Journal of Physics and Chemistry of Solids 70 (2009) 680–687

Contents lists available at ScienceDirect

Journal of Physics and Chemistry of Solids

journal homepage: www.elsevier.com/locate/jpcs

Dynamics of 2-D one electron quantum dots in pulsed field: Influence of size

Parikshit Mandal, Manas Ghosh *

Department of Chemistry, Physical Chemistry Section, Visva Bharati University, Santiniketan, Birbhum 731 235, West Bengal, India

ARTICLE INFO

Article history:
Received 9 December 2008
Received in revised form
30 January 2009
Accepted 4 February 2009

Keywords:
A. Electronic materials
A. Nanostructures
A. Quantum wells
A. Semiconductors
D. Lattice dynamics

ABSTRACT

We explore the dynamics of harmonically confined single electron quantum dots as a function of dot size when an external time varying pulsed electric field is switched on. The system of interest is a 2-D system in the presence of a perpendicular magnetic field. We show that for given strengths of the confining potentials, the pattern of time evolution of eigenstates of the unperturbed system reveals significant size-dependence. The pulse duration time is also found to modulate the dynamical aspects in a prominent way.

1. Introduction

In recent years, significant progress has been made in the fabrication of low-dimensional structures thereby reducing the effective dimensions from 3-D bulk materials, to quasi-2-D quantum wells, quasi-1-D quantum wires and even to quasi-0-D quantum dots (QD) [1,2]. Artificial atoms or QD were extensively studied by Chakraborty [3]. The researches on semiconductor QD are motivated primarily by the device applicability of these structures and partly by the scientific curiosity in modified physical properties of mesoscopic systems. The quantum confinement effects in such systems of reduced space dimension have attracted considerable attention. Maksym and Chakraborty [4,5] worked out the energy levels and found an incredibly rich structure. Recently Li and Xia have studied the electronic structures of N-*quantum dot molecule* (QDM). The effects of finite offset and valance band mixing were taken into account in their calculations [6]. Their results indicated that electron energy levels decrease monotonically and the energy differences between the N-QDMs decrease as the QD radius increases. They found strong valance band mixing in long radius QD. In another work they have studied electron and hole energy levels of an InAs self-assembled QD in the presence of perpendicular magnetic field [7]. Here along with finite band offset and valance band mixing they also incorporated the effects of strain. The hole levels exhibited strong anticrossings. The large strain and strong magnetic field decrease the effect of mixing between heavy hole and light hole. The hole energy levels have in general a weak field dependence compared with the corresponding uncoupled levels. The same group also has made some investigations on electronic structures and binding energy levels of 2, 1 and 0-D semiconductor nanostructures in the presence of hydrogenic acceptor impurity [8]. They performed the calculations in the framework of effective mass envelope function theory. The method was novel and could be widely applied in the calculation of the electronic structures and binding energy levels of a hydrogenic acceptor impurity in semiconductor nanostructures of various shapes and characteristics.

The dots are now supposed to be the final destination of microelectronics, with a hope to achieve giga-level integration on a single chip in near future. In QD the electron energy levels are quantized and the behavior is similar to that of an atom. The QD is regarded as the *artificial atom* [4,9]. The advantage of studying the QD system is that the properties of artificial atom can be extensively controlled by the external applied field. Hence the QD system have been exploited to implement the quantum devices e.g. QD laser [10,11], the single photon emitter [12,13], and the cavity QED [14–17]. Besides, the QD is one of the promising candidate of quantum information devices [18–21].

It is undoubtedly quite relevant and interesting to explore how the QD systems respond dynamically to external time varying electric fields and how the response varies from state to state. Creffield et al. investigated how an oscillatory electric field can drive the dynamics of a two-electron Wigner molecule held in a square QD by using a Hubbard-type of model to describe these states [22]. The possibility of manipulation of QD by a microwave field has important implications in quantum computing. Such manipulations could play important role in the study of dynamic

* Corresponding author. Tel.: +91 3463 261526, +91 3463 262751–6x467; fax: +91 3463 262672.
E-mail address: pcmg77@rediffmail.com (M. Ghosh).

0022-3697/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jpcs.2009.02.006

localization (DL), and photon assisted tunneling through excited states [23–28]. In the past two decades, attention of scientific community was drawn to a different and much less trivial example of saturation when the spectrum of H_0 is essentially unlimited in the energy space, yet after a certain time the absorption stops. This phenomenon is known as *DL*. Based on an analytical approach, Basko et al. obtained weak DL in complex quantum systems under time-dependent perturbation described by random matrix theory [26]. According to Floquet approach, the DL occurs when two quasienergies of states participating in the dynamics approach each other [29,30], and become either degenerate or close to degenerate. This phenomenon of quasienergy collapse happens not only in the QD systems but also in superlattices [31]. They also found localization effect in a 1-D QD array and proposed that an appropriate choice of external parameters is obvious for DL. Zhou et al. theoretically investigated electronic dynamic behavior in QD driven by an AC-field [32]. They reported that AC-field leads to the changes in the oscillatory behavior of the propagating wave packet in several frequency regimes. They found strong electronic localization in QD in the weak coupling limit so that single electron switch may be realized. The article by Creffield et al. [25] also reported DL in a quantum dot under AC-driving. The research of *localization effect* in QD is very important to the field of quantum computation [18] as a structure of this kind provides a promising method of implementing scalable arrays of quantum bits [33]. In all such situations, the response of the system to external electromagnetic fields of low frequency and intensity becomes important. In what follows recently we monitored the evolution of various properties of the 2-D dots in response to continuous or pulsed sinusoidal electric fields either in the presence or in the absence of symmetry breaking anharmonicity and impurity [34–37].

