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C. H. Yang
Chinese Academy of Sciences, China

W. Xu
Australian National University

Z. Zeng
Chinese Academy of Sciences, China

F. Lu
Fudan University, China

C. Zhang
University of Wollongong, czhang@uow.edu.au

Optical spectrum of a two-dimensional hole gas in the presence of spin-orbit interaction

C. H. Yang,[1] W. Xu,[1,2,*] Z. Zeng,[1] F. Lu,[3] and C. Zhang[4]
[1]*Key Laboratory of Materials Physics, Institute of Solid State Physics, Chinese Academy of Sciences and Graduate School of the Chinese Academy of Sciences, Hefei 230031, China*
[2]*Department of Theoretical Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia*
[3]*Department of Physics, Fudan University, Shanghai 200433, China*
[4]*School of Physics, University of Wollongong, Wollongong NSW 2522, Australia*
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We present a theoretical study on how the Rashba type of spin splitting affects the optical spectrum of a two-dimensional hole gas (2DHG) realized from a *p*-type $GaAs/Al_xGa_{1-x}As$ heterojunction. The optical conductivity is evaluated on the basis of the Kubo formula and a standard random-phase approximation for hole-hole interaction in different spin branches. It is found that similar to the case of a spin-split two-dimensional electron gas (2DEG), the optical spectrum of a spin-split 2DHG depends strongly on two opticlike plasmon modes caused by collective excitation between two different spin branches. The position and width of the absorption spectrum relate directly to important spintronic coefficients. Thus, the spin splitting induced by the Rashba effect can be identified optically and important spintronic properties of a 2DHG can be measured via optical experiments. The results are also compared to those obtained for a spin-split 2DEG.

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In recent years, the investigation into electronic systems with finite spin splitting has become an important and fast-growing research field in condensed matter physics and semiconductor electronics, owing to potential applications in future quantum computation and communication. It is known that in semiconductor quantum well systems, the lifting of the spin degeneracy for conducting carriers can occur at zero magnetic field and the spin splitting can be enhanced greatly by the inversion asymmetry of the microscope confining potential due to the presence of the heterostructure.[1] This enhancement is electrically equivalent to the Rashba spin splitting or Rashba effect.[2] It now becomes possible to achieve an experimentally observable Rashba effect in, e.g., $In_xGa_{1-x}As$-based two-dimensional (2D) electron gas (2DEG) (Refs. 1 and 3) and GaAs- and HgTe-based 2D hole gas (2DHG) systems.[1,4–6] It is found both experimentally and theoretically that a much stronger Rashba effect can be observed for heavy holes in (311)*A* grown $GaAs/Al_xGa_{1-x}As$ heterojunctions than for electrons in $In_xGa_{1-x}As/In_xAl_{1-x}As$ quantum well structures.[5] This is due to the fact that the spin splitting via spin-orbit interaction (SOI) in the valance band with a *p* symmetry is, in principle, larger than that in the conduction band with an *s*-like band structure. Moreover, in contrast to a spin-split 2DEG realized from a narrow-gap quantum well, the confinement of heavy holes along the growth direction in a $GaAs/Al_xGa_{1-x}As$ heterojunction enhances the difference in its effective mass for motion parallel and perpendicular to the heterointerface. As a result, the spin splitting of the valence band for heavy holes can be enlarged significantly. More importantly, similar to a spin-split 2DEG, the SOI in a 2DHG can also be controlled by applying a gate voltage or by varying the sample growth parameters. These interesting features have shed some light on using 2DHG-based systems as spin-electronic (or spintronic) devices, as pointed out recently by Winkler.[5]

