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Analyzing the correction factor relevant to Kerr nonlinearity in impurity doped quantum dots for a passage from non-absorbing to absorbing media: Role of noise

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ABSTRACT

kerr nonlinearity is an important nonlinear optical property exhibited by quantum dot (QD). Present study endeavors to explore the *correction factors (CFs)* relevant to *kerr nonlinearity* for *nonlinear refractive index (RI)* and *nonlinear absorption coefficient (AC)* of *GaAs* QD. The CF arises owing to a shift from *non-absorbing* to *absorbing media*. The QD is doped with *Gaussian impurity* and special stress has been given on appreciating the role of *Gaussian white noise*. The CFs for RI and AC have been scrutinized following the variations of a large number of important physical parameters. These parameters include e.g. electric field, magnetic field, confinement potential, dopant location, dopant potential, noise strength, aluminium concentration (only for $Al_xGa_{1-x}As$ alloy QD), carrier density, relaxation time, position-dependent effective mass, position-dependent dielectric constant, anisotropy, hydrostatic pressure and temperature. It has been found that the CF profiles are governed by the concerned physical parameter, presence/absence of noise and the route (additive/multiplicative) through which the ingression of noise to the system can take place. The CF for RI has been found to be orders of magnitude greater than that of CF for AC. Present study helps us identify the various conditions when CF would be extremely small, or, more preferably, minimized.

1. Introduction

A steady walk from bulk materials to low-dimensional semiconductor systems (LDSS) produces remarkable modifications in a number of properties such as energy spectrum, polarizability, electrical, optical and so on. The modifications emerge as an outcome of augmented quantum confinement in LDSS in comparison with their bulk relatives. Quantum dot (QD) is a prominent member of LDSS community which have earned unquestionable reputation so far as manufacture of high-performance microelectronic and optoelectronic devices is concerned. Apart from such technological relevance, study of LDSS also possesses academic importance through realization and appreciation of some rudimentary physical concepts.

Incorporation of impurity to LDSS enhances its structural subtleties as it engineers the confinement potential. As a result, various interactions present in the system are also modified leading to noticeable alterations in the optical and other properties of LDSS. Nowadays, impurity doping in LDSS is a routine phenomenon and is subjected to extensive investigation [1–36].

Third-order nonlinear optical (NLO) effects constitute the physical basis for a number of technology-driven applications related to high-capacity communication networks, in which ultrafast switching, signal regeneration and high-speed demultiplexing may be performed, all-optically [37]. Moreover, third-order nonlinearity also assumes importance in view of its potential applications in optoelectronic and photonic devices. LDSS witness enormous increase in third-order nonlinearity compared with the bulk materials [38], and, particularly, QDs possess large third-order nonlinearity due to presence of δ-like density of states. Thus, third-order nonlinearities have earned wide recognition in a large variety of LDSS-based materials. However, for further development of these materials, understanding the physical processes behind this nonlinear response is a prerequisite. In this context it needs to be mentioned that the real and imaginary parts of third-order optical susceptibility ($\chi^{(3)}$) are the physical quantities that deal with the microscopic origin of nonlinearity [37]. However, these quantities are not directly measurable in most cases. Instead, they are obtained through experimental methods that are sensitive to other macroscopic manifestations of $\chi^{(3)}$ such as phase modulation, nonlinear refraction, wave-mixing and nonlinear absorption [37].

Kerr effect or Kerr nonlinearity is a change in the refractive index of a material in response to an applied electric field. It is related to $\chi^{(3)}$ and

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plays a major role in nonlinear optics due to its applications such as optical communications, quantum optics and optical devices [39–41]. Moreover, nonlinear Kerr materials have the potential to act as one of the most important building blocks to realize optical quantum computer [41,42]. And for these applications a large nonlinear Kerr effect is essential [41]. It is because of its high nonlinearity, QD can be used for high Kerr-dispersion [43]. Enhanced Kerr nonlinearity with reduced linear absorption has potential applications in various quantum devices. It was shown that large Kerr nonlinearity with reduced linear and nonlinear absorption cause nonlinear optical studies at low light power [39,40]. This requires that linear susceptibility should be as small as possible for all pump and signal fields in order to minimize the absorption loss [39]. Naturally we can find a lot of important works related to Kerr effect in LDSS [37–51].

It needs to be mentioned now that for Kerr-type nonlinearities the refractive index (RI) and absorption coefficient (AC) are given by $n = n_0 + n_2 I$ and $\alpha = \alpha_0 + \alpha_2 I$ where, n, n_0, n_2, α, α_0, α_2 and I are total RI, linear RI, nonlinear RI, total AC, linear AC, nonlinear AC and intensity of electromagnetic wave, respectively. For systems with negligible absorption ($\alpha_0 \sim 0$) n_2 and α_2 become proportional to real and imaginary parts of $\chi^{(3)}$ (which is itself a complex quantity), respectively. If the material is subjected to a single, monochromatic, linearly polarized field, the intensity of the field can be given by the expression $I = 2\varepsilon_0 n_0 c|F|^2$; where c is the velocity of light, ε_0 is the electrical permittivity of free space ($= 8.85 \times 10^{-12}$ F/m) and $|F|$ is the amplitude of the electric field. However, in absorbing medium, n_2 and α_2 come out to be the consequence of interplay between real and imaginary parts of first and third-order susceptibilities and n_2 and α_2 no longer remain proportional to real and imaginary parts of $\chi^{(3)}$. Therefore, the expressions of n_2 and α_2 are considerably modified in absorbing medium from that where absorption is insignificant. In this context analyzing the magnitudes of n_2 and α_2 in absorbing medium relative to non-absorbing medium appear crucial. Such an analysis gives us a measure of estimating the corrections required to the values of n_2 and α_2 in absorbing materials. The aforesaid corrections depend on the ratios of linear AC and linear RI and that of imaginary and real parts of $\chi^{(3)}$. Moreover, in order to observe noticeable refractive nonlinearities it is preferred to have an absorbing medium with strong (very weak) imaginary (real) component of $\chi^{(3)}$; whereas, for observing substantial nonlinear absorption effects, similar medium with strong (very weak) real (imaginary) component of $\chi^{(3)}$ is desirable. A controlled doping of impurity to LDSS can effectively modulate the interplay between n_0, n_2, α_0, α_2 and $\chi^{(3)}$ (which is numerically equivalent to adjusting the two ratios as mentioned above) giving rise to desired nonlinear absorption effects and refractive nonlinearities [37].

