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Elementary electronic excitation from a two-dimensional hole gas in the presence of spin–orbit interaction

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Abstract
We present a theoretical study of the elementary electronic excitation associated with plasmon modes in a two-dimensional hole gas (2DHG) in the presence of spin–orbit (SO) interaction induced by the Rashba effect. The calculation is carried out using a standard random-phase-approximation approach. It is found that, in such a spintronic system, plasmon excitation can be achieved via intra- and inter-SO electronic transitions around the Fermi level. As a result, the intra- and inter-SO plasmon modes can be observed. More importantly, the plasmon modes induced by inter-SO transition are optic-like and these modes can be directly applied to identify the Rashba spin splitting in 2DHG systems through optical measurements. The interesting features of the plasmon excitation in a spin-split 2DHG are analysed and discussed in detail. Moreover, the results obtained for a 2DHG are compared with those obtained for a spin-splitting 2DEG reported very recently.

1. Introduction

Progress made in realizing spin-polarized electronic systems has led to recent proposals dealing with novel electronic devices, such as spin transistors [1], spin waveguides [2], spin filters [3], quantum computers [4], etc. In recent years, spin electronics (or spintronics) has become an important and fast-growing research field in condensed matter physics and semiconductor electronics. At present, spintronic systems and devices have been realized on the basis of diluted magnetic semiconductors and narrow-gap semiconductor nanostructures. In the former case the spin degeneracy of the carriers are lifted by the presence of an external magnetic field and in the latter case the spin–orbit (SO) interaction (SOI) is introduced due to the innate features of the material systems. Currently, one of the most important aspects in the field of spintronics is to investigate electronic systems with finite spin splitting in the absence of an external magnetic field. It has been realized that, in narrow-gap semiconductor quantum well structures, the higher-than-usual zero-magnetic-field spin splitting (or spontaneous spin splitting) can be achieved by the inversion asymmetry of the microscopic confining potential due to the presence of the heterojunction [5]. This kind of inversion asymmetry corresponds to an inhomogeneous surface electric field and, hence, this kind of spin splitting is electrically equivalent to the Rashba spin splitting or Rashba effect [6]. The state-of-the-art material engineering and micro- and nano-fabrication techniques have made it possible to achieve experimentally observable Rashba effects in, for example, InAs- and InGaAs-based two-dimensional electron gas (2DEG) systems [7] and GaAs-based two-dimensional hole gas (2DHG) systems [8]. In particular, it has been demonstrated very recently that a spin-split 2DHG with a relatively strong Rashba effect can be realized in a GaAs/AlGaAs heterojunction grown on a nominally undoped (311)A GaAs substrate with a weak p-type background doping [8]. More interestingly, in such a system a back gate can be applied to control the strength of the SOI in the device [8].

In recent years, the effect of SOI on electronic and transport properties of 2DEGs and 2DHGs has been intensively studied both experimentally and theoretically. At present, one of the most powerful and most popularly used experimental methods to identify Rashba spin splitting in 2DEG and 2DHG systems is magneto-transport measurements carried out at quantizing magnetic fields and low temperatures at which the Shubnikov–de Hass (SdH) oscillations are observable [7–11]. From the periodicity and profile of the SdH oscillations, the carrier density in different spin branches, together with the Rashba parameter, can be determined experimentally. However, in GaAs-based 2DHG systems, because the holes are much heavier than electrons, the magneto-transport measurements can only be applied to study the Rashba spin splitting in the low-density samples [8]; otherwise very high magnetic fields are required in order to observe the SdH oscillations. The experimental data showed that a stronger Rashba effect of the 2DHG can be achieved in a sample with a larger hole density [8]. Thus, optical measurements (e.g. optical absorption and transmission, Raman spectrum, ultrafast pump-and-probe experiments, etc) become one of the realistic options in determining the spintronic properties in the high-density 2DHGs. Furthermore, at present, most of the published work in the field of spintronics is focused on electronic and transport properties of 2DEGs and 2DHGs in the presence of SOI. In order to apply the optical experiments to identify the Rashba effect, to explore further applications of the spintronic systems as optical devices and to achieve a deeper understanding of these novel material systems, it is essential and necessary to examine the effects of SOI on elementary electronic excitation from a typical 2DHG and it becomes the prime motivation of the present theoretical study.

It is well known that, in an electron or a hole gas system, the electronic transitions through spin- and charge-density oscillations can result in a collective excitation associated with plasmon oscillation modes. The spintronic materials can therefore provide us with an ideal device system in examining how electronic many-body effects are affected by the SOI. In this paper, we consider an interacting 2DHG where SOI is induced by the Rashba effect. One of our aims is to obtain the modes of the elementary electronic excitation such as plasmons and to examine the unique features of these excitation modes. Very recently, the plasmon modes induced by intra- and inter-SO electronic transitions in InGaAs-based 2DEG systems in the presence of the Rashba effect have been studied theoretically [12]. It was found that the inter-SO transition can result in optic-like plasmon oscillations in a spin-split 2DEG and these plasmon modes can be used to identify the Rashba spin splitting. On the basis that there is a significant difference in the Rashba spin splitting in InGaAs-based 2DEGs and in GaAs-based 2DHGs, it is of value to study the consequence of different types of SOI in different spintronic systems such as spin-split 2DHGs. Furthermore, we would like to take this opportunity to present more detailed theoretical approaches used to study many-body effects in a 2DEG or 2DHG system in the presence of SOI. The paper is organized as follows. In section 2, we study spin-dependent carrier distribution along with several single-particle aspects for a spin split 2DHG in a GaAs-based structure. In section 3, the effects of the SOI on the dielectric function matrix and plasmon excitation are investigated analytically using a simple and standard many-body theory. The corresponding numerical results are presented and discussed in section 4 and the concluding remarks are summarized in section 5.

