Superlattices and Microstructures 88 (2015) 620–633

Contents lists available at ScienceDirect

Superlattices and Microstructures

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

Exploring optical refractive index change of impurity doped quantum dots driven by white noise

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ARTICLE INFO

Article history:
Received 30 June 2015
Received in revised form 10 October 2015
Accepted 15 October 2015
Available online 26 October 2015

Keywords:
Quantum dot
Impurity
Gaussian white noise
Total refractive index change
Noise strength

ABSTRACT

We make an extensive exploration of total refractive index (RI) change of impurity doped quantum dots (QDs) in presence and absence of noise. The noise invoked in the present study is a Gaussian white noise. The quantum dot is doped with repulsive Gaussian impurity. Noise has been incorporated to the system additively and multiplicatively. A perpendicular magnetic field acts as a source of confinement and a static external electric field has been applied. The total RI change profiles have been studied as a function of incident photon energy when several important parameters such as optical intensity, electric field strength, magnetic field strength, confinement energy, dopant location, relaxation time, *Al* concentration, dopant potential, and noise strength assume different values. Additionally, the role of mode of application of noise (additive/multiplicative) on the total RI change profiles has also been examined minutely. The total RI change profiles mainly comprise of interesting observations such as *shift of total RI change peak position* and *maximization/minimization of peak intensity*. However, presence of noise conspicuously alters the features of total RI change profiles through some interesting manifestations. Moreover, the mode of application of noise (additive/multiplicative) also governs the total RI change profiles in diverse as well as often contrasting manners. The observations indicate possibilities of tailoring the linear and nonlinear optical properties of doped QD systems in presence of noise.

1. Introduction

Over the last few decades we have observed a plethora of investigations on nonlinear optical (NLO) properties bearing formal proximity with the intersubband transitions in the low-dimensional semiconductor systems. The said systems include quantum wells (QWLs), quantum wires (QWRs) and quantum dots (QDs). The findings of the research have enriched our understanding of fundamental physics and simultaneously indicated potential hope for promising applications in electronic and optoelectronic devices. These low-dimensional systems reveal more encouraging optical properties than their bulk neighbors. The small energy separations between the subband levels and the large values of electric dipole matrix elements are the main factors behind the prominent manifestation of the said optical effects. The above factors also promote

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http://dx.doi.org/10.1016/j.spmi.2015.10.021
0749-6036/

occurrence of resonance conditions. The large value of dipole matrix element favors optical transition between the QD subbands. In consequence, photons, whose energies are of the order of intersubband transition energies, can lead to a huge change in the (complex) dielectric constant of host materials, which, in turn, changes the index of refraction and absorption coefficient [1]. Moreover, the nonlinear parts offer greater contribution to the dielectric constants and other important optical properties [1]. The various optical properties have a wide range of applications in high-speed electro-optical modulators, far IR photodetectors, left-handed materials, semiconductor optical amplifiers etc. QD, the 3-d confined low-dimensional system, displays prominent intersubband optical transitions. Research in this area has been further bolstered by rapid progress in semiconductor growth techniques such as molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD).

Impurity plays vital role in semiconductor devices as it modulates the electronic properties of quantum nanostructures [2]. Shallow impurity augments the conductivity of semiconductors by several orders of magnitude. Impurity effects in QD also appear to be quite evident in the emerging field of nanaoelectronics, an area that has drawn huge attention as it opens up immense possibilities in the domain of applied physics. The performance of a majority of optical devices involving both bulk and nanoscale semiconductors depends heavily on the presence of impurity. In QDs, presence of impurity strongly affects the basic physics and technological applications thereby necessitating detailed investigations on impurity states. The strong quantum confinement in QD has made their size and shape very much controllable which in effect modulates their electronic structure. In presence of impurities the modulation becomes much more delicate and ultimately modifies the energy spectrum of doped QD system to obtain adjustable optical transitions. A controlled optical transition is an essential ingredient to fabricate optoelectronic devices with tunable emission or transmission properties and ultranarrow spectral linewidths. Moreover, the intimacy between optical transition energy and the confinement strength (or the quantum size) favors fine-tuning of resonance frequency. In consequence, NLO properties of doped QDs have become a subject of full-fledged experimental and theoretical research [1,3–26].

