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Fast-electron magneto-optical spectrum of a two-dimensional electron gas in the presence of spin-orbit interaction and quantizing magnetic fields

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In this paper, we present a theoretical study of the optical spectrum induced by electron-electron interaction in a spin-split two-dimensional electron gas (2DEG) in the presence of high magnetic fields. The presence of the Zeeman splitting and the Rashba spin-orbit interaction (RSOI) is considered so that the profile of the magneto-optical conductivity depends strongly on spintronic coefficients. We find that in sharp contrast to the case of a spin-degenerate 2DEG, the presence of the RSOI in a 2DEG can open up new channels for magneto-optical transition via absorption scattering. The unique features of the selection rules for optical transition in a spin-split 2DEG are examined and the dependence of the magneto-optical spectrum on radiation frequency, magnetic field, and sample parameters is discussed. This study is relevant to the characterization of the Rashba spintronic systems using magneto-optical experiments and to the application of systems such as terahertz magneto-optical devices.

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I. INTRODUCTION

Magneto-optical investigation of semiconductors has been a powerful tool in the study and characterization of electronic systems.[1] In particular, fast-electron magneto-optical spectrum induced by electron-electron (e-e) interaction in a two-dimensional electron gas (2DEG) can be employed to study the effect of many-body interaction on important consequences such as the cyclotron resonance (CR)[2] and integer and fractional Landau-level (LL) occupancy.[3] It is known that when a 2DEG is subjected to a quantizing magnetic field and a polarized radiation field, the CR effect can be observed when the vector potential of the magnetic field couples to that of the radiation field, where a peak of optical absorption can be observed at $\Omega=\omega_c$, with Ω the radiation frequency and ω_c the cyclotron frequency. For a relatively high density 2DEG sample in which the correlation effect is weak, the CR effect depends rather weakly on the Zeeman spin splitting.[2] It has been found both experimentally[2] and theoretically[4] that in such a situation, optical transitions occur within the same spin state (i.e., $s=s'$, with s the spin index) and within the neighboring LL (i.e., $\Delta N=\pm 1$, with N the LL index). Hence, in the absence of spin-orbit interaction, the magneto-optical absorption in a 2DEG is mainly achieved through electronic transition within the same spin state and within the neighboring LLs. This is the main reason why only one absorption peak can often be observed for high-density samples in the magneto-optical experiments.

In recent years, the investigation of 2DEG systems in the presence of spin-orbit interaction (SOI) has become an important and fast-growing field of research in semiconductor physics and electronics, owing to potential applications in quantum communication and information. It is known that a spin-split 2DEG can be realized on the basis of narrow-gap semiconductor heterojunctions or quantum wells, such as those realized from InAlAs/InGaAs heterostructures.[5] In such systems, a strong Rashba SOI (RSOI) can be observed on top of the Zeeman spin splitting, due to the inversion asymmetry of the microscopic confining potential achieved by the presence of the heterojunction. The obtained experimental and theoretical results have indicated that in InAlAs/InGaAs-based spin electronic (or spintronic) systems, the spontaneous spin splitting (or spin splitting in the absence of a magnetic field) is mainly induced by the Rashba effect which is with an SU(2) symmetry and can be enhanced significantly by applying a gate voltage.[6] In InAlAs/InGaAs-based heterostructures, the contribution to the spin splitting of electrons from the Dresselhaus term [with an SU(1,1) symmetry] is relatively weak because it comes mainly from the bulk-inversion asymmetry of the material.[7] Furthermore, recent theoretical results[8] have suggested that in InAlAs/InGaAs heterojunctions, the higher-order Rashba terms proposed by Cartoixá *et al.*[9] along with the effects induced by the conduction-band nonparabolicity can be neglected for samples with the electron densities less than 10^{12} cm^{-2} (or $k_\parallel < 0.2$ nm^{-1}). This condition is normally satisfied in popularly used sample devices.[5,6] Therefore, InAlAs/InGaAs-based heterostructures are good device systems for examining the spin effects induced mainly by the RSOI.