2. Single-particle aspects

It has been shown that, for the case of a spin-spilt hole gas system, such as a p-doped AlGaAs/GaAs heterostructure, the effective SOI due to the Rashba effect can be obtained from, for example, a $\mathbf{k}\cdot\mathbf{p}$ band-structure calculation [8]. In GaAs-based quantum well structures with p-type doping, the heavy holes dominate and the effects of light holes can be neglected [8]. In this case the treatment of the spintronic properties for heavy holes can follow closely those for electrons [5, 13]. For a typical 2DHG formed in the xy plane and its growth direction taken along the z axis in semiconductor quantum wells, the single-particle Hamiltonian, including the lowest order of SOI involving the heavy holes, is given by [8, 14]

$$H = \frac{\mathbf{p}^2}{2m^*} I_0 + \beta_R(\sigma_+\nabla_-^3 + \sigma_-\nabla_+^3) + U(z), \tag{1}$$

where m^* is the hole effective mass, $\mathbf{p} = (p_x, p_y)$ with $p_x = -\mathrm{i}\hbar\partial/\partial x$ is the momentum operator, I_0 is the 2×2 unit matrix, $\sigma_\pm = (\sigma_x \pm \mathrm{i}\sigma_y)/2$ with σ_x and σ_y being the Pauli spin matrices, $\nabla_\pm = -(\mathrm{i}\partial/\partial y \pm \partial/\partial x)$, $U(z)$ is the confining potential of the 2DHG along the growth direction and β_R is the Rashba parameter which measures the strength of the SOI. This Hamiltonian is therefore a 2×2 matrix and the SOI does not affect the hole states along the z direction. The solution of the corresponding Schrödinger equation are readily obtained, in the form of a row vector, as

$$\Psi_{\mathbf{k}n\sigma}(\mathbf{R}) = 2^{-1/2}[1, \sigma(k_x + \mathrm{i}k_y)^3/k^3]\mathrm{e}^{\mathrm{i}\mathbf{k}\cdot\mathbf{r}}\psi_n(z). \tag{2}$$

Here, $\sigma = \pm 1$ refers to different spin branches, $\mathbf{R} = (\mathbf{r}, z) = (x, y, z)$, $\mathbf{k} = (k_x, k_y)$ is the hole wavevector in the 2D plane and $k = (k_x^2 + k_y^2)^{1/2}$. The energy spectrum of the 2DHG becomes

$$E_{n\sigma}(\mathbf{k}) = E_\sigma(k) + \varepsilon_n = \frac{\hbar^2 k^2}{2m^*} + \sigma\beta_R k^3 + \varepsilon_n. \tag{3}$$

In equations (2) and (3), the hole wavefunction $\psi_n(z)$ and subband energy ε_n along the growth direction are determined by a spin-independent Schrödinger equation. From the hole energy spectrum given by equation (3), one can immediately see that, in the presence of SOI, the energy dispersion of a 2DHG is not parabolic anymore and the energy levels for the $\pm$ spin branches depend strongly on hole wavevector (or momentum). These features are in sharp contrast to those for a spin-degenerate 2DEG or 2DHG. Furthermore, it is known [2] that, for a spin-split 2DEG, the electron wavefunction and energy spectrum are given respectively by $\Psi_{\mathbf{k}n\sigma}(\mathbf{R}) = 2^{-1/2}[1, \mathrm{i}\sigma(k_x + \mathrm{i}k_y)/k]\mathrm{e}^{\mathrm{i}\mathbf{k}\cdot\mathbf{r}}\psi_n(z)$ and $E_{n\sigma}(\mathbf{k}) = \hbar^2k^2/2m^* + \sigma\alpha_R k + \varepsilon_n$ with α_R being the Rashba parameter for a 2DEG. Thus, in contrast to a linear-in-k dependence of the energy separation between two spin branches in a spin-split 2DEG, the Rashba effect on a 2DHG results in a cubic-in-k term of the hole energy spectrum. This is the essential difference between a 2DEG and a 2DHG in the presence of SOI, which leads to a different density of states and, consequently, to different spintronic properties in a 2DEG and a 2DHG.

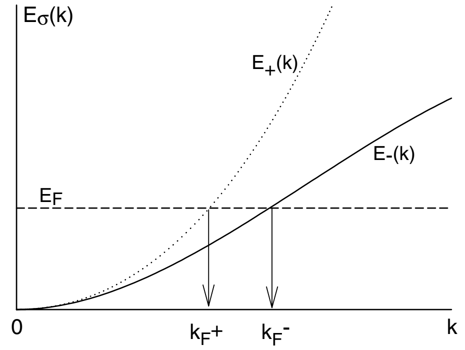

Figure 1. Dispersion relation $E_\sigma(k)$ versus k for a 2DHG in different spin branches. E_F (broken curve) is the Fermi energy and the intersections of the curves for $E_\pm(k)$ with the Fermi level, projected onto the k axis, give the Fermi wavevectors k_F^- and k_F^+.

