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Separation of the intrinsic and extrinsic mechanisms of the photo-induced anomalous Hall effect

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ABSTRACT

The photocurrent spectra induced by the anomalous Hall effect (AHE) of the (001)-oriented GaAs/AlGaAs quantum wells (QWs) with well width of 3 and 7 nm have been investigated at room temperature. Ultra-thin InAs layers with a thickness of 1 monolayer have been inserted at GaAs/AlGaAs interfaces to tune the asymmetry of the QWs. It is demonstrated that the AHE current can be effectively tuned by the inserted ultra-thin InAs layers and by the well width. A method has been proposed to separate the intrinsic and extrinsic mechanisms of the AHE, which can be also applied to spin Hall effect.

1. Introduction

Spintronics has gained much attention due to its potential application in the field of information technology as well as the challenging fundamental physical questions that it poses [1–7]. The spin-orbit coupling (SOC) provides us a powerful way using electric field to generate and manipulate of spins of electrons [1]. SOC of semiconductor quantum wells (QWs) can be engineered by changing the structures of the QWs, for example, Rashba SOC can be tuned by varying the delta-doping position [8], and Dresselhaus SOC can be tailored by changing the well width of the QWs [9]. Circular photogalvanic effect (CPGE) offers us a method to investigate the SOC in low-dimensional semiconductor materials as well as to design new spintronics devices [10–12]. Besides CPGE, photo-induced anomalous Hall effect (AHE), which originates from inverse spin Hall effect (ISHE) [13], suggests another approach utilizing SOC to realize semiconductor spintronics [13–20], and it has been used to design spin-photovoltaic devices recently [21]. Similar to spin Hall effect, there are two mechanisms proposed theoretically for the AHE. The extrinsic mechanism is based on asymmetric Mott-skew or side-jump scattering from impurities in a spin-orbit coupled system [2,22], while the intrinsic mechanism is dependent only on the band structure of the materials, which arises from Rashba [3,23] or Dresselhaus SOC [24,25]. For a given system, both of the extrinsic and intrinsic mechanism will contribute to the AHE, however, it is quite difficult to distinguish them [4,26]. Priyadarshi et al. distinguished the intrinsic and extrinsic contributions to the AHE in undoped GaAs QWs by subpicosecond time resolution technology [4]. In this paper, we propose another method combining CPGE and AHE to separate the intrinsic and extrinsic mechanisms of the AHE current. Besides, we also investigate the photocurrent spectra induced by the AHE of the (001)-oriented GaAs/AlGaAs multiple quantum wells (MQWs) with well width of 3 and 7 nm at room temperature. In order to enhance the asymmetry of the QWs, we insert InAs layers with a thickness of 1 monolayer (ML) at the interfaces of the QWs. We find that the AHE current can be effectively tuned by the inserted InAs layer and by the well widths of the QWs.

2. Sample and experiments

The samples studied in this experiment are three undoped GaAs/$Al_{0.3}Ga_{0.7}As$ MQWs, named as sample A, B and C, respectively, grown on (001) SI-GaAs substrates by molecular beam epitaxy (MBE), which are the same with those used in Ref. [27]. There are 20 periods of GaAs/AlGaAs quantum wells with well width of 7 nm in sample A. Sample B has the same structure with that of sample A except that the well width is 3 nm. Sample C also contains 20 periods of 7 nm-GaAs/AlGaAs QWs, and 1 monolaryer (ML)-thick InAs layer is inserted at the

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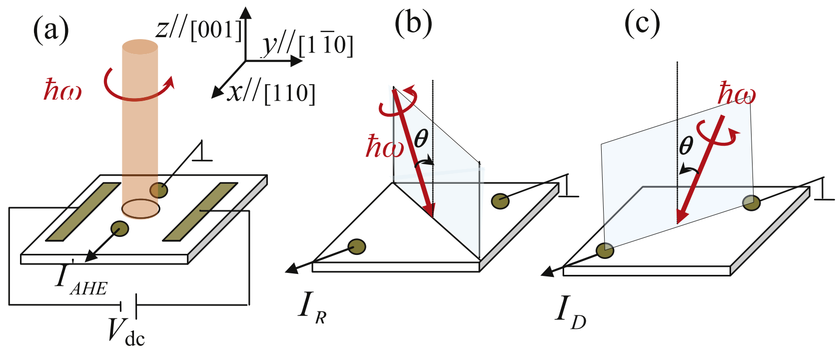

Fig. 1. (a) Schematic diagram of the AHE experiments. (b) and (c) are gGeometries used to measure the CPGE current induced by Rashba (I_R) and Dresselhaus (I_D) SOC, respectively.

interface of each GaAs/AlGaAs QWs, forming GaAs/InAs/$Al_{0.3}$ $Ga_{0.7}$ As structures. All of the samples are of high purity, which can be evident from the high resistance without lighting of the samples. The 2D densities of the photo-induced carriers in the three samples are about 10^9 cm^{-2} for the transition of 1H1E (the first valence subband of heavy holes to the first conduction subband of electrons) when they are excited by a laser with 60 mW at 840 nm.