Application of *noise* often emerges as a genuine cause to drive the functioning of LDSS-based devices. Often noise inhibits the performance of these devices to their full capacity. Introduction of noise to the system may be external or it may be produced internally due to structural changes of QD lattice effected by impurity. Thus, a minute study of noise effect on various properties of LDSS is surely important.

In the present work our objective is to analyze the *correction factor (CF)* for n_2 and α_2 of impurity doped QDs relevant to *Kerr nonlinearity* accompanying a passage from *non-absorbing* to *absorbing media*, specifically, in presence of *noise* and due to change of various important physical quantities. It has already been stated that the said CF depends on the ratios of linear AC and linear RI and that of imaginary and real parts of $\chi^{(3)}$. At this point we realize that a change in the various physical parameters of the system would be tantamount to affecting the said ratios. This, in turn, would help us understand the important aspect of how such a change of physical parameters of the system can affect the aforesaid CF. It is further anticipated that the presence of noise can also modulate the CF leading to some interesting features. In view of above objective, the present study has been divided into three segments. First segment analyzes the CF pursuing the variations of few relevant physical quantities like electric field (F), magnetic field (B), confinement potential (ω_0), dopant location (r_0), dopant potential (V_0), carrier density (σ_s), relaxation time (T_2) and noise strength (ζ). Same segment also considers $Al_xGa_{1-x}As$ QD to realize the role played by aluminium concentration (x) on the CF. The second segment observes the plots of CF due to *position-dependent effective mass (PDEM)* [52–60], *position-dependent dielectric screening function (PDDSF)* [52,54,61,62] and *geometrical anisotropy* [63–66] on the CF. Actually, the space-dependent effective mass, space-dependent dielectric constant and anisotropy, alter the binding energy (BE) of LDSS. Any change in the BE of LDSS has noticeable impact on the manufacture of novel optoelectronic devices. The third segment considers profiles of CF due to changes in *hydrostatic pressure (HP)* and *temperature (T)*. Change in these two quantities also noticeably affects the effective mass and dielectric constant of system [24–27,29,30,32,33]. As a result the BE is altered too bearing sufficient technological relevance.

Present inspection contemplates a 2-d QD (*GaAs*) carrying one electron in presence of an external static electric field along x and y-axes. The confining potential over the $x - y$ plane can be delineated by a parabolic function. Confinement in the z-direction is imposed by a magnetic field. The impurity (dopant) potential is modeled by a Gaussian function. We consider ingression of external *Gaussian white noise* to the system which is responsible for inducing disorder. However, the pathway (mode) through which noise enters the system conspicuously governs the intensity of the said disorder and diversely affect the nature of system-noise interplay. These modes are commonly known as *additive* and *multiplicative*. The outcomes of the investigation provide a vivid picture of analyzing and estimating the CF of doped QD system related to Kerr nonlinearity. The CF assumes significance for a switch from non-absorbing to absorbing media under the supervision of noise; when pertinent physical quantities have varying magnitudes.

2. Method

The system outlined above can be represented by the following Hamiltonian (H_0):

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

H_0' is the Hamiltonian for the impurity-free QD. Since the QD is subjected to a lateral parabolic arrest in the $x - y$ plane and there is a perpendicular magnetic field, then, under effective mass approximation, H_0' looks like

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

m^* and ω_0 are the effective mass of the electron in QD and the harmonic confinement frequency, respectively. The vector potential $\mathbf{A}$ comes out to be $A = (By, 0,0)$ in Landau gauge, where B denotes the magnetic field strength H_0' can be reduced to

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

$\Omega(=\sqrt{\omega_0^2 + \omega_c^2})$ turns out to be the effective confinement frequency along the y-axis and $\omega_c\left(=\frac{eB}{m^*c}\right)$ is designated as the cyclotron frequency.

V_{imp} designates the impurity (dopant) potential and in the present study assumes a Gaussian form given by $V_{imp} = V_0\, e^{-\gamma[(x-x_0)^2+(y-y_0)^2]}$. The components of V_{imp} viz. (x_0, y_0), V_0 and $\gamma^{-1/2}$ stand for the dopant coordinate, the dopant potential strength, and the spatial domain over which the impurity potential is spread out, respectively. γ can be envisaged as $\gamma = k\varepsilon$, where k and ε are a constant and the static dielectric constant of the medium, respectively.

The terms $|e|F(x + y)$ and V_{noise} of eqn (1) account for the applied electric field ($|e|$ is the magnitude of electronic charge and F is the strength of the applied electric field) and noise, respectively. Noise invoked here is of Gaussian white nature with typical features of possessing Gaussian profile, zero average and spatially δ-correlation