At present, most of the published work in the area of spintronics has been focused on electronic and transport properties of such systems. This is mainly motivated by the fact that the magnetotransport measurement via Shubnikov–de Haas (SdH) oscillations is one of the most powerful and popularly used experimental techniques to identify the Rashba spin splitting[5,6] in semiconductor heterostructures. Recently, we have proposed to use optical measurements for the determination of the spintronic coefficients in InAlAs/InGaAs-based spintronic devices.[10] This proposal is made on the basis of the unique features for optical properties induced by e-e interaction in spin-split 2DEG in the absence of a magnetic field. For a more detailed investigation and further application of the spintronic systems as electronic and optical devices, it is of great value and importance to study the magneto-optical properties of a spin-split 2DEG and this is the prime motivation of the present theoretical work. It is known that when the RSOI is present in a 2DEG subjected to a quantizing magnetic field, the LL shifting and mixing can occur. As a result, more channels can open up for electronic transition accompanied by the absorption of photons. Thus, magneto-optical absorption in a spin-split 2DEG may differ significantly from that in a spin-degenerate one. As a matter of fact, the experimental study on far-infrared magneto-optical absorption in InAlAs/InGaAs heterojunctions has demonstrated that in the presence of the RSOI, the peak of the CR is split into two dips in the modulated absorption signals under pulsed electric field excitation or photoexcitation.[11] This feature can be employed to determine the Rashba spin splitting via magneto-optical measurements.[11] Motivated by these experimental findings, in this paper, we examine the basic selection rules for magneto-optical transition induced by e-e interaction in a 2DEG in the presence of the Zeeman splitting and the RSOI. Here, we intend to study how the RSOI affects the magneto-optical spectrum and to relate theoretical results to magneto-optical identification and characterization of the Rashba spintronic systems. The theoretical approach of this study is presented in Sec. II. The numerical results are analyzed and discussed in Sec. III and the main conclusions obtained from this study are summarized in Sec. IV.

II. THEORETICAL APPROACH

In this study, we consider an InAlAs/InGaAs-based 2DEG formed in the xy plane (i.e., the growth direction of the 2DEG is taken along the z axis) and a static magnetic field with a strength B is applied along the z axis. Including the Zeeman spin splitting and the lowest order of the SOI induced by the Rashba effect, which can be obtained from, e.g., a $\mathbf{k}\cdot\mathbf{p}$ band-structure calculation, the single-electron Hamiltonian can be written, in the absence of the radiation field and e-e interaction, as

$$H=\frac{\Pi^2}{2m^*}-\frac{E_Z}{2}\sigma_z+\frac{\alpha}{\hbar}(\sigma_x\Pi_y-\sigma_y\Pi_x)+U(z). \tag{1}$$

Here, $\Pi=(\Pi_x,\Pi_y,\Pi_z)=\mathbf{P}-e\mathbf{A}$ with $\mathbf{P}=(p_x,p_y,p_z)$ the momentum operator and $\mathbf{A}=(0,Bx,0)$ the vector potential induced by the magnetic field in Landau gauge, m^* is the effective mass for an electron, α is the Rashba parameter which measures the strength of the RSOI, $E_Z=g\mu_BB$ is the Zeeman spin energy with g the bare g factor for electrons and μ_B the Bohr magneton, $U(z)$ is the confining potential energy along the growth direction, and $\sigma_i(i=x,y,z)$ is the Pauli matrix. It should be noted that for an InAlAs/InGaAs heterojunction, the term induced by the RSOI in Eq. (1) is exclusive when the growth direction of the 2DEG is taken along the crystallographic axis [001]. The corresponding Schrödinger equation can be solved analytically[12] and the electron wave function and energy spectrum are obtained, respectively, as

$$\Psi_\lambda(\mathbf{R})=e^{ik_yy}\psi_n(z)[\phi_N(X)\cos\theta_N^s,-\phi_{N-1}(X)\sin\theta_N^s], \tag{2}$$

in the form of a row matrix, and

$$E_\lambda=E_{N,s}+\varepsilon_n=N\hbar\omega_c+s\hbar\Omega_N/2+\varepsilon_n, \tag{3}$$

where $\mathbf{R}=(x,y,z)$, $\lambda=(N,k_y,n,s)$ refers to quantum numbers, N is the LL index, k_y is a good quantum number along the y direction, $s=\pm1$ refers to the up or down spin state, $X=(x-x_0)/l_B$ with $l_B=(\hbar/eB)^{1/2}$ the radius of the ground cyclotron orbit and $x_0=k_yl_B^2$, $\hbar\Omega_N=\sqrt{(\hbar\omega_c-E_Z)^2+8N(\alpha/l_B)^2}$, $\theta_N^s=\theta_N+(1-s)\pi/4$ with $\tan\theta_N=\sqrt{8N}(\alpha/l_B)/(\hbar\omega_c-E_Z+\hbar\Omega_N)$, $\omega_c=eB/m^*$ is the cyclotron frequency, and $\phi_N(x)=(\sqrt{\pi}l_B2^NN!)^{-1/2}e^{-x^2/2}H_N(x)$ with $H_N(x)$ the Hermite polynomials. Moreover, the wave function $\psi_n(z)$ and electronic subband energy ε_n are determined by a Schrödinger equation along the growth direction, which is independent of spin and magnetic field applied in this configuration. For the case of $N=0$, only $s=+1$ state exists along with $\sin\theta_0^{+1}=0$ and $\cos\theta_0^{+1}=1$. Thus, the lowest energy level of the system is $E_{0,+1}=\hbar\omega_c/2-E_Z/2$ with a wave function $\Psi_{0,k_y,n,+1}(\mathbf{R})=e^{ik_yy}\psi_n(z)[\phi_0(X),0]$. These results indicate that in the presence of the RSOI, LL shifting and mixing can occur (see Fig. 2). We note that the wave function shown as Eq. (2) looks much simpler than those obtained previously.[12]

