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Simultaneous influence of hydrostatic pressure and temperature on diamagnetic susceptibility of impurity doped quantum dots under the aegis of noise

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We explore the *diamagnetic susceptibility* (*DMS*) of impurity doped quantum dot (QD) in presence of *Gaussian white noise* and under the combined influence of hydrostatic pressure (*HP*) and temperature (*T*). Presence of noise and also its mode of application discernibly affect the DMS profile. Application of *HP* and *T* invites greater delicacies in the observed DMS profiles. However, whereas the interplay between *T* and noise comes out to be extremely sensitive in fabricating the DMS profile, the pressure-noise interplay appears to be not that much noticeable. Under all conditions of temperature and pressure, the presence of multiplicative noise diminishes the value of DMS in comparison with that in presence of its additive analogue. The present study renders a deep insight into the remarkable role played by the interplay between noise, hydrostatic pressure and temperature in controlling the *effective confinement* imposed on the system which bears unquestionable relevance.

1. Introduction

Low-dimensional semiconductor systems (LDSS) e.g. quantum wells (QWLs), quantum wires (QWRs) and quantum dots (QDs) are subjected to exhaustive applications in the field of applied physics. LDSS experience much more stringent confinement compared with their bulk neighbors which has accentuated enhanced research activities in studying their electronic, magnetic, and optical properties, both experimentally and theoretically [1]. Impurity states in LDSS deserve utmost importance as their presence causes a remarkable alteration of aforesaid properties [2,3]. Such alteration vindicates a thorough understanding of the effects of shallow impurities on the electronic states of LDSS. The scope of immense technological applications in electronic and optoelectronic devices has led to rigorous experimental and theoretical studies relevant to deciphering the physical properties of impurities in LDSS [4–15].

External perturbations, such as electric field, magnetic field, *hydrostatic pressure (HP)*, and *temperature (T)* provide precious information about LDSS [1,4,16–20]. The physical properties of LDSS can be fabricated by altering the strength of the external perturbations without hampering the physical size of the structure [2]. Therefore, it has become a custom to engineer the electronic structure of LDSS by means of external perturbations. In view of device applications, such designing makes the way of manipulating the energy spectrum of LDSS to generate desirable optical effects. Moreover, regulated variation of the size of the external perturbations can control the output of optoelectronic devices.

Magnetic field is a valuable external agent for studying various properties of impurities in LDSS. Well-controlled application of magnetic field is experimentally possible which modifies the wave function and thereby alters the quantum energy states. Consequent to above modification, the binding energy and other allied properties of these impurity doped LDSS are also changed. Naturally we find a significant volume of important investigations on LDSS in presence of a magnetic field [21–37]. *Diamagnetic susceptibility (DMS)* of doped LDSS is an important magnetic property that has been subjected to exhaustive research. Such study merits importance in view of understanding the underlying physics of quantum chaos and electronic conductivity. Moreover, from the perspective of promising technological applications in electronic and optoelectronic devices, study of DMS in presence of external perturbations such as *HP*, *T*, electric field, magnetic field etc. has become a crucial problem. As an inevitable consequence, in recent years theoretical investigations on DMS of LDSS have emerged as a hotly pursued topic [38–58].

High pressure investigations of LDSS have emerged as a highly important topic in condensed matter physics and materials

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sciences because of their profound influence on the optical properties relevant to various applications. Application of pressure into LDSS usually enhances the effective mass and reduces the dielectric constant of the system. Therefore, the band structure of LDSS and hence the transition between different energy levels of confined particles are also modified. In addition to this, applied *HP* can also affect the potential barriers, band-offset, lattice constant, and even the dimension of LDSS which are connected to the fractional change in volume. Apart from HP, T can also fabricate the electronic structure of LDSS and consequently the NLO properties which are very much linked with the electron-impurity interaction. As a natural consequence we can find an abundance of investigations involving *HP* and *T* in LDSS [19,20,59–80].

Noise profoundly affects the performance of LDSS. In view of this, in recent past, we have investigated the influence of noise on DMS of doped QDs [81]. Of late we have found some notable works that deal with DMS of doped mesoscopic systems under the control of *HP* and *T* by Rezaei and Doostimotlagh [50], Rezaei et al. [54] and Vaseghi and Sajadi [51], to mention a few. It needs to be noted that investigations on DMS of LDSS under the combined influence of *HP* and *T* and in presence of noise are sparse. Appreciating the need of such an investigation, therefore, in the present study we concentrate on the important aspect of how *Gaussian white noise* affects the DMS of impurity doped QD (*GaAs*) under the simultaneous presence of *HP* and *T*. In course of investigation, we have underscored the importance of role played by noise strength (ζ) and the mode of application of noise (additive/multiplicative) in modulating the DMS. The findings elegantly illuminate the fascinating interplay between HP, T and noise in harnessing the DMS of doped QD systems.