At present, most of the published work on 2DEG- and 2DHG-based spintronic systems has been focused on electronic and transport properties of these structures. As pointed out recently by Rashba,[7] dynamical and optical features of the spintronic systems can play an important role in spin dynamics and spin transport. In fact, the results obtained from recent theoretical work have indicated that[8–10] (i) the 2DEG- and 2DHG-based Rashba spintronic systems can be used not only as electronic devices but also as optical devices working at terahertz (10^{12} Hz or THz) or sub-THz bandwidths; (ii) due to the opening up of new channels for electronic transition accompanied by optical absorption and excitation, some unique optical properties can be observed in such systems; and (iii) the Rashba type of spin splitting can be identified via optical experiments instead of magnetotransport measurements. Hence, the topic dealing with optical properties of the Rashba spintronic systems is very rich in terms of basic physics and in device applications. In this paper, we examine how the SOI affects the dynamic and optical properties of a 2DHG and we compare the results with those obtained for a spin-split 2DEG. The theoretical approach for calculating the optical spectrum induced by the hole-hole interaction is developed in Sec. II. The numerical results obtained from this study are presented and discussed in Sec. III and the main conclusions are summarized in Sec. IV.

In this study, we consider a $GaAs/Al_xGa_{1-x}As$ heterojunction grown on a nominally undoped (311)*A* substrate with a weak *p*-type background doping. The higher-than-usual spin splitting has been observed experimentally for heavy holes in such structure and such a spin effect has been identified as the Rashab spin splitting.[11] Owing to relatively low hole density in these 2DHG systems, only the highest hole subband is occupied by heavy holes. Thus, in the calculations we can take only the highest heavy hole subband into consideration. It has been shown that for a spin-split 2DHG, the effective SOI effect can be studied by employing, e.g., a $\mathbf{k}\cdot\mathbf{p}$ band-structure calculation.[11] Using the lowest order of SOI ob-

tained from the $\mathbf{k}\cdot\mathbf{p}$ calculation for heavy holes in the highest hole subband, the hole wave function and energy spectrum are obtained, respectively, as[9]

$$\Psi_{\mathbf{k}\sigma}(\mathbf{R}) = 2^{-1/2}[1,\sigma(k_x+ik_y)^3/k^3]e^{i\mathbf{k}\cdot\mathbf{r}}\psi_0(z) \tag{1}$$

being in the form of a row vector, and

$$E_\sigma(\mathbf{k}) = -\hbar^2k^2/2m^* - \sigma\beta k^3 \tag{2}$$

measured from the top of the highest heavy hole subband. Here, $\sigma=\pm1$ refers to different spin branches, $\mathbf{R}=(\mathbf{r},z)=(x,y,z)$, $\mathbf{k}=(k_x,k_y)$ is the hole wave vector in the 2D plane, $k=\sqrt{k_x^2+k_y^2}$, m^* is the hole effective mass, β is the Rashba parameter which measures the strength of the SOI, and $\psi_0(z)$ is the ground-state hole wave function along the growth direction.

As can be seen from Eq. (2) and as being pointed out in the theoretical work published previously,[11,12] the essential difference of the Rashba effect between a 2DEG and a 2DHG is that, instead of a linear-in-k term for spin splitting in a 2DEG, a cubic-in-k term is achieved for spin energy of heavy holes in a 2DHG. From a theoretical point of view, in p-like valance bands, $\mathbf{k}\cdot\mathbf{p}$ mixing is not needed in order to achieve the lifting of the spin degeneracy, and this is the main reason why a cubic-in-k term can be seen for a spin-split 2DHG. This feature is in sharp contrast to the s-like conduction band in which the SOI is achieved mainly via $\mathbf{k}\cdot\mathbf{p}$ mixing into the electron wave functions for energies away from the band edge. It should be noted that these theoretical results are obtained on the basis of a SOI Hamiltonian induced by structural inversion asymmetry for heavy holes, where the anisotropic corrections and band mixing have been neglected.[5,13] To take these effects into consideration, a more complicated band-structure calculation is needed [e.g., using a multiband Lüttinger-Kohn model (LKM) (Ref. 14)]. However, it has been demonstrated recently[15] that, if the splitting of heavy hole subbands is large in a low-density 2DHG system and at low temperatures (so that only the highest heavy hole subband is occupied), the Rashba cubic model can be deduced from the LKM. Together with the fact that the Rashba cubic model can reproduce nicely the experimental findings such as the density and gate-voltage dependence[11] and the negative differential Rashba effect,[13] one believes that this model Hamiltonian can represent the main effect of SOI in GaAs-based 2DHG systems. Hence, the main features of the electronic and optical properties in such systems can be calculated on the basis of this simple and practical model.

