Physica E 75 (2016) 330–335

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Influence of spin–orbit interactions on the polaron properties in wurtzite semiconductor quantum well

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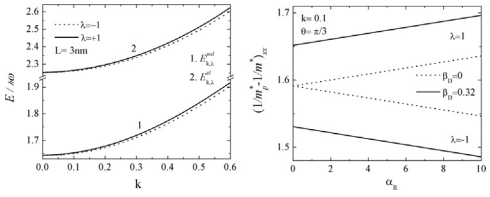
HIGHLIGHTS

- We have studied the effects of Rashba and Dresselhaus spin-orbit coupling on the polaron properties in wurtzite GaN quantum well.
- The electron-phonon interaction and polaron mass correction are both significantly enhanced by the spin-orbit coupling.
- For the interface optical phonon modes polaron self-energy takes the big values than for the confined optical phonon modes.
- The polaron effective mass exhibits anisotropy.
- The contribution of the Dresselhaus spin-orbit coupling term in the polaron effective mass is larger than Rashba one.

GRAPHICAL ABSTRACT

In this paper, we focus attention on the simultaneous effect of Rashba and Dresselhaus spin–orbit interactions on the polaron properties in wurtzite GaN/AlN semiconductor quantum well. The linear and cubic contributions of the bulk Dresselhaus SO coupling and the effects of phonon confinement on electron–PO phonon interaction Hamiltonians are taken into account. We have found analytical solutions for the polaronic states as well as polaron effective mass within the range of validity of perturbation theory. Fig. 1 The polaron (1) and electron (2) ground state energies as a function of the magnitude k in the presence of both SO coupling terms at $\lambda = \pm 1$. Fig. 2 Polaronic effective mass as a function of the Rashba (a) and Dresselhaus (b) SO interaction strength at $\lambda = \pm 1$.



ARTICLE INFO

Article history:
Received 23 July 2015
Received in revised form
16 September 2015
Accepted 21 September 2015
Available online 8 October 2015

Keywords:
Wurtzite nitride quantum wells
Polaron basic parameters
Rashba and Dresselhaus spin–orbit coupling terms

ABSTRACT

We have study the simultaneous effect of Rashba and Dresselhaus spin–orbit interactions on the polaron properties in wurtzite semiconductor quantum wells. The linear and cubic contributions of the bulk Dresselhaus spin–orbit coupling and the effects of phonon confinement on electron–optical-phonon interaction Hamiltonians are taken into account. We have found analytical solutions for the polaron energies as well as polaron effective mass within the range of validity of perturbation theory. It is shown that the polaron energy and effective mass correction are both significantly enhanced by the spin–orbit coupling. Wave number dependent phonon contribution on the electron energy has minima and varies differently of the spin-up and spin-down states. Polaron self-energy due to interface optical phonon modes has larger values than of the confined optical phonon modes ones. The polaron effective mass exhibits anisotropy and the contribution of the Dresselhaus spin–orbit coupling term on the polaron effective mass is dominated by Rashba one.

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http://dx.doi.org/10.1016/j.physe.2015.09.034
1386-9477/

1. Introduction

Wide band gap GaN, among other group-III–nitride-based semiconductors, has provoked a lot of interest in the past few years, largely due to the good optical properties as well as great potential in optoelectronics [1–5]. Although the pioneering work on the GaN wurtzite materials were implemented in the 1960s [6,7], most studies [8–14] of these materials increased dramatically only in the 1990s, after the demonstration of the light-emitting diodes using the GaN/$Al_xGa_{1-x}N$ semiconductors [8,9]. Recent years, big attention has been given to the spin dynamics in semiconductors, which is the key issue of semiconductor spintronics. Numerous studies have been focused on this emerging field of semiconductor physics [15–18]. It has been proposed a new type of spin transistor based on the special properties of the spin lifetime tensor due to the interplay between bulk inversion asymmetry and structure inversion asymmetry in the zinc-blende (ZB) [17] or wurtzite [18] quantum wells (QWs). In contrast to the ZB semiconductors, the existence of hexagonal c axis in wurtzite structures leads to an added intrinsic wurtzite structure inversion asymmetry in addition to the bulk inversion asymmetry [19,20]. Therefore, the electron spin splitting in wurtzite quantum wells is a result of the Dresselhaus and Rashba effects [21,22].

The spectrum of optical phonons in wurtzite-based low-dimensional structures becomes much more complex. A lot of works [23–37] have been devoted to the investigation of optical phonon modes in such structures based on the macroscopic dielectric continuum model (DCM) and uniaxial crystal model (UCM) of Loudon [23,24]. Particularly, the polar optical (PO) phonon confinement and dispersive spectra are investigated intensively in quasi-2-dimensional [25–27], quasi-1-dimensional [28,29], quasi-0-dimensional [30,31] and multi-layer wurtzite nitride quantum structures [32–37].

