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Noise-modulated self-polarization effect of impurity doped quantum dots under simultaneous presence of hydrostatic pressure and temperature

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ABSTRACT

We explore the profiles of self-polarization effect (SPE) of doped *GaAs* QD under simultaneous presence of hydrostatic pressure (HP), temperature and in presence of noise. Noise term carries Gaussian white character and it has been administered to the system via two different pathways; additive and multiplicative. Profiles of SPE have been monitored as a function of HP, temperature and noise strength. Under a given condition of HP and temperature, noise marks its prominent signature on the SPE profile. However, the extent to which noise affects the SPE profile visibly depends on the noise strength and the pathway through which noise is introduced. As interesting observations we have found that SPE exhibits minimization at a pressure of ~ 170 kbar in absence of noise and at ~ 150 kbar when noise is present. Furthermore, in presence of multiplicative noise SPE exhibits a very faint decrease with increase in T up to $T \sim 420$ K. However, beyond $T \sim 420$ K, further increase in temperature causes abrupt fall of SPE in a highly sharp way. The findings highlight viable ways of tuning SPE of doped QD system through subtle interplay between HP, temperature and noise.

1. Introduction

Existence of immense quantum confinement is a notable characteristic of low-dimensional semiconductor systems (LDSS) such as quantum wells (QWLs), quantum wires (QWRs) and quantum dots (QDs). The said confinement comes out to be orders of magnitude higher than their bulk relatives. Such extreme confinement reflects its existence through the emergence of partial or complete quantization of electrons in LDSS to a discrete spectrum of energy levels. Moreover, such stringent confinement has also become responsible for another promising aspect of LDSS. The aspect being the recognition of LDSS as prolific candidates to be used for the manufacture of high-performance optoelectronic devices with excellent optical and electrical characteristics. Apart from its technological importance, study of LDSS also enriches our understanding and appreciation of many fundamental physical concepts.

Presence of impurity has become part and parcel of LDSS. The probability distribution of electrons and consequently the spatial orientation of energy levels are affected by leaps and bounds by the presence of impurities. The curtailed spatial freedom in LDSS enforces the electrons reside a substantial amount of time in the vicinity of impurity. Such vicinity often gives rise to strong mutual interaction between them manifested through amplified binding energy (BE) of the system. Thus, ingression of impurity can cause perceptible changes in the thermal, transport, optical and electrical properties of LDSS, more conspicuously at low temperatures. These interesting features have become the driving force behind the large number of studies on various properties of LDSS doped with impurity [1–41].

Applied electric field marks its prominent signature on LDSS physics through polarization of carrier distribution, energy shift of quantum states and modification of effective well width. The change in the well width, in turn, modifies the effective confinement of the system leading to changed energy spectrum. As an obvious consequence of the changed energy spectrum of the confined states of the carriers; the electronic and optical properties of LDSS are also remarkably altered. Such alterations often highlight promising scope of fabricating elegant optoelectronic devices with improved nonlinear optical (NLO) properties. In addition to electric field, hydrostatic pressure (HP) and temperature are two important additional perturbations that principally change the effective mass, dielectric constant and energy interval of LDSS. All such alterations have profound impact on the NLO properties of LDSS.

Exploration of *polarizability* and *self-polarization effect (SPE)* of LDSS deserves relevance as it provides important information about the carrier dynamics and NLO properties of them. Thus, there exists a plenty of studies involving polarizability [42–63] and SPE [64–71] of LDSS. SPE is defined as the influence of well-potential on impurity. In this case the electronic wave function is simultaneously perturbed by impurity and

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well potential. The well potential (confinement potential) causes shifting of the electronic probability distribution with respect to the impurity location. The resulting polarization is called SPE.

Introduction of *noise* to LDSS can appreciably affect its performance. Noise may originate externally, or it may be inherent, arising out of the changes in the structure of QD lattice in the vicinity of impurity. It is therefore quite germane to enquire how presence of noise perturbs different properties of impurity doped LDSS. In the present work we examine the *SPE* of *GaAs* QD doped with impurity in presence of noise under the combined influence of *hydrostatic pressure (HP)* and *temperature (T)*. Despite a rigorous literature survey we could not find such type of study in presence of noise. However, effect of HP on SPE of LDSS has been studied by Rezaei et al. [64] and by Erdogan et al. [68]. Present study considers a 2-d QD (*GaAs*) carrying a single electron in presence of a static electric field. The confinement is parabolic in the $x-y$ plane. An orthogonal magnetic field is present too as an additional confinement. Impurity, represented by a Gaussian potential, has been doped into the QD system. Gaussian white noise has been externally applied to the system which initiates substantial disorder. There are two different pathways (modes) through which such introduction of disorder can be achieved. These two modes are additive and multiplicative which differ from one another by the extent of interaction with the system. The investigation illuminates how subtly noise (including its mode of application) interplays with HP and T to tune the SPE of doped QD.