From the hole wave function and energy spectrum given by Eqs. (1) and (2), the hole density-density correlation function (or pair bubble) can be obtained, in the absence of hole-hole (h-h) screening, as[9]

$$\Pi^0_{\sigma'\sigma}(\Omega,q) = \sum_{\mathbf{k}} \frac{\mathcal{A}^{\sigma'\sigma}_{\mathbf{kq}}\{f[E_{\sigma'}(\mathbf{k}+\mathbf{q})]-f[E_\sigma(\mathbf{k})]\}}{\hbar\Omega+E_{\sigma'}(\mathbf{k}+\mathbf{q})-E_\sigma(\mathbf{k})+i\delta}. \tag{3}$$

Here, $f(x)$ is the Fermi-Dirac function for holes, $\mathbf{q}=(q_x,q_y)$ is the change of the hole wave vector during a h-h scattering event, $\mathcal{A}^{\sigma'\sigma}_{\mathbf{kq}}=(1+\sigma'\sigma A_{\mathbf{kq}})/2$ is a spin-dependent factor induced by the overlap of the hole wave functions in different spin branches, and $A_{\mathbf{kq}}=[k^3+3k^2q^2\cos\theta+3kq^2\cos(2\theta)+q^3\cos(3\theta)]|\mathbf{k}+\mathbf{q}|^{-3}$ with θ being an angle between $\mathbf{k}$ and $\mathbf{q}$. Under the random-phase approximation, the dynamical dielectric function matrix is given by[9]

$$\epsilon(\Omega,q) = \begin{bmatrix} 1+a_1 & 0 & 0 & a_4 \\ 0 & 1+a_2 & a_3 & 0 \\ 0 & a_2 & 1+a_3 & 0 \\ a_1 & 0 & 0 & 1+a_4 \end{bmatrix}, \tag{4}$$

where we have defined $j=(\sigma'\sigma)$ with $j=1=(++)$, $2=(+-)$, $3=(-+)$, and $4=(--)$ for different transition channels, $j=1$ or 4 (2 or 3) corresponds to intra-SO (inter-SO) transition channels for h-h interactions, $a_j=-V_qF_q\Pi^0_j(\Omega,q)$, $V_q=2\pi e^2/\kappa q$ with κ being the dielectric constant of the material, and $F_q=\int dz'\int dz|\psi_0(z')|^2\,\psi_0(z)|^2e^{-q|z'-z|}$. In this work, we have used a matrix to represent the dielectric function. For a spin-split 2DHG which is essentially a two-level system when only the highest hole subband is included, there are four channels for electronic transition (i.e., $j=1\to4$ defined here) induced by h-h interactions. Together with the fact that a transition for h-h interactions is, in principle, affected by all other transition events, the dielectric function is therefore a 4×4 matrix. The inverse dielectric function matrix then takes the form

$$\epsilon^{-1}(\Omega,q) = \begin{bmatrix} 1-a_1^* & 0 & 0 & -a_4^* \\ 0 & 1-a_2^* & -a_3^* & 0 \\ 0 & -a_2^* & 1-a_3^* & 0 \\ -a_1^* & 0 & 0 & 1-a_4^* \end{bmatrix}, \tag{5}$$

where $a_1^*=a_1/(1+a_1+a_4)$, $a_2^*=a_2/(1+a_2+a_3)$, $a_3^*=a_3/(1+a_2+a_3)$, and $a_4^*=a_4/(1+a_1+a_4)$. With the inverse dielectric function matrix, the hole density-density correlation function in the presence of h-h screening can be calculated through

$$\Pi_i(\Omega,q) = \sum_j \epsilon^{-1}_{ij}(\Omega,q)\Pi^0_j(\Omega,q). \tag{6}$$

