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Exploring electro-optic effect of impurity doped quantum dots in presence of Gaussian white noise

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ABSTRACT

We explore the profiles of electro-optic effect (EOE) of impurity doped quantum dots (QDs) in presence and absence of noise. We have invoked Gaussian white noise in the present study. The quantum dot is doped with Gaussian impurity. Noise has been administered to the system additively and multiplicatively. A perpendicular magnetic field acts as a confinement source and a static external electric field has been applied. The EOE profiles have been followed as a function of incident photon energy when several important parameters such as electric field strength, magnetic field strength, confinement energy, dopant location, relaxation time, Al concentration, dopant potential, and noise strength possess different values. In addition, the role of mode of application of noise (additive/multiplicative) on the EOE profiles has also been scrutinized. The EOE profiles are found to be adorned with interesting observations such as *shift of peak position* and *maximization/minimization of peak intensity*. However, the presence of noise and also the pathway of its application bring about rich variety in the features of EOE profiles through some noticeable manifestations. The observations indicate possibilities of harnessing the EOE susceptibility of doped QD systems in presence of noise.

1. Introduction

The fascinating role played by impurity in designing the electronic and optical properties of low-dimensional semiconductor devices has garnered widespread recognition. Investigations on impurity states have been further augmented because of their importance in physics and technological applications of quantum dots (QDs). Impurity causes substantial change in the spatial disposition of the energy levels of doped QD system and helps attainment of desirable optical transitions. A well-harnessed optical transition is an integral part of designing optoelectronic devices with tunable emission or transmission properties and ultranarrow spectral linewidths. Furthermore, the adjacency of the optical transition energy and the confinement strength (or the quantum size) allows fine-tuning of the resonance frequency. As a natural follow-up, optical properties of doped QDs and other low-dimensional systems have visualized broad research activities [1–34].

Nonlinear optical (NLO) properties of semiconductor QDs and quantum wells (QWLs) possess profound capacity to be utilized as a probe for the electronic structure of mesoscopic media. Far-infrared spectroscopy of these systems provides the opportunity to study their internal excitation [35]. Moreover, NLO properties of low-dimensional materials appear prolific for application in electronic and optoelectronic devices in the infra-red region of the electromagnetic spectrum [36,37]. The NLO properties connected with intersubband transitions in low-dimensional systems illuminate important fundamental physics. The illumination occurs owing to the profound escalation of the nonlinear effects in these low-dimensional quantum systems over those in bulk materials exploiting quantum confinement effect [38]. The said confinement favors small energy separation between the subband levels, large value of electric dipole matrix elements and greater scope for the establishment of resonance conditions. Production of large optical nonlinearities accompanying the intersubband transitions of QD appears highly pertinent in the domain of integrated optics and optical communications [39,40]. In what follows, these nonlinear properties have become the cornerstone of fabricating many optoelectronic devices such as far-IR laser amplifiers, photo-detectors, and high-speed electro-optical modulators [41–43].

Among the NLO properties much attention has been devoted to

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the *second-order* nonlinear processes, e.g. *nonlinear optical rectification (NOR)*, *second harmonic generation (SHG)*, and *electro-optical effect (EOE)* over that of other NLO properties. This is because the second-order nonlinear processes are the simplest and the *lowest-order* nonlinear processes with enhanced magnitudes compared with the higher-order ones if the quantum systems are enriched with significant asymmetry [44,45]. Indeed, the second-order nonlinear susceptibility gets completely eliminated in symmetric systems as because optical transitions between the electronic states with the same parity are forbidden [37]. In general, *even-order* susceptibilities disappear in a symmetric quantum well structure and only a small contribution from bulk susceptibility persists. Therefore, in order to generate a strong second-order optical nonlinearity, the inversion symmetry of the quantum systems should be annihilated [37,44,46,47]. 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 through the introduction of an electric field to the system [44]. The second-order NLO effects actually undergoes pronounced enhancement with increase in the magnitude of the electric field.

