Aharonov-Bohm Magneto-Optical Spectroscopy and Photoluminescence of Spinor Excitons in Semiconductor Nano Rings

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Abstract: *We investigate the Aharonov-Bohm (AB) magneto-optical (MO) spectroscopy and the photoluminescence (PL) of excitons in semiconductor nano rings in the presence of Rashba and Dresselhaus spin-orbit interactions (SOI). With SOI, a blue shift is found for bright exciton region, in which PL intensity is rather depressed in subtle intervals due to spin conservation. The detection of AB effect represents a coherent circulation of excitons which may sustain dipole induced persistent charge and spin currents in the presence of SOIs. The system provides a prototype of a quantum switch and a current generator via coherent control of excitons in dark and bright regions.*

1. Introduction

More recently, the success on self-assembled formation of concentric quantum double rings (QDR) [1] provides a new system to explore electron dynamics by magneto-optical excitations which is essential for the eventual application in practical devices. The radius of flat double rings is about 100nm with thickness approximately 3nm. Therefore carriers are coherent all throughout these small geometries, and localization evidence of excitons in concentric QDRs would be revealed on PL images.

In semiconductor heterostructures, the Rashba SOI is caused by the structure inversion asymmetry of the confining potential of the 2D trapping well, whereas the presence of Dresselhaus SOI is due to the bulk inversion asymmetry and the interface inversion asymmetry. The contributions associated with RSOI and DSOI are remarkable compared to atomic systems and are adjustable through carrier concentrations hence make these nano structures bearing great potential in realizing spintronics.

In this project we investigated SOIs on MO properties of excitons in a semiconductor double-ring threaded by a perpendicular magnetic flux. While the AB effect of a neutral particle was naively suggested never to exist, experiments in recent years [2] nevertheless verify the theoretical predictions [3] and attract much attention to rethink about the phenomenon. From oscillatory MO and PL spectra, we found the coherent behavior of the exciton motion would directly determine the AB effect and classification of persistent currents. The main purpose of this work is to establish a theoretical approach that provides an opportunity in realizing quantum switch and current generator via coherent control of excitons with optical instrumentation.

2. Theoretical Models

The Hamiltonian of an exciton in a 2D QDR threaded by a perpendicular magnetic field with the presence of RSOI and DSOI can be written as

$$H_x = \frac{[-i\hbar\vec{\nabla}_e + \frac{e}{c}\vec{A}(\vec{r}_e)]^2}{2m_e^*} + \frac{[-i\hbar\vec{\nabla}_h - \frac{e}{c}\vec{A}(\vec{r}_h)]^2}{2m_e^*} + H_{\mathrm{zm}}^e + H_{\mathrm{zm}}^h + V_{\mathrm{trap}}^e + V_{\mathrm{trap}}^h + H_{\mathrm{soi}}^e + H_{\mathrm{soi}}^h + V_{\mathrm{coul}}\left(\vec{r}_e, \vec{r}_h\right), \quad (1)$$

in which $H_{\mathrm{zm}}^{e(h)}$ are Zeeman effects, $V_{\mathrm{trap}}^{e(h)}$ are trapping potentials,

$$H_{\mathrm{soi}}^e = \frac{\lambda_D}{\hbar}(p_e^x\sigma^x - p_e^y\sigma^y); \quad H_{\mathrm{soi}}^h = \frac{\lambda_R}{\hbar}\left(p_h^y\sigma^x - p_h^x\sigma^y\right) \quad (2)$$

are DSOI and SOI respectively, and $V_{\mathrm{coul}}\left(\vec{r}_e, \vec{r}_h\right)$ denotes Coulomb potential. The independent system can be diagonalized in the S_z subspace by applying unitary transformations setting

$$U = \exp[-i\frac{m_h^*}{\hbar^2}\lambda_R(y_h\sigma^x - x_h\sigma^y) - i\frac{m_e^*}{\hbar^2}\lambda_D(x_e\sigma^x - y_e\sigma^y)].$$

Then the wave functions of electron and hole are given by

$$\psi^u(\vec{r}_e) = [\phi_0^\uparrow(r_e) - i\frac{m_e^*}{\hbar^2}\lambda_D r_e e^{i\Phi_e}\phi_0^\downarrow(r_e)]e^{iM_e\phi_e},$$
$$\psi^d(\vec{r}_e) = [-i\frac{m_e^*}{\hbar^2}\lambda_D r_e e^{i\Phi_e}\phi_0^\uparrow(r_e) + \phi_0^\downarrow(r_e)]e^{iM_e\phi_e}, \quad (3)$$
$$\psi^u(\vec{r}_h) = [\phi_0^\uparrow(r_h) + \frac{m_h^*}{\hbar^2}\lambda_R r_h e^{-i\Phi_h}\phi_0^\downarrow(r_h)]e^{iM_h\phi_h},$$
$$\psi^d(\vec{r}_h) = [-\frac{m_h^*}{\hbar^2}\lambda_R r_h e^{-i\Phi_h}\phi_0^\uparrow(r_h) + \phi_0^\downarrow(r_h)]e^{iM_h\phi_h}. \quad (4)$$

In writing Eq. (3) and (4) we have assured the commutation property $[J_z, H] = 0$ in the rotation frame for both particles. Assuming the exciton wave function is to be constructed via linear combination of that of electron-hole pairs, the total system including Coulomb interaction is then solved in the exact diagonalization scheme.

