Radiation modulation of circular photogalvanic effect in two-dimensional electron gas system

Chongyun Jiang¹, Hui Ma, Jinling Yu, Yu Liu and Yonghai Chen*²

Key Laboratory of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy of Sciences, 100083 Beijing, China.

E-mail: (1) cyjiang@semi.ac.cn, (2) yhchen@semi.ac.cn

Abstract. We report on the observation of a modulation on the circular photogalvanic effect (CPGE) imposed by an extra optical radiation in a GaAs-based two dimensional electron gas system. The wavelength of the radiation for exciting the CPGE is 1064 nm and the wavelength of the modulation is 532 nm. The experiment is carried out from 77 K up to room temperature. The 1064 nm induced CPGE modulated by the 532 nm radiation increases as the increasing temperature. We also vary the power of the modulation beam to investigate the intensity dependence of the modulation effect. The modulation exhibits a linear dependence at low intensity. As the intensity increasing, we observe a saturation at certain level of the intensity and a suppression of the modulation when the intensity is further increased. The investigation of photoconductivity reveals that the change of the photoexcited charge carrier density has little contribution to the radiation modulation effect. Therefore, the microscopic mechanism of the radiation modulation effect can be attributed to the modulation of spin-orbit interaction in the structure.

Spin-related phenomena in condensed matter are of great interests since the last decade. Structure inversion asymmetry (SIA) and bulk inversion asymmetry (BIA)[1, 2, 3], usually also known as Rashba effect and Dresselhaus effect, are powerful tools for describing the spin-orbit interaction (SOI) of electron (or hole) systems. The SIA in a two-dimensional electron system, such as quantum wells (QWs) and heterostructures, arising from the asymmetry in the growth direction, can be tuned by an external electric field. Precursors have done extensive work on the tuning of SIA with respect to the effective electric field. Circular photogalvanic effect (CPGE)[4, 5, 6, 7, 8, 9, 10] is a way to access to the SIA and BIA in a two-dimensional electron system. In this work, we show another approach of tuning the SIA in a GaAs/AlGaAs heterostructure, i.e. applying a perpendicularly incident radiation, which gives rise to a photogenerated electric field parallel to the growth direction and enhances the built-in effective electric field, namely, the Rashba effect.

Our sample is a GaAs/AlGaAs heterostructure grown by molecular beam epitaxy technique. A two-dimensional electron gas is formed in the vicinity of the heterojunction. The sample is cut into 10 × 5 mm in size and two contacts are alloyed in the middle of the opposite long edges. Thus, the current flows along the [110]-direction. We put the sample into an liquid nitrogen cryostat and carry out the experiment from 77 K up to room temperature. The experimental geometry is depicted in Fig. 1. The excitation beam with a wavelength of 1064 nm is aligned at 30° of oblique incidence, of which the polarization state is modulated by a photoelastic modulator (PEM). A perpendicularly incident beam with a wavelength of 532 nm
is employed as a modulation radiation for tuning the SIA. The power of the modulation beam can be tuned from 0.01 up to 250 mW, whereas the power of the excitation beam is 133 mW. The polarization independent signals are chopped by an optical chopper and all the signals are picked up by standard lock-in technique. The total current can be written as

\[ j = j_{C,1f} + j_{L,2f} + j_0, \]  

where \( j_{C,1f} \) is the CPGE current referenced to the base frequency of the PEM, \( j_{L,2f} \) is the linear photogalvanic effect (LPGE) current referenced to the second harmonic frequency of the PEM, which is out of the scope of this work, \( j_0 \) is the polarization independent current referenced to the frequency of the chopper.

Several parameters of the sample, for instance, the carrier mobility, vary according to temperature. We should take them into account when discussing the change of the photocurrents in the sample. One of a useful methods is to investigate the photoconductivity [11, 12, 13] of the samples at various temperature. The photoconductivity is expressed as

\[ \Delta \sigma = e(\Delta n \mu_n + \Delta p \mu_p), \]  

where \( \Delta n \) and \( \Delta p \) are the number of photoexcited electrons and holes, respectively. \( \mu_n \) and \( \mu_p \) are the mobility of electrons and holes. \( e \) is the elementary charge. By using the photoconductivity as a denominator for normalizing the photogalvanic effect. Thus, we can compare the results at different temperature after the normalization. The experimental results of the photoconductivity excited by the 1064 nm radiation as a function of the power of the 532 nm modulation beam are shown in Fig. 2. It is seen in the figure that the photoconductivity has a higher value at low temperature and increases as the increasing power of the modulation radiation. We attribute the increase to the contribution of charge carrier density of the carrier transport induced by the 1064 nm excitation beam.

The CPGE currents modulated by the 532 nm light at different temperatures are shown in Fig. 3. The CPGE increases as the increasing temperature, which can be ascribed to the ionization of the n-type dopant in the AlGaAs layer. At low temperature the ionization rate, namely, the built-in potential associated with the SIA, is low. Therefore, we observe a lower signal at low temperature. On the other hand, the CPGE current increase as the intensity of the modulation beam and reaches maxima at around 30 mW, and then decrease slightly to a saturation level. Since the contribution of the modulation beam to the charge carrier density is relatively small and has been already taken into account when normalized to the photoconductivity, we suggest that the modulation of the CPGE does not depend solely on the change of the charge carrier density.