In recent times we have come across some important studies on second-order EOE by Guo et al. [35], Zhang and Xie [48], and Yu and Guo [49]. Guo et al. also put special emphasis on the role played by the applied magnetic field in modulating EOE [35]. The emphasis originates because of the fact that the NLO properties of a material can be modified 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. These effects can be conceived as nonlinear optical mixing effects in the limit where one of the electromagnetic field components is having either zero or vanishingly small frequency. Physically, electro-optic effects result from both ionic or molecular movement and deformation of electronic cloud induced by the applied magnetic field. Thus, EOEs have been widely used as optical modulators [35].

In some of our recent works we have made thorough discussions on how *noise* modifies the optical properties of QD devices [50–52]. In these works the role of *Gaussian white noise* on the *polarizabilities* of doped QDs has been rigorously explored. In the current paper we make an exhaustive analysis of the influence of *Gaussian white noise* on the *second-order electro-optic effect (EOE)* susceptibility of doped QD. The system under investigation is a 2-d QD (GaAs) consisting of single carrier electron under parabolic confinement in the x–y plane. The QD is doped with an impurity represented by a Gaussian potential in the presence of a perpendicular magnetic field which provides additional confinement. An external static electric field has also been applied to the system. Gaussian white noise has been administered to the doped QD via two different pathways, i.e. additive and multiplicative [50–52]. It needs to be mentioned that the static electric and/or magnetic fields, and possible impurities are important means for fine-tuning the electronic and optical properties in semiconductor QDs. Recently, Zeng et al. have systematically addressed the impurity-related properties under the combined effects of the static fields [53,54]. In the present work the profiles of EOE coefficients are meticulously monitored with variations of confinement frequency (ω_0), electric field strength (F), dopant location (r_0), magnetic field strength (B), impurity potential (V_0), relaxation time (τ), noise strength (ζ), and the mode of application of noise (additive/multiplicative). In addition, $Al_xGa_{1-x}As$ QD has also been explored in order to inspect the role played by Al concentration (x) on the profiles of EOE coefficients in presence and absence of noise.

2. Method

The impurity doped QD Hamiltonian, exposed 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 with single carrier electron arrested by 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^* stands for 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

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

$\omega_c = eB/m^*$ being the cyclotron frequency. $\Omega^2 = \omega_0^2 + \omega_c^2$ can be envisaged as the effective confinement frequency in the y-direction.

V_{imp} is the impurity (dopant) potential formulated by a Gaussian function [50–52] viz. $V_{imp} = V_0\, e^{-\gamma[(x-x_0)^2+(y-y_0)^2]}$. Positive values for γ and V_0 represent repulsive impurity. (x_0, y_0) is the site of dopant inclusion, V_0 is the strength of the dopant potential, and γ^{-1} represents the spatial region over which the influence of impurity potential is disseminated. γ here acts equivalent to that of static dielectric constant (ε) of the medium and can be written as $\gamma = k\varepsilon$, where k is a constant. At this point of discussion we would like to mention that Khordad and his co-workers used a new type of confinement potential for spherical QD's called *modified Gaussian potential, MGP* [55,56]. It needs to be mentioned here that we have neglected the dielectric mismatch effect as an approximation. However, if one desires to use the results presented herein to have an approximate idea about EOE in some other material systems (e.g. colloidal quantum dot-matrix systems where high dielectric mismatch exists), the local field effect will be very important and should be carefully taken into account [57].

The term V_{noise} represents the noise contribution to the Hamiltonian H_0. It comprises of a spatially δ-correlated Gaussian white noise $[f(x, y)]$ which assumes a Gaussian distribution (generated by Box–Muller algorithm) having strength ζ and is described by the set of conditions [50–52]:

$$\langle f(x, y)\rangle = 0, \tag{4}$$

the zero average condition, and

$$\langle f(x, y)f(x', y')\rangle = 2\zeta\delta\big((x, y) - (x', y')\big), \tag{5}$$

the spatial δ-correlation condition. The Gaussian white noise can be applied to the system by means of two different modes (pathways), i.e. additive and multiplicative [50–52]. These two different modes actually modulate the extent of system–noise interaction. In case of additive white noise V_{noise} becomes

$$V_{noise} = \lambda_1 f(x, y). \tag{6}$$

And with multiplicative noise we can write