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Stark shift of impurity doped quantum dots: Role of noise

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ABSTRACT

Present study makes a punctilious investigation of the profiles of *Stark shift (SS)* of doped *GaAs* quantum dot (QD) under the supervision of Gaussian white noise. A few physical parameters have been varied and the consequent variations in the SS profiles have been monitored. The said physical parameters comprise of magnetic field, confinement potential, dopant location, dopant potential, noise strength, aluminium concentration (only for $Al_xGa_{1-x}As$ alloy QD), position-dependent effective mass (PDEM), position-dependent dielectric screening function (PDDSF), anisotropy, hydrostatic pressure (HP) and temperature. The SS profiles unfurl interesting features that heavily depend upon the particular physical quantity concerned, presence/absence of noise and the manner (additive/multiplicative) noise enters the system. The study highlights feasible means of maximizing SS of doped QD in presence of noise by suitable adjustment of several control parameters. The study deems importance in view of technological applications of QD devices where noise plays some prominent role.

1. Introduction

Passage from bulk materials to low-dimensional semiconductor systems (LDSS) leads to severe enhancement of carrier confinement. Such enhanced confinement in LDSS gives rise to varieties of interesting phenomena in rather different ranges compared with the bulk materials. As a consequence LDSS finds potential technological applications in electronic and optoelectronic devices. Quantum wells (QWLs), quantum wires (QWRs) and quantum dots (QDs) are a few noteworthy examples of LDSS. Besides its technological relevance, study of LDSS also enriches our concepts related to basic physics. The electrical and optical properties of LDSS undergo immense modification by the presence of impurities. This is a particularly important fact as, more often than not, various electronic devices made up of LDSS are doped with impurity. Thus, impurity doping often enables us to tune many properties of LDSS and provides an authentic means to monitor their performances. As a result, there is no dearth of important works that deal with diverse aspects of LDSS carrying impurity [1–29].

Application of external electric field (F) to LDSS assumes importance in view of examining several physical properties. F generally destroys the symmetry of the system by polarizing the carrier distribution which has noticeable impact on the energy spectra of LDSS. This may be used to control and modulate the intensity output of devices. This fact makes F an effective tool for studying the physical properties of LDSS. *Stark shift (SS)* is an important property observed in LDSS in presence of electric field. SS comes out to be relevant in investigations concerning semiconductor heterostructures [30] in view of a better understanding of internal charge distribution. SS causes alteration of electronic probability density distribution [31] and thus influences the spatial separation between carriers in LDSS. Large SS leads to high spatial separation of the carriers which are relevant to optical processes such as emission and absorption [32]. Thus, large SS of LDSS appears as a basis for new kinds of optoelectronic devices, e.g. optical modulators and optical bistable devices [33,34]. Moreover, SS reflects the action of F on carrier distribution and energy levels of QD [35]. In addition to this SS also helps us realize the binding energy (BE) of excitons and impurities in LDSS [36]. SS, therefore, may be used to tune the energy levels of QD. As a natural extension, fine-tuning and manipulating the electronic states via SS appear essential for applications to quantum information technology [37]. Therefore, studies on SS serve a twofold purpose; firstly, from the viewpoint of applied physics, it can make predictions on optical nonlinear effects which are highly useful for quantum computation, and, secondly, from the perspective of understanding basic physics, it provides detailed insight into interdot charge distribution [38]. Thus, we can see a lot of important works concerning SS of LDSS [30–50].

The performance of devices made up of LDSS heavily depends on presence of *noise*. Often noise appears as an obstacle to various applications of these devices. Noise can enter the system externally or it may be generated internally because of changes in the QD lattice structure in the neighborhood of doped impurity. Thus, a rigorous study of noise effect on various properties of LDSS is undoubtedly important.

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In the present work we carry out a thorough inspection of *SS* of *GaAs* QD doped with impurity in presence of noise. The investigation is divided into three compartments. In the first compartment the profiles of SS have been monitored following the variations of a few important quantities such as magnetic field (B), confinement potential (ω_0), dopant location (r_0), dopant potential (V_0) and noise strength (ζ). In the same compartment $Al_xGa_{1-x}As$ QD has also been invoked to understand the role of aluminium concentration (x) on SS. The second compartment explores the variation of SS due to *Position-dependent effective mass (PDEM)* [51–59], *position-dependent dielectric screening function (PDDSF)* [53,51,60,61], and *geometrical anisotropy* [62–65]. In fact, the spatially-varying effective mass, spatially-varying dielectric constant, and anisotropy alter the BE of the system. A change in BE of LDSS drastically affects its various properties and thereby plays remarkable role in the fabrication of novel optoelectronic devices. Finally, the third compartment considers modulation of SS due to variations in *hydrostatic pressure (HP)* and *temperature (T)*. Variation of these two physical quantities eventually affects the effective mass and dielectric constant of the system [21,26,27]. As a result, the BE is also modified and carries significant technological pertinence.