Electric field is a major external perturbation that elucidates the important aspects of confined impurities [27–38]. The interplay between impurity and the applied field modulates the optical properties and turns out to be useful in view of fundamental physics and device applications. The electric field modifies the electronic structure and thus provides a feasible way of tailoring the energy spectrum to attain desirable optical transitions. It deserves to be mentioned now that the NLO properties of semiconductor QD is governed by the asymmetry of the confining potential. Controllable asymmetry of confinement potential turns out to be conducive for generation of NLO properties which usually vanish in a symmetric quantum structure. Among the NLO properties the second order ones are found in noncentrosymmetric structures whereas the third order nonlinearities become evident in both centrosymmetric and noncentrosymmetric structures. In this context application of electric field bears immense significance owing to its capacity of producing such asymmetry in confinement potential. Hence, both from theoretical and experimental perspectives, the involvement of an applied electric field in the study of physical properties of low-dimensional systems have become a widely followed research topic looking at the development of innovative semiconductor devices. An electric field, applied in the growth direction of heterostructures, causes an energy shift of quantum states and polarization of the spatial disposition of the carriers. These effects are utilized to harness and modulate the intensity output of optoelectronic devices [34]. Additionally, enhanced influence of external electric field has been found for dopants introduced into far off-center locations [35].

The magnetic field is also an important additional perturbation. The applied magnetic field modifies the symmetry of the impurity states and hence the nature of the wave functions. Owing to above modification subtle changes are observed in the binding energy and consequently in other auxiliary properties of doped QD systems [39–41]. Magnetic field can be applied very much under experimental control and thus offers a suitable means of altering the electronic structure. Magnetic field applied perpendicular to the QD plane has been found to be much more effective in tailoring the energy spectrum than a parallel one. This fact has a straightforward impact on the nature of electronic and optical properties of these systems [42–44]. Naturally we find an abundance of notable investigations on NLO properties of QD in presence of a magnetic field [45–51].

Of late, we have made detailed discussions on the importance of *noise* in governing the performances of QD devices [52–55]. In these works the influence of *Gaussian white noise* on the *polarizability* profiles of doped QDs has been rigorously studied. In the present study we make a detailed analysis of the influence of *Gaussian white noise* on the *total change of optical refractive index (RI)* (which is a combination of linear and the third-order nonlinear changes of RI) of doped QD relevant to transition between $|\psi_0\rangle$ and $|\psi_1\rangle$ states. We have considered a 2-d QD (*GaAs*) containing single carrier electron laterally arrested (parabolic) in the $x-y$ plane. In connection with the model described here it needs to be mentioned that QDs are created mainly by imposing a lateral confinement to electrons in a very narrow quantum well. QDs fabricated in this way usually have the shape of a flat disk with lateral dimension considerably exceeding their thickness. The energy of single electron excitation can be considered as strictly 2-d. In most studies a harmonic oscillator potential was used to describe the lateral confinement of electrons. Thus, optical properties of impurity in a 2-d disc-like QD with parabolic confinement potential in an applied electric field is a problem which is very much in vogue. In the present study the QD is doped with a repulsive Gaussian impurity in the presence of a perpendicular magnetic field. And the doped system is subjected to an external static electric field. Gaussian white noise has been incorporated to the system additively and multiplicatively [52–55]. Thus, the full system is under the influence of external probes: crossed axially directed homogeneous magnetic (perpendicular to the quantum disk plane) and in-plane electric fields. In view of a comprehensive investigation the RI profiles are monitored as several pertinent parameters viz. the confinement frequency (ω_0), electric field strength (F), dopant