Superlattices and Microstructures 82 (2015) 584–591

Contents lists available at ScienceDirect

Superlattices and Microstructures

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

Rashba spin–orbit coupling in a two-dimensional quantum ring superlattice

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ARTICLE INFO

Article history:
Received 21 January 2015
Received in revised form 27 February 2015
Accepted 2 March 2015
Available online 11 March 2015

Keywords:
Quantum ring
Spin orbit interaction
Supperlattice

ABSTRACT

The effect of the Rashba spin–orbit coupling on electronic states in $GaAs/Ga_{1-x}Al_xAs$ two-dimensional quantum ring superlattice is investigated. The conduction band structure and the Bloch amplitudes of the superlattice are obtained by the exact diagonalization procedure using the Fourier transformation to the momentum space. The splitting of the mini-bands as well as the crossing of the dispersion surfaces at the high symmetry points in the Brillouin zone are obtained. It is shown that spin–orbit interaction brings an asymmetry to the Bloch amplitudes of the conduction mini-band.

1. Introduction

Quantum dots (QD) or the artificial atoms [1] containing few interacting electrons have received considerable attention for over a decade because of the rich physics they exhibit. Just as the QDs, quantum rings (QR) are also nanometer-sized structures that confine electrons in all three directions. The observation of the Aharonov–Bohm oscillations [2] and the persistent current [3] in small conducting rings, and recent experimental realization of QRs with only a few electrons [4,5], have made QRs an attractive topic of experimental research and a new playground for the many-particle theory in quasi-one-dimensional systems [6,7].

QRs are of particular interest due to their unique electronic, magnetic, and optical properties [8–10]. For example, quantum phase coherence effects on carrier transport such as in the Aharonov–Bohm and Aharonov–Casher effects are observed in QRs [11]. Some research groups have predicted and

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http://dx.doi.org/10.1016/j.spmi.2015.03.001

demonstrated the optical Aharonov–Bohm effect which may lead to potential applications in quantum information systems [12–14]. QRs have also found use in various practical applications in the last few years. Photodetectors based on semiconductor nanorings have been fabricated in the mid-infrared and THz spectral ranges [15,16]. Nanorings also demonstrate superior potential for high density magnetic memory [17]. Lasers incorporating nanorings in the gain medium have also been reported [18].

A very useful mechanism based on Rashba spin–orbit interaction (SOI) for coherent spin manipulation in quantum nanostructures has been demonstrated [19,20]. 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 [21].

Our earlier works involving the Rashba SOI on the electron and hole states in QDs [22,23] and in QRs [24] 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. 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 [25–27]. Since the strength of the SOI can be tuned with external gate voltages, QRs, or systems involving those will also have possible spintronic applications [28].

During the last decade impressive progress has been made in the field of manufacturing of ordered structures composed of two or three dimensional arrays of QRs [29–32]. For example stacked layers of self assembled quantum rings have been studied for laser applications by Suárez et al. [30]. The optical properties of the arrays of strain-free quantum ring solar cells have been studied by Wu et al. [31]. 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 [33]. It has been shown that the lateral ordering pattern can be controlled by using differently oriented surfaces. The described technique has been shown to be capable of fabricating the large scale ordered quantum ring structures for many applications.

The dispersion curves and the Bloch amplitudes of one layer quantum ring suprlattice (QRSL) and a three-dimensional QRSL composed of Gaussian-shaped double quantum rings have been obtained in our previous works, taking into account the interdiffusion between the compound materials of heterostructure [34,35].

In this work the effect of Rashba SOI on the electronic mini-bands and Bloch amplitudes of two-dimensional QRSL is considered using the exact diagonalization technic in the framework of the momentum space approximation. As it has previously been shown [36], this approximation provides a good representation of physical situation and reasonable accuracy for comparatively small sizes of Hamiltonian matrix.

2. Theoretical framework

Let us consider a two dimensional QRSL with the lattice constants a_x and a_y in the x and the y directions respectively. The model of two-dimensional SL is reasonable because of the strong quantum confinement in the direction perpendicular to the SL plane. For the SL model discussed in our work the concentration of the rings is of order 10^{11} cm^{-2} which is larger than the concentration of 2D electron gas in GaAs quantum layers at low temperatures. That is why the probability to find more than one electron in the same ring is very small. This means that the Coulomb interaction between the electrons is also small and can be neglected in our model. The Hamiltonian of this system in the Ben Daniel–Duke approach is:

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{SO}. \tag{1}$$

where

$$\mathcal{H}_0 = -\frac{\hbar^2}{2m(\vec{r})}\nabla^2 + \nabla\frac{1}{m(\vec{r})}\nabla + V(\vec{r}), \tag{2}$$