2. Method

The impurity doped QD Hamiltonian in presence of 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 having single carrier electron arrested by 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 becomes

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

$\omega_c = \frac{eB}{m^*c}$ being the cyclotron frequency, where c is the velocity of light. $\Omega = \sqrt{\omega_0^2+\omega_c^2}$ can be regarded as the effective confinement frequency in the y-direction.

In presence of HP and temperature, the effective mass becomes a function of pressure and temperature and is given by (for *GaAs*) [1]

$$m^*(P,T) = m_0\left[1 + E_P^\Gamma\left\{\frac{2}{E_g^\Gamma(P,T)} + \frac{1}{E_g^\Gamma(P,T)+\Delta_0}\right\}\right]^{-1}, \tag{4}$$

where m_0 is the single free-electron mass. $E_P^\Gamma = 7.51$ eV is the energy related to momentum matrix element. $\Delta_0 = 0.341$ eV is the spin–orbit splitting of the valence band (VB) for *GaAs*. The pressure and temperature-dependent energy gap for *GaAs* QD at Γ point in units of eV is given by

$$E_g^\Gamma(P,T) = E_g^\Gamma(0,T) + 1.26\times10^{-2}P - 3.77\times10^{-5}P^2,$$

in the above expression P is in Kbar unit and the factors 1.26×10^{-2} and 3.77×10^{-5} have units eV/Kbar and eV/Kbar^2, respectively. $E_g^\Gamma(0,T)$ is the energy gap at zero pressure and is given by

$$E_g^\Gamma(0,T) = 1.519 - \frac{5.405\times10^{-4}T^2}{T+204}.$$

The Pressure and temperature-dependent dielectric constant (for *GaAs*) is given by [1]

$$\epsilon(P,T) = 12.74\ \exp\left[-1.73\times10^{-3}P\right].\exp\left[9.4\times10^{-5}(T-75.6)\right], \quad \text{for } T \leqslant 200\text{ K}, \tag{5}$$

and

$$\epsilon(P,T) = 13.18\ \exp\left[-1.73\times10^{-3}P\right].\exp\left[20.4\times10^{-5}(T-300)\right], \quad \text{for } T > 200\text{ K}. \tag{6}$$

V_{imp} is the Gaussian impurity (dopant) potential [81] given by $V_{imp} = V_0\, e^{-\gamma[(x-x_0)^2+(y-y_0)^2]}$. $(x_0,y_0), V_0$ and $\gamma^{-1/2}$ are the site of dopant incorporation, strength of the dopant potential, and the spatial spread of impurity potential, respectively. γ can be written as $\gamma = k\varepsilon$, where k is a constant and ε is the dielectric constant of the medium.

The term V_{noise} [cf. Eq. (1)] stands for white noise [$f(x,y)$] which follows a Gaussian distribution (generated by Box-Muller algorithm), has a strength ζ and is characterized by zero-average and spatial δ-correlation conditions [81]. Such white noise can be introduced to the system via two different modes (pathways) i.e. additive and multiplicative [81]. These two different modes can be discriminated on the basis of extent of system-noise interaction.

The time-independent Schrödinger equation has been solved by generating the sparse Hamiltonian matrix (H_0). The relevant matrix elements involve the function $\psi(x,y)$ which is a superposition of the products of harmonic oscillator eigenfunctions. In this context sufficient number of basis functions have been included after performing the convergence test. H_0 is diagonalized afterwards in the direct product basis of harmonic oscillator eigenfunctions to obtain the energy levels and wave functions.

DMS or Larmor DMS (in a.u.) is given by the Langevin formula [57,58] and in presence of *HP* and temperature, following Rezaei et al. [54] we write

$$\chi_{dia} = -\frac{e^2}{6m^*(P,T)\varepsilon(P,T)c^2}\langle(r-r_0)^2\rangle, \tag{7}$$

where ε is the dielectric constant of the medium and r_0 is the dopant location. Thus, $\langle(r-r_0)^2\rangle$ indicates the mean square distance of donor impurity from dot confinement center.

3. Results and discussion

The calculations are performed using the following parameters: $\varepsilon = 12.4$ (without considering pressure and temperature dependence), $m^* = 0.067m_0$ (without considering pressure and temperature dependence), where m_0 is the free electron mass. $\hbar\omega_0 = 250.0$ meV, $B = 20.0$ T, $\zeta = 1.0\times10^{-4}$, $V_0 = 280.0$ meV and $r_0 = 0.0$ nm. The parameters are suitable for *GaAs* QDs. Moreover,