Temperature dependence of circular photogalvanic effect in GaAs/Al$_{0.3}$Ga$_{0.7}$As two-dimensional electron system

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Abstract. Structure inversion asymmetry (SIA) related circular photogalvanic effect (CPGE) has been investigated under near-infrared radiation at temperatures ranging from 80 K to 290 K in GaAs/Al$_{0.3}$Ga$_{0.7}$As heterostructures. The result shows nonmonotonic changes of CPGE with temperature variation; obviously larger signal at low temperature and sign inversions in the temperature range between 140 K and 170 K are observed. We suggest this result is not only related to the photoconductivity and Rashba spin splitting, but other factors superpose on them.

Recently, spin-related phenomena in semiconductors have attracted considerable attentions. In two dimensional structures, the spin splitting originates from two sources [1]-[5]: structure inversion asymmetry (SIA) and bulk inversion asymmetry (BIA), usually known as Rashba effect and Dresselhaus effect. Compared with BIA arising from the absence of an inversion centre in bulk crystal, SIA is more important for spin devices based on the consideration that it arises from different kinds of asymmetries which can be modulated by electric field in heterostructures.

The circular photogalvanic effect (CPGE) [6]-[8] induced by circular polarized radiation enables the generation of spin polarized current, which is a usual method to investigate the spin splitting. In two dimensional systems, the CPGE current can be written as [6], [9]

\[
J_{c,j} = e \Delta \tau_p \frac{\gamma}{\hbar \omega} \eta I P_e \hat{e}_x
\]

(1)

\(\Delta \tau_p\) is the difference of momentum relaxation time of ground and excited states, \(I\) is the intensity of the radiation, \(\eta\) is the relative absorbance for the considered optical transitions, \(\hbar \omega\) is the photon energy of excitation, \(P_e\) describes the helicity of the radiation, \(\hat{e}_x\) is the x component of the unit vector of the electric field amplitude, and \(\gamma\) is a second rank pseudotensor which is correlated with Rashba and Dresselhaus spin splitting. For a system of C$_2$v symmetry, the relative magnitude of SIA and BIA can be extracted via measuring the components of the current in different directions [1],[3].

Temperature is known as an important parameter, which plays a tremendous role on most physical phenomena. In this paper, we have investigated the temperature dependence of CPGE. It shows larger signals at low temperature and sign inversions in the temperature range between 140 K and 170 K. We suggest that photoconductivity and Rashba spin splitting are just part of the reason for this phenomenon, other factors also play important roles.

The sample studied here is grown on semi-insulating (001)-oriented GaAs substrates by molecular-beam epitaxy (MBE). Two dimensional electron gas (2DEG) is sandwiched between GaAs/Al$_{0.3}$Ga$_{0.7}$As interface with the Si-\(\delta\) doping in AlGaAs layer. Moreover, one monolayer InAs is
inserted in the interface. The mobility and sheet concentrations of 2DEG vary with temperature. The sample is cut into 4x4 mm$^2$ in size with cleaved edges oriented along [110] and [110] axes. One pair of Ohmic contacts is prepared by Indium deposition on two opposite corners with a distance of ~4 mm. We put the sample into a liquid nitrogen cryostat and carry out the experiments from 80 K to 290 K. The experimental geometry is depicted in the figure 1. The excitation beam with a diameter of ~2mm and a wavelength of 1342 nm is aligned at 30° of oblique incidence after circularly polarized by photoelastic modulator (PEM). CPGE current is extracted by lock-in amplifier with changing the retardation in wavelength of PEM. In our experimental geometry, i.e. the current collection direction perpendicular to the incident plane, the CPGE current is related to the Rashba spin splitting.

Since CPGE current is proportional to the electron density in 2DEG, intensity of the radiation and light absorption as equation (1) shows, we first investigate the temperature dependence of photoconductivity, which is written as

$$\Delta \sigma = \Delta n e (\mu_2 - \mu_1) = [\eta(T) g I \tau_n] e(\mu_2 - \mu_1)$$

Figure 1. Experimental setup

$\Delta n$ is the density of photoexcited electrons, $\mu_2$ and $\mu_1$ are electron mobility of excited and ground states, which are correlated with the momentum relaxation time of equation (1), $\eta(T)$ is the absorption coefficient, $g$ is the generation rate of the carrier pairs, $I$ is the radiation intensity, and $\tau_n$ is the life time of excess electrons. The experiment of photoconductivity was carried out by applying a dc-bias between the two contacts and recording the current referenced to the optical chopper on the load resistor. Figure 2 shows the photoconductivity vs temperature. Complicated variation is obtained with the mixture of temperature dependence of factors, including electron density in 2DEG, light absorptivity, generation rate of the carrier pairs and the mechanisms of scattering.

Figure 2. Photoconductivity as a function of temperature.
According to the experimental principle, the CPGE current can be written as \[^{11,12}\]

\[ j_C(\phi, T) = \chi(T) J_1(\phi) \sin(\omega t) \]  

(3)

Here \( \phi \) is the phase amplitude tuned by PEM, and \( T \) is the temperature of sample. \( \omega = 2\pi v \) and \( v = 50 \) kHz, which corresponds to the fixed frequency of PEM. \( J_1 \) is the first-order Bessel function, ranging from \( \lambda \) to \( \lambda/2 \); \( \chi(T) \) is the temperature dependent coefficient. All measured curves can be well fitted by the same Bessel function with the only difference of \( \chi(T) \), and one example at 90 K is shown in figure 3. It demonstrates that CPGE current increases up to saturate, and then slightly declines with the wavelength retardation increasing. Figure 4 gives the temperature dependence of CPGE. It shows nonmonotonic changes, and the signal at lower temperature is obviously larger than that at higher temperature. Besides, sign inversions appear in the temperature range between 140 K and 170 K.

![Figure 3](image)

**Figure 3.** (Color online) Measured (red dots) and fitted (black line) CPGE currents as a function of wavelength retardation at 90 K.

![Figure 4](image)

**Figure 4.** CPGE current as a function of temperature

After deducting the contribution of photoconductivity, we find that CPGE current still obviously changes with temperature. One part of reason we attribute to Rashba spin splitting for the specific experimental geometry as depicted above. It is known that such factors as the ionization of the n-type dopant in AlGaAs layer \[^{13}\], the band gap discontinuity (\( \Delta E_C \)) \[^{14}\] and the sheet carrier density \[^{13,15}\] are related with temperature, which can result in the variation of built-in electric field \[^{13}\]. It is also
known that Rashba spin splitting can be tuned by electric field\textsuperscript{[16], [17], [18]}. Therefore, we deduce that temperature dependent Rashba spin splitting probably contributes to the change of CPGE current. But ref. 19 indicates that Rashba spin splitting doesn’t change a lot with temperature. It is apparently seen that some other factors also have an effect on the CPGE, and it is prone that when temperature gets down other effects probably superpose on the CPGE current.

In summary, we have investigated the temperature dependence of CPGE current in GaAs/Al\textsubscript{0.3}Ga\textsubscript{0.7}As heterostructures under the radiation of 1342 nm laser. Nonmonotonic changes and sign inversions are observed. This result can not be completely illustrated by photoconductivity and Rashba spin splitting, and we suggest that other unknown factors probably play important roles on the temperature dependent CPGE.

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