Since an external electric field can tune the SIA in the two-dimensional electron system, we could focus on the photo induced electric field to find out the origin of the modulation. The
Figure 2. Photoconductivity excited by 1064 nm radiation and modulated by 532 nm beam.

Figure 3. CPGE as a function of the power of the 532 nm modulation beam. The inset shows the relative magnitude of the CPGE at the modulation power of 20 mW and 0.3 mW.

perpendicularly incident modulation beam may induce an effective electric field along $x \parallel [110]$, $y \parallel [1\bar{1}0]$ or $z \parallel [001]$. For the electric field along $x$ or $y$ direction, we apply an external electric field along the corresponding axis as an analogue to the effective electric field but observe no obvious change of the CPGE. Therefore, the modulation does not come from the inhomogeneous distribution of the beam profile which leads to a carrier concentration gradient. Since the photon energy of the 532 nm modulation beam is 2.34 eV, which is higher than the band gaps of both GaAs (1.424 eV) and AlGaAs (1.424 $\sim$ 1.9 eV), the 532 nm excitation could generate excess charge carriers in these two layers. The photogenerated potential in the heterostructure drives the electric current flow in a loop between the two layers. Hence, an effective electric field along the $z \parallel [001]$ direction is built up. The electric field along the [001] direction interplays with the built-in electric field associated with the Rashba effect, and thus influence the spin-orbit interaction in the system. The effective potential may consist of two components, one of which is an electrostatic potential related to the change of charge density, the other is an electrodynamical potential related to the diffusion of the charge carriers, namely, the net current in $z$-direction. The direction of the electrostatic potential is opposite to the built-in electric field due to the
generation of majority carriers, whereas that of the diffusion potential is the same as the built-in potential due to the diffusion of the minority carriers. The total photogenerated effective potential is the superposition of the two potentials. For low excitation intensity, the electrostatic potential dominates and thus the Rashba effect decreases. As the increasing intensity of the excitation, the diffusion potential increase much more rapidly than the electrostatic potential. Therefore, the modulation of the Rashba effect becomes positive. It is also seen in the inset of Fig. 3 the temperature dependence of the relative changes of the CPGE modulated by different powers of the modulation beam. The maximum of the modulation occurs at around 160 K. It may be attributed to the superposition of the increase of the diffusion coefficients of the charge carriers and the decrease of the carrier mobilities. In the [1 ¯10] direction, the CPGE current consists of SIA and BIA components[5, 9]. Besides the change of the SIA modulated by the modulation beam, the current related to the BIA is also mixed in the results. Since the BIA cannot be tuned by an effective electric field in z-direction and solely correlated with the charge carrier density in this experiment, the influence of the BIA can be omitted.

In summary, we investigated the CPGE modulated by a perpendicularly incident radiation and observed a remarkable change of the CPGE imposed by the modulation beam. It can be attributed to the modulation of the SIA in the manner that an effective electric field is generated perpendicular to the sample plane and interplays with the built-in potential associated with the SIA.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (Grant Nos. 10804105, 60990313) and the 973 Program.

References

[1] Tahan C and Joynt R 2004 Phys. Rev. B 71 075315
[2] Winkler R 2003 Spin-Orbit Coupling Effects in Tow-Dimensional Electron and Hole Systems (Springer)
[3] Ivchenko E 2005 Optical Spectroscopy of Semiconductor Nanostructures (Alpha Science Int., Harrow, UK)
[4] Ganichev S and Prettl W 2003 Journal of Physics-Condensed Matter 15 R935–R983
[5] Ganichev S D, Bel’kov V V, Golub L E, Ivchenko E L, Schneider P, Giglberger S, Eroms J, Boeck J D, Borghs G, Wegscheider W, Weiss D and Prettl W 2004 Phys. Rev. Lett. 92 256601
[6] Ivchenko E L and Ganichev S D 2008 Spin Physics in Semiconductors: Spin-Photogalvanics (Solid-State Sciences vol 157) (Springer) chap 9, pp 245–277
[7] Ivchenko E L 2005 Circular Photo-Galvanic and Spin-Galvanic Effects (Springer) chap 6, pp 23–50
[8] Pershin Y V and Piernarocchi C 2005 Appl. Phys. Lett. 86 212107
[9] Giglberger S, Golub L E, Bel’kov V V, Danilov S N, Schuh D, Gerl C, Rohlfiing F, Stahl J, Wegscheider W, Weiss D, Prettl W and Ganichev S D 2007 Phys. Rev. B 75 035327
[10] Lechner V, Golub L E, Olbrich P, Stachel S, Schuh D, Wegscheider W, Bel’kov V V and Ganichev S 2009 Appl. Phys. Lett. 94 242109
[11] Mosimann R, Haertle D, Jazbinsek M, Montemezzani G and Günter P 2006 Applied Physics B: Lasers and Optics 83 115–119
[12] Moss T S 1965 Rep. Prog. Phys. 28 15
[13] Wright D A 1958 Br. J. Appl. Phys. 9 205