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Role of carrier density on the nonlinear optical properties of doped quantum dots under the supervision of noise

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ABSTRACT

Present work studies the profiles of a few nonlinear optical (NLO) properties of doped GaAs quantum dot (QD) with special stress on the role played by carrier density under the governance of noise. Noise employed here is a Gaussian white noise and it has been added to the system via two different approaches; additive and multiplicative. Variation of carrier density particularly affects the peak height of the NLO properties. Introduction of noise brings about some remarkable changes in the profiles of NLO properties over the entire range of variation of carrier density. These changes, however, depend on the pathway by which noise has been applied and also on the noise strength. The interplay between carrier density and noise gives rise to some interesting observations that possess relevance in the related field of research.

1. Introduction

Low-dimensional semiconductor systems (LDSS) such as quantum wells (QWLs), quantum wires (QWRs) and quantum dots (QDs) are well-established materials which exhibit outstanding nonlinear optical (NLO) properties. Such remarkable NLO properties of LDSS find extensive applications in designing technology-oriented optoelectronic devices through proper appreciation of strength of fundamental physics [1–6]. Impurity states in LDSS have earned successful reputation thanks to dramatic alteration of the optical and transport properties by their presence. Such alterations have necessitated meticulous inspection of the effects of shallow impurities on electronic states of LDSS, with special emphasis on deciphering their NLO properties induced by varieties of external perturbations [7–55].

Presence of *noise* in LDSS can noticeably alter the performance of LDSS. Noise can result externally, or it may be intrinsic, arising out of the changes in the configuration of QD lattice in the vicinity of impurity. It is therefore quite important to inquire how presence of noise affects the NLO properties of impurity doped LDSS. Driven by above, in the present work we investigate the profiles of a few important NLO properties of doped LDSS in presence of noise. These NLO properties include *total optical absorption coefficient* (*TOAC*) [3,11–16,24,27,28,35,36,42,46], *total optical refractive index change* (*TORIC*) [15,24,27,35], *nonlinear optical rectification* (*NOR*) [3–8,23,29,39,40,48], *second harmonic generation* (*SHG*) [2,4,5,48] and *third harmonic generation* (*THG*) [4,11,48]. To be more specific, in the present work we concentrate on how the above NLO properties are modulated by a variation of *carrier density* (σ_s), in presence of noise. A variation in carrier density, in effect, alters the influence of noise which could have some recognizable signature on the profiles of above NLO properties. However, since σ_s does not affect the energy intervals of QD, no *peak shift* of above NLO properties is expected with a change in the frequency of

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external electromagnetic radiation to which the QD is exposed. Only a change in the *peak height* can be realized under such circumstance. In the present work we consider a 2-d QD (*GaAs*) carrying a single electron in presence of a static electric field. The confinement is parabolic in the x–y plane. An orthogonal magnetic field is present too as an additional confinement. Impurity, modeled by a Gaussian potential, has been doped into the QD system. Gaussian white noise has been externally applied to the system which initiates substantial disorder. There are two different pathways (modes) through which such introduction of disorder can be accomplished. These two modes are additive and multiplicative which differ from one another by the extent of interaction with the system. The investigation elucidates subtle interplay between carrier density and noise (which conspicuously depends on its mode of application) that eventually monitors the above NLO properties of doped QD.

2. Method

The system Hamiltonian with impurity (H_0) contains four terms and reads as

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

In the above expression, the first, second, third and the fourth terms on the right hand side of the equation stand for impurity-free system containing single carrier electron, the impurity potential, the externally applied electric field having field strength F and noise contribution, respectively. The static electric field has been applied along x and y-directions. $|e|$ is the absolute value of electron charge. The noise term characterizes zero mean and spatially δ-correlated Gaussian white noise (additive/multiplicative).

In view of a lateral parabolic confinement in the x–y plane and presence of a perpendicular magnetic field, H_0', under effective mass approximation, can be written as

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

where m^* is the effective mass of the electron in QD and ω_0 is the harmonic confinement frequency. $\mathbf{A}$ is the vector potential which in Landau gauge becomes $A = (By, 0, 0)$, where B is the magnetic field strength. In this gauge H_0' can be further written as

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

where the quantity $\Omega(=\sqrt{\omega_0^2+\omega_c^2})$ represents the effective confinement frequency in the y-direction, $\omega_c(= eB/m^*c)$ being the cyclotron frequency.

V_{imp} represents the Gaussian impurity (dopant) potential and can be expressed as $V_{imp} = V_0 \quad e^{-\gamma[(x-x_0)^2+(y-y_0)^2]}$. The relevant parameters belonging to this dopant potential are (x_0, y_0), V_0 and $\gamma^{-1/2}$. They represent the site of dopant incorporation, magnitude of the dopant potential, and the spatial region over which the impurity potential is dispersed, respectively. γ can be given by $\gamma = k\varepsilon$, where k is a constant and ε is the static dielectric constant of the medium. The noise term of eqn.(1) can be generated by Box-Muller algorithm with necessary characteristics as mentioned before. The interaction of noise with system can be tuned in two distinct modes (pathways); additive and multiplicative. These two modes actually signify varied extents of system-noise interaction. The time-independent Schrödinger equation has been solved numerically by diagonalizing the Hamiltonian matrix (H_0). The said matrix has been generated by the direct product basis of the harmonic oscillator eigenfunctions. The necessary convergence test has been performed and finally we have obtained the energy levels and wave functions.

In view of determination of various NLO properties it is customary to explore interaction between a polarized monochromatic electromagnetic field of angular frequency ν with an ensemble of QDs. It becomes a tacit assumption that the wavelength of progressive electromagnetic wave supersedes the QD dimension. Under this assumption, the wave maintains a nearly fixed amplitude throughout QD and electric dipole approximation appears to be quite judicious. Now, using standard density matrix approach and iterative procedure the expressions of various NLO properties can be obtained. Thus, the linear $[\alpha^{(1)}(\nu)]$ and the third-order nonlinear $[\alpha^{(3)}(\nu, I)]$ absorption coefficients, under two-state system approximation, can be written as

$$\alpha^{(1)}(\nu) = \nu\sqrt{\frac{\mu}{\varepsilon_R}}\cdot\frac{\sigma_s|M_{ij}|^2\hbar\Gamma_{ij}}{(\hbar\nu-\Delta E_{ij})^2+(\hbar\Gamma_{ij})^2} \tag{4}$$

and

$$\begin{aligned}\alpha^{(3)}(\nu, I) = & -\nu\sqrt{\frac{\mu}{\varepsilon_R}}\left(\frac{I}{2\varepsilon_0 n_r c}\right)\cdot\frac{\sigma_s|M_{ij}|^2\hbar\Gamma_{ij}}{[(\hbar\nu-\Delta E_{ij})^2+(\hbar\Gamma_{ij})^2]^2} \\ & \times\left[4|M_{ij}|^2 - \frac{\left(M_{jj}-M_{ii}\right)^2\left\{3\Delta E_{ij}^2 - 4\Delta E_{ij}\hbar\nu + \hbar^2\left(\nu^2-\Gamma_{ij}^2\right)\right\}}{\Delta E_{ij}^2+\left(\hbar\Gamma_{ij}\right)^2}\right].\end{aligned} \tag{5}$$