Applying the electron wave function and energy spectrum to a standard technique to derive the electron density-density (d-d) correlation induced by e-e interaction in a 2DEG in the presence of high magnetic fields,[13] the electron d-d correlation function for a spin-split 2DEG can be obtained as

$$\Pi_{n'n}(\Omega,q)=\frac{1}{2\pi l_B^2}\sum_{N',N,s',s}\frac{C_{N'N}^{s's}(u)[f(E_{\lambda'})-f(E_\lambda)]}{\hbar\Omega+E_{\lambda'}-E_\lambda+i\Gamma}, \tag{4}$$

where $\mathbf{q}=(q_x,q_y)$ is the change of electron wave vector during an e-e scattering event, $u=q^2l_B^2/2$, $f(x)$ is the Fermi-Dirac function, Ω is the excitation frequency, Γ is the broadening of the scattering state, $C_{N'N}^{s's}(u)=[M!/(M+J)!]e^{-u}u^JI_{N',N}^{s',s}(u)$ is a form factor for e-e interaction with $M=\min(N',N)$ and $J=|N'-N|$, and $I_{N',N}^{s',s}(u)=[L_M^J(u)\cos\theta_{N'}^{s'}\cos\theta_N^s+(1-\delta_{M,0})\sqrt{(M+J)/M}L_{M-1}^J(u)\sin\theta_{N'}^{s'}\sin\theta_N^s]^2$ with $L_N^J(x)$ the Laguerre polynomials. Applying the electron d-d correlation function along with the bare e-e interaction in such a system to the diagrammatic techniques to derive effective e-e interaction under the random-phase approximation (RPA), the dynamical dielectric function matrix element is obtained as

$$\epsilon_{m'mn'n}(\Omega,q)=\delta_{m',n'}\delta_{m,n}-V_qF_{m'mn'n}(q)\Pi_{n'n}(\Omega,q),$$

where $V_q=2\pi e^2/\kappa q$, κ is the dielectric constant of the material, and $F_{m'mn'n}(q)=\int dz_1\int dz_2\psi_{m'}^*(z_1)\psi_m(z_1)\psi_{n'}^*(z_2)\psi_n(z_2)\times e^{-q|z_1-z_2|}$ is the form factor for e-e interaction in a 2D system. In a narrow-gap semiconductor heterostructure such as that realized from an InAlAs/InGaAs heterojunction, because of small electron effective mass ($m^*/m_e\sim0.042$), large dielectric constant ($\kappa \sim 13$), and relatively high electron density ($n_e \sim 2 \times 10^{11}$ cm^{-2}), the interaction parameter $r_s = e^2 m^* / (4\pi\kappa\hbar^2\sqrt{\pi n_e}) \sim 0.06 \ll 1$ can often be satisfied. Hence, for an InAlAs/InGaAs-based spintronic system, the usual RPA approximation can be employed to evaluate the dielectric response induced by e-e interaction.

It is known that the optical spectrum is one of the most important quantities to determine almost all optical properties of an electronic system. For an electron gas under the action of a linearly polarized radiation field, the optical absorption coefficient can be calculated through[14]

$$\alpha_{op} = 2P(\Omega)/(\sqrt{\kappa}\epsilon_0 c F_0^2) = \sigma_{xx}(\Omega)/(\sqrt{\kappa}\epsilon_0 c), \tag{5}$$

where ϵ_0 is the dielectric constant of the free space, c is the speed of light in vacuum, F_0 and Ω are, respectively, the electric field strength and frequency of the light radiation, and $P(\Omega) = \sigma_{xx}(\Omega) F_0^2/2$ is the electronic energy transfer rate with $\sigma_{xx}(\Omega)$ the longitudinal optical conductivity. Thus, optical conductivity is a central quantity to determine the strength of the optical absorption. With the dynamical dielectric function matrix induced by e-e interaction, we can calculate the optical conductivity attributed from the dielectric response. For the case where the electron current-current correlation is achieved through electron interactions with a weak external light field polarized along the 2D plane (taken along the x direction) of a spin-split 2DEG, the optical conductivity can be derived from the Kubo formula,[15] which reads for the longitudinal magneto-optical conductivity as

