Spin-orbit interaction enhanced polaron effect in two-dimensional semiconductors

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It is shown that in two-dimensional semiconductors, the electron-phonon interaction and polaron mass correction are both significantly enhanced by the Rashba spin-orbit coupling. The mass correction is positive for the upper Rashba branch and negative for the lower Rashba branch. Both Rashba branches have the same polaron binding energy, which is higher than that for systems in the absence of spin-orbit interaction. To the leading order, the correction to the binding energy is proportional to the square of the spin-orbit coupling strength. © *2007 American Institute of Physics.*
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The recent advancement in spin electronics (spintronics) and spintronic materials[1] has provided opportunities in developing optoelectronic devices whose optical properties can be tuned by the intrinsic spin-orbit interaction. Spintronic material systems have been realized and many advanced electronic devices have been proposed recently, such as spin transistors,[2] spin waveguides,[3] spin filters,[4] etc. In narrow-gap semiconductor nanostructures, such as InAs and In$_{1-x}$Ga$_x$As quantum wells, the inversion asymmetry of the confining potential due to the presence of the heterojunction[5] results in the spin splitting (or spontaneous spin splitting) of the carriers in the absence of any applied magnetic field. Such an effect is similar to that under an inhomogeneous surface electric field. Therefore the inhomogeneous heterostructure confining potential is an electrical equivalence to the Rashba spin splitting or Rashba effect.[6] This confining potential can be further tuned with an applied gate voltage. Phenomena related to Rashba effects in, e.g., InAs- and In$_{1-x}$Ga$_x$As-based two-dimensional electron gas (2DEG) systems have been observed.[7,8] The value of the Rashba parameter in these semiconductor systems can be as high as 4 $\times 10^{-11}$ eV m. The experimental results[7,8] have shown that in InAs- and In$_{1-x}$Ga$_x$As-based 2DEG systems, the Rashba effect is responsible for the spontaneous spin splitting. Other contributions such as the Dresselhaus term can also be significant in systems with wide gaps, because they come mainly from the bulk-inversion asymmetry of the material.[9] We have shown recently that the spin-orbit interaction (SOI) can lead to a finite transverse electrical current in the absence of any magnetic field.[10] The SOI can also be used to produce spin polarized current in a magnetic superlattice.[11] Under the SOI, the optical spectral weight among various collective excitations[12] can be tuned.

Electron-phonon interaction plays an important role in a number of physical phenomena such as superconductivity, magnetophonon anomalies,[13] polaronic effect, localization, hot carrier transport,[14] and hypersound generation.[15] Electron longitudinal-optical (LO)-phonon scattering also plays a significant role in inelastic light scattering in semiconductor quantum wells because of the coupling between the LO phonons and the intersubband plasmons. In this letter we investigate the electron–LO-phonon interaction and the polaron effect in two-dimensional semiconductors with a Rashba SOI. Our results show that the polaron effect can be significantly enhanced by the SOI.

We consider a two-dimensional electronic system in the *x-y* plane in narrow-gap semiconductor nanostructures (e.g., InGaAs/InAlAs quantum wells). The Hamiltonian of a free electron is given as

$$H_0 = \frac{1}{2m^*}(p_x^2 + p_y^2) + \frac{\alpha}{\hbar}(\sigma_y p_x - \sigma_x p_y), \tag{1}$$

where m^* is the electron effective mass in the absence of electron-phonon interaction and SOI, α is the Rashba SOI parameter, σ_x and σ_y are Pauli spin matrices, and p_x and p_y are the electron momentum operators. p_x is taken to be along the [100] direction and p_y along the [010] direction; the wave function can be written in the form of $\psi(x,y) = u_{\mathbf{k}}(x,y)\xi_{k,\lambda}$, where $u_{\mathbf{k}}(x,y)$ is given by $u_{\mathbf{k}}(x,y) = \exp(ik_x x + ik_y y)$ because of translation invariance. The eigenvalue is

$$\varepsilon_\lambda^{(0)} = \frac{\hbar^2 k^2}{2m^*} + \lambda \alpha k, \tag{2}$$

with $k = \sqrt{k_x^2 + k_y^2}$ and $\lambda = \pm 1$. The corresponding eigenfunctions of spinors $\xi_{k,\lambda}$ are found to be

$$\xi_{k,\lambda} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -\lambda(k_y - ik_x)/k \end{pmatrix}. \tag{3}$$