In the experiments, the samples are cleaved into squares of 4×4 mm^2 along [110] and [1$\bar{1}$0] directions. Two point contacts with a diameter of 0.5 mm and 3 mm apart, and two strip electrodes (0.5 mm×3 mm) with a distance of 3 mm, are made by indium deposition and annealed at about 420 ° in nitrogen atmosphere, as shown in Fig. 1(a). In the experiments, a mode-locked Ti-sapphire laser with a repetition rate of 80 MHz and with a full width at half maximum (FWHM) of 7 nm is used as the radiation source. Going through a polarizer and a photoelastic modulator (PEM), the light emitted from the laser become a circularly polarized light, whose polarization state is oscillating between right- (σ^-) and left- (σ^+) hand periodically. Then, the light with a light spot of 2.5 mm-diameter and with a power of 60 mW at 840 nm irradiates at the central line between two point contacts. It is worth noting that the contacts should not be illustrated by laser to avoid collecting the signal due to contacts (i.e., current induced by rectification at the contacts), and that the laser spot should have equal distances with the two point contacts in order to exclude the current due to the optically excited gradient of the carrier density (i.e., Dember effect). A longitudinal electric field is applied by the two strip electrodes, and the transverse photocurrent (i.e. AHE current, see Section 3) is collected by a lock-in amplifier in phase with the PEM through the two point contacts. The photoconductive current I_0 with a DC bias of 1.5 V applied between two point contacts is obtained by collecting the photocurrent I_0 at the same point contacts using a lock-in amplifier and a chopper. The spectra in the wavelength range of 750–870 nm are measured.

In order to obtain the ratio of Rashba and Dresselhaus SOC and thus to separate the intrinsic and extrinsic mechanism of AHE, CPGE measurements are also performed. The samples with 4×4 mm^2 cleaved along [110] and [1$\bar{1}$0] directions are prepared. Then, one pair of point contacts, with a distance of 3 mm, along [100] direction is prepared by indium deposition and annealed at about 420 °C in nitrogen atmosphere, as shown in Fig. 1 (b) and (c). In the CPGE measurement, a similar experimental setup with that used in AHE measurements is used except that the light irradiates obliquely on the sample with a angle of incidence ranges from −30 to 30° and that no electric field is applied on the sample. It should be noted that, (001)-grown zinc-blende structure-based QW belongs to point group C_{2v} [11], in which the photocurrent can be only induced under oblique incidence of irradiation. The CPGE current is collected by the lock-in amplifier in phase with the PEM through the two electrodes. The CPGE current induced by Rashba and Dresselhaus SOC can be obtained by adopting the geometries shown in Fig. 1 (b) and (c), respectively [28,29]. In Fig. 1, I_R (I_D) denotes the CPGE current induced by Rashba (Dresselhaus) SOC, and θ is the angle of incidence. In order to eliminate the influences of the anisotropic carrier mobility and carrier density in different samples, the photoconductive current I_0 under DC bias are also measured.

3. Results and discussions

Fig. 2(a) shows the normalized transverse photocurrent spectra under different longitudinal electric fields (i.e., AHE current) in sample A. The solid symbols are the experimental data, and the solid lines are guides for eyes. The spectra are normalized by I_0/E_0 corresponding to the transition of excitonic state 1H1E, where I_0 is the photoconductive current detected at the point contacts when applying a DC-bias of 1.5 V between the point contacts, and E_0 is the electric field between the two point contacts when applying a DC-bias of 1.5 V. It can be seen that the AHE current increases with the increasing of the longitudinal field, and the current flow reverses with the direction of the longitudinal field. Denoting I'_{AHE_+} (I'_{AHE_-}) as the transverse current collected by the two point contacts at positive (negative) longitudinal field, one can obtain the AHE current accurately by $(I'_{AHE_+} - I'_{AHE_-})/2$, as shown in Fig. 3. The solid symbols are the experimental data, and the solid lines are guides for eyes. One can see that, the energy positions of the excitonic state 1H1E and 1L1E can not be clearly distinguished in the AHE spectra due to the large FWHM of the Ti-sapphire laser. In order to find out the exact energy position of the excitonic transition 1H1E and 1L1E, we replace the Ti-sapphire laser with a 250 W tungsten lamp combined with a monochromator, which has a spectral resolution of 1 nm. The measurement results are shown in Fig. 2(b), from which the energy positions of the excitonic states 1H1E and 1L1E, indicated by solid and dashed arrows in Fig. 2(b) respectively, can be clearly located. The energy positions of the excitonic state 1H1E and 1L1E are also indicated by vertical dashed in Fig. 3.

The generation of transverse photocurrent under longitudinal electric field is described as follows. Firstly, the spin polarized carriers are produced under the radiation of circularly polarized light, whose photon energy is equal to or larger than the excitonic states of the QWs, by two ways: (1) direct formation of free electrons and holes, and (2) creation of free carriers through excitons [19]. For the first case, under the irradiation of circularly polarized light, taking left-handed (σ^+) circularly polarized light as an example, the electron in the valence band with spin angle momentum $m_s = -3/2$ will jump to the conduction band with spin angle momentum $m_s = -1/2$, according to the optical selection rule. For the second case, excitons consisting of well-defined spins are created by circularly polarized light, and then the excitons are dissociated to produce free carriers by interaction with phonons, impurities and other excitons [19]. Then the spin polarized carriers will show lateral deflection due to spin Hall effect (SHE). To be