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Research paper

Influence of anisotropy and position-dependent effective mass on electro-optic effect of impurity doped quantum dots in presence of Gaussian white noise

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ABSTRACT

We study the modulation of *electro-optic effect* (*EOE*) of impurity doped QD under the influence of *geometrical anisotropy* and *position-dependent effective mass* (*PDEM*) in presence of *Gaussian white noise*. Always a comparison has been made between *fixed effective mass* (*FEM*) and PDEM to understand the role of the latter. In addition, the role of mode of application of noise (additive/multiplicative) has also been analyzed. The EOE profiles are found to be enriched with *shift of peak position* and *maximization of peak intensity*. The observations reveal sensitive interplay between noise and anisotropy/PDEM to fine-tune the features of EOE profiles.

1. Introduction

Low-dimensional semiconductor systems (LDSS) such as quantum wells (QWLs), quantum wires (QWRs) and quantum dots (QDs) are widely acclaimed for their remarkably large nonlinear optical (NLO) properties. Extremely large quantum confinement effect prevailing in LDSS favors such elevated nonlinear effects and the said confinement comes out to be much stronger in comparison with the bulk materials [1]. Such strong confinement in LDSS gives rise to small energy separation between the subband levels and large value of electric dipole matrix elements. These two factors promote achievement of resonance conditions. Such enhanced NLO properties of LDSS assume immense importance in probing the electronic structure of mesoscopic media [2], application of electronic and optoelectronic devices in the infra-red region of the electromagnetic spectrum [3,4], exploring the area of integrated optics and optical communications [5], fabricating many optoelectronic devices such as far-IR laser amplifiers, photo-detectors, and high-speed electro-optical modulators [6,7] and most significantly, understanding and appreciation of fundamental physics.

Among the various NLO properties, the *second-order* nonlinear processes e.g. *nonlinear optical rectification* (*NOR*), *second harmonic generation* (*SHG*), and *electro-optical effect* (*EOE*) have drawn much more serious attention over that of other NLO properties. This is because the second-order nonlinear processes are the simplest *lowest-order* nonlinear processes having magnitude greater than the higher-order ones for quantum systems exhibiting significant asymmetry [8]. The second-order nonlinear susceptibility vanishes in symmetric systems because of forbidden optical transitions between the electronic states of same parity [3]. In general *even-order* susceptibilities disappear in a symmetric quantum well structure and only a marginal contribution from bulk susceptibility survives. Therefore, it needs total removal of the symmetry of the confinement potential for generation of a strong second-order optical nonlinearity [3,9,10]. Thus, in order to achieve desired finite second-order susceptibilities, tunable asymmetry of the confinement potential is of prime importance [6]. In general, these asymmetries in the confinement potential can be obtained in two ways, one is by using the advanced material growing technology such as molecular beam epitaxy (MBE) and metal–organic chemical vapor deposition (MOCVD), and the other is by the application of an electric field to the system. The second-order NLO effects actually undergoes profound enhancement with increase in the magnitude of the electric field.

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Of late, we use to find a lot of important works on second-order EOE of LDSS by Guo et al. [2], Zhang and Xie [11], and Yu and Guo [12]. Guo et al. have studied in great detail the role played by the applied magnetic field in modulating EOE [2]. The emphasis originates because of the fact that the NLO properties of a material can be altered in presence of a magnetic field. The changes in refractive index as a functions of the applied magnetic field are responsible for many electro-optic effects. Physically, electro-optic effects result from both ionic or molecular movement and distortion of electronic cloud induced by the applied magnetic field. Thus, EOEs have been extensively used as optical modulators [2].

Introduction of impurity (dopant) into LDSS invites profound interplay between the dopant potential with the confinement potential of LDSS, which, in turn, modifies the energy level distribution. Such modification, in effect, severely affects the electronic and optical properties of LDSS. Thus, a controlled inclusion of dopant could be prudent in achieving desirable optical transitions. Such desirable optical transition has become an integral part of manufacturing optoelectronic devices with tunable emission or transmission properties and ultranarrow spectral linewidths. This has largely opened up new paradigms of technological applications of LDSS. Moreover, the close link between the optical transition energy and the confinement strength (or the quantum size) can eventually fine-tune the resonance frequency. In what follows, optical properties of doped LDSS have witnessed research activities in full swing [13–37].

Of late, we witness a few important studies which deal with influence of *geometrical anisotropy* on the optical properties of LDSS. Among them the important works of Xie and his coworkers [38–40] and Safarpour et al. [41,42] merit citation. In practice, in most cases LDSS are not at all isotropic which justifies the requirement of understanding how anisotropy influences their optical properties. In practice anisotropic QDs can be manufactured by chemically controlling the nanostructure aspect ratio [39]. Thus, study of anisotropic systems has generated sufficient interest in view of obtaining novel as well as useful devices.