$$\begin{aligned}\sigma_{xx}(\Omega) &= \lim_{q\to 0} \frac{\kappa\Omega}{2\pi q} \sum_{m',m,n',n} \operatorname{Im} \epsilon_{m'mn'n}(\Omega,q) \\ &= -e^2\Omega \lim_{q\to 0}(1/q^2) \sum_{n',n} \operatorname{Im} \Pi_{n'n}(\Omega,q),\end{aligned} \tag{6}$$

where $q \to 0$ reflects a fact that the electron-photon scattering does not change the wave vector of an electron and $\lim_{q\to 0} F_{m'mn'n}(q) \to \delta_{m',m}\delta_{n',n}$. It should be noted that the fast-electron optical conductivity is induced mainly by dielectric response due to e-e interaction accompanied by the emission or absorption of photons via elementary electronic excitation. Normally, such effect can only be observed at relatively low temperatures.[2] This mechanism differs from another kind of optical conductivity induced by direct electron-photon interaction, which can be measured at relatively high temperatures. Although the electronic scattering mechanisms in the two optical conductivities are different, they occur within the same optical transition channels.[16] Therefore, the basic features of the absorption spectra caused by these two mechanisms do not differ significantly.

In the present study, we consider a strongly confined 2DEG so that only the lowest electronic subband along the growth direction is occupied by electrons (i.e., we take $n = n' = 0$) and we measure the energy from $\varepsilon_0 = 0$. From Eq. (6) and from the form factor $C_{N'N}^{s's}(q^2 l_B^2/2)$ shown in Eq. (4), we can find out the selection rules for e-e scattering accompanied by the absorption of a photon. Firstly, the transition within the lowest LL $N=0$ does not contribute to optical conductivity. Secondly, for the case of intra-LL transition, intra-SO transition (i.e., $s' = s$) does not give rise to optical conductivity and for inter-SO transition (i.e., $s' = -s$), we have $\lim_{x\to 0} C_{NN}^{-ss}(x) \simeq x^2 \sin^2\theta_N^{-s} \sin^2\theta_N^{s} \ll 1$. Therefore, the contribution to optical conductivity from intra-LL transition is rather weak. Thirdly, at a long-wavelength limit (i.e., $q \to 0$), the major contribution to optical conductivity comes from the processes with $J=1$ (i.e., transition between neighboring LLs). In such a case, $\lim_{x\to 0} C_{MM+1}^{ss'}(x) \simeq x I_{M,M+1}^{s,s'}(0)/(M+1)$. Thus, the magneto-optical conductivity can be calculated through

$$\sigma_{xx}(\Omega) \simeq \frac{\sigma_0}{4\pi} \sum_{s',s,N=1} [G_{N+1}^{s',s}(\Omega) + G_{N-1}^{s',s}(\Omega)], \tag{7}$$

where $\sigma_0 = e^2/\hbar$ and

$$G_{N\pm 1}^{s',s}(\Omega) = [I_{N\pm 1}^{s',s}]^2 \frac{\Gamma\hbar\Omega[f(E_{N,s}) - f(E_{N\pm 1,s'})]}{(\hbar\Omega + E_{N,s} - E_{N\pm 1,s'})^2 + \Gamma^2}, \tag{8}$$

with

$$\begin{aligned}I_{N\pm 1}^{s',s} = {}& [\sqrt{N + (1\pm 1)/2} + \sqrt{N - (1\mp 1)/2}]\cos[\theta_{N\pm 1} - \theta_N \\ & + (s - s')\pi/4] - [\sqrt{N + (1\pm 1)/2} - \sqrt{N - (1\mp 1)/2}] \\ & \times \sin[\theta_{N\pm 1} + \theta_N - (s + s')\pi/4].\end{aligned} \tag{9}$$

For the case of $\alpha = 0$, $I_{N\pm 1}^{s',s} = \delta_{s',s}[(1-s)\sqrt{N+(1\pm 1)/2} + (1+s)\sqrt{N-(1\mp 1)/2}]$. Thus, when the RSOI is absent, only the transition events within the same spin states are allowed. This is a well-known result obtained previously.[2,4] From these theoretical results, we see that in the presence of the RSOI, due to the coupling of the magnetic field to the spin orbits, inter-SO scattering is allowed for electronic and magneto-optical transitions.