2. Method

The system Hamiltonian with impurity (H_0) contains four terms and reads as

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

In the above expression, the first, second, third and the fourth terms on the right hand side of the equation stand for impurity-free system containing single carrier electron, the impurity potential, the externally applied electric field having field strength F and noise contribution, respectively. The static electric field has been applied along x and y-directions. $|e|$ is the absolute value of electron charge. The noise term characterizes zero mean and spatially δ-correlated Gaussian white noise (additive/multiplicative).

In view of a lateral parabolic confinement in the $x-y$ plane and under the presence of an orthogonal magnetic field, H_0', under effective mass approximation, can be written as

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

where m^* is the effective mass of the electron in QD and ω_0 is the harmonic confinement frequency. $\mathbf{A}$ is the vector potential which in Landau gauge becomes $A = (By, 0, 0)$, where B is the magnetic field strength. In this gauge H_0' can be further written as

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

where the quantity $\Omega(=\sqrt{\omega_0^2+\omega_c^2}\,)$ represents the effective confinement frequency along the y-direction, $\omega_c\left(=\frac{eB}{m^*c}\right)$ stands for the cyclotron frequency.

In the present problem the effective mass depends on pressure (Π) and temperature (T) and can be written as (for *GaAs*) [72]

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

where m_0 is the mass of a free electron. $E_\Pi^\Gamma = 7.51$ eV is the energy that depends on the momentum matrix element. $\Delta_0 = 0.341$ eV represents the spin-orbit splitting of the valence band (VB) for *GaAs*. The energy gap for *GaAs* QD at Γ point also depends on pressure and temperature and is given by (in units of eV)

$$E_g^\Gamma(\Pi,T) = E_g^\Gamma(0,T) + a\Pi - b\Pi^2,$$

where $a = 1.26\times10^{-2}$ and $b = 3.77\times10^{-5}$. In the above relation Π is expressed in unit of kbar and the coefficients a and b are expressed in eV/kbar and eV/kbar^2 units, respectively. $E_g^\Gamma(0,T)$ denotes the energy gap under zero pressure and can be represented as

$$E_g^\Gamma(0,T) = c - \frac{dT^2}{T+204},$$

where $c = 1.519$ and $d = 5.405\times10^{-4}$. The dependence of dielectric constant on pressure and temperature (for *GaAs*) is expressed as [72]

$$\varepsilon(\Pi,T) = 12.74\exp[-a_1\Pi].\exp[b_1(T-75.6)],\ \text{for } T \le 200K, \tag{5}$$

where $a_1 = 1.73\times10^{-3}$ and $b_1 = 9.4\times10^{-5}$ and

$$\varepsilon(\Pi,T) = 13.18\exp[-a_2\Pi].\exp[b_2(T-300)],\ \text{for } T > 200K, \tag{6}$$

where $a_2 = 1.73\times10^{-3}$ and $b_2 = 20.4\times10^{-5}$. It needs to be mentioned that although we have used the same expressions for $m^*(\Pi, T)$, $E_g^\Gamma(\Pi, T)$ and $\varepsilon(\Pi, T)$ as that given in Ref. [72], there is a basic difference in our model and the model considered in Ref. [72]. In that model the authors considered an electron and a hole moving in a spherical QD with a parabolic confinement, under an electric field applied in the z-direction of the spherical QD. Moreover, it is a fact that the presence of impurity can significantly affect the band structure, and, as a result, the dielectric function and band gap are changed, compared with the impurity-free case. Nevertheless, the validity of the expressions of $m^*(\Pi, T)$, $E_g^\Gamma(\Pi, T)$ and $\varepsilon(\Pi, T)$ used in the present study can be justified owing to the fact that in both the works, *GaAs* QD has been considered and the simultaneous presence of electron and hole [72] can be considered equivalent to presence of impurity in *GaAs* QD containing only single electron (present study).

V_{imp} represents the Gaussian impurity (dopant) potential [73] and can be expressed as $V_{imp} = V_0\, e^{-\gamma[(x-x_0)^2+(y-y_0)^2]}$. The relevant parameters belonging to this dopant potential are (x_0, y_0), V_0 and $\gamma^{-1/2}$. They represent the site of dopant incorporation, magnitude of the dopant potential, and the spatial domain over which the impurity potential is disseminated, respectively. γ can be given by $\gamma = k\varepsilon$, where k is a constant and ε is the static dielectric constant of the medium. The noise term of eqn. (1) can be generated by Box-Muller algorithm with necessary characteristics as mentioned before. The interaction of noise with system can be tuned in two distinct modes (pathways); additive and multiplicative. These two modes actually signify varied extents of system-noise interaction. The time-independent Schrödinger equation has been solved numerically by diagonalizing the Hamiltonian matrix (H_0). The said matrix has been generated by the direct product basis of the harmonic oscillator eigenfunctions. The necessary convergence test has been performed and finally we have obtained the energy levels and wave functions.

SPE of impurity doped QD can be given by

$$\frac{P}{e} = -\langle\psi|(x-x_0)|\psi\rangle + \langle\psi'|(x-x_0)|\psi'\rangle - \langle\psi|(y-y_0)|\psi\rangle + \langle\psi'|(y-y_0)|\psi'\rangle, \tag{7}$$

where ψ is the wave function describing the system and ψ' is the wave function in absence of confinement effects.