Two color plasmon excitation in an electron-hole bilayer structure controlled by the spin-orbit interaction

C. H. Yang
Key Laboratory of Materials Physics, Institute of Solid State Physics, Chinese Academy of Sciences, Hefei 230031, China and School of Engineering Physics, University of Wollongong, New South Wales 2522, Australia

A. Wright, F. Gao, and C. Zhang[a)]
School of Engineering Physics, University of Wollongong, New South Wales 2522, Australia

Z. Zeng
Key Laboratory of Materials Physics, Institute of Solid State Physics, Chinese Academy of Sciences, Hefei 230031, China

W. Xu
Department of Theoretical Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra ACT 0200, Australia

(Received 7 February 2006; accepted 18 April 2006; published online 30 May 2006)

The dispersion and intensity of coupled plasma excitation in an electron-hole bilayer with Rashba spin-orbit coupling is calculated. We propose to use the spin-orbit coupling in individual layers to tune the intensity of two plasmons. The mechanism can be used to develop a two color terahertz source with tunable intensities. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2208380]

In recent years, the terahertz plasma effects in high-mobility electronic systems have attracted much attention theoretically[1–3] and experimentally.[4–6] Plasma excitation in the terahertz regime can be used for generation, detection, and frequency multiplication of terahertz radiation. A channel of a field-effect transistor with sufficiently high electron mobility can serve as a resonant cavity for the plasma oscillation. When the signal period is in the vicinity of the electron transit time, self-excitation of plasma oscillation can occur. If the typical plasma frequency is in the terahertz regime, the phenomenon can be used as a terahertz source.

Among various plasma phenomena, the excitation of two plasmons in a device is of great importance and interest. Excitation of two plasmons with distinct frequencies (or two color excitation) can be employed as a two colour terahertz radiation source which has potential applications in science and technology. In principle, any two-component system can have two color plasmon excitation, as long as the plasma frequency for each single component is distinct. Such two color excitation can be achieved in systems with two different types of electrons (e.g., electrons with different effective masses) or two different charged carriers, (e.g., electron-hole systems). An electron-hole bilayer system[7,8] consists of an electron layer and a hole layer separated by a distance d. Such a bilayer system has two plasma modes, a high frequency optical mode corresponding to both charges which are oscillating in phase and a low frequency acoustic mode corresponding to the heavier particle screened by the lighter particle. The acoustic mode is stable and undamped only if the layer separation satisfies certain requirements.[9] The energy and intensity of each mode are dependent on the mass ratio and the layer separation. However, none of these two parameters are adjustable in a real device.

In this letter we study the plasma excitation in an electron-hole bilayer system in the presence of Rashba spin-orbit interaction (SOI) in both layers, or in a spintronic bilayer system. The study of spintronics has attracted tremendous attention in recent years, both in theoretical and experimental circles,[10] thanks to the discovery of the long-lived (100 ns) coherent electron spin states in n-type semiconductors.[11–18] In InAs- and GaAs-based two-dimensional electron (hole) gas [2DEG (2DHG)] systems, the spontaneous spin splitting is mainly induced by the Rashba effect, which can be enhanced further by increasing the applied gate voltage. The unique properties of energy dispersion and the density of states in spintronic materials can be used to control and tune the plasma excitation. We shall show that the Rashba SOI can be used effectively to tune the position and intensities of the coupled plasma excitation in an electron-hole bilayer.

Our model system is a double quantum well structure. One well is n type and the other is p type. We consider both 2DEG and 2DHG formed in the x-y plane. In the presence of SOI, the degeneracy parabolic energy in the x-y plane splits into two nonparabolic spin branches. The SOI does not affect the motion along the z direction, and the subbands are determined by the spin-independent confining potential. The carriers can move freely in the x-y plane, and the two layers interact only via the Coulomb potential. A dc bias V_e (V_h) is applied across the electron (hole) layer to individually control the Rashba coupling strength. To the first approximation that only the lowest subband is occupied in each well, both electrons and holes can be regarded as two dimensional and the system is an electron-hole bilayer. The SOI in the electron or the hole layer can be written as

$$H_{so}^{s} = \eta^{s}(\hat{\sigma} \times \mathbf{p})_{z}^{j}. \tag{1}$$

When $s=e$, $j=1$ is for electrons and $\eta^e=\alpha$ is the electron SOI parameter. When $s=h$, $j=3$ is for heavy holes and $\eta^h=\beta$ is the hole SOI parameter. $\hat{\sigma}$ is the Pauli matrix.

