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Noise-driven diamagnetic susceptibility of impurity doped quantum dots: Role of anisotropy, position-dependent effective mass and position-dependent dielectric screening function

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ABSTRACT

We explore *Diamagnetic susceptibility (DMS)* of impurity doped quantum dot (QD) in presence of Gaussian white noise introduced to the system additively and multiplicatively. In view of this profiles of DMS have been pursued with variations of *geometrical anisotropy* and dopant location. We have invoked *position-dependent effective mass (PDEM)* and *position-dependent dielectric screening function (PDDSF)* of the system. Presence of noise sometimes *suppresses* and sometimes *amplifies* DMS from that of noise-free condition and the extent of suppression/amplification depends on mode of application of noise. It is important to mention that the said suppression/amplification exhibits subtle dependence on use of PDEM, PDDSF and geometrical anisotropy. The study reveals that DMS, or more fundamentally, the effective confinement of LDSS, can be tuned by appropriate mingling of geometrical anisotropy/effective mass/dielectric constant of the system with noise and also on the pathway of application of latter.

1. Introduction

Investigations on impurity states in low-dimensional semiconductor systems (LDSS) are absolutely essential not only for academic interest but also for their immense technological relevance. Impurity plays significant role in modulating a wide number of physical properties of LDSS comprising of thermal, optical, electrical, magnetic and transport phenomena at low temperature. Intrinsically, above properties of LDSS are quite conspicuous in comparison with the bulk semiconductors because of prevalence of additional confinement in LDSS. And presence of impurities in LDSS further modifies the magnitude of above properties which in turn alters the performance of quantum devices. The huge scope of tailoring the device performance has nurtured extensive research works on LDSS doped with impurity [1–3].

Magnetic field is an important tool for studying the properties of impurities in LDSS. Presence of magnetic field modifies the symmetry of the impurity states and hence the characteristics of the wave functions. In consequence, application of magnetic field causes a shift of quantum energy states thereby altering the energy spectrum of carriers. As a result of above alteration, the binding energies and other associated properties of these impurity energy levels are also affected. Experimentally, magnetic field can be applied in a well-controlled way and primarily alters the electronic structure. A parallel magnetic field insignificantly affects the energy spectrum of LDSS whereas a magnetic field applied perpendicular to the quantum well (QWL) plane profoundly affects the same. Thus, the nature of electronic and optical properties of LDSS can be regulated by suitable application of magnetic field [4,5]. It has also been found that magnetic field effects become more discernible at higher field strengths [6]. Moreover, 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 [7]. Therefore, as expected, we find an abundance of important investigations on LDSS in presence of magnetic field [8–31].

Study of magnetic properties of LDSS reveals interesting physics that provides us with additional avenues to control the electronic magnetism in nanoscale level. Furthermore, the said study is also meaningful for improvement of spintronics and for expedient interpretation of semiconductor–metal transitions in LDSS [32]. All these aspects can be exploited to control and alter the intensity output of devices. Accompanying the developments of spintronics, *diamagnetic susceptibility (DMS)* of doped LDSS has emerged as a

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topic of active research. Such study carries importance in view of understanding quantum chaos and electronic conductivity. Moreover, looking at the prolific 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 vital problem. As a natural outcome, in recent years theoretical investigations on DMS of LDSS have drawn considerable attention, particularly, through the works of [33–58].

Of late, we have come across a few important studies concerned with influence of *geometrical anisotropy* on the optical properties of LDSS. Among them the important contributions were made by [59–64]. In reality, in most cases LDSS are not at all isotropic which justifies the need of realizing how anisotropy governs their optical properties. In practice anisotropic QDs can be manufactured by chemically controlling the nanostructure aspect ratio [60]. Thus, study of anisotropic systems has produced substantial interest in view of obtaining novel as well as useful devices.

In recent times we also envisage a considerable number of investigations which involve *position-dependent effective mass (PDEM)* of LDSS. PDEM gives rise to perceptible change in the binding energy of the doped system and thus alters the optical properties. Such change in the optical properties has induced lots of studies on LDSS with spatially varying effective mass. With reference to above the works of [33,65–72] deserve attention.