In the present study we envisage a 2-d QD (*GaAs*) confining single electron in presence of a static electric field. The overall confinement potential in the $x-y$ plane becomes parabolic in nature. Simultaneous presence of magnetic field in the z-direction ensures further confinement. The QD has been doped with impurity where the impurity potential assumes a Gaussian form. External noise maintaining *Gaussian white* characteristics has been introduced to the doped QD and disorder sets in. However, the extent of disorder created depends on the nature of system-noise interaction which can be controlled by the application of noise in desired modes (pathways). To be specific, these modes are known as *additive* and *multiplicative*. The findings of the investigation depict viable routes of modulating and tuning the SS of doped QD system under the aegis of noise; when various relevant physical parameters are varied over a range.

2. Method

The doped QD system, subjected to static electric field of strength F applied along x and y-directions and fed with noise can be represented by a four-term Hamiltonian (H_0) viz.

$$H_0 = H'_0 + V_{imp} + |\, e \,|\, F(x+y) + V_{noise}. \tag{1}$$

Let's now explain the various terms on the right hand side of Eq. (1). H'_0 is the Hamiltonian representing the impurity-free QD. If QD possesses a lateral parabolic confinement in the $x-y$ plane and there is a perpendicular magnetic field, then, under effective mass approximation, H'_0 reads

$$H'_0 = \frac{1}{2m^*}\left[-i\hbar\nabla + \frac{e}{c}\mathbf{A}\right]^2 + \frac{1}{2}m^*\omega_0^2(x^2+y^2). \tag{2}$$

m^* and ω_0 are the effective mass of the electron in QD and the harmonic confinement frequency, respectively. In Landau gauge the vector potential $\mathbf{A}$ can be written as $A = (By, 0, 0)$, where B indicates the magnetic field strength. After a few mathematical steps H'_0 reduces to

$$H'_0 = -\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) + \frac{1}{2}m^*\omega_0^2x^2 + \frac{1}{2}m^*\Omega^2y^2 - i\hbar\omega_c y\frac{\partial}{\partial x}. \tag{3}$$

The quantity $\Omega(=\sqrt{\omega_0^2+\omega_c^2})$ comes out as a measure of the effective confinement frequency in the y-direction, and one of its component, viz. $\omega_c(=\frac{eB}{m^*c})$ represents the cyclotron frequency.

V_{imp} designates the impurity (dopant) potential and in the present study assumes a Gaussian form given by $V_{imp} = V_0\, e^{-\gamma\left[(x-x_0)^2+(y-y_0)^2\right]}$. The important parameters characterizing the dopant potential are $(x_0, y_0), V_0$ and $\gamma^{-1/2}$. They represent the dopant coordinate, the strength of the dopant potential, and the spatial spread over which the influence of impurity can be appreciated, respectively. γ can be written as $\gamma = k\varepsilon$, where k is a constant and ε stands for the static dielectric constant of the medium.

The third and the fourth terms on the right hand side of Eq. (1) represent the contributions from electric field ($|\, e \,|$ is the absolute value of electron charge) and noise, respectively. Noise invoked in the present study is white, exhibits Gaussian profile and is endowed with zero mean and spatially δ-correlation condition. And it can be termed as additive/multiplicative depending upon its mode of application to the system. A switch from one mode to other, in effect, leads to varied degrees of QD-noise interaction. In view of generating noise in desired mode and with required features we invoke Box-Muller algorithm [66] on all occasions.

The spatially δ-correlated white noise $[f(x,y)]$ which assumes a Gaussian distribution (generated by Box-Muller algorithm) having strength ζ can be described by the set of conditions:

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

the zero average condition, and

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

the spatial δ-correlation condition. In reality, there exist a variety of physical situations in which noise can be realized and bears interest. Noise can generate externally, or it may be intrinsic. It is usually the rearrangement of impurity configurations that gives rise to intrinsic noise [67]. Experimentally, noise can be generated by using a function generator (Hewlett-Packard 33,120A) and its characteristics i.e. Gaussian distribution and zero mean can be maintained [68]. Additive noise is a random term that does not involve into any kind of coupling with system coordinates. A multiplicative noise term is a random term that gets coupled with the system coordinates. The multiplicative character indicates that it depends on the instantaneous value of the variables of the system. It does not scale with system size and is not necessarily small [69,70]. 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

$$V_{noise} = \lambda_2 f(x,y)(x+y). \tag{7}$$

The parameters λ_1 and λ_2 absorb in them all the neighboring influences in case of additive and multiplicative noise, respectively. At a first glance, it appears that the presence of multiplicative noise would bring about greater deviation of the optical properties from that of noise-free condition than due to the presence of additive noise. This is because of greater involvement of noise with system coordinates in case of multiplicative noise than the additive counterpart.

We now construct the Hamiltonian matrix (H_0) in the direct product basis of the harmonic oscillator eigenstates. The time-independent Schrödinger equation (TISE) has been solved numerically by diagonalizing H_0 to gather the energy levels and wave functions. It is needless to mention that essential convergence test has been carried out for this purpose.

SS is defined as the energy difference in presence and in absence of electric field and is given by [31,35,39].

$$\Delta E_{SS} = [E(F \neq 0) - E(F = 0)]. \tag{8}$$