The MO properties can be investigated firstly by

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calculating the transition rate $\Gamma_{i\to f} = \frac{e^2\eta^3\omega_{\alpha\beta}}{6\pi\hbar\epsilon c^3}|r_{\alpha\beta}|^2$, where $\omega_{\alpha\beta}$ is angular frequency between exciton eigenstates and $r_{\alpha\beta}$ is the matrix element under polarization operator

$$\hat{P}_{eh} = \sum_{\lambda\lambda'} \hat{e}_\lambda^\dagger \hat{h}_{\lambda'}^\dagger \int d\boldsymbol{R}\ F_\lambda^{*e}(\boldsymbol{R}) F_{\lambda'}^{*h}(\boldsymbol{R}) \int_{\substack{unit\\cell}} \mathrm{d}\boldsymbol{r}\ e\boldsymbol{r}\, u_c^*(\boldsymbol{r}) u_v(\boldsymbol{r}) \quad (5)$$

defined in terms of correlations between envelope functions and Bloch functions of conduction and valance bands. Eq. (5) indicates that the recombination of electron and hole to a vacuum state may be observed if the conditions of conservation of spin and orbital angular momenta are fulfilled which restrict possible contributors to PL spectrum provided that the angular momentum of exciton is zero and electron and hole possess opposite spins. And finally PL intensity in finite temperatures can be expressed as

$$I = \sum_j I_j e^{-E_j/k_BT} / \sum_j e^{-E_j/k_BT}, \qquad (6)$$

where I_j includes recombination from all open channels at some Φ. The circulation of charge particles may bring persistent currents and the charge and spin current densities can be written as

$$j_c(\boldsymbol{r}) = q\mathrm{Re}[\psi^\dagger(\boldsymbol{r})\, \hat{v}\, \psi(\boldsymbol{r})], \qquad (7)$$

$$j_s(\boldsymbol{r}) = \mathrm{Re}[\psi^\dagger(\boldsymbol{r})\, \hat{v}\hat{s}\, \psi(\boldsymbol{r})]. \qquad (8)$$

Consequently the circumference current is shown to be

$$I_\phi = 1/2\pi \int d\phi \int_{r_1}^{r_2} dr\, j_\phi(r).$$

In the 1D-ring, it is found that charge current is simply equivalently to the negative derivative of the eigen energies $I_n = -\partial E_n/\partial\Phi$. Then the measurement of periodic I_n is another manifestation of AB speciality.

3. Results and Discussions

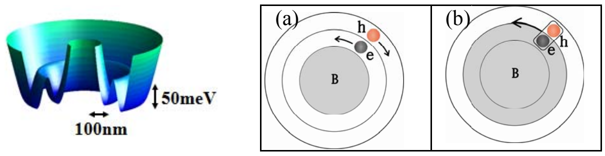

Fig.1 Sketch of the double-ring system representing (a) incoherent motion; (b) coherent motion

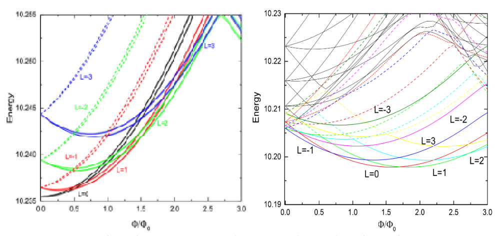

Fig. 2 Energy spectra of coherent-moving exciton in the absence or presence of SOIs

In Fig. 1 we show the sketch of the double-ring threaded by perpendicular magnetic flux. We found that if the electron and hole move incoherently, the resultant exciton ground state spectrum would oscillate periodically as a function of $\Phi_0 = \frac{\mathrm{hc}}{\mathrm{e}}$, but its angular momentum L_z is kept without varying, showing no predicted AB feature. On the contrary, the available creation of a coherent-moving exciton by tuning the field threading region do successfully bring us AB spectrum that was supposed impossible to occur for a neutral particle. But the mechanism behind can be conceived by viewing the exciton as a electric dipole moving in the magnetic field thus to acquire a geometric phase and is called the dual Aharonov-Casher effect [4]. We show in Fig. 2 the dimensionless MO spectra of the coherent-moving exciton in the absence or presence of SOIs. Here we also ground the energy gap $E_g = 430$meV of InAs.

The presence of magnetic field breaks the time-reversal symmetry but Kramer's degeneracy remains unaffected when even including SOIs. Therefore a two-fold degeneracy can be observed on single-particle spectrum. We found that SOIs not only blue shift the bright exciton region where $J_z = L_z = 0$ but split the energy levels in high magnetic fields. As a result, the PL intensity must be depressed in the presence of SOIs. Fig. 3 clearly verifies this argument. It should be addressed that SOIs favor down-spin exciton to occupy the ground state and therefore the weakly detected PL must come from the nearest spinless exciton. In Fig. 3 the finite temperature effect on PL intensity followed Eq. (6) is shown. The additional thermal energy allows the exciton recombination from higher spinless states and enlarges the bright regimes.

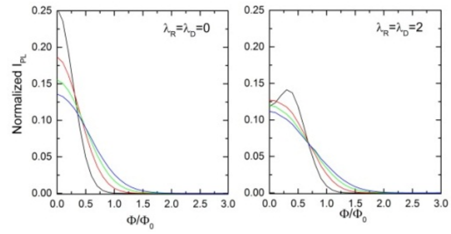

Fig. 3 Normalized PL spectra at T=0.05K(black), 0.1K(red), 0.15K(green), and 0.2K(blue)

It is worth of address that within appropriate modulation of trapping potentials and magnetic flux we are able to create alternating dark-bright regimes. Furthermore, by adjusting strengths of RSOI and DSOI, we are also capable to generate persistent spin currents. In this work we have theoretically analyzed the MO properties of a spinor exciton in the quantum rings and show that we are arriving at realizing optical switch via coherent control of exciton dynamics.

Acknowledgement

This work is supported partially by the Ministry of Science and Technology of Taiwan under grant NSC 101-2221-E-845-001-MY3.

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