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Electric field effect on the quadratic electro optic effects and electro absorption process in GaN/AlGaN spherical quantum dot

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ABSTRACT

In this paper the influence of electric field on quadratic electro optic effects (QEOE) and electro absorption (EA) process in spherical quantum dot are theoretically investigated. The third order nonlinear susceptibilities of GaN/AlGaN off centered defect spherical quantum dot are calculated by taking into account of the external electric field. The results show that electric field has important influence on the third order nonlinear susceptibilities. It is found that with increase of electric field quadratic electro optic effect and electro absorption process susceptibilities are varied semi sinusoidally and blue shifted. Results also show that the resonance wavelength of the third order susceptibility is decrease slowly in the greater electric field.

1. Introduction

Quantum dots have unique optoelectronic properties. So, they are mostly used for various applications such as medical science [1–4], quantum dot lasers [5–7], light emitting diodes (LEDs) [8], ultrafast all-optical modulator [9,10], infrared and THZ-IR photodetectors [11–14], photovoltaic devices [15] and quantum computing [16,17]. GaN and AlN are wide band gap III–V nitride semiconductors. Hence, they are mostly suitable to optoelectronic instruments fabrication.

There are very remarkable works in the literature about achieving high level optical nonlinear susceptibilities. Some of them are reviewed in the following. The authors of Ref. [18] review the hottest progress in GaN-based quantum devices for infrared optoelectronics applications. Also, they were debate about the development toward intersubband light emitters in nitride nanostructures.

A study of the third-order nonlinear optical susceptibility has been done in [19]. In this paper the third-order susceptibility for $In_xGa_{1-x}N/GaN$ cylindrical quantum dots has been investigated. The third-order susceptibilities corresponding to the intraband transition in the conduction band are calculated for wurtzite $In_xGa_{1-x}N/GaN$ strained cylindrical quantum dots. It is shown that the peak position and value of the nonlinear susceptibility is extremely dependent on the dots size.

The spherical centered defect quantum dot (SCDQD) and centered defect quantum box (CDQD) are proposed for enhancement of optical nonlinearity of GaN/AlGaN nanostructures in Refs. [20–22]. In these papers the proposed structures based on the effective mass approximation are studied and nonlinear optical properties of the introduced structures are investigated by using density matrix method. The authors have been shown that these nanostructures have high and adjustable nonlinear third order susceptibilities proper to optoelectronic instruments performance.

The authors of Refs. [23,24] are introduced a new off centered defect spherical quantum dot to manage nonlinear optical properties. They are shown that with control of GaN/AlGaN spherical quantum dot parameters unusual behavior is obtained. For example with increase of the well width, third order susceptibility is decreased but with more increasing the well width one observed increasing the nonlinear susceptibility. Also, in these references were shown that with varying of quantum dot structure one can be tuned magnitude and resonance wavelength of quadratic electro optic effects and electro absorption Process. Also, optimum values of system parameters are obtained for achieving maximum susceptibilities.

The aim of this study is investigated proposed GaN/AlGaN off centered defect spherical quantum dot from quadratic electro optic effect and electro-absorption process point of view. In this paper the effect of external electric field on the quadratic electro optic effect and electro-absorption process of GaN/AlGaN quantum dot is studied. The numerical results are shown that in the off centered defect spherical quantum dot resonance wavelengths of third-order nonlinear susceptibilities are blue shifted by increasing electric field.

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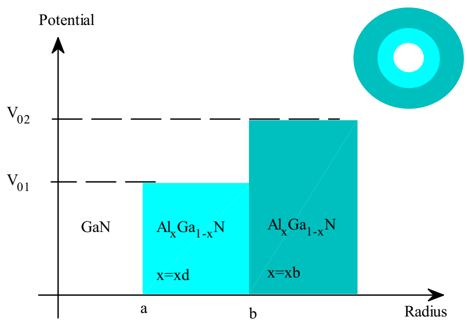

Fig. 1. Structure of spherical quantum dot and related potential distribution.

This paper is organized in the following way. In Section 2 the theoretical model and mathematical background of third order nonlinear susceptibility is briefly explained. Section 3 is devoted to the numerical results and discussion. Finally main conclusions of this work are summarized in the last section.

2. Theory

In this section mathematical background of the third order nonlinear properties of GaN/AlGaN off-centered defect spherical quantum dot is presented. The shape of off-centered defect spherical quantum dot and potential distribution are shown in Fig. 1. There are three region consisting of a spherical well (with radius a), an off-centered defect shell (with thickness b–a) and an outer barrier (with radius b). The proposed spherical off-centered defect quantum dot can be performed by adjust of Aluminum mole fraction.