The dispersion relation $E_\sigma(k)$ versus k resulting from equation (3) is shown in figure 1. We see that, when a 2DHG is in equilibrium so that a single Fermi level (E_F) exists, the Fermi wavevector in different spin branches are different, i.e. $k_F^+ < k_F^-$. This implies that the holes in the ± spin branches have a different density of states (DoS) below the Fermi level. In figure 1 the intersections of the curves for $E_\pm(k)$ with the Fermi level E_F, projected onto the k axis, give the Fermi wavevectors k_F^- and k_F^+. The difference $k_F^- - k_F^+$ leads to a difference in k-space area: $\pi(k_F^-)^2 > \pi(k_F^+)^2$. Accordingly, the hole densities in the ± branches are different. Using the hole energy spectrum given by equation (3), the Green function and the corresponding DoS for a 2DHG with SOI can be easily obtained. Due to the energy difference between $E_+(\mathbf{k})$ and $E_-(\mathbf{k})$, the DoS for holes in the '−' branch is always larger than that in the '+' branch and, as a result, the hole density in the '−' channel is always larger than that in the '+' channel. Applying the DoS to the condition of hole number conservation, for the case of a narrow-width quantum well in which only the lowest hole subband is present (i.e. $n = n' = 0$) and at a low-temperature limit (i.e. $T \to 0$), the hole density n_σ in the spin channel σ can be obtained by solving

$$n_\sigma/n_h - 1/2 + \sigma A_\beta[(1 - n_\sigma/n_h)^{3/2} + (n_\sigma/n_h)^{3/2}] = 0 \tag{4}$$

for the case of $\beta_R < \hbar^2/(4m^*\sqrt{\pi n_h})$, where $n_h = n_+ + n_-$ is the total hole density of the 2DHG system and $A_\beta = 2m^*\beta_R\sqrt{\pi n_h}/\hbar^2$. When $\beta_R \geqslant \hbar^2/(4m^*\sqrt{\pi n_h})$, only the '−' spin branch is occupied by holes and, therefore, the system is fully spin-polarized (i.e. $n_+ = 0$ and $n_- = n_h$). However, it should be noted that the condition $\beta_R \geqslant \hbar^2/(4m^*\sqrt{\pi n_h})$ can only be satisfied in a device system with very high hole density and very large Rashba parameter, which has not yet been realized experimentally. Therefore, in this paper, we only consider the situation where both ± spin branches are occupied by holes, namely the situation where $\beta_R < \hbar^2/(4m^*\sqrt{\pi n_h})$. To see the difference of the carrier distribution in a 2DEG and in a 2DHG when both spin branches are occupied, we note that, for a 2DEG at a low-temperature limit, the electron density in the ± spin channel is given simply by [12]: $n_\pm = (n_e/2) \mp (k_\alpha/2\pi)\sqrt{2\pi n_e - k_\alpha^2}$, where $n_e = n_+ + n_-$ is the total electron density and $k_\alpha = m^*\alpha_R/\hbar^2$. These results suggest that, in the presence of SOI, the spin polarization (i.e. $(n_- - n_+)/(n_- + n_+)$) increases with the Rashba parameter for both 2DEG and 2DHG. However, for a spin-split 2DHG the spin polarization increases with *increasing* total hole density, whereas the spin polarization in a 2DEG increases with *decreasing* total electron density (see figures 1 and 2 in [12]).

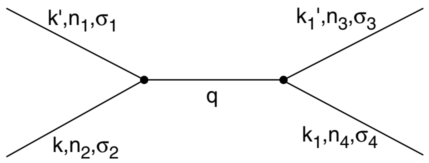

Figure 2. The bare hole–hole interaction in the presence of SOI. Here **q** is the change of the hole wavevector during a scattering event.

3. Dielectric function matrix and plasmon modes

We now study many-body effects of a 2DHG in the presence of SOI. Applying the hole wavefunction given by equation (2) to the hole–hole (h–h) interaction Hamiltonian induced by the Coulomb potential (see figure 2), the space Fourier transform of the matrix element for a bare h–h interaction is written as

$$V_{\sigma_1\sigma_2\sigma_3\sigma_4;n_1n_2n_3n_4}(\mathbf{k},\mathbf{q}) = \delta_{\mathbf{k}'+\mathbf{k},\mathbf{k_1}'+\mathbf{k_1}} V_q \int \mathrm{d}^3\mathbf{R}_1 \int \mathrm{d}^3\mathbf{R}_2\, \Psi_{\mathbf{k}'n_1\sigma_1}(\mathbf{R}_1)\Psi_{\mathbf{k}n_2\sigma_2}(\mathbf{R}_1) \times \mathrm{e}^{\mathrm{i}\mathbf{q}\cdot(\mathbf{r_1}-\mathbf{r_2})}\mathrm{e}^{-q|z_1-z_2|}\Psi_{\mathbf{k_1}'n_3\sigma_3}(\mathbf{R}_2)\Psi_{\mathbf{k_1}n_4\sigma_4}(\mathbf{R}_2), \tag{5}$$