Using these eigenfunctions the electron quantum field operators are constructed, $\hat{\Psi}(x,y) = \Sigma_{k,\lambda}\hat{a}_{\mathbf{k}\lambda}u_{\mathbf{k}}(x,y)\xi_{\mathbf{k}\lambda}$ and $\hat{\Psi}^\dagger(x,y) = \Sigma_{k,\lambda}\hat{a}_{\mathbf{k}\lambda}^\dagger u_{\mathbf{k}}^*(x,y)\xi_{\mathbf{k}\lambda}^*$, where $\hat{a}_{\mathbf{k}\lambda}$ ($\hat{a}_{\mathbf{k}\lambda}^\dagger$) is the creation (annihilation) operator for an electron with wave number $\mathbf{k}$ and spin state λ. The electron–LO-phonon interaction in semiconductors is modeled by the Fröhlich coupling,

$$H_{e\text{-ph}} = \sum_{k,\lambda} M(q)\hat{a}_{\mathbf{k}+\mathbf{q}\lambda}^\dagger \hat{a}_{\mathbf{k}\lambda}(\hat{b}_{\mathbf{q}} + \hat{b}_{-\mathbf{q}}^\dagger), \tag{4}$$

where $\hat{b}_{\mathbf{q}}^\dagger$ and $\hat{b}_{\mathbf{q}}$ are the creation and annihilation operators for the LO phonons. The coupling strength is given as $M(q) = \sqrt{2\pi e^2 \hbar \omega_{\text{LO}}/q(1/\epsilon_\infty - 1/\epsilon_s)}$. Here ϵ_∞ and ϵ_s are the

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90, 112103-1

high frequency and static dielectric constants of the semiconductor. The electron energy including the self-energy correction due to the electron–LO-phonon interaction is described by the Rayleigh-Schrödinger perturbation theory:[16]

$$\varepsilon_{\mathbf{k},\lambda} = \varepsilon_{\mathbf{k},\lambda}^0 - \sum_{\mathbf{q},\boldsymbol{\lambda}'} \frac{|M(q)|^2 |g^{\lambda,\lambda'}(\mathbf{k},\mathbf{k}+\mathbf{q})|^2}{\varepsilon_{\mathbf{k}+\mathbf{q},\lambda'}^0 - \varepsilon_{\mathbf{k},\lambda}^0 + \hbar\omega_{\mathrm{LO}}}, \tag{5}$$

where ω_{LO} is the frequency of the LO phonons and the structure factor is given by

$$|g^{\lambda,\lambda'}(\mathbf{k},\mathbf{k}+\mathbf{q})|^2 = \frac{1}{2}\left[1 + \lambda\lambda' \frac{k+q\cos\varphi}{\sqrt{k^2+q^2+2kq\cos\varphi}}\right].$$

The φ is the angle between the $\mathbf{k}$ vector and the $\mathbf{x}$ axis.

After introducing the following dimensionless parameters, we have $u=k/k_F(0)$, $z=q/k_F(0)$, $\Omega_{\mathrm{LO}}=2m_0\hbar\omega_{\mathrm{LO}}/\hbar^2 k_F^2(0)$, $k_\alpha=2m_0\alpha/\hbar^2$, $\alpha_s = (e^2/\hbar)\sqrt{m_0/2\hbar\omega_{\mathrm{LO}}}(1/\epsilon_\infty - 1/\epsilon_s)$, and $y=k_\alpha/k_F(0)$. The electron energy is then written as