It is known that optical conductivity is one of the central quantities to determine almost all optical properties of an electron and/or hole gas system. For a case where the optical transition is induced mainly by a dielectric response of the carriers through the carrier-carrier interaction, the optical conductivity can be obtained simply from Maxwell's field equations[16] or, more strictly, from the Kubo formula in which the current-current correlation is mainly caused by carrier interactions with a weak external light field.[17] Proposed by Halperin and Mishchenko,[17] the optical conductivity for a 2D system in the presence of SOI can be calculated through

$$\sigma(\Omega) = -e^2\Omega\lim_{q\to0}(1/q^2)\sum_{\sigma',\sigma}\mathrm{Im}\,\Pi_{\sigma'\sigma}(\Omega,q), \tag{7}$$

where Ω is the radiation (or excitation) frequency and $\Pi_{\sigma'\sigma}(\Omega,q)$ is the density-density correlation function for transitions from a spin branch σ' to a branch σ in the

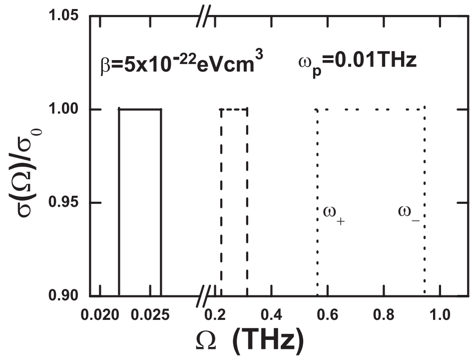

FIG. 1. Optical conductivity $\sigma(\Omega)$ as a function of excitation frequency Ω at a fixed Rashba parameter β for different total hole densities (solid, dashed, and dotted curves are, respectively, for $n_h=10^{10}$, 5×10^{10}, and 10^{11} cm^{-2}). Here $\omega_p=(2\pi e^2 n_h q/\kappa m^*)^{1/2}$, $\sigma_0=3e^2/16\hbar$, and $\omega_\pm=2\beta(4\pi n_\pm)^{3/2}/\hbar$. Note a different scale is used for case of $n_h=10^{10}$ cm^{-2}.

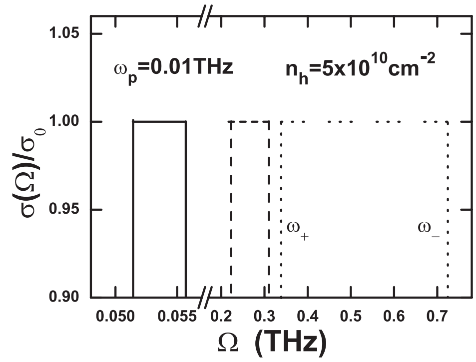

FIG. 2. Optical spectrum at a fixed total hole density n_h for different Rashba parameters (solid, dashed, and dotted curves are, respectively, for $\beta=10^{-22}$, 5×10^{-22}, and 10^{-21} eV cm^3). Note a different scale is used for case of $\beta=10^{-22}$ eV cm^3.

presence of h-h screening. Here the $q\to0$ limit reflects a fact that the hole-photon interaction does not change the hole wave vector (or momentum). This result implies that the optical transition can be accompanied by the spin-flip transition in different spin branches. At the long-wavelength (i.e., $q\to0$) limit, we have $\lim_{q\to0}q^{-2}\,\mathrm{Im}\,\Pi_{++}(\Omega,q)=\lim_{q\to0}q^{-2}\,\mathrm{Im}\,\Pi_{--}(\Omega,q)=0$, which implies that the intra-SO interaction does not contribute to an optical transition. On the other hand, we find that a strong optical absorption can occur via inter-SO interactions, especially for transition from a lower "−" spin branch to a higher "+" branch. When $q\to0$ and for low temperatures (i.e., $T\to0$), after considering only the processes for optical absorption (i.e., $\Omega>0$), the optical conductivity induced by inter-SO transition is given by

$$\sigma(\Omega)=\sigma_0\Theta(\omega_--\Omega)\Theta(\Omega-\omega_+)\times\left[\frac{2[1+2\,\mathrm{Re}\,a_2+2(\mathrm{Re}\,a_2)^2]}{(1+\mathrm{Re}\,a_2+\mathrm{Re}\,a_3)^2+(\mathrm{Im}\,a_3)^2}-1\right], \quad (8)$$