III. NUMERICAL RESULTS AND DISCUSSIONS

In this paper, we present the numerical results for magneto-optical conductivity in an InGaAs-based 2DEG at a low-temperature limit $T \to 0$. The electron effective mass for InGaAs is $m^* = 0.042 m_e$, with m_e the electron rest mass, and we take the bare g factor to be $g=2$. We take the typical sample parameters for an InAlAs/InGaAs heterojunction in the calculation. It has been found experimentally[17] that in such a spintronic system, when the total electron density n_e is about 5×10^{11} cm^{-2}, the Rashba parameter α is about $(2-3) \times 10^{-11}$ eV m. In the calculation, the filling of electrons in the LLs and spin states is determined by the condition of electron number conservation, which reads for the filling factor $\nu = 2\pi l_B^2 n_e = \Sigma_{N,s} f(E_{N,s})$. Furthermore, we use a simple and well-known result to calculate the LL broadening $\Gamma = (2e\hbar^2\omega_c/\pi\mu_0 m^*)^{1/2}$, with μ_0 the electron mobility at $B=0$ and $T \to 0$, which is obtained from short-range scattering approximation.[18] In the calculation, we take the typical experimental value[17] $\mu_0 \sim 20$ m^2/V s to calculate the broadening Γ.

In Fig. 1, we show optical conductivity as a function of radiation frequency at a fixed magnetic field for different Rashba parameters (upper and lower panels) and for different

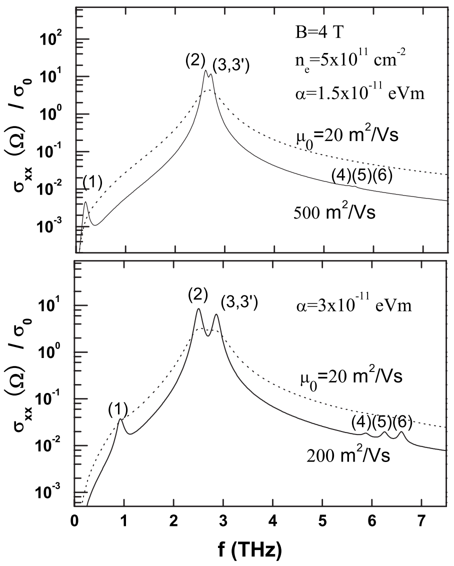

FIG. 1. Optical conductivity as a function of radiation frequency $f=\Omega/2\pi$ at the fixed total electron density n_e and magnetic field B for different sample mobilities μ_0 as indicated. The upper and lower panels show results obtained for different Rashba parameters α. These results correspond to a filling factor $\nu=5.17$ and the index at the peak position, (i), corresponds to a transition event shown in Fig. 2 for the upper and lower panels, respectively. Note that (3) and (3′) have roughly the same transition energies and $\sigma_0=e^2/\hbar$.

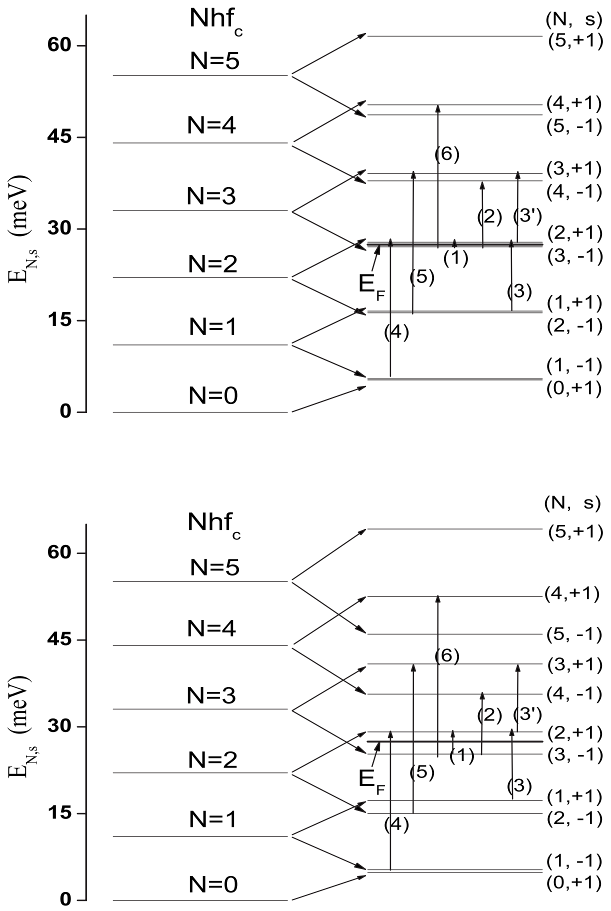

FIG. 2. Schematic illustration of the spin-split LL structure and optical transition channels via absorption scattering. The results are presented for electron density $n_e=5\times10^{11}$ cm^{-2}, magnetic field $B=4$ T (i.e., the filling factor $\nu=5.17$), and Rashba parameter $\alpha=1.5\times10^{-11}$ eV m (upper panel) and $\alpha=3\times10^{-11}$ eV m (lower panel). Here, E_F is the Fermi energy, $hf_c=\hbar\omega_c$, and the transition channel, (i), corresponds to a peak shown in Fig. 1. Note that (3) and (3′) have roughly the same transition energies.