The Hamiltonian of the system is given by $H=H_0+H_{so}+H_I$ where the first term is the kinetic energy of the carriers,

[a)]Electronic mail: c.zhang@uow.edu.au

$$H_0 = \frac{1}{2}\sum_{\mathbf{p},s} \frac{\mathbf{P}^2}{m_s^*}. \quad (2)$$

Here s can be electrons or holes ($s=e$ or h) and m_s^* is the effective mass of electrons or holes. The third term is the Coulomb interaction of a many-particle system. The eigenenergy and wave function of a single particle is given as $E_s^\sigma(k)=\hbar^2k^2/2m_s^* + \sigma\eta^s k^j$, where $k=\sqrt{k_x^2+k_y^2}$, σ can be ± 1, and the eigenfunction is given as

$$\psi_s^\sigma(\mathbf{r}) = \begin{pmatrix} 1 \\ \sigma\eta^{s(k_y-ik_x)j/k^j} \end{pmatrix} e^{-i\mathbf{k}\cdot\mathbf{r}}. \quad (3)$$

The interaction Hamiltonian can be written as

$$H_I = \frac{1}{2}\int\int d\mathbf{r}_1 d\mathbf{r}_2 \psi_s^*(\mathbf{r}_1)\psi_{s'}^*(\mathbf{r}_2)\frac{e^2}{\kappa|\mathbf{r}_1-\mathbf{r}_2|}\psi_{s'}(\mathbf{r}_2)\psi_s(\mathbf{r}_1). \quad (4)$$

In the momentum space, the Coulomb interaction parameters (e-e, h-h, and e-h interactions) are given as $V_{ee}(q)=V_{hh}(q)=2\pi e^2/q=V_q$ and $V_{eh}(q)=V_{he}(q)=-V_q e^{-qd}$, where d is the distance between the two layers.

The frequency and wave vector dependent excitation spectral function of the systems is given as

$$S(q,\omega) = \int_\infty^\infty \frac{dt}{2\pi} e^{i\omega t}\sum_{ss'} \frac{e^2}{m_s m_{s'}}\langle n_s(q,t)n_{s'}(-q,0)\rangle, \quad (5)$$

where $n_s(q,t)$ is the Fourier transform of the density operator for the s species. By using the random-phase approximation, we obtain

$$S(q,\omega) = \frac{1}{m_e^2}\frac{q[\rho(\omega)+1]}{\pi}\,\mathrm{Im}\,F(q,\omega), \quad (6)$$

$$F(q,\omega) = [\Pi_0^e(1-V_q\Pi_0^h) + \gamma^2\Pi_0^h(1-V_q\Pi_0^e) - 2\gamma\Pi_0^e\Pi_0^h V_q e^{-qd}]\frac{V_q}{\epsilon(q,\omega)}, \quad (7)$$

where γ is the ratio of m_e^*/m_h^*. Here we have introduced the dielectric function

$$\epsilon(q,\omega) = (1-V_q\Pi_0^e)(1-V_q\Pi_0^h) + \Pi_0^e\Pi_0^h V_q^2 e^{-2qd}. \quad (8)$$

The electronic polarizability is written as

$$\Pi_0^s(q,\omega) = \sum_{\sigma,\sigma'}\int \frac{d\mathbf{k}}{8\pi^2}(1 + \sigma\sigma' A_{kq})\frac{f_\mathbf{k}^\sigma(s) - f_{\mathbf{k+q}}^{\sigma'}(s)}{\omega + E_s^\sigma(\mathbf{k}) - E_s^\sigma(\mathbf{k+q}) + i\delta}. \quad (9)$$

Here $f_\mathbf{k}^\sigma(s)$ is the Fermi distribution function for s species. $A_{kq}=(k+q\cos\theta)/|\mathbf{k}+\mathbf{q}|$ for electrons and $A_{kq}=[k^3+3k^2q\cos\theta+3kq^2\cos(2\theta)+q^3\cos(3\theta)]/|\mathbf{k}+\mathbf{q}|^3$ for holes; θ is the angle between $\mathbf{k}$ and $\mathbf{q}$.

In our numerical calculation, we use the parameters $m_e^*=0.04m_0$ and $m_h^*=0.45m_0$, where m_0 is the free electron mass. All densities are in cm^{-2}, d is in nanometers, α is in eV m, and β is in eV cm^3. The level broadening is $\delta=10^{-3}E_F$, where E_F is the electron Fermi energy without SOI and Coulomb interaction. All information on the density-density correlation is contained in the function $\mathrm{Im}\,F(q,\omega)$.

