Photogalvanic effects for interband transition in $p\text{-Si}_{0.5}\text{Ge}_{0.5}/\text{Si}$ multiple quantum wells

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Circular photogalvanic effect (CPGE) and linear photogalvanic effect for interband transition have been observed simultaneously in $\text{Si}_{0.5}\text{Ge}_{0.5}/\text{Si}$ multiple quantum wells. The signature of the CPGE is evidenced by the change of its sign upon reversing the radiation helicity. It is found that the observed CPGE photocurrent is an order of magnitude greater than that obtained for intersubband transition. The dependences of the CPGE on the angle of incidence and the excitation intensities can be well interpreted based on its characteristics. The large signal of spin generation observed here at room temperature should be very useful for the realization of practical application of spintronics.

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Lately, the manipulation of spin generation and transport in semiconductors has attracted great interest.^{1–5} The control of spin dynamics in materials has become a topical issue in basic research and material science under the perspective of spin-based electronic devices. One particular part is the generation of spin-polarized carriers in semiconductor quantum structures. Various semiconductor materials, such as III–V heterostructures, are involved in the spintronics activities and already good candidates for spintronics.^{6–8} In recent years, SiGe heterostructures have also been shown to be suitable materials for spintronic applications due to the long spin relaxation time.⁹ Based on the consideration of band structure effect, one way to generate spin-dependent current is the inclusion of k -linear terms in the Hamiltonian.¹⁰ These k -linear terms can lift the spin degeneracy of energy bands. The terms linear in k appear if the time reversal or the spatial inversion symmetry of the heterostructure is lower than that of the corresponding bulk materials. In the case of quantum wells (QWs), the spatial inversion symmetry is broken. By irradiating circularly polarized radiation on the materials with certain asymmetry, one can obtain spin-polarized current resulting from the nonuniform distribution of photoexcited carriers in k space due to optical selection rules and energy and momentum conservation. Such an interesting phenomenon is the so-called circular photogalvanic effect (CPGE).¹¹ The CPGE has been observed in various semiconductor heterostructures for both interband and intersubband transitions.^{6–8,12–14} However, the CPGE for interband transition has never been studied so far in $\text{Si}_{0.5}\text{Ge}_{0.5}/\text{Si}$ heterostructures. In this letter, we demonstrate the interband transition induced CPGE in $\text{Si}_{0.5}\text{Ge}_{0.5}/\text{Si}$ multiple quantum wells (MQWs) by the signature that the CPGE photocurrent changes its sign upon reversing the radiation helicity. It is stressed that the possibility of spin generation in SiGe-based materials at room temperature could pave a key step for the realization of practical application of spintronics.

To illustrate the photocurrent due to the CPGE, a schematic diagram is shown in Fig. 1(a). The CPGE can be re-

garded as a transfer of the photon angular momentum into a directed motion of a free charge carrier.¹⁰ Owing to the restriction of the selection rules, light with different degrees of helicity can cause variable population of carriers in k space and result in a spin-polarized photocurrent in real space. The photocurrent will reverse its direction due to different spin excitations if one changes the polarization of the radiation from positive helicity to negative helicity.

The $\text{Si}_{0.5}\text{Ge}_{0.5}/\text{Si}$ MQWs were grown on a p -type Si (001) substrate by a commercial ultrahigh-vacuum chemical vapor deposition system. The Si wafer was cleaned by dipping in HF solution, prior to the deposition of MQWs. The growth temperature and pressure were maintained at 600 °C and 5×10^{-9} torr, respectively, for all epitaxial layers. After depositing a 25 nm undoped Si layer on the substrate, the 40 periods of $\text{Si}_{0.5}\text{Ge}_{0.5}/\text{Si}$ MQWs were grown. Each period of the QW consists of 3.9 nm thick $\text{Si}_{0.5}\text{Ge}_{0.5}$ well and 3 nm thick Si barrier. Then, 24 nm thick undoped Si blocking layer and top Si layer of 48 nm thick with boron doped were grown on the MQWs. One pair of Ohmic contacts is made by indium deposition and the annealing temperature is at 300 °C. The two-dimensional free carrier concentration in each QW is about $1.2 \times 10^9 \text{ cm}^{-2}$. Because there exists internal strain due to lattice mismatch as well as built-in electric fields resulting

FIG. 1. (Color online) (a) The microscopic picture describing the origin of the spin current. The solid arrows are the σ^+ transitions from $s=-3/2$ (valence band), to $s=-1/2$ (conduction band), whereas the dashed arrows are the σ^- transitions from $s=3/2$ to $s=1/2$. Both σ^+ and σ^- cause unbalanced occupation in momentum space, resulting in a spin current in real space. (b) A schematic diagram showing the geometry of the experiment.