$$\varepsilon_{\mathbf{u},\lambda} = \frac{\hbar^2 k_F^2(0)}{2m_0}\left[u^2 + \lambda \frac{k_\alpha}{k_F(0)}u + \delta\varepsilon\right], \tag{6}$$

where $\delta\varepsilon$ is the electron self-energy correction due to the electron–LO-phonon interaction, which is found as $\delta\varepsilon = -(\Omega_{\mathrm{LO}}^{3/2}\alpha_s/4\pi)\Sigma^\lambda(\mathbf{u})$ and $\Sigma^\lambda(\mathbf{u})=\Sigma_{\lambda'}\int_0^\infty dz\int_0^{2\pi}d\varphi|g^{\lambda,\lambda'}(\mathbf{u},\mathbf{u}+\mathbf{z})|^2/(\Omega_{\mathrm{LO}}+\varepsilon_{\mathbf{u}+\mathbf{z},\lambda'}^0 - \varepsilon_{\mathbf{u},\lambda}^0)$. This result contains only the leading order contribution in Rayleigh-Schrödinger perturbation theory for a single electron in either Rashba branch interacting with the polar lattice. The polaron binding energy is obtained as

$$E_0 = -\frac{\pi}{2}\alpha_s\hbar\omega_{\mathrm{LO}}\frac{1}{\sqrt{1-y^2/(4\Omega_{\mathrm{LO}})}}. \tag{7}$$

It is found that the polaron binding energy is enhanced in systems with finite SOI as compared to that in systems with zero SOI. The enhancement factor is $[\sqrt{1-y^2/(4\Omega_{\mathrm{LO}})}]^{-1}$. To the leading order of SOI, the energy enhancement $\Delta E \propto \alpha^2$. The correction to the free electron energy due to SOI is $\pm\alpha k$. The splitting of the original parabolic band into two Rashba bands provides an efficient channel for LO-phonon scattering via interlevel transitions. In addition, the linear energy correction makes the intralevel phonon scattering more efficient. This result, if confirmed experimentally, is very interesting. It demonstrates an intrinsic correlation between the electron-lattice coupling and the spin-orbit coupling.

The polaron effective mass is given as $1/m_{ij} = \partial^2\varepsilon/\partial k_i\partial k_j$. For a system with SOI, the effective mass is not constant even near the band minimum. The energy (or k) dependent effective mass is common to electrons and holes where the band dispersions are nonparabolic.[17,18] Such a nonparabolic dispersion can be caused by various interactions, e.g., high order electron-phonon interaction. In the present system, it is due to both the electron SOI and the electron-phonon interaction. From Eq. (6), the polaron effective mass is obtained,

$$\left(\frac{1}{m^*}\right)_{xx} = \frac{1}{2m_0}\frac{\partial^2}{\partial u_x^2}\left(u^2 + \frac{\lambda k_\alpha u}{k_F(0)} - \frac{\alpha_s\Omega_{\mathrm{LO}}^{3/2}\Sigma^\lambda(\mathbf{u})}{4\pi}\right). \tag{8}$$

In Fig. 1, we show the dependence of the inverse effective mass correction at $k=0$ on the Rashba SOI parameter. The dependence is almost linear. For the present system at
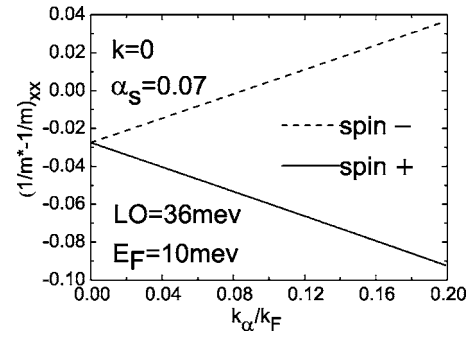

FIG. 1. Polaronic effective mass correction at $k=0$ as a function of the SOI strength.