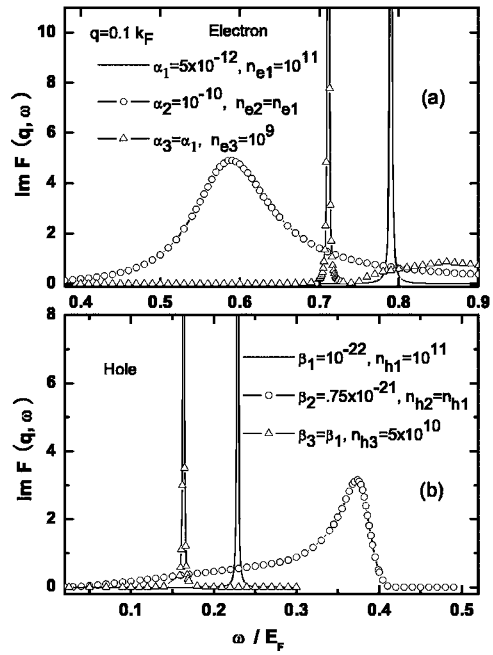

FIG. 1. The excitation spectra of the electron layer (a) and the hole layer (b).

The excitation spectra show resonances when $\epsilon(q,\omega)$ is zero. The strength of the resonance is determined by the single electron polarizability, the interparticle interactions, and SOI in each layer.

Figure 1 depicts the excitation spectra for an electron layer or a hole layer only. For a single layer, $\mathrm{Im}\,F(q,\omega)=\mathrm{Im}\,1/\epsilon(q,\omega)$. As the strength of the SOI increases or the carrier concentration decreases, the excitation peak broadens and shifts to the low energy. When polarization $p=(n_- - n_+)/(n_- + n_+)$ (where $n_\pm$ is the electron or hole density in the $\sigma=\pm$ spin branch) is large, the SOI can have a dominant effect on the plasma mode. In the absence of the spin splitting, there is a single value of momentum transfer corresponding to the transition energy for a photon absorption. Due to Rashba splitting, there are four different momentum transfers for a given frequency, two intra- and two interlevel transitions. This leads to the fine structures in both the real and imaginary parts of ϵ. These fine structures are only resolved if η^s is sufficiently large. The excitation spectra $\mathrm{Im}[1/\epsilon]$ contains both a particle-hole contribution at large q and a plasma contribution at small q. The change of the single particle energy due to Rashba coupling is $\sigma\alpha k$. For an excitation of at a given frequency, the required momentum transfer of the electron q is less for a state with large α. This results in a shift of the particle-hole contribution in the spectral weight towards the low q. The q shift of the plasma contribution is much less compared to that of the particle-hole contribution. By varying the SOI coupling parameter, one can shift the spectral weight from the plasmon mode to the particle-hole mode, or vice versa.

Comparing Figs. 1(a) and 1(b), it can be seen that when the SOI parameter decreases, the plasma energy of electrons decreases, while that of holes increases. For electrons, the main contribution is the intralevel transition in the "−" spin branch. However, to holes, it is the interlavel transition from "−" to "+." Therefore the plasma energy for electrons and for holes shifts in the opposite direction. It is known[17,18] that increasing α or decreasing n_e leads to a larger polarization of

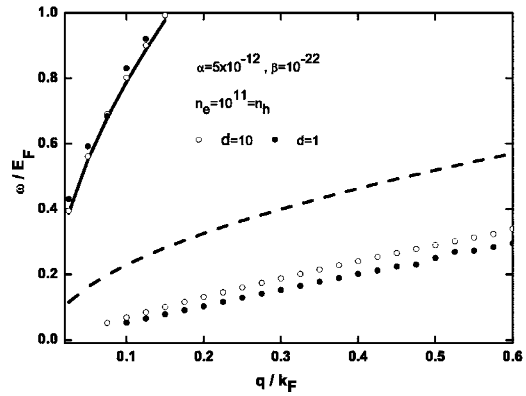

FIG. 2. The plasmon dispersion relation of the electron layer (solid line), the hole layer (broken line), and an electron-hole bilayer system (circles) at two different separations.

electrons. However, in order to increase the p of holes, it should increase β or n_h. So only increasing n_h can shift the hole's plasma energy higher. These differences come from the energy dispersion. The spin split energy is k linear for electrons and k cubic for holes.

When there are Coulomb interactions between the electron layer and the hole layer, the plasmons of the electrons and the holes are coupled, resulting in a high frequency mode and a low frequency mode. The plasma dispersion curves are plotted in Fig. 2 for $n_e=n_h=10^{11}$ cm^{-2}, $\alpha=5\times10^{-12}$ eV m, $\beta=10^{-22}$ eV cm^3, and $d=10$ or 1 nm. In the presence of H_I^{e-h}, the two coupled modes lie between the plasma energies of two individual components.