where $\mathbf{q} = (q_x, q_y)$ is the change of the hole wavevector along the 2D plane during a h–h scattering event and $V_q = 2\pi e^2/\kappa q$, with κ being the dielectric constant of the material. From now on, we consider a narrow-width quantum well structure in which only the lowest heavy-hole subband is present (i.e. $n' = n = 0$). After defining $\alpha = (\sigma'\sigma)$, the bare h–h interaction in the presence of SOI becomes

$$V_{\alpha\beta}(\mathbf{k},\mathbf{q}) = V_q F_0(q)\left[\frac{1+\alpha A_{\mathbf{kq}}}{2}\delta_{\alpha,\beta} + \frac{\mathrm{i}\alpha B_{\mathbf{kq}}}{2}(1-\delta_{\alpha,\beta})\right], \tag{6}$$

where $F_0(q) = \int \mathrm{d}z_1 \int \mathrm{d}z_2\, |\psi_0(z_1)|^2|\psi_0(z_2)|^2\mathrm{e}^{-q|z_1-z_2|}$ with $\psi_0(z)$ being the hole wavefunction along the growth direction, $A_{\mathbf{kq}} = [k^3 + 3k^2q\cos\theta + 3kq^2\cos(2\theta) + q^3\cos(3\theta)]|\mathbf{k}+\mathbf{q}|^{-3}$, $B_{\mathbf{kq}} = [3k^2q\sin\theta + 3kq^2\sin(2\theta) + q^3\sin(3\theta)]|\mathbf{k}+\mathbf{q}|^{-3}$ and θ is an angle between $\mathbf{k}$ and $\mathbf{q}$. It should be noted that, in contrast to a spin-degenerate 2DEG or 2DHG for which the bare e–e or h–h interaction does not depend on $\mathbf{k}$ [15], $V_{\alpha\beta}(\mathbf{k},\mathbf{q})$ for a spin-split 2DHG depends not only on $\mathbf{q}$ but also on $\mathbf{k}$, because the spin splitting depends explicitly on $\mathbf{k}$. Furthermore, for the case of a 2DEG [12], due to different wavefunctions induced by the SOI, $A_{\mathbf{kq}} = (k + q\cos\theta)/|\mathbf{k}+\mathbf{q}|$ and $B_{\mathbf{kq}} = q\sin\theta/|\mathbf{k}+\mathbf{q}|$. These results indicate that the SOI in different systems can even lead to a different bare particle–particle interaction.

From the hole energy spectrum given by equation (3), we can derive the retarded and advanced Green functions for holes when the effect of SOI is taken into consideration. Applying these Green functions along with the bare h–h interaction to the diagrammatic techniques to derive effective h–h interactions under the random-phase approximation (RPA) (see figure 3), we obtain the effective h–h interaction as

$$V^{\mathrm{eff}}_{\alpha\beta}(\Omega;\mathbf{k},\mathbf{q}) = V_{\alpha\beta}(\mathbf{k},\mathbf{q})\epsilon^{-1}_{\alpha\beta}(\Omega;\mathbf{k},\mathbf{q}). \tag{7}$$

Here

$$\epsilon_{\alpha\beta}(\Omega;\mathbf{k},\mathbf{q}) = \delta_{\alpha,\beta}\delta(\mathbf{k}) - V_{\alpha\beta}(\mathbf{k},\mathbf{q})\Pi_\beta(\Omega;\mathbf{k},\mathbf{q}) \tag{8}$$

is the dynamical dielectric function matrix element and

$$\Pi_{\sigma'\sigma}(\Omega;\mathbf{k},\mathbf{q}) = \frac{f[E_{\sigma'}(\mathbf{k}+\mathbf{q})] - f[E_\sigma(\mathbf{k})]}{\hbar\Omega + E_{\sigma'}(\mathbf{k}+\mathbf{q}) - E_\sigma(\mathbf{k}) + \mathrm{i}\delta}$$

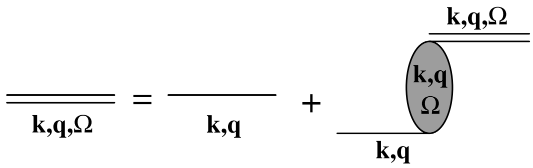

Figure 3. The effective hole–hole interaction (double full lines) in the presence of SOI under the random-phase approximation. Here, the single full line is the bare h–h interaction and the bubble refers to the bare pair bubble.

is the pair bubble or density–density correlation function in the absence of h–h interaction, with $f(x)$ being the Fermi–Dirac function. For a spin-split 2DHG, the effective h–h interaction and the dielectric function matrix depend not only on $\mathbf{q}$ but also on $\mathbf{k}$, in contrast to a spin-degenerate 2DHG. After summing the dielectric function matrix over $\mathbf{k}$ and noting $\sum_{\mathbf{k}} B_{\mathbf{kq}}\Pi_{\sigma'\sigma}(\Omega;\mathbf{k},\mathbf{q}) = 0$, the dielectric function matrix for a 2DHG with Rashba spin splitting is obtained as

$$\epsilon = \begin{bmatrix} 1+a_1 & 0 & 0 & a_4 \\ 0 & 1+a_2 & a_3 & 0 \\ 0 & a_2 & 1+a_3 & 0 \\ a_1 & 0 & 0 & 1+a_4 \end{bmatrix}. \tag{9}$$