zero SOI, the electron–LO-phonon interaction results in a polaron effective mass which is slightly heavier than the electron effective mass. The value at zero α in Fig. 1 represents this mass correction. The effective mass of the low Rashba band decreases with the SOI and that of the upper Rashba band increases with the SOI. The average of $1/m_{xx}^*$ (up) and $1/m_{xx}^*$ (down) represents the polaron effective mass in the absence of SOI. The variation of m_{xx}^* (up) and m_{xx}^* (down) with SOI can be understood as follows. Near $k=0$, electron-phonon interaction generally leads to a reduction of electron energy by an amount around the polaron binding energy. In terms of electron energy dispersion, this reduction in energy is equivalent to an increase in the effective mass. This is the polaron effect in the absence of the SOI. The situation with SOI is quite different. Near $k=0$, the effective mass of the Rashba bands are given as $1/m_{xx}^* = 1/m^* \pm \alpha k_y^2/2k^3$. Therefore, the electron effective mass of the upper band is reduced by the SOI but remains positive. The lighter effective mass makes the electron-phonon interaction more effective and as a result the polaronic mass correction is enhanced by the SOI (the solid line of Fig. 1). For the lower Rashba band the electron effective mass is heavier than that without SOI and the polaronic mass correction is smaller. Furthermore, in the case of sufficiently strong SOI, the electron effective mass can be negative. In this case lowering the energy further by the electron-phonon interaction actually reduces the effective mass. For the present system, this happens when $k_\alpha/k_F > 0.08$.

Unlike electrons in a parabolic band, the electron and polaron effective masses depend on the magnitude and the direction of wave vector k at small k. This k dependence is shown in Figs. 2 and 3. The θ is the angle between the $\mathbf{k}$ vector and the x axis. For the upper Rashba band, increasing k will show the interplay of two countereffects. On the one
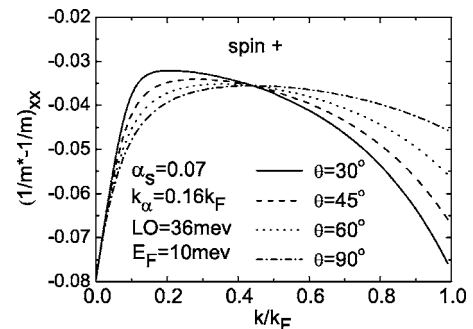

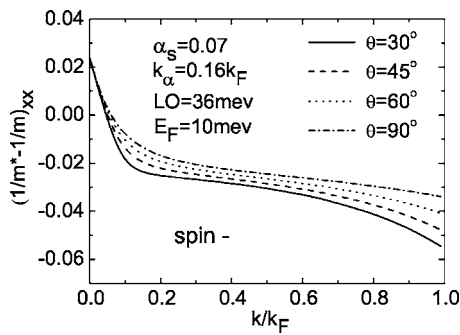FIG. 2. Wave number dependent polaronic effective mass correction for the upper Rashba band.

FIG. 3. Wave number dependent polaronic effective mass correction for the lower Rashba band.

hand, the linear-k term in the energy dispersion becomes less important as k increases and thus the polaronic mass correction is reduced. On the other hand, the polaronic mass correction due in a pure parabolic band[13] increases with k. As a result, the polaronic mass correction decreases with k in the small-k regime and increases with k in the large-k region. This behavior is shown in Fig. 2. For the lower Rashba band, the two effects mentioned above are not in a counterplay but rather support each other. As a result, the polaronic mass correction increases with k monotonically. This is shown in Fig. 3.

We suggest to perform far infrared magnetoabsorption measurements[19,20] on InAs quantum well structures in order to test the enhanced polaron effect reported here. The measurement of effective masses using the far infrared magneto-spectroscopy should reveal information about the interaction of an electron with the periodic potential as well as formation about electronic quasiparticles such as polarons. The SOI dependence of the polaron effect can be measured by varying the gate voltage.

In conclusion, we have shown that the SOI leads to quite different polaronic effect in two-dimensional semiconductors. The polaronic binding energy is enhanced by the SOI and the polaronic effective mass varies differently in different Rashba bands.

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