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

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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 and experimentally. 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 or the hole layer can be written as

\[ \hat{s} = e \hat{\sigma} \times \hat{p} \hat{j}. \]  

When \( s = e, j = 1 \) is for electrons and \( \eta = \alpha \) is the electron SOI parameter. When \( s = h, j = 3 \) is for heavy holes and \( \eta = \beta \) 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,
The electronic polarizability is written as

$$\varepsilon_{\text{el}} = \sum_{i=1}^{N} \frac{\mathbf{P}^2_{\mathbf{f}_i}}{m_i^*}.$$  \hspace{1cm} (2)

Here $s$ can be electrons or holes ($s = e$ or $h$) and $m_i^*$ 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

$$E_{\mathbf{k}}(\mathbf{r}) = \hbar^2 k^2/2m^*_e + \alpha \mathbf{r} \cdot \mathbf{k},$$

where $k = \sqrt{k_x^2 + k_y^2}$, $\sigma$ can be $\pm$, and the eigenfunction is given as

$$\psi_{\mathbf{k}}(\mathbf{r}) = \left( \frac{1}{\sqrt{2\pi \hbar}} \right)^3 e^{-i \mathbf{k} \cdot \mathbf{r}}.$$  \hspace{1cm} (3)

The interaction Hamiltonian can be written as

$$H_1 = \frac{1}{2} \int d\mathbf{r}_1 d\mathbf{r}_2 \psi_1^*(\mathbf{r}_1) \psi_2^*(\mathbf{r}_2) \frac{e^2}{\kappa} \psi_1(\mathbf{r}_2) \psi_2(\mathbf{r}_1).$$  \hspace{1cm} (4)

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

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

$$S(q, \omega) = \int_{-\infty}^{\infty} \frac{dt}{\pi} \sum_{s,s'} e^{2i \omega t} \langle n_s(q, t) n_{s'}(-q, 0) \rangle,$$  \hspace{1cm} (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

$$S(q, \omega) = \frac{1}{m_e^*} \frac{d\varepsilon}{d\omega} \frac{1}{\pi} \text{Im} F(q, \omega),$$  \hspace{1cm} (6)

$$F(q, \omega) = [\Pi_0^d(1 - V_q \Pi_0^d) + \gamma^2 \Pi_0^d(1 - V_q \Pi_0^d) - 2\gamma \Pi_0^d V_q e^{-q} \Pi_0^d V_q e^{-q} \Pi_0^d V_q e^{-q}],$$  \hspace{1cm} (7)

where $\gamma$ is the ratio of $m^*_e/m^*_h$. Here we have introduced the dielectric function

$$\varepsilon(q, \omega) = (1 - V_q \Pi_0^d)(1 - V_q \Pi_0^d) + \Pi_0^d V_q e^{-q} \Pi_0^d V_q e^{-q}.$$  \hspace{1cm} (8)

The electronic polarizability is written as

$$\Pi_0^d(q, \omega) = \sum_{\sigma, \sigma'} \int \frac{d\mathbf{k}}{8\pi^2} (1$$

$$+ \sigma\sigma' A_{\mathbf{k}q}) \frac{f_{\mathbf{k}}^\sigma(s) - f_{\mathbf{k}q}^{\sigma'}(s)}{\omega + E^\sigma_\mathbf{k}(k) - E^{\sigma'}_\mathbf{k}(k + q) + i\delta}.$$  \hspace{1cm} (9)

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

In our numerical calculation, we use the parameters $m_e^*$ = 0.04$m_0$ and $m_h^*$ = 0.45$m_0$, where $m_0$ is the free electron mass. All densities are in $\text{cm}^{-2}$, $d$ is in nanometers, $\alpha$ is in $\text{eV m}$, and $\beta$ is in $\text{eV cm}$. 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-distribution content is contained in the function $F(q, \omega)$.

The excitation spectra show resonances when $\varepsilon(q, \omega)$ 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, $F(q, \omega) = \Pi_0^d(q, \omega)$ = $\Pi_0^d(1 - V_q \Pi_0^d)$ as the strength of the SOI increases or the carrier concentration decreases, the excitation peak broadens and shifts to the low energy. When polarization $p = (n_e - n_n)/(n_e + n_n)$ (where $n_e$ 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 $\varepsilon$. These fine structures are only resolved if $\gamma$ is sufficiently large. The excitation spectra $\text{Im}[1/\varepsilon]$ 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 $\alpha k \delta$. For an excitation of at a given frequency, the required momentum transfer of the electron $q$ is less for a state with large $\alpha$. 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 hole shifts in the opposite direction. It is known that increasing $\alpha$ or decreasing $n_e$ leads to a larger polarization of...
As Figure 3 shows the variation of the relative intensity at the mode and a low frequency mode. The plasma dispersion and the holes are coupled, resulting in a high frequency plasmon layer and the hole layer, the plasmons of the electrons by the structure parameters. For systems with finite SOI, the positions and intensities of the two modes are predetermined for one component is significant in the regime where the particle-hole excitation of the other component is nonzero. Now the dominant contribution to the SOI 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 (β = 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 $H_p^a$ 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 $n_h$.

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

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