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Effect of Rashba spin-orbit coupling on polaron properties in CdSe nanowire under electric field

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ABSTRACT

In the frame of Lee-Low-Pines variational theory the effect of the Rashba spin-orbit coupling (SOC) on the properties of the quasi-one-dimensional Fröhlich polaron in the weak and intermediate coupling limits of the electron-phonon interaction has been studied. Polaron self-energy and effective mass are numerically investigated for the free-standing CdSe nanowire as functions of the Rashba spin-orbit coupling parameter, the confining fequency, the electric field strength and the dielectric constant of the surrounding medium. Our results show that the Rashba SOC can be used as an effective means for controlling polaron states and therefore, we hope that the obtained results will stimulate further experiments in CdSe nanowires.

1. Introduction

Nanowires (NWs) have attracted much attention due to their unique properties [1] including ballistic transport, tunable band gaps, strong excitonic effects [2] and optical anisotropy [3]. The growing interest of the scientific community is caused by the possibility to use NWs in the construction of numerous classes of devices [4–9]. The researchers and scientists focus on the physical properties of CdSe NWs due to their unique opto-electrical properties, high length-diameter aspect ratio, and high surface-to-volume ratio. CdSe NWs have been successfully synthesized by various methods [10–13].

Spin-orbit coupling (SOC), enabling electrical manipulation of electron spin degree of freedom in semiconductor nanostructures, is crucial in the realization of spintronic devices [14]. For this purpose, the Rashba [15] and Dresselhaus [16] mechanisms of SO coupling of confined electrons are relevant to low-dimensional systems. Recently, the generation of Rashba SOC in the CdSe nanowire by ionic liquid gate has been reported [17]. Over the past years a lot of studies have focused on the role of SOC in the context of electron-polar optical phonon interaction in low-dimensional systems [18–24]. Particularly, it has been shown that when the spin-orbit coupling energy is larger than the phonon energy, the polaron retains only one of the spin-polarized bands in its coherent spectrum [18]. The results obtained in Refs. [19,20,24,25] illustrate that in low-dimensional semiconductors, both the electron-phonon interaction and Fröhlich polaron mass correction are significantly enhanced by the spin-orbit coupling.

In the present work, we utilize the Lee-Low-Pines variational method to clarify the effects of the Rashba spin-orbit coupling on the properties of the Fröhlich polaron in free-standing CdSe nanowire.

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Still, there are enough open questions and challenging problems in the polaronic states with spin-orbit interaction. Here we treat relevant physical problems, such as the dependencies of the self-energy and the effective polaron mass in spin-up and spin-down states in nanowire on the energy of the confining potential, the electric field strength and the dielectric constant of the surrounding medium. These problems which are interesting in view of optoelectronic applications, were not considered in Ref. [25]. In this work, the dependencies of the self-energy and the effective mass of a polaron in a free-standing nanowire on the Rashba parameter have been studied. A similar problem was considered in Ref. [25], assuming however that the nanowire is embedded in a dielectric medium, with a dielectric constant $\varepsilon_d = 2.5$. The main objective of this paper is to clarify the possibility of the control and manipulation of polaron states via spin-orbit coupling. Therefore, we present the polaron self-energy and effective mass dependencies on experimentally controllable agents such as external electric field strength, confining potential, Rashba spin-orbit coupling parameter and dielectric constant of surrounding médium. Assuming the weak or intermediate electron-phonon couplings, the Lee-Low-Pines method [26] for studing the polaron problem in a nanowire can be adopted. The analitical expressions for the polaron self-energy and effective mass have been obtained [25]:

$$E_{pol}^{self} = \sum_{sq\sigma} \frac{\left|\Gamma_{sq}^{\sigma}\right|^2 \left|P_{sq}^{\sigma}\right|^2}{\hbar\omega_\sigma + \frac{\hbar^2 q^2}{2m^*} - \lambda\alpha q}, \quad m_{pol} = \frac{m^*}{1 - \eta_{LO} - \eta_{IO}}, \tag{1}$$

where $\lambda = \pm 1$ is the chirality quantum number, α is the Rashba parameter, $\sigma = LO$ and $\sigma = IO$ denote the bulk-type and the interface-type optical phonon modes with one-dimensional wave number q and frequencies ω_{LO} and ω_{IO} [27], respectively. The index s is the set of quantum numbers ($m = 0, \pm 1, \pm 2, \cdots, l = 0, 1, 2, \cdots,$ for the bulk-type phonon and $m = 0, \pm 1, \pm 2, \cdots$ for the interface-type phonon),

$$P_{sq}^{\sigma} = \langle \zeta(\rho, \varphi) | G_{sq}^{\sigma}(\rho) e^{im\varphi} | \zeta(\rho, \varphi) \rangle, \tag{2}$$

$$\frac{\eta_\sigma}{1 - \eta_\sigma} = \sum_{sq} \frac{2\hbar^2 q^2}{m^*} \frac{\left|\Gamma_{sq}^{\sigma}\right|^2 \left|P_{sq}^{\sigma}\right|^2}{\left(\hbar\omega_\sigma + \frac{\hbar^2 q^2}{2m^*} - \lambda\alpha q\right)^3}, \tag{3}$$

$$G_{mlq}^{LO}(\rho) = J_m\left(\alpha_{ml}\frac{\rho}{R}\right), \quad G_{mq}^{IO}(\rho) = \begin{cases} K_m(qR) I_m(q\rho), & \rho \le R, \\ I_m(qR) K_m(q\rho), & \rho > R, \end{cases} \tag{4}$$

$J_m(x)$ is the Bessel function of the mth order, α_{ml} is the lth zero of $J_m(x)$, $K_m(x)$ and $I_m(x)$ are the first and second kind modified Bessel functions, respectively, $\zeta(\rho, \phi)$ is the electron lateral wave function of the ground-state [25]. $\Gamma_{ml}^{LO}(\Gamma_m^{IO})$ is the electron-bulk-type (interface-type) phonon interaction strength and given by Ref. [27].

$$\left|\Gamma_{ml}^{LO}(q)\right|^2 = \frac{4e^2 \hbar\omega_{LO}}{L\left(\alpha_{ml}^2 + R^2 q^2\right) J_{m+1}^2(\alpha_{ml})} \left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_s}\right), \tag{5}$$

$$\left|\Gamma_m^{IO}(q)\right|^2 = \frac{4e^2 \hbar\omega_{IO}}{L I_m(qR) K_m^2(qR) qR [I_{m-1}(qR) + I_{m+1}(qR)]} \left(\frac{1}{\varepsilon - \varepsilon_s} - \frac{1}{\varepsilon - \varepsilon_\infty}\right) \tag{6}$$

where ε_s and ε_∞ are the static and high frequency dielectric constants. The interface phonon frequency, ω_{IO}, is derived from Ref. [27].

$$\varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 - \frac{\omega_{IO}^2}{\omega_{TO}^2}} = -\frac{I_m(qR)[K_{m-1}(qR) + K_{m+1}(qR)]}{K_m(qR)[I_{m-1}(qR) + I_{m+1}(qR)]} \varepsilon_d, \tag{7}$$

where ω_{TO} is the transverse optical phonon frequency.

2. Numerical results and discussion

The main aim of the numerical calculations is to clarify the contributions of various phonon modes as well as the Rashba SOC to the energy of the electronic state and to the basic parameters of the polaron in CdSe nanowire. Here, we have assumed a lateral parabolic confinement for the electron in the wire with frequency ω. $R = \pi\sqrt{\hbar/2m^*\omega}$ is the nominal radius of the