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# Effect of Rashba spin-orbit coupling and external magnetic field on electronic minibands in highly strained one-layer quantum ring superlattice

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The Rashba spin-orbit coupling for electronic states in a strained one layer superlattice, composed of InAs/GaAs quantum rings has been investigated in the presence of uniform magnetic field directed perpendicular to the lattice plane. The dispersion surfaces and the energy dependencies on the magnetic field induction are obtained by the exact diagonalization procedure using the Fourier transformation to the momentum space. The characteristic splitting of the mini-bands as well as the crossings of the dispersion surfaces at the high symmetry points in the Brillouin zone have been observed. An upward shift of the minibands by about 60 meV due to strain in superlattice has been observed.


## 1. Introduction

Quantum dots (QD) and quantum rings (QR) containing few interacting electrons have received considerable attention for over a decade because of the rich physics they exhibit [1,2]. Just as the QDs, QRs are also nanometer-sized structures that confine electrons in all three directions. Aharonov-Bohm oscillations [3] and the persistent current [4] have been observed recently in small conducting rings. On the other hand the possibility of the experimental realization of QRs with only a few electrons have been demonstrated in Refs. [5] and [6]. So the experimental study of QRs properties as well as the development of the many-particle theory in QRs is of great interest [7–9]. QRs are of particular interest due to their unique electronic, magnetic, and optical properties [10–12].

In most cases, these structures are fabricated with an intrinsic elastic strain field arising from the lattice mismatch between the QR (QD) and matrix materials [13]. Knowledge of this strain field is crucial for further device modeling since the strain substantially modifies the electronic band structure which, in turn, strongly effects on the performance of optoelectronic devices [14,15]. The introduction of strain may provide a facile way to fabricate from mid-wavelength to long-wavelength multi-color infrared detectors via InAs or InGaAs QDs capped by GaAs, InGaAs, InP, or GaInP [16]. On the other hand the inhomogeneous strain relaxation in strained quantum structures can be utilized to fabricate QRs [10].

Recently impressive progress has been made in the field of manufacturing of ordered structures composed of two or three dimensional arrays of QRs [17–19]. For example, stacked layers of self-assembled InGaAs/GaAs quantum rings have been

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studied for laser applications by Suarez et al. [20]. Laterally ordered InGaAs quantum rings have been fabricated by a simple technique with combination of ordering quantum dots by strain engineering and dot-to-ring transformation by partially capping [21]. This technique has been shown to be capable of fabricating the large scale ordered quantum ring structures for many applications such as quantum ring solar cells and lasers.

A very useful mechanism based on Rashba spin-orbit interaction (SOI) for coherent spin manipulation in quantum nanostructures has been demonstrated in Refs. [22,23]. The SOI can arise in a QD and a QR due to the confinement and lack of inversion symmetry of the nanostructure, which creates a local electric field. The SOI strength can be varied by changing the asymmetry of the quantum structure with an external electric field. The Rashba SOI is also the driving mechanism for making futuristic devices based on controlled spin transport, such as spin transistors and spin filters [24].

The recent works involving the Rashba SOI on the electron and hole states in QDs [25,26] and in QRs [27] revealed that the SOI is responsible for multiple level crossings and level repulsions in the energy spectrum that was due to the interesting interplay between the Zeeman effect and the SOI. Our another work has been devoted to the effect of Rashba coupling on the non-linear intraband light absorbtion in a GaAs/AlGaAs QR [28]. QRs made of semiconducting materials exhibiting Rashba-type SOI have attracted considerable attention due to fundamental spin-dependent quantum interference phenomena that are observable in these systems [29–31]. Since the strength of the SOI can be tuned with external gate voltages, QRs, or systems involving those will also have possible spintronic applications [32].

The energy dispersion and the Bloch amplitudes in one layer quantum ring superlattice (QRSL) have been obtained in our previous works, taking into account the interdiffusion between the compound materials of heterostructure [33] and the Rashba SOI [34].

In the present work the Rashba spin-orbit coupling for electronic states in a strained one layer superlattice, composed of InAs/GaAs quantum rings has been investigated in the presence of uniform magnetic field directed perpendicular to the lattice plane. Green's function technique, developed by Andreev et al. [15] and based on the method of inclusions suggested by Eshelby [35] has been implied to calculate the strain distribution in considered structure taking into account material anisotropy. This method produces a nearly analytical solution for the Fourier components of the strain tensor. The energy dispersion surfaces and the energy dependencies on the magnetic field induction are obtained by the exact diagonalization procedure using the Fourier transformation to the momentum space. As it has previously been shown [33,36,37], this approximation provides a good representation of physical situation and reasonable accuracy for comparatively small sizes of Hamiltonian matrix.

## 2. Theory

Let us consider an one-layered QRSL with the lattice constants $a_x$ and $a_y$ in the $x$ and the $y$ directions respectively. Fig. 1 illustrates a schematic sketch of this structure. As is known the misfit strain for InAs/GaAs heterojunction (about 6.7%) leads to a considerable strain distribution which significantly effects on the SL band structure [15,38]. An analytical expression can be obtained for the Fourier transform of the strain tensor [15] which has the following form for a single QR (SQR) or QD in a materials of cubic symmetry:

$$\tilde{E}^{s}_{ij}\left(\overrightarrow{\xi}\right)=\varepsilon_0\tilde{\chi}_{QR}\left(\overrightarrow{\xi}\right)\left(\delta_{ij}-\frac{(C_{11}+2C_{12})\xi_i\xi_j/\xi^2}{1+(C_{12}+C_{44})\sum_p\frac{\xi_p^2}{C_{44}\xi^2+C_{an}\xi_p^2}}\times\frac{1}{2}\left[\frac{1}{C_{44}+C_{an}\xi_i^2/\xi^2}+\frac{1}{C_{44}+C_{an}\xi_j^2/\xi^2}\right]\right), \tag{1}$$

where

$$\tilde{\chi}_{QR}\left(\overrightarrow{\xi}\right)=\frac{1}{2\pi^2}\sin\left(\frac{h\xi_z}{2}\right)\frac{R_2J_1(R_2\xi_\perp)-R_1J_1(R_1\xi_\perp)}{\xi_z\xi_\perp} \tag{2}$$

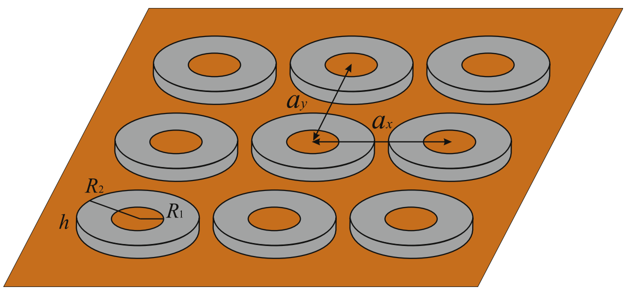


**Fig. 1.** Schematic view of QRSL.