where $\sigma_0=3e^2/16\hbar$, $\mathrm{Re}\,a_2=-(\omega_p^2/\omega_0\Omega)\ln[(\omega_+/\omega_-)^3(\Omega+\omega_-)/(\Omega+\omega_+)]$, $\mathrm{Re}\,a_3=-(\omega_p^2/\omega_0\Omega)\ln|(\omega_-/\omega_+)^3(\Omega-\omega_+)/(\Omega-\omega_-)|$, and $\mathrm{Im}\,a_3=(\pi\omega_p^2/\omega_0\Omega)\Theta(\omega_--\Omega)\Theta(\Omega-\omega_+)$. Here, $[\ldots]$ part comes from h-h screening, $\Theta(x)$ is a unit-step function, $\omega_p^2=2\pi e^2 n_h q/\kappa m^*$ is the plasmon frequency of a spin-degenerate 2DHG, $\omega_0=16\pi n_h\hbar/3m^*$, $\omega_\pm=2\beta(4\pi n_\pm)^{3/2}/\hbar$ with n_σ being the hole density in the σ spin branch, and $n_h=n_++n_-$ is the total density of the 2DHG.

The theoretical results shown above are seemingly similar to those obtained for a spin-split 2DEG.[10] From a theoretical point of view, the basic difference between an $\mathrm{In}_x\mathrm{Ga}_{1-x}$As-based 2DEG and a GaAs-based 2DHG is the nature of the SOI via the Rashba spin splitting, which leads to different wave functions and energy spectra. In particular, 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 leads to a different density of states between a spin-split 2DEG and a 2DHG. As a result, (i) σ_0 here is three times larger than that for a 2DEG; (ii) ω_0 for a 2DHG is three times smaller than that for a 2DEG; (iii) $\omega_\pm$ differ from those for a 2DEG; and (iv) the hole distribution in different spin branches is different from that for a 2DEG, which is determined, for $T\to0$, by solving[9]

$$n_\sigma/n_h-1/2+\sigma A_\beta[(1-n_\sigma/n_h)^{3/2}+(n_\sigma/n_h)^{3/2}]=0, \quad (9)$$

with $A_\beta=2m^*\beta\sqrt{\pi n_h}/\hbar^2$.

It has been shown that $\omega_\pm$ correspond to frequencies of two opticlike plasmon modes induced by an inter-SO interaction in a 2DHG.[9] Thus, similar to the case of a 2DEG,[10] the two edges of the optical spectrum for a spin-split 2DHG are, respectively, at $\Omega\sim\omega_\pm=2\beta(4\pi n_\pm)^{3/2}/\hbar$. Using Eq. (7), the width of the optical spectrum for a 2DHG is

$$\omega_--\omega_+=\frac{2\pi\hbar n_h}{m^*A_\beta^2}[(1-4A_\beta^2)^{3/2}+6A_\beta-1], \quad (10)$$

which depends not only on the Rashba parameter β but also on total hole density n_h, in sharp contrast to a 2DEG for which $\omega_--\omega_+$ depends only on the Rashba parameter.[10]

In the present study we limit ourselves to the study of p-doped $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$-based spintronic systems. The heavy hole effective mass in GaAs is taken as $m^*=0.45m_e$ with m_e being the electron rest mass. In the calculations, we also take the typical sample parameters such as $\beta\sim5\times10^{-22}$ eV cm^3 and $n_h\sim5\times10^{10}$ cm^{-2}, realized experimentally in such spintronic devices.[11] Using these parameters, the opticlike plasmon frequency induced by the inter-SO transition is of the order $\omega_\pm\sim0.3$ THz.[9] The plasmon frequency $\omega_p\sim q^{1/2}=0.01$ THz taken in the calculations is much smaller than $\omega_\pm$.