Dielectric screening function (DSF, ε) is of supreme importance in delineating electro-optical properties and energy levels in QD. Previously it was thought that DSF inside a QD decreases compared with the bulk due to reduction in the band gap. Later, using microscopic electric fields and response analysis, it was proposed that the said decrease originates from surface bond breaking, and not due to opening of band gap. DSF can thus engineer the construction of devices at desired wavelengths exploiting transitions associated with different electronic subbands [67]. Moreover, *Position-dependent DSF (PDDSF),* $\varepsilon(r_0)$, affects the binding energy and consequently optical and magnetic properties of doped mesoscopic systems [33]. Also PDDSF appears useful for describing screened interactions in real space [37]. As a matter of fact, in recent times we witness a good number of studies on PDDSF by [33,37,45,67,73,74].

Noise prominently affects the performance of LDSS. In view of this, of late, we have investigated how noise fabricates various nonlinear optical (NLO) properties of QDs [75]. A thorough literature survey reveals the scarcity of studies on how noise perturbs DMS of LDSS. We, therefore, in the present study, focus on the important aspect of how *Gaussian white noise* affects the DMS of impurity doped QD (*GaAs*) which bears unquestionable technological relevance. Special emphasis has been given on understanding the influence of *geometrical anisotropy*, *PDEM* and *PDDSF* on *DMS* of doped QD in presence of *Gaussian white noise*. The DMS profiles are monitored for different extents of geometrical anisotropy (to understand the anisotropy effect), simultaneously with *fixed effective mass (FEM)* and *dopant position-dependent effective mass (PDEM)* (to realize the role of PDEM), and with *static dielectric constant (SDC)* and PDDSF (to appreciate the role of PDDSF). Moreover, the influence of pathway of application of noise (additive/multiplicative) has also been explored for a comprehensive analysis. The findings nicely illuminate the noticeable role played by the interplay between anisotropy/PDEM/PDDSF and noise, as well as its mode of application, in fabricating 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. Following the notable works of Xie the ratio $\eta = \frac{\Omega}{\omega_0}$ could be defined as the *anisotropy parameter* [60–62].

V_{imp} is the impurity (dopant) potential represented by a Gaussian function [75] viz. $V_{imp} = V_0\, e^{-\gamma\left[(x-x_0)^2+(y-y_0)^2\right]}$. (x_0, y_0) is the site of dopant incorporation, V_0 is the strength of the dopant potential, and γ^{-1} represents the spatial spread of impurity potential. γ can be written as $\gamma = k\varepsilon$ where ε is the *static dielectric constant (SDC)* of the medium and k is a constant. 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 ~ 0.8.

The dopant location-dependent effective mass $m^*(r_0)$ where $r_0 = \sqrt{x_0^2+y_0^2}$ is given by [33,67]

$$\frac{1}{m^*(r_0)} = \frac{1}{m^*} + \left(1-\frac{1}{m^*}\right)\exp(-\beta r_0), \tag{4}$$

where β is a constant chosen to be 0.01 a.u. The choice of above form of PDEM indicates that the dopant is strongly bound to the dot confinement center as $r_0 \to 0$ i.e. for on-center dopants whereas $m^*(r_0)$ becomes highly significant as $r_0 \to \infty$ i.e. for far off-center dopants.

Hermanson's impurity position-dependent dielectric constant/dielectric screening function (PDDSF) is given by [33,37,45,67,73,74]

$$\frac{1}{\varepsilon(r_0)} = \frac{1}{\varepsilon} + \left(1-\frac{1}{\varepsilon}\right)\exp(-r_0/\beta), \tag{5}$$

where ε is the SDC, $\beta = 1.1$ a.u. is the screening constant and r_0 is the dopant location. The concept of SDC is useful only for distances farther away from the perturbation (i.e. the impurity center). The choice of above form of PDDSF ensures that $\varepsilon(r_0) \to 1$ as $r_0 \to 0$ i.e. for on-center dopants and approaches ε as $r_0 \to \infty$ i.e. for far off-center dopants. Such large r_0 can be viewed as the *screening radius* [37].

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 [75]:

$$\langle G(x,y)\rangle = 0, \tag{6}$$