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FIG. 2. The photocurrent j in $\text{Si}_{0.5}\text{Ge}_{0.5}/\text{Si}$ multiple quantum wells normalized by the excitation power P as a function of phase angle φ with different incidence angles Θ_0 . These results are obtained at room temperature by a semiconductor laser diode with wavelength 1064 nm and excitation power of 150 mW.

from the asymmetric doping level, it will lead to a reduction of the microscopic symmetry of the sample from D_{2h} or D_{2d} to C_{2v} (Ref. 12) and, therefore, the CPGE can be expected.

The sample was studied at room temperature for the CPGE measurement. For interband excitation, a semiconductor laser diode with a wavelength of 1064 nm was used as the pumping source. The emitted light of the semiconductor laser diode was focused to a spot of about 0.01 mm^2 . The semiconductor laser diode emits linearly polarized light primitively. In order to obtain circularly polarized light, a quarter-wave plate of 1064 nm was placed between the sample and the laser. Changing the angle φ between the initial plane of linear polarization and the optical axis of the quarter-wave plate, the helicity $P_{\text{circ}} = \sin 2\varphi$ of the incident light can be varied from left-handed ($P_{\text{circ}} = -1$) to right-handed ($P_{\text{circ}} = 1$) circular polarization. The circularly polarized light inducing a photocurrent across a contact pair is obliquely irradiated on the $\text{Si}_{0.5}\text{Ge}_{0.5}/\text{Si}$ MQWs, as sketched in Fig. 1(b).

The photocurrents of the sample as a function of the helicity of the incident light with different incident angles are shown in Fig. 2. Compared with the case for intersubband transition in SiGe QWs, our result of the CPGE measurement for interband transition shows a more complicated dependence of the photocurrent on the helicity of the incident light. According to the previous reports,^{10,12,15} the photocurrent j_λ can be expressed as

$$j_\lambda = i\gamma_{\lambda\kappa}(\mathbf{E} \times \mathbf{E}^*)_\kappa + \frac{1}{2}\chi_{\lambda\mu\nu}(E_\mu E_\nu^* + E_\mu^* E_\nu) + j_0, \quad (1)$$

where $\chi_{\lambda\mu\nu}$ is a third-rank tensor and $\gamma_{\lambda\kappa}$ is a second-rank pseudotensor, $\mathbf{E}$ is the complex amplitude of the electric field of the incident light, and j_0 is the background current. The complex formula may be simplified by the following expression:¹⁰

$$j_\lambda = j_C \sin 2\varphi + j_L \sin 2\varphi \cos 2\varphi + j_0, \quad (2)$$

where j_C and j_L are the amplitudes of $\sin 2\varphi$ and $\sin 2\varphi \cos 2\varphi$, respectively. The first terms on the right-hand side of both Eqs. (1) and (2) are responsible for the CPGE

FIG. 3. (Color online) The fitting results of the CPGE and the LPGE photocurrents normalized by the power P of the incident radiation as a function of the incident angle Θ_0 at room temperature. The solid curve in (a) is the fitting result according to Eq. (3).

caused by the nonuniform momentum distribution in k space. Owing to the selection rules of electronic transition, the photocurrent is sensitive to the circular polarization of the radiation. In other words, the photocurrent induced by the CPGE will reverse its direction due to different spin excitations if the polarization of the radiation is changed from positive helicity to negative helicity. Therefore, this phenomenon will result in a period of π in the CPGE current. The second terms on the right-hand side of Eqs. (1) and (2) result from the linear photogalvanic effect (LPGE).^{10,11} The LPGE results from the asymmetric electron scattering on phonon or other defects and, consequently, the photocurrent caused by the LPGE will maintain its direction and amplitude when the polarization of the radiation is replaced from positive to negative helicity. In other words, both positive and negative helicities give the same physical phenomenon and result in the oscillation period of $\pi/2$. Therefore, in accordance with the characteristics of the LPGE, the photocurrent caused by the LPGE is independent of the spin orientation.