sample mobilities which determine the widths of the LLs. Accordingly, the spin-split LL structure and corresponding optical transition channels are shown in Fig. 2. For a spin-split 2DEG, when the energy separations in the main transition channels are large enough, a two-peak structure can be observed in the optical spectrum. The two-peak profile is more pronounced for less broadened LL structure (i.e., for high-mobility samples) and the amplitudes of the two absorption peaks corresponding to the main resonances are about 2–3 orders of magnitude larger than those induced by other transition channels. In Fig. 2, we see that in the presence of the RSOI, due to the energy level shifting and mixing, new channels open up for optical transition. When the filling factor is at $\nu=5.17$, there are seven allowed transition channels according to the selection rules. In such a case, the two main absorption peaks shown in Fig. 1 are induced by transition events with the same spin index. Namely, they come from the processes from $(3,-1)$ to $(4,-1)$ [i.e., (2) in Fig. 2], from $(1,+1)$ to $(2,+1)$ [i.e., (3) in Fig. 2], and from $(2,+1)$ to $(3,+1)$ [i.e., $(3')$ in Fig. 2]. Because the energy difference between processes (3) and $(3')$ is much smaller than the photon energy and the LL broadening, two main absorption peaks can be observed. In fact, the analytical result given by Eq. (9) has implied that the largest contribution to optical conductivity comes from transition events with the same spin orientation. In the presence of the RSOI, although the transitions between different spin states [i.e., processes (1) and (4)–(6) in Fig. 2] are allowed, the resonances induced by inter-SO transition contribute very weakly to the overall optical conductivity (see Fig. 1). It is well known that in a 2DEG in the absence of the RSOI, a spin-flip transition between the Zeeman split states cannot be achieved simply through e-e interaction[4] which is spin invariant [i.e., $I_N^{s'\neq s}=0$ in Eq. (8) when $\alpha=0$]. As a result, the fast-electron magneto-optical spectrum for a pure 2DEG is characterized as the single absorption peak corresponding to the cyclotron resonance due to the single electronic excitation between two neighboring LLs. Consequently, for such a 2D translational invariant system, the optical absorption depends very little on the Zeeman spin splitting and the CR is independent of the SOI. In contrast, in the presence of the RSOI, due to the coupling of the magnetic field to the spin orbit, the spin-flip transition induced by e-e interaction through the Coulomb potential becomes possible, namely, $I_N^{s'\neq s}\neq0$ when $\alpha\neq0$. Thus, the optical absorption via electronic excitation induced by e-e interaction can be achieved also via spin-flip transition. However, because the overlaps of the eigenfunctions for different spin states are relatively small in comparison to those with the same spin orientation, the contribution from spin-flip transition to the overall optical absorption is small, as shown in Fig. 1. To the best of our knowledge, although

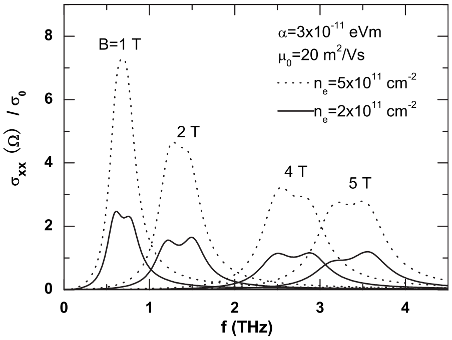

FIG. 3. Magneto-optical spectrum at a fixed Rashba parameter α for different magnetic fields B and total electron densities n_e.

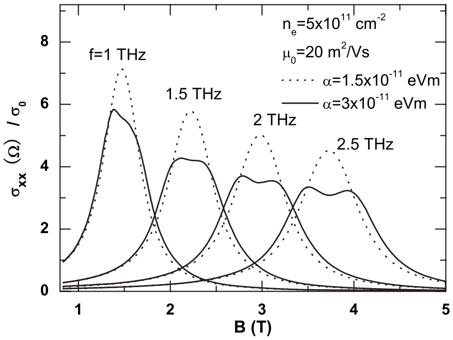

FIG. 4. Magneto-optical conductivity as a function of magnetic field B at a fixed total electron density n_e for different radiation frequencies $f=\Omega/2\pi$ and different Rashba parameters α.

the optical spin-flip transition in a Rashba spintronic system in the weak magnetic fields has been noticed in the recent theoretical work,[19] magneto-optical spin-flip transition in the presence of Landau quantization in a spin-split 2DEG has not yet been well documented in the literature.

