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Optical detection of zero-field spin precession of high mobility two-dimensional electron gas in a gated GaAs/AlGaAs quantum well

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ABSTRACT

We investigated the effective magnetic field induced by spin–orbit interaction in a gated modulation-doped GaAs/AlGaAs quantum well (QW) structure. We measured the precession of the optically injected electron spins at zero magnetic field by a time-resolved Kerr rotation (TRKR) technique as a function of the gate voltage V_g. The V_g-dependence of the effective magnetic field extracted from the TRKR data was quantitatively analyzed by considering both Rashba and Dresselhaus spin–orbit interaction in a Monte Carlo simulation. With the Dresselhaus spin–orbit coupling parameter γ and the scattering time as fitting parameters, we reproduced the experimental TRKR data, from which we estimated $\gamma \sim 13$ eV Å^3.

1. Introduction

Spin–orbit interaction in III–V semiconductors plays an important role in semiconductor spintronics [1]. In particular, the spin–orbit interaction originating from the lack of the space inversion symmetry of potential in the bulk crystal structure and heterostructures results in the spin splitting in the conduction band, which enables generation of spin current in zero magnetic field: For example, spin injection in a quantum point contact has been proposed [2]. Tuning of the spin–orbit interaction is also of great importance and can open a new approach to spintronics, as represented by realization of the persistent spin helix [3,4].

Spin dynamics of two-dimensional electron gases (2DEGs) in a GaAs/AlGaAs quantum wells (QWs) has been extensively studied so far. Recently, in particular, the spin dynamics near the Fermi energy of high mobility 2DEGs in GaAs/AlGaAs QW has been optically explored [5–9]. The spin–orbit interaction results in the relaxation of coherent electron spin dynamics, which is known as the D'yakonov–Perel spin relaxation mechanism [10]. On the other hand, oscillatory evolution of photoexcited electron spins has been observed in high mobility 2DEG systems, which has long momentum relaxation time, without applying external magnetic field [5]. So far, the effect of the electron–electron scattering [7], the QW width [8] and the energy dependence [9] of such electron spin dynamics have been studied in high mobility 2DEG system. For the analysis of the experimental data of the time-resolved optical measurements, Monte Carlo simulation has been employed to evaluate the effective magnetic field and the electron–electron scattering [5].

In this work, we investigate the effective magnetic field induced by spin–orbit interaction in a gated modulation-doped GaAs/AlGaAs quantum well (QW) structure. We measured the zero-field precession of the optically injected electron spins by a time-resolved Kerr rotation (TRKR) technique as a function of the gate voltage V_g. We reproduced the experimental results by the Monte Carlo simulation calculation with reasonable fitting parameters.

2. Experimental details

The sample studied in the present work is a modulation-doped GaAs/$Al_{0.3}Ga_{0.7}As$ single QW structure grown on a semi-insulating (0 0 1) GaAs substrate by molecular beam epitaxy. It consists of, from the top, a 5 nm thick undoped GaAs cap layer, a 20 nm thick n-$Al_{0.3}Ga_{0.7}As$ with Si donor concentration of 6×10^{18} cm^{-3}, a 30 nm thick undoped $Al_{0.3}Ga_{0.7}As$ spacer layer, a 20 nm thick GaAs QW layer and undoped $Al_{0.3}Ga_{0.7}As$ buffer layer. Fig. 1(a) shows the conduction band profile and the wave function calculated by solving the Schrödinger and the Poisson equations at $V_g = 0$ V self-consistently. The electric field in the QW is evaluated to be 3.2×10^6 V/m. The electron density n and mobility μ, measured by using a Hall-bar sample without gate electrode at 2.5 K after irradiation of light, are found to be 4.6×10^{11} cm^{-2} and 8.8×10^5 cm^2/V s, respectively. In order to

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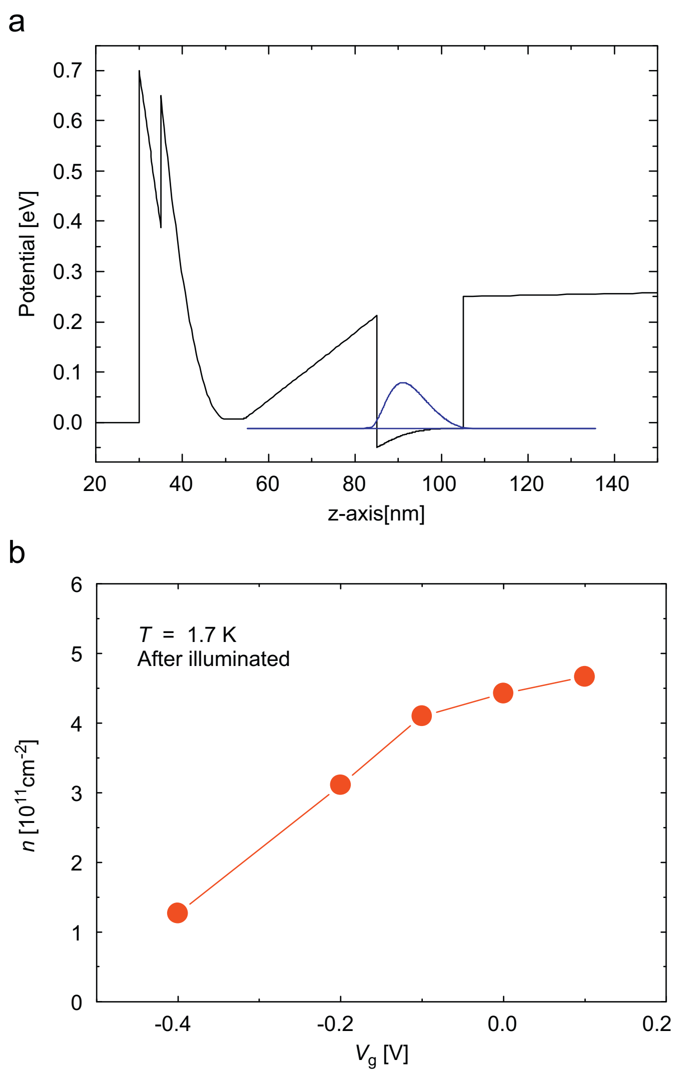