Here, the indexes 1 = (++), 2 = (+−), 3 = (−+) and 4 = (−−) are defined with regard to different transition channels and $a_j = -(V_q F_0(q)/2)\sum_{\mathbf{k}}(1 \pm A_{\mathbf{kq}})\Pi_j(\Omega;\mathbf{k},\mathbf{q})$ where the upper (lower) case letters refer to $j = 1$ or 4 for intra-SO transition ($j = 2$ or 3 for inter-SO transition). The determinant of the dielectric function matrix is then given by

$$|\epsilon| = (1 + a_1 + a_4)(1 + a_2 + a_3), \tag{10}$$

which results from intra- and inter-SO electronic transitions. Thus, the modes of plasmon excitation are determined by $\mathrm{Re}\,|\epsilon| \to 0$ which implies that, in the presence of SOI, the collective excitation such as plasmons can be achieved via intra- and inter-SO transitions. It should be noted that the theoretical approach presented here for a 2DHG can also be used for a 2DEG in the presence of SOI and the results have been reported in [12].

Because most of the conventional optical experiments measure the long-wavelength plasmon modes, in the present work we limit ourselves to the case of the long-wavelength limit (i.e. $q \ll 1$). When $q \ll 1$, we have

$$\mathrm{Re}\, a_j \simeq -\frac{2\pi e^2 q n_\sigma}{\kappa \Omega^2 m^*}\left[1 + \sigma \frac{9\beta_{\mathrm{R}} m^*}{4\pi\hbar^2 n_\sigma}\int_0^\infty \mathrm{d}k\, k^2 f(E_\sigma(k))\right] \tag{11}$$

for intra-SO transition (i.e. for $\sigma' = \sigma$) and

$$\mathrm{Re}\, a_j \simeq -\frac{9e^2 q}{8\kappa}\int_0^\infty \frac{\mathrm{d}k}{k}\frac{f(E_{\sigma'}(k)) - f(E_\sigma(k))}{\hbar\Omega + (\sigma' - \sigma)\beta_{\mathrm{R}} k^3} \tag{12}$$

for inter-SO transition (i.e. for $\sigma' \neq \sigma$).

At a low-temperature limit (i.e. $T \to 0$), we have

$$\mathrm{Re}(1 + a_1 + a_4) = 1 - \frac{\omega_{\mathrm{p}}^2}{\Omega^2}\left(1 - \frac{\omega_- - \omega_+}{\omega_0/2}\right) \tag{13}$$

for an intra-SO transition and

$$\mathrm{Re}(1 + a_2 + a_3) = 1 - \frac{\omega_{\mathrm{p}}^2}{\omega_0\Omega}\ln\left(\frac{\Omega + \omega_-}{\Omega - \omega_-}\frac{\Omega - \omega_+}{\Omega + \omega_+}\right) \tag{14}$$

for an inter-SO transition. Here, $\omega_p = (2\pi e^2 n_h q/\kappa m^*)^{1/2}$ is the plasmon frequency of a spin-degenerate 2DHG, $\omega_0 = 16\pi\hbar n_h/3m^*$ and $\omega_\pm = (4\pi n_\pm)^{3/2}\beta_R/\hbar$ connected directly to the hole density in different spin branches and to the Rashba parameter. Thus, at the long-wavelength and low-temperature limit, we have

$$\mathrm{Re}\,|\epsilon| = \left[1 - \frac{\omega_p^2}{\Omega^2}\left(1 - \frac{\omega_- - \omega_+}{\omega_0/2}\right)\right]\left[1 - \frac{\omega_p^2}{\omega_0\Omega}\ln\left(\frac{\Omega+\omega_-}{\Omega-\omega_-}\frac{\Omega-\omega_+}{\Omega+\omega_+}\right)\right]. \quad (15)$$

Consequently, the plasmon frequencies induced by intra- and inter-SO excitation are given, respectively, by

$$\Omega_0 = \omega_p\left(1 - \frac{\omega_- - \omega_+}{\omega_0/2}\right)^{1/2} \quad (16)$$

and by solving

$$\ln\left(\frac{\Omega+\omega_-}{\Omega-\omega_-}\frac{\Omega-\omega_+}{\Omega+\omega_+}\right) = \frac{\omega_0\Omega}{\omega_p^2}. \quad (17)$$

The theoretical results shown above indicate that, in the presence of SOI, new transition channels open up for the h–h interaction and, as a result, the collective excitation from a 2DHG can be achieved via intra- and inter-SO transition channels. Furthermore, three plasmon modes can be observed where one mode is caused by intra-SO transition and two modes are induced due to inter-SO excitation.

Because the SOI results in different wavefunctions and energy spectra in a 2DEG and in a 2DHG, although the formulae shown above for a 2DHG look similar to those for a 2DEG [12], the frequencies are defined differently. For a spin-split 2DEG, $\omega_0 = 16\pi n_e\hbar/m^*$ and $\omega_\pm = 4\alpha_R\sqrt{\pi n_\pm}/\hbar$, for comparison. On the basis that $n_\pm$ for a 2DEG and for a 2DHG depends differently on the total carrier density, $\omega_\pm$ for a 2DEG and a 2DHG has a different dependence on the total electron and hole density.