The dependence of optical conductivity on the Rashba parameter β and total hole density n_h is shown in Figs. 1 and 2. It is known that in an electron or a hole gas system, the electronic transition through charge- and spin-density oscillations can result in optical absorption and/or excitation. For a spin-split 2DHG, optical absorption can be achieved via electronic transition between different spin branches. This process can be accompanied by an excitation of opticlike plasmon modes through h-h interactions. Thus, the shape and profile of the optical spectrum of a spin-split 2DHG is deter-

mined mainly by $\omega_\pm$ which depends on both β and n_h. From Figs. 1 and 2, we can see some interesting optical properties of a spin-split 2DHG. First, similar to a spin-split 2DEG, the optical conductivity induced by *h*-*h* interactions via plasmon excitation takes roughly a rectangular shape, where the two absorption edges are at $\omega_\pm=2\beta(4\pi n_\pm)^{3/2}/\hbar$ and the height is at a universal value $\sigma_0=3e^2/16\hbar$. This feature has also been observed by Rashba for a spin-split 2DEG [see the case of $Q=0$ in Fig. 2 in Ref. 7 and note that the response function is proportional to $\sigma(\Omega)$]. The numerical results show that the *h*-*h* screening affects rather weakly the optical spectrum [see Eq. (6)] due to a relatively low hole density. When $q\to 0$, $\omega_p^2\sim q\ll\Omega\omega_0$. Consequently, $\mathrm{Re}\,a_2\sim\mathrm{Re}\,a_3\sim\mathrm{Im}\,a_3\sim q\ll 1$ in Eq. (6). Second, similar to a spin-split 2DEG, a blueshifted and more broadened optical spectrum can be achieved at a larger Rashba parameter (see Fig. 2). This is due to the fact that both $\omega_\pm$ and ω_--ω_+ increase with β. Third, in line with a spin-split 2DEG, the blueshift of $\sigma(\Omega)$ for a 2DHG can also be achieved by increasing total hole density because $\omega_\pm$ increases with n_h. Fourth, in a shape contrast to a 2DEG where the width of $\sigma(\Omega)$ does not depend on total electron density, the width of the optical spectrum for a 2DHG depends strongly on total hole density n_h [as indicated by Eq. (8)]. For a spin-split 2DHG, the width of $\sigma(\Omega)$ increases with n_h (see Fig. 1). Furthermore, our numerical results indicate that when $\omega_p<0.1$ THz, $\sigma(\Omega)$ depends very little on the value of ω_p, similar to the dispersion relation of the inter-SO plasmon modes $\Omega_\pm$ shown in Ref. 9.

From a fundamental perspective, the *h*-*h* interaction in a 2DHG with the Rashba spin splitting and the corresponding optical properties have some unique features. In such a system, the spin orientation can change continuously with the momentum orientation when a hole moves in **k** space. Under the action of the SOI, the spectra of the ±spin branches can also be shifted continuously in **k** space instead of a quantized spectrum in energy space for the usual case (e.g., Zeeman splitting in the presence of a magnetic field). Together with the fact that the *h*-*h* interaction in a 2DHG is achieved mainly through altering the hole wave vector (or momentum) and/or spin orientation, the optical transition via plasmnon excitation or absorption can be achieved through changing the momentum (or wave vector) and/or spin of the holes in different spin branches. More importantly, the lifting of the spin degeneracy in **k** space opens up new channels for electronic transitions of spin-split holes. In the presence of *h*-*h* interactions, the conducting holes are able to change their spin orientation and spin branch location simply through a momentum exchange which can be more easily achieved than that through an energy exchange for the usual case. This becomes the main reason why the optical spectrum of a spin-split 2DHG is mainly induced by inter-SO interaction through excitation of two inter-SO plasmon modes which are opticlike. Moreover, in contrast to fully quantized electronic states in energy space in a spin-degenerate electron or hole gas system, the optical transition in a spin-split 2DHG via momentum and spin exchange should satisfy both the momentum and energy conservation laws during a *h*-*h* scattering event. As a result, the optical transition is allowed only when $\omega_+\leqslant\Omega\leqslant\omega_-$ and a roughly rectangular shape of the optical spectrum can be observed in a spin-split 2DHG.