The fitting results of the CPGE and the LPGE photocurrents normalized by the power P of the incident radiation as a function of the incident angle Θ_0 at room temperature are shown in Fig. 3. The maximum of the CPGE photocurrent in the fitting result is about 109.26 nA/W at $\Theta_0 = 40^\circ$. Compared with the case for intersubband transition on p -SiGe QWs done by Ganichev *et al.*,¹² the CPGE photocurrent for interband transition we obtained is about three orders of magnitude greater than that for intersubband transition of about 0.1 nA/W . Even if we divide our observed signal by the total number of QWs in our measurement, the interband transition induced CPGE is still about 30 times larger than that of intersubband transition. The difference can be easily understood by the fact that the number of the photoexcited carriers due to interband absorption are much more than that caused by intersubband absorption.

FIG. 4. (Color online) The photocurrent j normalized by the intensity I as a function of I for CPGE and LPGE at room temperature. The measurements are fitted for each state of polarization according to Eq. (4). The solid and dashed lines are the fitting results for CPGE and LPGE, respectively. The arrows mark the obtained saturation intensities I_s .

The dependence of the CPGE photocurrent on the angle of incidence is ready to be compared with the theoretical prediction. The first term on the right-hand side of Eq. (1) can be written as $i(\mathbf{E} \times \mathbf{E}^*)_{\kappa} = \hat{e}_{\kappa} P_{\text{circ}} E_0^2$ with E_0 and $\hat{e}_{\kappa}$ being the amplitude of the electric field of the incident radiation and the projection onto the heterostructure plane of the unit vector $\hat{e}$ pointing in the direction of light propagation, respectively. According to the previous investigations,^{7,8,10} $\hat{e}_{\kappa}$ can be described by Fresnel's formula as follows:

$$\hat{e}_{\kappa} = \frac{4 \cos^2 \Theta_0 \sin \Theta_0}{n(\cos \Theta_0 + \sqrt{n^2 - \sin^2 \Theta_0})(n^2 \cos \Theta_0 + \sqrt{n^2 - \sin^2 \Theta_0})}, \quad (3)$$

where n is the refractive index of the QW and Θ_0 is the incident angle. As shown in Fig. 3(a), the experimental result is in good agreement with the theoretical calculation. The obtained refraction index, as a fitting parameter, is about 3.6 which is in close agreement with that of SiGe alloy.¹⁶ Unlike the dependence of the CPGE photocurrent on the angle of incidence, the LPGE photocurrent increases with Θ_0 , as shown in Fig. 3(b). This growing tendency of the LPGE can be attributed to the stronger electric field of the incident radiation projected onto the heterostructure plane. After extracting the contributions of the CPGE and LPGE from the total photocurrent, there still exists a background current j_0 . Even at normal incidence, the background current remains. The origin of j_0 is not known at present. However, the helicity independent signal is most likely a result of the photovoltaic effect at contacts or the Dember effect when interband excitation is employed.¹⁰

In order to investigate further the photogalvanic effect, we have performed similar measurements with different excitation intensities at a fixed Θ_0 of 20°. The extracted contributions of the CPGE and LPGE are shown in Fig. 4. The result displays a bleaching tendency, which can be attributed to the effect of the absorption saturation under an intense excitation.¹⁷ Under this condition, the absorption coefficient is proportional to the photogalvanic current normalized by the radiation intensity. The photoresponse corresponding to

the absorption coefficient of circularly or linearly polarized radiation is therefore observed.¹¹ The empirical formula for the dependence of photocurrent j on the radiation intensity I can be described as

$$\frac{j}{I} = \frac{A}{1 + \frac{I}{I_s}}, \quad (4)$$

where I_s is the saturation intensity and A is a proportional constant. The fitted saturation intensities for the CPGE and LPGE are 479 and 1148 W/cm², respectively. The difference may be related to several dissimilar factors in the CPGE and LPGE processes, such as selection rule and carrier relaxation time. More detailed theoretical and experimental studies are still needed.

In summary, we have demonstrated the photogalvanic effects for interband transition in Si_{0.5}Ge_{0.5}/Si MQWs at room temperature. The observed CPGE photocurrent here is an order of magnitude greater than that for intersubband transition. The dependences of the CPGE on the angle of incidence and excitation intensities can be well interpreted in terms of its basic characteristics. In view of a wide range of applications of SiGe-based heterostructures, our results shown here can pave a key step for the practical application of spintronics.

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