Fig. 1. (a) The conduction band profile and the wave function calculated by solving the Schrödinger and Poisson equations self-consistently at $V_g = 0$ V. (b) The gate voltage dependence of the electron density measured after illumination by light at 1.7 K.

apply V_g to control n and the effective electric field in the QW, ohmic contact to the 2DEG in the QW was formed by alloying InSn, and a semi-transparent Schottky gate was formed by deposition of a thin gold film (10 nm) on the epilayer. Fig. 1(b) shows the V_g-dependence of n after light irradiation measured at 1.7 K. When V_g is higher than -0.1 V, n tends to saturate. This suggests the possibility that the electrons are partly accumulated in a heavily doped n-$Al_{0.3}Ga_{0.7}As$ barrier region.

The electron spin dynamics was measured by using a TRKR technique. The pump and probe light pulses were generated by a mode-locked Ti:sapphire laser: the pulse width was 3 ps and the repetition rate was 76 MHz. The sample was set in a cryostat, and cooled by direct flow of He gas down to 2.5 K. The pump beam was left- or right-circular polarized by using a quarter wave length plate, while the probe beam is linear polarized. The intensities of the circular polarized pump beam and the liner polarized probe beam were 1 mW and 100 μW, respectively. Roughly estimating, about 1.5×10^9 cm^{-2} electron–hole pairs were generated in the QW by a single pump pulse. The Kerr rotation angle of the reflected probe beam was detected by using a balanced detector and lock-in technique.

3. Experimental results

Fig. 2(a) shows the photoluminescence (PL) and photoluminescence excitation (PLE) spectra measured at 2.5 K and $V_g = 0$ V. The absorption edge of the PLE spectra is about 10 meV above the PL peak due to the occupation of the conduction band by 2DEG (Burstein–Moss shift). By tuning the photon energies of the pump and probe beams indicated by arrows A, B and C in Fig. 2(a), we carried out TRKR measurements at zero magnetic field. The results are shown in Fig. 2(b). Clear oscillation is observed as a function of the time delay Δt between pump and probe beams only when the photon energy is 1.5335 eV (B), i.e., close to the Fermi energy E_F of the 2DEG in the QW. This oscillatory decaying TRKR reflects the precession of photoexcited electron spins due to the effective magnetic field induced by the spin–orbit interaction. As the photon energy is lower than E_F (C), little number of spin polarized electrons are excited and thus we do not observe the TRKR signal. As the photon energy is higher than E_F (A), on the other hand,

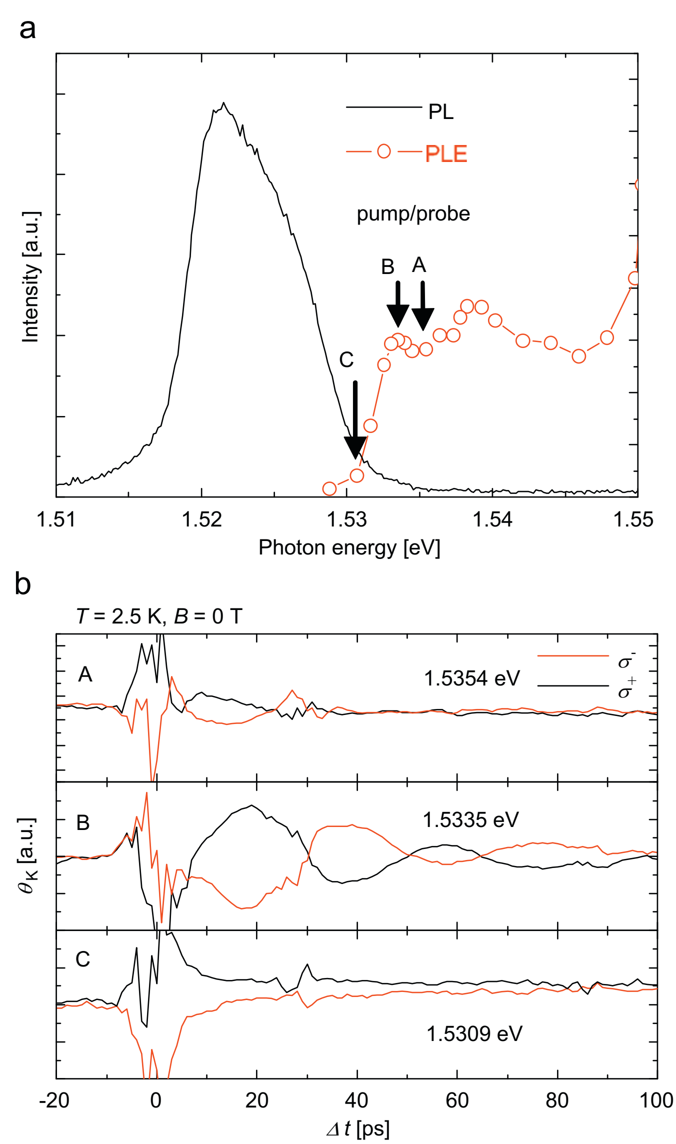

Fig. 2. (a) Photoluminescence (PL) and photoluminescence excitation (PLE) spectra measured at 2.5 K and $V_g = 0$ V. (b) Kerr rotation angles measured at different energies (indicated by arrows in (a)) are shown as a function of the time delay.