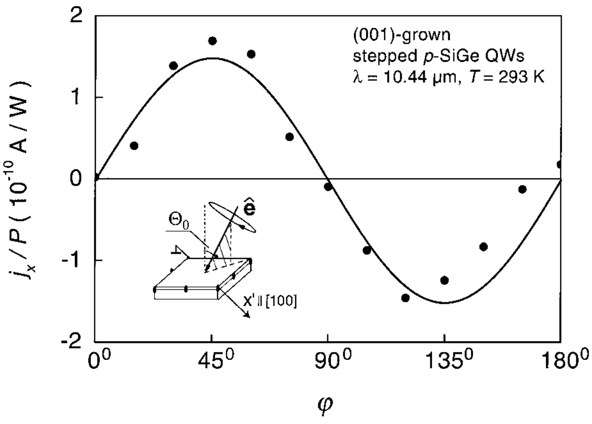

Fig. 1. Photogalvanic current j_x in (001)-grown compositionally stepped SiGe QWs normalized by the light power P measured at room temperature as a function of the phase angle φ. The data were obtained under oblique incidence $\Theta_0 = 30^\circ$ of irradiation at $\lambda = 10.44$ μm. The full line is fitted after Eq. (3).

With illumination by MIR radiation of the CO_2 laser in (001)-oriented samples with asymmetric quantum wells, a current signal proportional to the helicity P_{circ} is observed under oblique incidence as shown in Fig. 1. The full line is $\propto \sin 2\varphi$ ordinate scaled to the experimental data in agreement to Eq. (3). We note that the samples were unbiased, thus the irradiated samples represent current sources. The magnitude of the current cannot be predicted as there is no microscopic theory for the tensor γ. The current follows the temporal structure of the laser pulse intensity and changes sign if the circular polarization is switched from left to right hand. For $\langle 110\rangle$ as well as $\langle 100\rangle$ crystallographic directions, the photocurrent flows perpendicular to the wavevector of the incident light. Therefore only a transverse CPGE was observed. It means that effect of the Dresselhaus $\boldsymbol{k}$-linear term $(\sigma_x k_x - \sigma_y k_y)$ is negligible. The wavelength dependence of the photocurrent obtained between 9.2 and 10.6 μm corresponds to the spectral behavior of direct intersubband absorption between the lowest heavy-hole and light-hole subbands [6].

In the FIR range a more complicated dependence of the current as a function of helicity has been observed. In (001)-grown asymmetric quantum wells as well as in (113)-grown samples the observed dependence of the current on the phase angle φ may

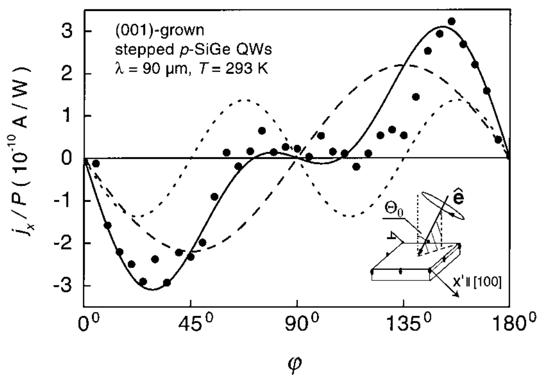

Fig. 2. Helicity dependence of photogalvanic current j_x in (001)-grown and compositionally stepped SiGe QWs normalized by the light power P. The data were obtained under oblique incidence $\Theta_0 = 30^\circ$ of irradiation at $\lambda = 90\,\mu$m. Broken and dotted lines show $j_x \propto \sin 2\varphi$ and $j_x \propto \sin 2\varphi \cdot \cos 2\varphi$, respectively. The full line is the sum of both.

be described by the sum of two terms, one of them is $\propto \sin 2\varphi$ and the other $\propto \sin 2\varphi \cdot \cos 2\varphi$. In Fig. 2 experimental data and a fit to these functions are shown for a step bunched (001)-grown SiGe sample. The first term is due to the CPGE and the second term is caused by the linear photogalvanic effect [6,11]. For circularly polarized radiation the $\sin 2\varphi \cdot \cos 2\varphi$ term is equal to zero and the observed current is due to the CPGE only.

With (001)-grown samples the signal vanishes at normal incidence, $\Theta_0 = 0$. The variation of the angle of incidence from positive to negative results in a change of direction of current flow (Fig. 3). For (113)-grown samples the current does not change its sign by the variation of Θ_0 and assumes a maximum at $\Theta_0 = 0$ (Fig. 3). In symmetrically (001)-grown and symmetrically doped SiGe quantum wells no photogalvanic current has been observed in spite of the fact that these samples, in order to increase their sensitivity, contain substantially more quantum wells than the asymmetric structure described earlier.

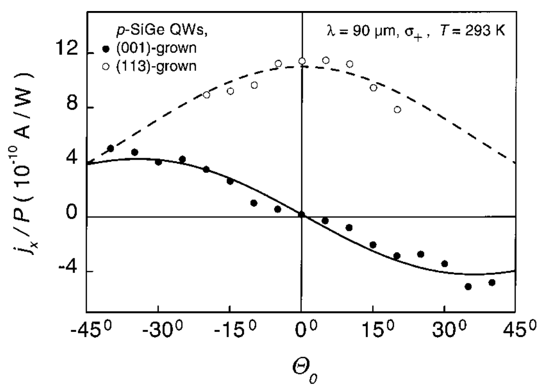

Fig. 3. Photogalvanic current j_x normalized by the light power P as a function of the angle of incidence. The data were obtained for (001)-grown compositionally stepped and (113)-grown SiGe QWs irradiated by right-handed circularly polarized light, σ_+, at $\lambda = 90\ \mu$m. The full line shows the result of calculation after the phenomenological theory.

4. SUMMARY

We have shown that in asymmetric SiGe QWs the absorption of circularly polarized radiation leads to spin photocurrents. This is demonstrated by the observation of a helicity-driven current due to the CPGE. Analysis of the CPGE with respect to the symmetry of the QWs allows to conclude on the spin-dependent $\boldsymbol{k}$-linear terms in the Hamiltonian. Our results provide the important information that spin-related phenomena, which so far have been considered to be specific for QW structures based on zinc blende structure materials, exist also in the SiGe QW systems.

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