However, in all the model problems we addressed so far, we have assumed that the confinement potential (parabolic) extends up to infinity. The dot wave function was therefore assumed to vanish at $x, y \to \pm\infty$. QD are now realizable in various shapes and sizes and device applications are being made. For making further progress it is necessary that we can correlate the dynamical aspects of the dot with dot size. As the physical dimensions of the dot approach the nanometer scale, size effect begins to play an important role, leading to drastic change in measured properties [38]. As fabrication processes improve, control of dot size is enhanced. In the last few years, semiconductor QD with tunable size have attracted a great deal of attention, particularly in the $1.3-1.55\,\mu$m range of optical communications [39–42]. In consequence, of late, we also investigated the influence of size in manipulating the linear and non-linear response of the QD [43,44] and also on its electronic structure and dynamics (under external sinusoidal electric field) [45]. In the present paper, we examine whether any significant change occurs in the dynamics (under pulsed field) of single carrier dots when the condition of finite and variable spatial extension of the dot is imposed on the wave function.

2. Method

A mesoscopic system like a QD would always be expected to experience damping [46]. We are probing a model in which damping is weak enough to be neglected. That means, we can describe the system by Schrödinger equation. We may explore the effects of damping later, treating it as a perturbation. We assume that the electron in the dot atom has an effective mass m^* and has been confined by a harmonic potential $[V_0(x,y) = \frac{1}{2}m^*\omega_0^2(x^2+y^2)]$ in the simultaneous presence of a static perpendicular magnetic field B $(=\nabla\times A)$, A being the vector potential. The stationary states of the system are given by the eigenstates of the Hamiltonian

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

For the perpendicular magnetic field ($B_x = B_y = 0$), and Landau gauge used for A, the motion along z-axis is continuous while the motion in the $x-y$ plane is quantized and the quantized energy levels are obtainable from the following energy eigenvalue equation (in Cartesian coordinate system):

$$H_0\psi_n(x,y) = E_n\psi_n(x,y), \tag{2}$$

where

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

$\omega_c = eB/m^*c$ is the cyclotron frequency. Introducing $\Omega^2 = \omega_0^2 + \omega_c^2$ we have Eq. (3) transformed into an energy eigenvalue equation of a pair of interacting harmonic oscillator Hamiltonians H_x and H_y with harmonic frequencies ω_0 and Ω, respectively, the interaction operator being given by

$$\hat{V}_{int} = -i\hbar\omega_c y\frac{\partial}{\partial x}.$$

That is, our problem reduces to modelling the energy eigenvalues and eigen vectors of the 2-D hamiltonian H_0:

$$H_0(x,y,\omega_c,\omega_0)\psi_n(x,y) \equiv \left[H_x(\omega_0) + H_y(\Omega) - i\hbar\omega_c y\frac{\partial}{\partial x}\right]\psi_n(x,y) = E_n\psi_n(x,y). \tag{4}$$

Eq. (3) reduces to the energy eigenvalue equation of a 2-D harmonic oscillator as ω_c (i.e. B) $\to 0$. It would be natural therefore to seek diagonalization of $H(x,y,\omega_c,\omega_0)$ in the direct product basis of eigenfunctions of $H_x(\omega_0)$ and $H_y(\Omega)$. Thus, we write the trial wave function $\psi(x,y)$ as a superposition of the product of harmonic oscillator eigenfunctions $\phi_n(x)$ and $\phi_m(y)$ of $H_x(\omega_0)$ and $H_y(\Omega)$, respectively, as follows:

$$\psi(x,y) = \sum_{n,m} C_{n,m}\phi_n(x)\phi_m(y). \tag{5}$$

In order to investigate the size-dependent properties, the spatial extension of the dot wave function can no longer be kept same as before, but it must be truncated at some finite value. Thus, in this case the spatial extension of the wave function ranges from $-L$ to $+L$ (instead of $\pm\infty$) where L represents the dot size. Accordingly the basis functions $\phi_n(x)$ and $\phi_m(y)$ have to be modified. The normalized, but non-orthogonal basis functions for the finite-sized dot in the x-direction reads

$$\phi_n(x) = a_nH_n(x)\exp\left(-\frac{x^2}{2}\right), \tag{6}$$

where a_n is the normalization constant of the basis function $\phi_n(x)$ for the finite-sized dot. Analogously, for y-direction it reads

$$\phi_m(y) = a_mH_m(y)\exp\left(-\frac{y^2}{2}\right). \tag{7}$$

The normalization constant a_n is given by the following expression:

$$a_n = \left(\frac{1}{I_{nn}}\right)^{1/2}, \tag{8}$$