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Polaronic effects due to quasi-confined optical phonons in wurtzite nitride nanowire in the presence of an electric field

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ABSTRACT

Considering the effect of an external electric field in wurtzite nitride cylindrical nanowire (NW), the polaron self-energy and effective mass due to the electron interaction with the quasi-confined optical phonons are studied theoretically by means of Lee–Low–Pines variational approach. The analytical expressions for the quasi-one-dimensional Fröhlich polaron self-energy and effective mass are obtained as functions of the wire radius and the strength of the electric field applied perpendicular to the wire axis. It is found that the main contribution to polaron basic parameters is from higher frequency optical phonon modes. The numerical results on the GaN material show that the polaron self-energy increases with the increase of the electric field and is more sensitive to the field when the wire radius is larger. It is also found that the polaron self-energy in GaN NWs is higher than that in zinc-blende GaAs-based cylindrical NWs.

1. Introduction

In recent years, a lot of effort has been devoted to the investigation of optical, electronic and lattice dynamical properties of quantum heterostructures based on the group III nitride semiconductors since

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the wide band gap, high carrier mobility, prominent thermal stability, and high optical efficiency make them an excellent candidate for optoelectronic devices operating in the green, blue, and ultraviolet spectral region [1–4]. Among the numerous studies of physical properties in nitride quantum structures with low-dimensionalities, the quasi-one dimensional nitride nanowires have attracted special interest [5–12]. This is mainly because the confinement of carriers in two directions and freedom in the third direction in NWs promise more efficient lasers and optical gain as well as possible applications for optical waveguide and photovoltaic cells in comparison with quantum wells and quantum dots. For example, the self-organized wurtzite GaN NW ultraviolet lasers have revealed a narrow emission linewidth and relatively low threshold [10,13,14]. The electron-optical phonon interaction has important influence on the physical properties of low-dimensional polar semiconductors. Due to the anisotropy of wurtzite crystal, the phonon modes and electron–phonon interactions in the wurtzite NWs are drastically different from those in cubic lattice NW systems [15–17]. The Raman scattering spectra of wurtzite GaN NWs have also shown more complicated phonon vibration properties than those in the zinc-blende planar and cylindrical heterostructures [18–20]. On the other hand, the polaron effect is one of the important issues affecting physical properties, such as the electronic self-trapped energy and effective mass, impurity and exciton binding energies, in nanostructures. These effects become more interesting in the presence of external fields.

A number of studies have focused on the various aspects of polaronic processes in quantum-well wires (QWR) (see e.g. [17,21–28]). Degani and Hipólito [21] have calculated the polaron self-energy (PSE) and the effective mass (PEM) in the GaAs/GaAlAs QWR using a variational approach which is based on the canonical transformation method of Lee, Low and Pines (LLP) [29]. It has shown that the PEM is dramatically dependent on the wire sizes and also larger than its values in corresponding two- and three-dimensional structures. Zhu and Gu [22] have studied the PSE due to the interaction of the electron with the LO-phonons that incorporate effects of phonon confinement in a rectangular QWR. They have found that in a very small wire the PSE has a peak at the beginning and then increases gradually to two-dimensional limit value as the wire expands in one direction while keeping fixed in the other direction. Using the LLP variational method Li et al. [23] have studied the basic parameters of the polaron ground state in a rectangular GaAs QWR under an additional parabolic potential. The PSE as well as the PEM in the cylindrical QWR have been investigated taking into account the size quantization of LO-phonons [24,25]. Xie [26] has considered a freestanding cylindrical QWR and obtained the PSE and correction to the electron effective mass due to electron–LO-phonon interaction and also electron–surface optical phonon interaction using the second-order perturbation theory and taking into account the contributions from higher energy subbands. Within the framework of Lee–Low–Pines–Huybrechts variational theory Krishna et al. [27,28] have investigated the polaronic binding energies corresponding to the ground state and the first excited state of an electron in a polar quantum wire with parabolic confinement in the transverse direction, and it has been shown that even the longitudinal PEM is strongly enhanced by the transverse confinement in a QWR. Recently, the ground state PSE and PEM due to the quasi-confined and surface optical phonon modes in a freestanding wurtzite GaN NW are studied by employing the second-order perturbation approach [17,30] and LLP variational approach [31]. The polaronic properties of the wurtzite 1D GaN NWs are compared with those of wurtzite GaN-based 2D quantum wells. The physical origins leading to these characteristics and their distinction in the different-dimensionality systems are analyzed [30,31].

The effects of external fields on general properties of low-dimensional polarons are important both from a fundamental and a device application point of view. In our previous works, we have studied the influence of external fields on Fröhlich polaron basic parameters focusing on the zinc-blende NW structures [32–36]. The free moving polaron properties in a rectangular GaAs and CdSe QWRs embedded in a polar matrix, in the presence of an external electric field applied along the growth direction are studied in [32,33], where the analytical expressions for the PSE, the PEM and the average number of virtual phonons are obtained without including the effect of phonon confinement. In [34] the influence of phonon confinement as well as of an electric field applied perpendicular to the cylindrical GaAs NW axis on the polaron basic parameters has been investigated. The influence of both electric and magnetic fields on the properties of confined and interface polarons in cylindrical CdSe nanowires with infinite [35] and finite [36] confining potentials is studied in detail. It is shown that the effects of