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Exploring diamagnetic susceptibility of impurity doped quantum dots in presence of Gaussian white noise

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A B S T R A C T

We explore *diamagnetic susceptibility* (*DMS*) of impurity doped quantum dot (QD) in presence of *Gaussian white noise*. Noise has been introduced to the system additively and multiplicatively. In view of these profiles of DMS have been pursued with variations of several important quantities e.g. magnetic field strength, confinement frequency, dopant location, dopant potential, and aluminium concentration, both in presence and absence of noise. We have invariably envisaged *noise-induced suppression* of DMS. Moreover, the *extent of suppression* noticeably depends on *mode of application* (*additive*/*multiplicative*) of noise. The said mode of application also plays a governing role in the onset of saturation of DMS values. The present study provides a deep insight into the promising role played by noise in controlling *effective confinement* imposed on the system which bears significant relevance.

1. Introduction

Investigations on impurity states in low-dimensional semiconductor systems (LDSS) are absolutely essential not only for pedagogical interest but also for their tremendous technological relevance. Impurity plays fundamental role in governing a wide number of physical properties of LDSS comprising of thermal, optical, electrical, magnetic and transport phenomena at low temperature. Inherently, above properties of LDSS are quite pronounced in comparison with the bulk semiconductors because of existence of additional confinement in LDSS. And presence of impurities in LDSS further alters the magnitude of above properties which in turn alters the performance of quantum devices. The huge scope of harnessing the device performance has fostered extensive research works on LDSS doped with impurity [1–13].

Magnetic field is a valuable tool for studying the properties of impurities in LDSS. Application of magnetic field modifies the symmetry of the impurity states and hence the nature of the wave functions. Thus, application of magnetic field causes a shift of quantum energy states producing considerable changes in the energy spectrum of carriers. As a result of above modification we find complicated change in the binding energy and consequently in other ancillary properties of these impurity energy levels. Magnetic field can be applied experimentally in a well-controlled way and primarily alters the electronic structure. A parallel magnetic field has been found to bear little impact on the energy spectrum of LDSS whereas a magnetic field applied perpendicular to the quantum well (QWL) plane affects the energy spectrum significantly. Thus, the nature of electronic and optical properties of LDSS can be regulated accordingly [14,15]. Magnetic field effects become more prominent at higher field strengths [16]. Application of magnetic field may diminish the absorption coefficient (AC) of an on-center impurity and shift the threshold energy towards high energy and low energy transitions [17]. Naturally we find a wealth of significant investigations on LDSS in presence of a magnetic field [18–42].

Study of magnetic properties of LDSS reveals fascinating physics that provides us with additional pathways to control the electronic magnetism in nanoscale level. Furthermore, the said study is also important for improvement of spintronics and for succinct interpretation of semiconductor-metal transitions in LDSS [43]. All these initiatives can be used to control and alter the intensity output of devices. In parallel with developments of spintronics, *diamagnetic susceptibility* (*DMS*) of doped LDSS has been subjected to rigorous research. Such study assumes importance in view of understanding quantum chaos and electronic conductivity. Moreover, looking at the promising technological applications in electronic and optoelectronic devices, study of DMS in presence of external perturbations such as hydrostatic pressure, temperature, electric field, magnetic field etc. has become a crucial problem. In recent years theoretical investigations of DMS in LDSS have drawn considerable attention [44–69].

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Noise profoundly affects the performance of LDSS In view of this, in recent past, we have investigated the influence of noise on various nonlinear optical (NLO) properties of QDs [70,71]. After a thorough literature survey we have hardly found any investigation that deals with how noise perturbs DMS of LDSS. Realizing the need of such an investigation, therefore, in the present study we focus on the important aspect of how *Gaussian white noise* affects the DMS of impurity doped QD (GaAs) which bears tremendous technological relevance. We, therefore, examine the profiles of DMS with variation of several important parameters e.g. confinement frequency (ω_0), dopant location (r_0), magnetic field (B), impurity potential (V_0), both in absence and presence of noise. Special emphasis has been given on appreciating the role of noise strength (ζ) and the mode of application of noise (additive/multiplicative) in the present perspective. Additionally we have also explored $Al_xGa_{1-x}As$ QD in order to inspect the role played by Al concentration (x). The findings nicely illuminate the fascinating role played by noise, as well as its mode of application, in tuning DMS of doped QD systems.