4. Numerical results and discussions

Using equation (4) we can determine the hole distribution n_σ in different spin branches and the plasmon frequencies induced by different transition channels can then be calculated. In the present study we limit ourselves to p-doped AlGaAs/GaAs-based spintronic systems. In the numerical calculations we take the hole effective mass $m^* = 0.45\ m_e$ with m_e being the electron rest mass.

In figure 4 the dispersion relation of the long-wavelength plasmon modes induced by different transition events is shown at a fixed total hole density and a fixed Rashba parameter. When the SOI is present, the plasmon frequency Ω_0 due to intra-SO excitation is proportional to $\omega_p \sim q^{1/2}$ (the plasmon frequency for a spin-degenerate 2DHG) and Ω_0 is always smaller than ω_p (see equation (16)). Therefore, intra-SO plasmons are essentially acoustic-like, similar to those in a spin-degenerate 2DHG. In principle, the plasmon frequencies $\Omega_\pm$ induced by inter-SO transition should depend on q via ω_p (see equation (17)). However, our numerical results suggest that, at a long-wavelength limit (i.e. $\omega_p < 0.1$ THz in figure 4), $\Omega_\pm$ is optic-like (i.e. $\Omega_\pm$ depends very little on q) and $\Omega_\pm \to \omega_\pm = (4\pi n_\pm)^{3/2}\beta_R/\hbar$. The most important result shown in figure 4 is that, at a long-wavelength limit, inter-SO plasmons are optic-like, in sharp contrast to intra-SO plasmons and to those observed in a spin-degenerate 2DHG. It should be noted that $n_h \sim 10^{10}$ cm^{-2} and $\beta_R \sim 10^{-22}$ eV cm^3 are typical sample parameters realized in p-doped AlGaAs/GaAs quantum well structures [8]. The results shown in figure 4 indicate that, in these spintronic systems, the optic-like plasmon frequencies ($\Omega_\pm$) and $\Omega_- - \Omega_+$ are

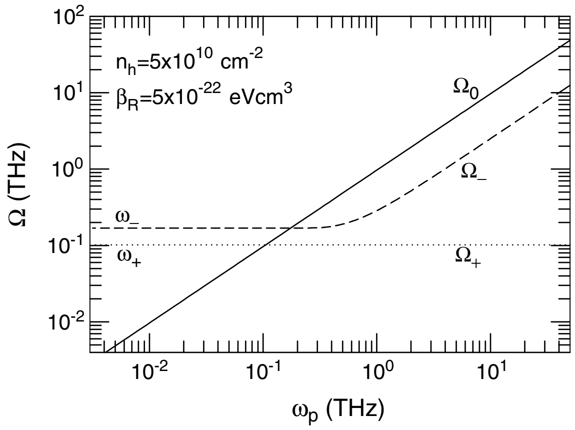

Figure 4. Dispersion relation of the long-wavelength plasmon frequency in a spin-splitting 2DHG at a fixed total hole density $n_{\rm h}$ and a fixed Rashba parameter $\beta_{\rm R}$. Here, $\omega_{\rm p} = (2\pi e^2 n_{\rm h} q/\kappa m^*)^{1/2} \sim q^{1/2}$, Ω_0 and $\Omega_\pm$ are induced respectively by intra- and inter-SO transitions, with $\omega_\pm = (4\pi n_\pm)^{3/2}\beta_{\rm R}/\hbar$ with $n_\pm$ being the hole density in the $\pm$ branch.

within the sub-THz or high-frequency microwave bandwidth. The similar dispersion relation of the intra- and inter-SO plasmon modes have been observed in InGaAs-based 2DEG systems (see figure 3 in [12]). This indicates that the SOI can result in new collective excitation modes in both 2DEG and 2DHG systems.

The hole density in different spin branches and the plasmon frequency induced by intra- and inter-SO excitation are shown in figure 5 as a function of the Rashba parameter $\beta_{\rm R}$ at a fixed total hole density $n_{\rm h}$ and a fixed q factor via $\omega_{\rm p} \sim q^{1/2}$. With increasing the strength of the Rashba spin splitting or $\beta_{\rm R}$, more and more holes are in the '$-$' spin branch because it has a lower energy and more DoS below the Fermi level. As a result, with increasing $\beta_{\rm R}$, because when $\omega_{\rm p} = 0.01$ THz $\Omega_\pm \to \omega_\pm = (4\pi n_\pm)^{3/2}\beta_{\rm R}/\hbar$ (see figure 4),

(i) Ω_- always increases and Ω_+ first increases then decreases;
(ii) Ω_- and Ω_+ due to inter-SO excitation are more markedly separated;
(iii) the difference between Ω_0 (induced by intra-SO transition) and $\omega_{\rm p}$ (obtained for a spin-degenerate 2DHG) becomes more pronounced; and
(iv) at a very large value of $\beta_{\rm R}$, the plasmon excitation via intra-SO transition can be greatly suppressed.

These effects are similar to those observed in a spin-split 2DEG (see figure 1 in [12]).