At present, one of the most popularly and effectively used experimental techniques to identify the Rashba spin splitting in a 2DEG or 2DHG is magnetotransport measurements under the condition where the Shubnikov–de Hass (SdH) oscillations are observable.[5,11] However, such measurements require relatively high magnetic fields, especially for high-density samples. For a spin-split 2DHG, because of much heavier heavy hole mass, only the low-density samples can be identified using the magnetotransport measurements. For cases where the strength of SOI is controlled by applying the gate voltages which can alter both β and n_h, from the SdH oscillations and Hall effect alone it is very difficult to determine whether the change of the observed spin splitting is mainly caused by varying β or n_h. Hence, from a technical point of view, in order to carry out a sample characterization more accurately and easily it is more favorable to use optical experiments for the measurement of the spintronic properties of a 2DHG. The theoretical results obtained from this study indicate that if we can measure the optical spectrum induced by plasmon excitation in a spin-split 2DHG, important spintronic coefficients can be obtained optically. We find that if the edges (note only the edges) of the spectrum (i.e., $\omega_\pm$) are measured, the Rashba parameter and hole density in different spin branches can be determined, respectively, through

$$\beta=\frac{\hbar}{2}\left(\frac{\hbar}{m^*}\frac{\omega_-^{2/3}-\omega_+^{2/3}}{\omega_-+\omega_+}\right)^{3/2}\quad\text{and}\quad n_\pm=\frac{1}{4\pi}\left(\frac{\hbar\omega_\pm}{2\beta}\right)^{2/3}. \tag{11}$$

Thus, other spintronic properties [e.g., total hole density $n_h=n_++n_-$, spin-polarization $P=(n_--n_+)/n_h=m^*(\omega_-+\omega_+)/(4\pi\hbar n_h)$, etc.] can be obtained easily. In particular, it should be noted that in GaAs-based 2DHG systems the Rashba spin splitting increases with increasing total hole density, found both experimentally[11] and theoretically.[9] This is in shape contrast to $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$-based 2DEG systems in which the strength of the Rashba spin splitting decreases with increasing total electron density.[8] In a 2DHG, a stronger spin splitting can, therefore, be achieved in a sample with larger hole density. Moreover, a more pronounced separation between ω_- and ω_+ can be observed in a higher density sample (see Fig. 1). Hence, optical experiments are very favorable in identifying the Rashba effect in high-density 2DHG samples which can be more possibly used as spintronic devices.

For spin-degenerate 2DEG or 2DHG systems, optical spectra induced by plasmon excitation have been measured using conventional techniques such as optical absorption spectroscopy,[18,19] inelastic-resonant-light-scattering spectroscopy,[18] Raman spectrum,[20] ultrafast pump-and-probe experiments,[21] etc. These state-of-the-art optical and optoelectronic techniques can also be used to measure an optical spectrum of a spin-split 2DHG although a low temperature experiment is required. It should be noted that the plasmon modes induced by *h*-*h* interactions via an inter-SO transition are opticlike.[9] They can, therefore, be more easily measured optically than those for a spin-degenerate 2DHG which have a dispersion relation $\omega_p\sim q^{1/2}$.

In this work, we have found that the optical spectrum induced by *h-h* interactions in a spin-split 2DHG relates directly to important spintronic properties. Through examining the position and the width of the spectrum, these spintronic properties can be measured easily and accurately using optical experiments. We have proposed a way to determine optically the spintronic coefficients such as the Rashba parameter, hole density in different spin orbits, spin polarization, etc. As a conclusion, we believe that the Rashba spin splitting in a GaAs-based 2DHG can be identified optically in order to carry out the sample characterization more easily and accurately. We have also compared the present results with those obtained for a spin-split 2DEG. Finally, we suggest that the important and interesting theoretical predictions in this paper merit attempts at experimental verification.

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*Electronic address: wen105@rsphysse.anu.edu.au

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[20] See, e.g., D. Olego *et al.*, Phys. Rev. B **25**, 7867 (1982).

[21] See, e.g., M. Voßebürger *et al.*, J. Opt. Soc. Am. B **13**, 1045 (1996).