In this paper the potential in the well region is supposed zero and the potential difference between two materials is constant. There are various methods to exploration of the electronic structures of quantum dot systems [25–27]. The effective mass approximation is employed in this study. The Hamiltonian for an electron in a spherical off-centered defect quantum dot under an electric field $\vec{F}$ has the form

$$H = -\frac{\hbar^2}{2}\nabla\left(\frac{1}{m_i{}^*}\nabla\right) + V_i(r) + e\vec{F}.\vec{r} \tag{1}$$

where the first term is the kinetic energy operator for a effective mass [28]:

$$m_i^* = \begin{cases} m_1^* = 0.228m_e & 0<r<a \\ m_2^* = (0.252xd + 0.228)m_e & a<r<b \\ m_3^* = (0.252xb + 0.228)m_e & b<r \end{cases} \tag{2}$$

and $V_i(r)$ represents the potential in different regions.

$$V_i(r) = \begin{cases} 0 & 0<r<a \\ V_{01} = \Delta E_c(xd) & a<r<b \\ V_{02} = \Delta E_c(xb) & b<r \end{cases} \tag{3}$$

where xd and xb are aluminum molar fraction of defect and barrier region, respectively. The rest mass of electron is denoted by m_e and conduction band offset is $\Delta E_c(x) = 0.7 \times \left[E_g(x) - E_g(0)\right]$ [28]. The band gap energy of $Al_xGa_{1-x}N$ is taking $E_g(x) = 6.13x + (1-x)(3.42-x)(\text{eV})$ [28,29]. The third term in Hamiltonian is denoted electrostatic energy of an electron in external electric field. In this paper the second-order perturbation theory is employed for taking electric field effect.

The third-order susceptibility for two energy levels can be calculated [30,31] after determining the eigenvalues and wave functions associated with the Hamiltonian Eq. (1). Thus, the nonlinear optical susceptibility consequent to optical mixing between two incidents light fields with frequencies ω_1 and ω_2 can be obtained under the density matrix method. The third order nonlinear susceptibility is given by [30–33]:

$$\chi^{(3)}(-2\omega_1+\omega_2;\omega_1,\omega_1,-\omega_2) = \frac{-2iNq^4\left|\alpha_{fg}\right|^4}{\varepsilon_0\hbar^3} \times \left[\frac{1}{[i(\omega_0-2\omega_1+\omega_2)+\Gamma][i(\omega_2-\omega_1)+\Gamma]}\right] \times \left[\frac{1}{i(\omega_0-\omega_1)+\Gamma} + \frac{1}{i(\omega_2-\omega_0)+\Gamma}\right] \tag{4}$$

where q is electron charge, N is carrier density, $\alpha_{fg} = \langle\psi_f\,|r|\,\psi_g\rangle$ indicates the dipole transition matrix element, $\omega_0 = \left(E_f - E_g\right)/\hbar$ is resonance frequency between first excited and ground states (transition frequency) and Γ is relaxation rate. For calculation of third order susceptibility of quadratic electro optic effect (QEOE), we take $\omega_1 = 0$, $\omega_2 = -\omega$ in Eq. (4). The third order nonlinear optical susceptibility $\chi^{(3)}(-\omega, 0, 0, \omega)$ is a complex function. The nonlinear quadratic electro optic effect (DC-Kerr effect) and electro absorption (EA) frequency dependence susceptibilities are related to the real and imaginary part of $\chi^{(3)}(-\omega, 0, 0, \omega)$ [34–36].

$$\begin{cases} \chi^{(3)}_{\text{QEOE}}(\omega) = Re\left[\chi^{(3)}(-\omega,0,0,\omega)\right] \\ \chi^{(3)}_{\text{EA}}(\omega) = Im\left[\chi^{(3)}(-\omega,0,0,\omega)\right] \end{cases} \tag{12}$$

These nonlinear susceptibilities are important characteristics for photoemission or detection applications of quantum dots. In the next section results of numerical calculation of these susceptibilities are presented and discussed.

3. Numerical results and discussion

In this section the results of electric field effects on quadratic electro optic effect and electro-absorption process of the proposed off-centered defect spherical quantum dot are presented. The Schrödinger equation with the Hamiltonian given by Eq. (1) was solved numerically by a finite element method. Some parameters of the material used in this paper are taken as follows. The number density of carriers is $N = 1 \times 10^{24}\,\text{m}^{-3}$, electrostatic constant is $\varepsilon = (-0.3x + 10.4)\varepsilon_0$ and typical relaxation time is 15 ps [28,29]. The external electric field is varied from zero to hundred kV/cm [37,38]. In this work two quantum dot structure with well radiuses 15 and 30 Å are considered. The dot size of both structures is 75 Å, and aluminum molar fractions of defect and barrier regions are taken 0.05 and 0.1, where corresponding to 0.062 and 0.127 eV defect and dot potential, respectively.

The quadratic electro optic effect and electro absorption process susceptibilities of 15 Å well width spherical quantum dot versus pump photon wavelength are demonstrated in Fig. 2. In this figure the external electric field is changed as parameter. It is clear that with increase of the external electric field both QEOE and EA susceptibilities are shown same behavior. It is observed that with increase of electric field QEOE and EA susceptibilities are varied semi sinusoidally and blue shifted. These behaviors can be related to quantum confinement effect.

The third order susceptibility of 15 Å well width spherical off-centered defect quantum dot as a function of pump photon wavelength is illustrated in Fig. 3. The resonance wavelength of third order susceptibility is blue shifted by increasing electric field. The amplitude of third order susceptibility is varied semi sinusoidally similar to QEOE and EA susceptibilities. So, the resonance wavelength and magnitude of third order susceptibility can be managed by applying and varying electric field.