For an electron-hole bilayer, the particle-hole mode is suppressed in the structural function. The main reason for this suppression is that the real part of the dielectric function for one component is significant in the regime where the particle-hole excitation of the other component is nonzero. Now the dominant contribution to $S(q,\omega)$ is from the coupled plasma modes. The excitation spectra contain sharp resonances at plasma frequencies. These sharp resonances are the basic requirement for two color emission and detection. For a bilayer system with zero SOI ($\alpha=0$ and $\beta=0$), the positions and intensities of the two modes are predetermined by the structure parameters. For systems with finite SOI, the intensity of each mode can be tuned by varying α or β. Figure 3 shows the variation of the relative intensity at the coupled plasma modes as a function of the SOI parameter. As α increases, the energy of the high frequency mode decreases slightly, while the intensity of the mode decreases very rapidly. As β increases, the energy of the low frequency mode increases and its intensity decreases.

To summarize, the SOI can be used as an effective controlling parameter for the two color plasma excitation in an electron-hole bilayer. The energy separation of the two excitations increases with the interlayer interaction $H_I^{e\text{-}h}$ but decreases with the SOI in either layer. The intensity of the excitation decreases with the SOI. In an experiment setup, one can use the gate voltage to control the α, β, n_e, and n_h.

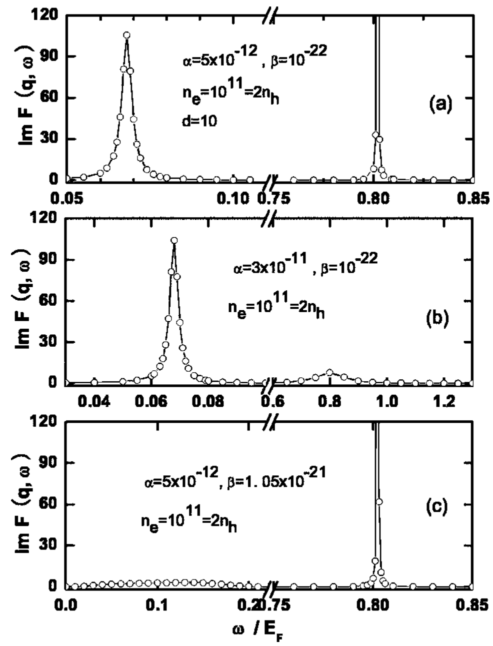

FIG. 3. The excitation spectra of a coupled electron-hole bilayer system; the separation d is the same for all three panels.

The system can be used as a device for two color emission with individual intensities tuned by a dc bias.

This work was supported by the Australian Research Council, the NSF of China under Grant No. 10374091 and the special Funds for Major State Basic Research Projects of China (973) under Grant No. 2005CB623603. Part of the calculations were performed in the Center for Computational Science, Hefei Institutes of Physical Sciences.

[1] V. Ryzhii, A. Satou, I. Khmyrova, A. Chapik, and M. S. Shur, J. Appl. Phys. **96**, 7625 (2004).
[2] J. C. Cao and X. L. Lei, Phys. Rev. B **67**, 085309 (2003).
[3] X. W. Mi, J. C. Cao, and C. Zhang, J. Appl. Phys. **95**, 1191 (2004).
[4] H. C. Liu, C. Y. Song, A. J. SpringThorpe, and J. C. Cao, Appl. Phys. Lett. **84**, 4068 (2004).
[5] J. Q. Lü and M. S. Shur, Appl. Phys. Lett. **78**, 2587 (2002).
[6] W. Knap, Y. Deng, S. Rumyantsev, and M. S. Shur, Appl. Phys. Lett. **81**, 4637 (2002).
[7] N. Tzoar and C. Zhang, Phys. Rev. B **34**, 1050 (1986).
[8] C. Zhang and Y. Takahashi, J. Phys.: Condens. Matter **5**, 5009 (1993).
[9] A. C. Tselis and J. J. Quinn, Phys. Rev. B **29**, 3318 (1984).
[10] G. A. Prinz, Science **282**, 1660 (1998).
[11] D. Loss and D. P. DiVincenzo, Phys. Rev. A **57**, 120 (1998).
[12] *Semiconductor Spintronics and Quantum Computation*, edited by D. D. Awschalom, D. Loss, and N. Samarth (Springer, Berlin, 2002).
[13] S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. von Molnár, M. L. Roukes, A. Y. Chtchelkanova, and D. M. Treger, Science **294**, 1488 (2001).
[14] A. T. Filip, B. H. Hoving, F. J. Jedema, and B. J. van Wees, Phys. Rev. B **62**, 9996 (1999).
[15] G. Schmidt, D. Ferrand, L. W. Molenkamp, A. T. Filip, and B. J. van Wees, Phys. Rev. B **62**, R4790 (2000).
[16] C. Zhang and Z. S. Ma, Phys. Rev. B **71**, 121307 (2005).
[17] W. Xu, Appl. Phys. Lett. **82**, 724 (2003).
[18] W. Xu and L. B. Lin, J. Phys.: Condens. Matter **16**, 1777 (2004).