2. Method

The impurity doped QD Hamiltonian subject to spatially δ-correlated Gaussian white noise (additive/multiplicative) can be written as

$$H_0 = H_0' + V_{imp} + V_{noise}. \tag{1}$$

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.

V_{imp} is the impurity (dopant) potential represented by a Gaussian function [70,71] viz. $V_{imp} = V_0e^{-\gamma\left[(x-x_0)^2+(y-y_0)^2\right]}$. (x_0, y_0) is the site of dopant incorporation, V_0 is the strength of the dopant potential, and $\gamma^{-1/2}$ represents the spatial spread of impurity potential. γ can be written as $\gamma = k\varepsilon$ where ε is the static dielectric constant of the medium and k is a constant having dimensionality $[L]^{-2}$. Actually γ here plays the role analogous to static dielectric constant (ε) of the medium and therefore we presume the above relation. k is actually an adjustable parameter; its value can be fixed by comparing the results of the present study under noise-free condition with other models of QD that deal with GaAs. Based on such adjustment the value of k comes out to be $\sim$0.8. In real QDs the electrons are confined in 3-dimensions i.e. the carriers are dynamically confined to zero dimension. The confinement length scales R^1, R^2, and R^3 can be different in three spatial directions, but typically $R^3 \ll R^1 \simeq R^2 \simeq 100$ nm. In models of such dots R^3 is often taken to be strictly zero and the confinement in the other two directions is described by a potential V with $V(x) \to \infty$ for $|x| \to \infty$, $x = (x^1, x^2) \in R^2$. QDs are created mainly through producing a lateral confinement restricting the motion of the electrons, which are initially confined in a very narrow quantum well (QW), and they usually have the shape of a flat disk, with transverse dimensions considerably exceeding their thickness. The energy of single-electron excitations across the disk surpasses other characteristic energies of the system and the confined electrons can be regarded as 2-d. From this perspective the present impurity potential can be used as a realistic and at the same time computationally convenient approximation, assuming that the z-extension could be effectively considered zero [72]. The Gaussian potential stands for the finite range of quantum dot confinement potential. It bears a smoothly varying form and therefore is a good approximation of confinement potential in electrostatic quantum dots [73,74], in which the confinement originates from an inhomogeneous electric field. In self-assembled quantum dots [75] with a composition modulation [76], the confinement potential can also be substituted by the Gaussian potential [77]. Such Gaussian potentials can be assumed to simulate nanocrystals fabricated by means of colloidal chemical synthesis [78–80].

The term V_{noise} represents the noise contribution to the Hamiltonian H_0. It consists of a spatially δ-correlated Gaussian white noise $[G(x, y)]$ which assumes a Gaussian distribution (generated by Box–Muller algorithm) having strength ζ and is described by the set of conditions [70,71]:

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

the zero average condition, and

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

the spatial δ-correlation condition. The Gaussian white noise can be applied to the system via two different modes (pathways) i.e. additive and multiplicative [70,71]. In case of additive white noise V_{noise} becomes

$$V_{noise} = \Lambda_1 G(x, y). \tag{6}$$

And with multiplicative noise we can write

$$V_{noise} = \Lambda_2 G(x, y)(x + y). \tag{7}$$

The parameters Λ_1 and Λ_2 absorb in them all the neighboring influences in case of additive and multiplicative noise, respectively. From above expressions it becomes evident that additive noise term is a random term that does not depend on coordinates of system whereas a multiplicative noise gets coupled with the system coordinates. Such varied extent of association with the system coordinates results in seemingly different outcomes (with respect to effects on electronic properties and allied aspects of impurity doped quantum dots), as noise is applied additively or multiplicatively. It is because of their weak association with system coordinates, additive noise simply adds on to the Hamiltonian and thus perturbs all the eigenstates to more or less equal extents. Thus, on the whole, the relative separations between all the eigenstates remain quite unaltered so that electronic properties and other related features are affected to a much lesser extent. Multiplicative noise, on the other hand, exploits its greater association with system coordinates and affects above features in more prominent as well as in more delicate manner.

In order to solve the time-independent Schrödinger equation we have generated the sparse Hamiltonian matrix (H_0) where the matrix elements involve the function $\psi(x, y)$, constructed as a superposition of the products of harmonic oscillator eigenfunctions. In this context requisite number of basis functions have been