From Eq. (8), we see that the fast-electron magneto-optical conductivity is determined not only by the overlap of the electron wave functions due to e-e interaction (i.e., the factor $I_N^{s',s}$) but also by the occupancy of electrons to different energy states [i.e., the second term on the right-hand side of Eq. (8)]. The filling of electrons to different LLs can be seen in Fig. 2 for a certain filling factor $\nu=5.17$. Thus, the selection rules for magneto-optical transition in a spin-split 2DEG depend not only on the features of e-e interaction but also on the fact that at low temperatures, the transition occurs only from occupied states to the empty states through absorption scattering. As can be seen in Fig. 2 and Eq. (8), although the transition channels (1), (2), (3), (3′), (4), (5), and (6) are possible for optical absorption scattering, the features of e-e interaction in such a system lead to that only the transition channels (2), (3), and (3′) contribute significantly to the overall optical conductivity. An important conclusion we can draw here is that in the presence of the RSOI, magneto-optical absorption is mainly induced by transitions between the neighboring LLs within the same spin states. This is similar to the case of a 2DEG in the absence of the RSOI. This finding also suggests that in the presence of a high magnetic field, the spin flip induced by electron-photon coupling via e-e interaction is very weak. The analytical result shown in Eq. (9) indicates that the effect of e-e interaction via spin-flip scattering is relatively weak due to a less overlap of electron wave functions with different spin orientations. Moreover, from the results shown in Fig. 1, we see that the fine structure of the magneto-optical spectrum can be observed for a sample with a high electronic mobility and a large Rashba parameter.

The dependences of the magneto-optical conductivity on magnetic field and radiation frequency are shown, respectively, in Figs. 3 and 4. We find that the two main absorption peaks can more possibly be observed at relatively high magnetic fields. At a low magnetic field (e.g., $B=1$ T), one absorption peak can be seen. The reason for this phenomenon can be understood as follows. For example, when $B=1$ T and $n_e=5\times 10^{11}$ cm^{-2}, the filling factor is $\nu=20.68$. In such a case, due to LL shifting and mixing, (i) the highest occupied LL is $N=8$, (ii) the lowest unoccupied LL is $N=13$, (iii) the LLs in between (i.e., $8<N<13$) are partially filled, (iv) for $9\leqslant N<12$, the $s=-1$ states are occupied with $E_{N,-1}<E_{12,-1}$, whereas the $s=+1$ states are empty with $E_{N,+1}>E_{12,-1}$, and (v) the $(12,-1)$ state is partially occupied with a filling factor about 0.68. As a result, at $B=1$ T, there are three main transition processes with the same spin orientation, $(8,+1)\rightarrow(9,+1)$, $(11,-1)\rightarrow(12,-1)$, and $(12,-1)\rightarrow(13,-1)$, and eight weak transition precesses within different spin states, $(12,-1)\rightarrow(11,+1)$, $(12,-1)\rightarrow(13,+1)$, $(11,-1)\rightarrow(10,+1)$, $(11,-1)\rightarrow(12,+1)$, $(10,-1)\rightarrow(9,+1)$, $(10,-1)\rightarrow(11,+1)$, $(9,-1)\rightarrow(10,+1)$, and $(8,-1)\rightarrow(9,+1)$. From the electronic energy spectrum given by Eq. (3), we know that even at $\alpha=3\times 10^{-11}$ eV m, the difference of the transition energies for the major channels [i.e., within the same spin states: $(8,+1)$ to $(9,+1)$, $(11,-1)$ to $(12,-1)$, and $(12,-1)$ to $(13,-1)$] is not significant in comparison with the photon energy and LL broadening. Thus, a seemingly one peak can be observed at low magnetic fields. With increasing magnetic field, the energy difference between different spin states increases [see Eq. (3)] and the transitions occur within the lower index LLs. In such a case, the difference of transition energies for different main resonant processes can be enhanced and a two-peak profile can therefore be observed at high B fields. It should be noted that at a very high magnetic field, because the Zeeman splitting depends more strongly on magnetic field than the Rashba splitting does [see Eq. (3)] and only the lower index LLs are occupied, the splitting of the LLs is mainly induced by Zeeman effect. In such a case, the transition energy for the main resonant process is $\Delta E=\hbar\omega_c+s\hbar(\Omega_{N+1}-\Omega_N)/2\propto B$.

