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Magnetic field induced diamagnetic susceptibility of a hydrogenic donor in a GaN/AlGaN quantum dot

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ABSTRACT

The binding energies of a hydrogenic donor in a GaN/AlGaN quantum dot are calculated in the influence of magnetic field. The calculations are carried out using the single-band effective mass approximation within a variational scheme. The magnetic field induced binding energy and diamagnetic susceptibility of the hydrogenic donor are obtained as a function of dot radius. Calculations have been carried out with and without the Zeeman effect through the energy-dependent effective mass. The diamagnetic shift of the hydrogenic donor is found for different dot radii. Our results show that (i) the binding energy is higher for smaller dot radii and the magnetic field effects are predominant for larger dot sizes, (ii) the binding energy is higher when the Zeeman effect is included for all the magnetic fields, (iii) the diamagnetic susceptibility increases with the magnetic field and is not pronounced for smaller dot radii and (iv) the diamagnetic shift has a good influence of larger dot radii.

1. Introduction

Quantum dots in which charge carriers (electrons and holes) are confined in all the three directions so a strong band-to-band emission can be achieved due to formation of quantum dots in the group-III N-based quantum structures [1]. GaN quantum dots have attracted significant attention as promising

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candidates for applications in optical, optoelectronic, and electronic devices. Group-III nitrides can be formed in a thermodynamically stable configuration with the wurtzite crystal structure and in the metastable modification with the zinc blende structure [2]. The reduction of bandgap occurs due to the spontaneous and piezoelectric polarization existing in a wurtzite quantum dot; on the other hand, due to the high crystal symmetry in the zinc blende structure, these features are negligible. A binding energy calculation of excitonic trions in spherical quantum dots with the quantum adiabatic theorem has been carried out by Baskoutas et al. [3,4] recently.

GaN can exist in either the wurtzite crystal structure with $a = 3.19$ Å and $c = 5.19$ Å or the zinc blende crystal structure with $a = 4.52$ Å and $c = 4.5$ Å. GaN and its alloys with Al and In have been the basic materials for short-wavelength photo-electronics, and high-power, high-temperature electronic devices and sensors. This is due to its large direct bandgap ($E_g = 3.5$ eV), high thermal stability, high electron mobility ($1000\ \mathrm{cm}^2/\mathrm{Vs}$), and other physical properties. At present, GaN based high-brightness blue and green light emitting diodes and low-power blue laser diodes are commercially available. GaN/AlGaN high electron mobility transistors have also shown promise for gas and liquid sensor applications for the following reasons: (i) they comprise a high electron sheet carrier concentration channel induced by both piezoelectric polarization of the strained AlGaN layer and the difference in spontaneous polarization between GaN and AlGaN and (ii) the carrier concentration strongly depends on the ambient [5–7]. In addition, sensors fabricated from these wide-bandgap semiconductors could be readily integrated with solar blind UV detectors or high-temperature, high-power electronics on the same chip. For these reasons, nitride high electron mobility transistors are compatibility devices that may be used for a variety of sensing applications.

The impurity plays an elementary role in some physical properties like optical, electrical and transport phenomena at low temperature. The main conception of the addition of impurities into the electronic states of semiconductor heterostructures lies in altering the performance of quantum devices. Recently, there has been an increasing attention in zinc blende GaN/AlN quantum dots due to the enhancement of their growth with sophisticated processes [8,9].

We have calculated the binding energies of a hydrogenic donor in a GaN/AlGaN quantum dot in the presence of magnetic field. The calculations are carried out with the single-band effective mass approximation within a variational scheme. The binding energy and diamagnetic susceptibility of the donor are obtained as a function of dot radius and magnetic field. The binding energy with and without the inclusion of the Zeeman effect has been computed through the energy-dependent effective mass. The diamagnetic shift is computed for different dot radii. In Section 2, we briefly describe the method and the quantum dot model used in our calculation. The results and discussion are presented in Section 3. A brief summary and results are presented in the last section.

2. Model and calculations

2.1. Binding energies

In the effective mass approximation, the Hamiltonian of an electron in a parabolic quantum dot in the presence of a magnetic field $\vec{B}$, along the z-direction, may be written as

$$H_D = \frac{1}{2m_i^*}\left(\vec{p} - \frac{e\vec{A}}{c}\right)^2 + V_D + H_{\mathrm{zee}} \tag{1}$$

where $V_D = \frac{V_0(B)r^2}{R^2}$ *for* $r < R$ *while* $V_D = V_0(B)$ *for* $r \geq R$, and V_0 (B) is the barrier height of the parabolic dot, which is taken to be 70% of the difference in the bandgap between GaN and $Al_xGa_{1-x}N$.

The electron effective mass m_i^* is given by

$$m_i^* = \begin{cases} m_{li}^* & r < R \\ m_{lli}^* & r \geq R \end{cases} \tag{2}$$

where m_{lj}^* denotes the effective mass of GaN and m_{llj}^* denotes the effective mass of the outer material, $Al_xGa_{1-x}N$. The material-dependent effective mass has been used in this calculation since it has a