The dependence of the hole distribution and plasmon frequency due to different transition channels on total hole density $n_{\rm h}$ is shown in figure 6 at a fixed $\beta_{\rm R}$ and a fixed $\omega_{\rm p}$. With increasing $n_{\rm h}$, due to a cubic-in-k term in the energy spectrum of the 2DHG with SOI (see equation (3)), the difference between n_- and n_+ increases. This is in sharp contrast to the case of a 2DEG in which $n_- - n_+$ decreases with increasing $n_{\rm e}$ (see figure 2 in [12]). In fact, a stronger spin polarization achieved in a 2DHG with larger hole density has been verified experimentally [8]. From figure 6, one can see that, with increasing $n_{\rm h}$,

(i) Ω_0 induced by intra-SO transition decreases and the excitation of this branch of plasmons can be largely suppressed at a very high hole density;
(ii) the difference between $\Omega_\pm$ due to inter-SO excitation is enhanced; and

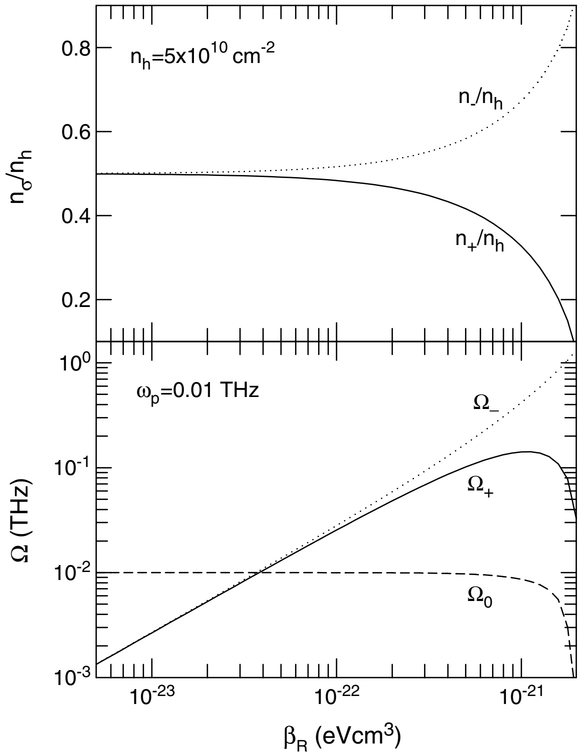

Figure 5. Hole density in the ± spin branches n_σ and plasmon frequency (Ω_0 and $\Omega_\pm$ induced, respectively, by intra- and inter-SO excitation) as a function of the Rashba parameter β_R at a fixed total hole density n_h and ω_p as indicated.

(iii) Ω_- always increases whereas Ω_+ first increases then decreases, similar to the dependence of the plasmon frequencies on β_R shown in figure 5.

Because $n_\pm$ in a 2DEG and in a 2DHG depends differently on the total carrier density, $\Omega_\pm$ induced by an inter-SO transition in a 2DHG shows a different dependence on n_h from that in a 2DEG on n_e (compare figure 6 here to figure 2 in [12]).

Since plasmon excitation from a 2DHG (2DEG) is achieved by electronic transition around the Fermi level through h–h (e–e) interaction, changing sample parameters such as β_R (α_R) and n_h (n_e) implies that Fermi energy is varied and, therefore, Ω_0 and $\Omega_\pm$ depend strongly on β_R (α_R) and n_h (n_e). Moreover, a nonparabolic subband structure of the 2DHG with SOI (see equation (3)) results in an Ω_0 different from ω_p obtained from a parabolic energy spectrum. In the presence of SOI, the electronic transition due to h–h or e–e interaction in a 2DHG or a 2DEG has some unique features. In a spin-split 2DHG or 2DEG induced by the Rashba effect, the spin orientation can change continuously with the momentum orientation when a hole or an electron moves in **k** space. Furthermore, the SOI can also shift the ± branch of the energy spectrum continuously in **k** space, instead of a quantized spectrum in energy space for the usual case. Thus, conducting holes or electrons are able to change their spin orientation simply through momentum exchange via intra- and inter-SO transition channels due to, for example, h–h or e–e interaction. This process can be more easily achieved than that through energy exchange for the usual case. Hence, although h–h or e–e interaction is essentially an elastic scattering mechanism which mainly alters the momentum states of holes or electrons, the momentum

