Superlattices and Microstructures 98 (2016) 385–399

Contents lists available at ScienceDirect

Superlattices and Microstructures

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

Modulating optical rectification, second and third harmonic generation of doped quantum dots: Interplay between hydrostatic pressure, temperature and noise

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ARTICLE INFO

Article history:
Received 13 July 2016
Received in revised form 24 August 2016
Accepted 28 August 2016
Available online 30 August 2016

Keywords:
Quantum dot
Impurity
Nonlinear optical properties
Hydrostatic pressure
Temperature
Gaussian white noise

ABSTRACT

We examine the profiles of optical rectification (OR), second harmonic generation (SHG) and third harmonic generation (THG) of impurity doped QDs under the combined influence of hydrostatic pressure (HP) and temperature (T) in presence and absence of Gaussian white noise. Noise has been incorporated to the system additively and multiplicatively. In order to study the above nonlinear optical (NLO) properties the doped dot has been subjected to a polarized monochromatic electromagnetic field. Effect of application of noise is nicely reflected through alteration of *peak shift (blue/red)* and variation of *peak height* (*increase/decrease*) of above NLO properties as temperature and pressure are varied. All such changes again sensitively depends on mode of application (additive/multiplicative) of noise. The remarkable influence of interplay between noise strength and its mode of application on the said profiles has also been addressed. The findings illuminate fascinating role played by noise in tuning above NLO properties of doped QD system under the active presence of both hydrostatic pressure and temperature.

1. Introduction

Low-dimensional semiconductor systems (LDSS) e.g. quantum wells (QWLs), quantum wires (QWRs) and quantum dots (QDs) are renowned for their extensive applications in the field of applied physics. The strong confinement existing in LDSS compared with their bulk neighbors has insisted enhanced research activities in studying the electronic, magnetic, and optical properties of them, both experimentally and theoretically [1]. Impurity states in LDSS are extremely significant as their presence dramatically alters the optical and transport properties of LDSS [2–4]. This necessitates a deep realization of the effects of shallow impurities on electronic states of LDSS. The opportunities of tremendous technological applications in electronic and optoelectronic devices have fomented experimental and theoretical studies pertinent to deciphering the physical properties of impurities in LDSS [5–13].

External perturbations, such as electric field, magnetic field, hydrostatic pressure (HP), and temperature provide valuable information about LDSS [1,2,14–22]. The physical properties of LDSS can be manipulated by altering the strength of external

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http://dx.doi.org/10.1016/j.spmi.2016.08.052

perturbations without hampering the physical size of the structure [3]. Therefore, it has become a regular practice to fabricate the electronic structure of LDSS by means of external perturbations. In view of device applications, such fabrication paves the way of tailoring the energy spectrum of LDSS to produce desirable optical effects. Moreover, controlled variation of strength of external perturbations can regulate the performance of optoelectronic devices. Thus, external perturbations are marked as important candidates for studying the linear and nonlinear optical (NLO) properties of LDSS [23].

High pressure investigations of LDSS have emerged as a crucial topic in condensed matter physics and materials sciences because of their immense influence on the tunable optical properties relevant to applications in optoelectronics, QD lasers, high-density memory, bio-engineering etc. [24–26]. Application of pressure into LDSS generally causes enhancement of effective mass and reduction of dielectric constant of the system. In consequence, the band structure of LDSS is also affected, which, in turn, affects the transition between different energy levels of confined particles [26,27]. Besides the said modification of band gap, applied HP can also perturb the potential barriers, band-offset, lattice constant, and even the dimension of LDSS which are related to the fractional change in volume. Above discussions nicely highlight the importance of HP as a powerful means of modulating the electron-related NLO properties of LDSS. Naturally we find a plethora of notable studies on LDSS involving HP [28–45]. Apart from HP, temperature effects also tailor the electronic structure of LDSS [27] and consequently the NLO properties which are very much linked with the electron-impurity interaction [29,37,38,43,44,46–50].

Optical rectification (OR) and *second harmonic generation (SHG)* are the two simplest second-order nonlinear processes having magnitudes usually greater than those of higher-order ones. These two properties are prominently manifested whenever LDSS possess noticeable asymmetry [51–57]. The *third-order* NLO properties assume importance in LDSS having inversion symmetry. In this case, while the second-order susceptibilities become insignificant because of the inversion symmetry, the third-order one exhibits huge enhancement compared with the bulk material. NLO materials with large third-order nonlinear susceptibilities χ^3 are regularly utilized as important components to manufacture all-optical switching, modulating and computing devices [58,59]. Recently higher harmonic generation in AC electric field driven by the gate electrodes and not light field is observed in carbon nanotubes [60]. As a natural consequence, we can find lots of noticeable works on OR, SHG and *third harmonic generation (THG)* under the influence of HP and temperature [30,32,61–67].

Recently we have explored the role of *noise* in regulating the above NLO properties of doped QD [68]. In the present manuscript we have inspected the influence of *Gaussian white noise* on OR, SHG and THG of doped QD under the combined influence of *hydrostatic pressure (HP)* and *temperature*. The system under study is a 2-d QD (*GaAs*) consisting of single carrier electron under parabolic confinement in the x–y plane. The QD is doped with an impurity modeled by a Gaussian potential in the presence of a perpendicular magnetic field which provides an additional confinement. Gaussian white noise has been incorporated to the doped QD via two different pathways i.e. additive and multiplicative [68]. The investigation delineates subtle interplay between noise (which manifestly depends on its mode of application), HP and temperature that finally settles OR, SHG and THG of doped QD. The findings seem to carry practical relevance.

2. Method

The impurity doped QD Hamiltonian, subject to external static electric field (F) applied along x and y-directions and spatially δ-correlated Gaussian white noise (additive/multiplicative) can be written as

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

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

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

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

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

$\omega_c = \frac{eB}{m^*}$ being the cyclotron frequency. $\Omega^2 = \omega_0^2 + \omega_c^2$ can be viewed as the effective confinement frequency in the y-direction. The Hamiltonian [cf. eqn. (2)] represents a 2-d quantum dot with a single carrier electron [69,70]. The form of the confinement potential conforms to kind of lateral electrostatic confinement (parabolic) of the electrons in the x–y plane. In real QDs the electrons are confined in 3-dimensions i.e. the carriers effectively possess a quasi-zero dimensional domain. The confinement length scales R^1, R^2, and R^3 can, in general, be different in three spatial directions, but usually $R^3 \ll R^1 \simeq R^2$. Whenever such QDs are modeled R^3 is often taken to be strictly zero and the confinement in the other two directions is described by a potential V with $V(x) \to \infty$ for $|x| \to \infty$, $x = (x^1, x^2) \in R^2$. x^1 and x^2 represent the coordinates in x and y directions,