The theoretical results shown above indicate that for a high-mobility 2DEG sample at high magnetic fields, two main absorption peaks can be observed and they correspond to transition energies $\hbar\Omega=\hbar\omega_c+s\hbar(\Omega_{N+1}-\Omega_N)/2$ with different LL indices and spin indices $s=\pm 1$. Because the fast-electron optical spectrum is induced in the same optical transition channels as those for direct electron-photon scattering, one would expect that the two absorption peaks can also be observed in the absorption spectrum induced by direct interactions between electrons and radiation fields. This feature can be used for optical identification of the Rashba spintronic devices. From the position of two main absorption peaks, one can determine the occupied (i.e., those $\leqslant N$) and unoccupied (i.e., those $\geqslant N+1$) LLs and the Rashba parameter. With these results, one can determine the filling factor and then the total electron density. At present, the spintronic coefficients of InGaAs-based 2DEG systems are commonly obtained through magnetotransport measurement via the SdH oscillations. The magnetotransport measurement requires Ohmic contacts to be made on a sample. The SdH oscillations are the mixtures of the Zeeman splitting and the Rashba splitting, which are hard to be separated from the measured data. Furthermore, the SdH oscillations can only be observed for relatively low density samples otherwise much higher magnetic fields are needed. If the spintronic properties can be determined from the magneto-optical experiments, these drawbacks can be overcome and the spintronic coefficients can be obtained more easily and more accurately. The results shown in this paper demonstrate that it is possible to characterize the Rashba spin slitting via magneto-optical experiments such as the fast-electron magneto-optical spectrum.

It should be noted that the two absorption dips observed experimentally in InAlAs/InGaAs heterojunctions by Fujii *et al.*[11] are measured in the presence of extra electrical or optical excitation. As pointed out by the authors, although the two dips in the magneto-optical absorption relate directly to the LL structure in a 2DEG in the presence of the RSIO, *this characteristic profile of the modulated absorption signals may be caused by the heating of the 2DEG*. Hence, whether the theoretical results obtained from this work (e.g., two absorption peaks) can be related to these experimental findings (e.g., two absorption dips) can only be answered with further experimental and theoretical work. In particular, the presence of the extra electrical or optical excitation has not been included with the present calculation and their effects on magneto-optical transition in a spin-split 2DEG need to be examined theoretically. However, these theoretical and experimental results have indicated clearly that in the presence of the RSOI, the magneto-optical spectrum can have some unique features in sharp contrast to those observed for spin-degenerate 2DEG systems.

The results obtained from this work show that when the applied magnetic fields are of the order of tesla, the magneto-optical absorption can occur at terahertz (10^{12} Hz or 1 THz) bandwidth for InGaAs-based 2DEG systems. On the basis that the magneto-optical spectrum of a spin-split 2DEG depends strongly on spintronic properties of a sample, the Rashba spintronic structures can be employed as photodetectors working at terahertz bandwidth. It has been realized experimentally that in InGaAs-based heterojunctions, the spintronic properties can been altered artificially via techniques such as varying the sample growth parameters[20] or applying the gate voltage.[17] Hence, the InGaAs-based spintronic systems can be used as tunable terahertz detectors operating at low temperatures and tesla magnetic fields.

IV. CONCLUSIONS

In this work, we have developed a simple and transparent theoretical approach to study magneto-optical spectrum caused by fast-electron process in a spin-split 2DEG system. We have examined the dependence of the magneto-optical conductivity on magnetic field, radiation frequency, and broadening of the LLs. The main conclusions obtained from this study can be summarized as follows.

In the presence of the Zeeman splitting and Rashba effect, the LL shifting and mixing can occur in a 2DEG in the presence of high magnetic fields. This opens up new channels for electron-electron interaction accompanied by the absorption of the photons. As a result, the magneto-optical spectrum induced by e-e interaction in a spin-split 2DEG has some unique features.

Similar to a spin-degenerate 2DEG, the magneto-optical conductivity in a spin-split 2DEG is mainly induced by inter-LL transition within the neighboring LLs (i.e., $\Delta N = \pm 1$). For a spin-split 2DEG, although inter-SO transition is allowed, this mechanism contributes very little to the overall optical conductivity. Therefore, the optical absorption is mainly achieved through transitions within the same spin states (i.e., $s' = s$). This effect is similar to the case where the RSOI is absent in a 2DEG with a high electron density.

For a spin-split 2DEG, two main absorption peaks can be observed for high-mobility samples at relatively high magnetic fields. This effect can be employed for magneto-optical characterization of the Rashba spintronic systems. From the positions of these two absorption peaks, important spintronic coefficients, such as the Rashba parameter and total electron density, can be determined easily and accurately. Furthermore, the obtained results have indicated that in the presence of quantizing magnetic fields, InGaAs-based 2DEG systems can be used as photodetectors working at terahertz bandwidth. Finally, we hope the theoretical predictions discussed in this paper will be verified experimentally.

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