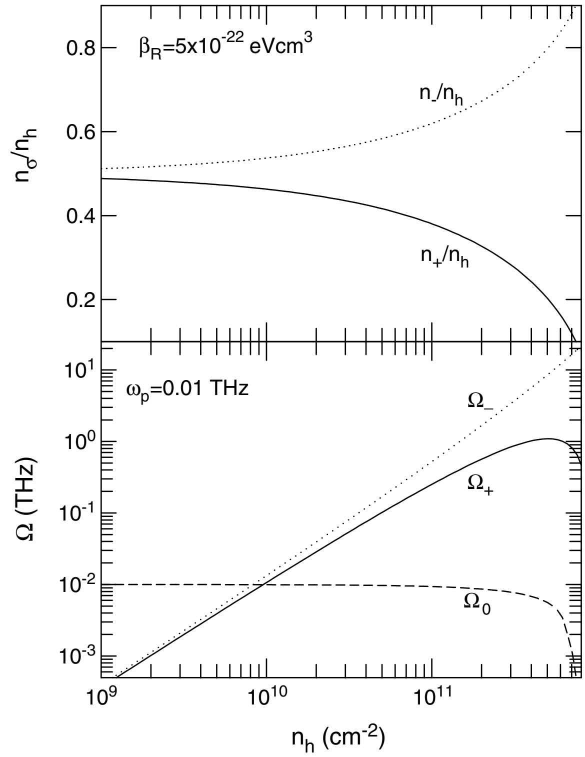

Figure 6. Hole distribution (upper panel) and plasmon frequency induced by different transition channels (lower panel) as a function of the total hole density $n_{\rm h}$ at a fixed $\beta_{\rm R}$ and a fixed $\omega_{\rm p}$ as indicated.

variation in a spin-split 2DHG or 2DEG can lead to a significant energy exchange caused by the exchange of spin orientation. As a result, the h–h or e–e interaction in a semiconductor-based spintronic system can result in an efficient momentum and energy exchange through changing the spin orientations of the holes or electrons. Together with a non-parabolic energy spectrum, the requirement of the momentum and energy conversation during a h–h or e–e scattering event in a spin-split 2DHG or 2DEG differs essentially from a spin-degenerate 2D electronic system.

Normally, optical-like plasmon modes in an electronic gas system can be measured rather conveniently by optical experiments such as optical absorption spectroscopy [16, 17], inelastic-resonant-light-scattering spectroscopy [16], Raman spectrum [18], ultrafast pump-and-probe experiments [19], etc. Acoustic-like plasmons can be detected by applying techniques such as grating couplers to these experiments [19], which in general are not so easy to measure. The optic-like plasmon modes generated via inter-SO excitation from a spin-split 2DHG can be detected optically. In particular, if we can measure the long-wavelength plasmon frequencies $\Omega_\pm \simeq \omega_\pm = (4\pi n_\pm)^{3/2}\beta_{\rm R}/\hbar$ (the magnitude of the frequencies and their separation are of the order of 0.1 THz in a p-doped AlGaAs/GaAs heterojunction), we are able to determine the Rashba parameter and the hole density in different spin branches. Thus, the spintronic properties of the device system can be obtained using optical measurements. In particular, it is hard to use magneto-transport measurements to identify the Rashba spin splitting in a high-density 2DHG device, because very high magnetic fields are required to observe the SdH oscillations. For a spin-split 2DHG, larger hole density can lead to a stronger Rashba effect (see figure 6) and to a more pronounced separation between Ω_- and Ω_+. Therefore, optical experiments are very favourable in identifying the Rashba spin splitting in high-density 2DHG samples.

On the other hand, plasmon excitation from an electronic system can be used in realizing advanced optical devices such as light generators and photon detectors. The results obtained from this study indicate that, for p-doped AlGaAs/GaAs heterostructures, the frequencies of the optic-like plasmons induced by inter-SO transitions can be of the order of sub-THz or high-frequency microwaves. On the basis that in these novel material systems the strength of the SOI can be altered by applying a back gate [8], the 2DHG-based spintronic systems can therefore be applied as tunable sub-THz light generators and photon detectors.

5. Concluding remarks

In this paper, we have examined the effect of SOI on elementary electronic excitation from a 2DHG in which the SOI is induced by the Rashba effect. This work has been motivated by the recent experimental work in which the spin-split 2DHG are realized from p-doped AlGaAs/GaAs heterostructures with a relatively strong Rashba effect. We have demonstrated that the presence of the SOI in a 2DHG can open up new channels for electronic transition via hole–hole interactions. As a result, plasmon excitation can be achieved via intra- and inter-SO electronic transitions, similar to the case of a spin-split 2DEG. The interesting and important features of these collective excitation modes have been analysed and been compared with those obtained for a spin-split 2DEG. The main theoretical results obtained from this study are summarized as follows.

In the presence of SOI, three branches of the plasmon excitation can be generated from a 2DHG system, where one acoustic-like branch is induced by intra-SO excitation and two optic-like branches are due to inter-SO transition. These plasmon modes depend strongly on sample parameters such as the total hole density and the Rashba parameter. At a long-wavelength limit, two optic-like plasmon modes induced by inter-SO excitation are directly connected to the Rashba parameter and to the hole density in different spin branches. These features are similar to those observed in a spin-split 2DEG [12]. Thus, the spintronic properties in these device systems can be determined by conventional optical measurements. Furthermore, in a p-doped AlGaAs/GaAs heterostructure, the frequencies of the inter-SO plasmons are of the order of sub-THz or high-frequency microwaves. These spintronic systems can then be used as optical devices such as tunable sub-THz light generators and photon detectors.

In the presence of SOI, the hole wavefunction and energy spectrum in a 2DHG differ significantly from those in a 2DEG. As a result, the hole distribution in different spin branches and the corresponding plasmon excitation modes in a 2DHG depend differently on the total hole density from those in a 2DEG on the total electron density. These theoretical results can be helpful in designing optical devices based on spintronic materials. Finally, we suggest that the important and interesting theoretical predications merit attempts at experimental verification.

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