Recently, we also envisage a substantial number of investigations which deal with *position-dependent effective mass* (*PDEM*) of LDSS. PDEM leads to considerable change in the binding energy of the doped system and thus alters the optical properties. Such change in the optical properties has induced sincere research activities on LDSS with spatially varying effective mass in recent years. In this respect the works of Rajashabala and Navaneethakrishnan [43,44], Peter and Navaneethakrishnan [45], Khordad [46] and Peter [47] deserve mention.

In one of our very recent works we have made thorough discussions on how *Gaussian white noise* modifies the *second-order electro-optic effect* (*EOE*) susceptibility of doped QD [48] where the profiles of EOE coefficients are meticulously monitored with variations of confinement frequency, electric field strength, dopant location, magnetic field strength, impurity potential, relaxation time, noise strength, *Al* concentration and the mode of application of noise (additive/multiplicative). We have also investigated the interplay between noise and anisotropy [49] and between noise and PDEM [50] in view of a few NLO properties. However, despite a thorough literature survey we have not found any study that deals with influence of noise on EOE under the purview of anisotropy and/or PDEM. We, therefore, in the present work, explore the influence of *geometrical anisotropy* and *PDEM* on *EOE* of doped QD in presence of *Gaussian white noise*. The EOE profiles are monitored as a function of frequency of incident radiation, for different extents of geometrical anisotropy (to understand the anisotropy effect) and simultaneously with *fixed effective mass* (*FEM*) and *dopant position-dependent effective mass* (*PDEM*) (to understand the role of PDEM). Moreover, the influence of pathway of application of noise (additive/multiplicative) has also been explored for a comprehensive analysis.

2. Method

The impurity doped QD Hamiltonian, subject to external static electric field (F) applied along x and y-directions and spatially δ-correlated Gaussian white noise (additive/multiplicative) can be written as

$$H_0 = H_0' + V_{imp} + |e|F(x+y) + V_{noise}. \tag{1}$$

Under effective mass approximation, H_0' represents the impurity-free 2-d quantum dot containing single carrier electron under lateral parabolic confinement in the $x-y$ plane and in presence of a perpendicular magnetic field. $V(x,y) = \frac{1}{2}m^*\omega_0^2(x^2+y^2)$ is the confinement potential with ω_0 as the harmonic confinement frequency. H_0' is therefore given by

$$H_0' = \frac{1}{2m^*}\left[-i\hbar\nabla + \frac{e}{c}A\right]^2 + \frac{1}{2}m^*\omega_0^2(x^2+y^2). \tag{2}$$

m^* represents the effective mass of the electron inside the QD material. Using Landau gauge [$A = (By,0,0)$, where A is the vector potential and B is the magnetic field strength], H_0' reads

$$H_0' = -\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) + \frac{1}{2}m^*\omega_0^2x^2 + \frac{1}{2}m^*(\omega_0^2+\omega_c^2)y^2 - i\hbar\omega_c y\frac{\partial}{\partial x}, \tag{3}$$

$\omega_c = \frac{eB}{m^*}$ being the cyclotron frequency. $\Omega^2 = \omega_0^2 + \omega_c^2$ can be viewed as the effective confinement frequency in the y-direction. Following the notable works of Xie the ratio $\eta = \frac{\Omega}{\omega_0}$ could be defined as the *anisotropy parameter* [38,39].

V_{imp} is the impurity (dopant) potential represented by a Gaussian function [34,48–50] viz. $V_{imp} = V_0\, e^{-\gamma[(x-x_0)^2+(y-y_0)^2]}$ with $V_0 > 0$ and $\gamma > 0$. (x_0, y_0), V_0 and γ^{-1} represent the site of dopant incorporation, the dopant potential and the spatial spread of impurity potential, respectively. γ can be written as $\gamma = k\varepsilon$, where k is a constant and ε is the static dielectric constant of the medium. The dopant location-dependent effective mass $m^*(r_0)$ where $r_0 = \sqrt{x_0^2+y_0^2}$ is given by [43,45]

$$\frac{1}{m^*(r_0)} = \frac{1}{m^*} + \left(1 - \frac{1}{m^*}\right)\exp(-\beta r_0), \tag{4}$$

where β is a constant chosen to be 0.01 a.u. The choice of above form of PDEM indicates that the dopant is strongly bound to the dot confinement center as $r_0 \to 0$ i.e. for on-center dopants whereas $m^*(r_0)$ becomes highly significant as $r_0 \to \infty$ i.e. for far off-center dopants.

The term V_{noise} represents the participation of noise to the Hamiltonian H_0. It consists of a spatially δ-correlated Gaussian white noise $[f(x,y)]$ which maintains a Gaussian distribution (generated by Box-Muller algorithm) having strength ζ and is described by the set of conditions [48–50]:

$$\langle f(x,y)\rangle = 0, \tag{5}$$

the zero average condition, and

$$\langle f(x,y)f(x',y')\rangle = 2\zeta\delta((x,y)-(x',y')), \tag{6}$$

the spatial δ-correlation condition. The Gaussian white noise has been applied to the system by means of two different modes (pathways) i.e. additive and multiplicative [48–50]. In case of additive white noise V_{noise} becomes