Nearly all of the theoretical and experimental investigations devoted spin properties have been carried out on materials with the ZB structure [38–43]; therefore the Dresselhaus and Rashba effects in such materials have been well understood. A lot of studies have focused on the role of spin–orbit (SO) coupling in the context of electron-PO phonon interaction. In [38–40], an enhancement of polaronic properties has been obtained for a two-dimensional electron gas with Rashba and Dresselhaus SO couplings. The results illustrate that the SO coupling terms may significantly affect the polaronic properties [40].

However, along this research direction there has also been work on wurtzite materials. Particularly, it is shown, that in bulk wurtzite structures, there are two wurtzite bulk inversion asymmetry effects; Dresselhaus effect which leads to a k^3 term and the wurtzite structure inversion asymmetry effect (which may be called as the Rashba effect) in bulk wurtzite which yields a linear-k term in the two-band $\mathbf{k}\cdot\mathbf{p}$ model [19,44]. The spin-splitting energies of the conduction band for ideal wurtzite materials are calculated [45] within the nearest-neighbor tight-binding method. It is found that ideal wurtzite bulk inversion asymmetry yields not only a spin-degenerate line but also a minimum-spin-splitting surface, which can be regarded as a spin-degenerate surface. The coefficients of the electron and hole Dresselhaus terms of ZnO and GaN in wurtzite structure and GaN in ZB structure are calculated using the nearest-neighbor and tight-binding models, respectively [46]. De and Pryor [47] calculated the band-structure parameters of several binary compounds which normally display the ZB structure in the bulk assuming that they have the wurtzite structure, in order to make them available for studies of wurtzite nanowires made of those same materials. Harmon et al. predict that QWs consisting of GaN/GaAlN wurtzite materials can be tuned to achieve very long spin lifetimes. These lifetimes are better for spin injection and transistor devices operating at mesoscopic length scales. They predict the longest spin lifetimes (0.5 ms) for AlN at room temperature [48]. In [49] has been derived the effect of the SO interaction on the electronic states and the acoustic-phonon-induced spin relaxation rates of cylindrical quantum dots defined on quantum wires having wurtzite lattice structure, taking into account the linear and cubic Dresselhaus SO couplings and a weak applied magnetic field.

In this paper, we focus attention on the simultaneous effect of Rashba and Dresselhaus spin–orbit interactions on the polaron properties in wurtzite GaN/AlN semiconductor quantum well. The linear and cubic contributions of the bulk Dresselhaus SO coupling and the effects of phonon confinement on electron–PO phonon interaction Hamiltonians are taken into account. Consideration of Fröhlich polaron states in the range of perturbation theory is justified, when electron–phonon coupling constant $\alpha < 1$ (in this case $\alpha = 0.4$). We have found analytical solutions for the polaronic states as well as polaron effective mass within the range of validity of perturbation theory.

2. Theory

We take the z axis along the direction of the crystallographic c axis, which is assumed to be perpendicular to the heterointerfaces. The width of the well is l and the z coordinates of the interfaces are $\mp l/2$. The Hamiltonian of a free electron is given as

$$H = H_{el} + H_{ph} + H_{el-ph}, \tag{1}$$

where H_{el} is the Hamiltonian of the electron without phonons and is written as [45,48,49]:

$$H_{el} = \frac{1}{2m^*}(p_x^2 + p_y^2) + V_c(z) + H_{SO} \tag{2}$$

$$H_{SO} = \left(\alpha_R - \gamma_D(k_\parallel^2 - bk_z^2)\right)(k_x\sigma_y - k_y\sigma_x) \tag{3}$$

where m^* is the electron effective mass in the absence of electron–phonon and SO couplings, p_x and p_y are the electron momentum operators, $V_c(z)$ is a nanoscale confinement potential, which confines the electrons only along the z direction, α_R is the Rashba [45] and γ_D and $b = 4.28$ Dresselhaus SO coupling parameters [46], $k_z^2 = \langle k_z\rangle^2 \approx (\pi/l)^2$ [48], σ_x and σ_y are Pauli spin matrices.

The well-known solution of eigenvalue problem of Hamiltonian H_{el} can be given as [38]:

$$\psi_{k,\lambda} = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\ -\lambda(k_y - ik_x)/k\end{pmatrix}\exp(ik_x x + ik_y y), \tag{4}$$

$$E_{k,\lambda}^{el} = E_k^0 + \lambda\left(\alpha_R - \gamma_e(k^2 - bk_z^2)\right)k, \tag{5}$$

where $E_k^0 = \frac{\hbar^2k^2}{2m^*}$, $k = |\mathbf{k}| = k_\parallel = \sqrt{k_x^2 + k_y^2}$ and $\lambda = \pm 1$.

The expressions and assumptions of the phonon spectra and electron–PO phonon interaction given follow are supported by many studies on the DCM and UCM of Loudon as surveyed extensively in [26,27], where the direction-dependent dielectric functions, $\varepsilon_\perp$ and ε_z are given by

$$\varepsilon_\perp(\omega) = \varepsilon_\perp^\infty\frac{\omega^2 - \omega_{TL}^2}{\omega^2 - \omega_T^2}, \tag{6}$$