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Effect of interdiffusion on electronic states of strain-free Gaussian-shaped double quantum ring superlattice

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HIGHLIGHTS

- The effect of interdiffusion on electronic states in a quantum ring superlattice is studied.
- The Gaussian-Shaped double quantum rings have been considered.
- Both the cases of superlattice of cubic and tetragonal symmetry have been considered.
- The first two minibands shift to the region of higher energies due to interdiffusion.
- As a result of interdiffusion the minibands become wider.

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ABSTRACT

The effect of interdiffusion on band structure and Bloch amplitudes of three dimensional superlattice composed of Gaussian shaped double quantum rings is investigated using the Fourier transformation to the momentum space. It is shown that the sequence of the principal quasimomentum vectors which correspond to the energy increase depends on superlattice symmetry. Due to interdiffusion both the first and the second minibands of conduction band shift to the region of higher energies and broaden, meanwhile the difference between the behaviors of the dispersion curves in different directions of momentum space gradually disappears. The obtained results indicate to the opportunity of purposeful manipulation of structure characteristics by means of interdiffusion both quantitatively and qualitatively.

1. Introduction

Quantum rings (QRs) are a special class of nanostructures that have attracted a lot of attention due to the occurrence of the Aharonov–Bohm effect, which is specific to the doubly-connected topology of a ring [1–3]. Particularly interesting are the magnetic properties of such quantum systems, which are related to the possibility of inducing persistent currents. Recent development of nanofabrication technology allows us to create and assemble atomic units in an artificial manner, such as in the fabrication of quantum dots (QD) [4–7] molecule-like alignment of two QDs [8,9] and the formation and characterization of QR complexes [10], which open a new route, promised by ring geometry, to measurement of quantum interference effects [11,12]. Using droplet epitaxial technique, authors of Ref. [10] performed self-assembly of concentric double quantum rings (DQR) with high uniformity and excellent rotational symmetry. The generation and detection of terahertz (THz) radiation have gained importance for their potential applications in the areas of security, biomedical imaging, quality control, and submillimeter astronomy [13–16]. Semiconductor-based QD intersublevel detectors have been used for the detection of infrared radiation in the 15–100 THz range [17–21] but it is difficult to access the 3–10 THz range. QRs are derived from epitaxially grown self-organized QDs by post-growth annealing [22,23] and confinement in these nanostructures is stronger than that in QDs because of the altered shape [24]. In Ref. [25] it was found that the QR intersublevel detectors exhibit very low dark current and strong response in the 1–3 THz range, with the peak response at 1.82 THz in the temperature range of 5–10 K.

The potential application of QRs in nano-devises has given rise to theoretical investigation of their optoelectronic properties [26]. In some works the influences of spin–orbit coupling [27,28], hydrostatic pressure [29] and polaronic effects [30] are examined. Analytical treatments of electronic states in QRs with non-trivial geometry has also been suggested [31,32].

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Recently, strain-free nanostructures grown by droplet epitaxy have been proposed and demonstrated for photovoltaic applications [33] and have also gained popularity in lasers and photodetectors [34,35]. In Ref. [36] strain-free DQR (SFDQR) solar cells were fabricated by droplet epitaxy. Rapid thermal annealing (RTA) was used to improve the optical quality of the solar cells. It was shown that RTA plays a major role in modifying the electronic structure and in the improvement of material quality.

In this work the effect of interdiffusion induced by RTA on electron energy levels and Bloch amplitudes in DQR superlattice (DQRSL) is modeled using the Fourier transformation to momentum space. The cases of SL of cubic and tetragonal symmetry are considered. Two shifted Gaussians are used as a shape function for DQRs, which can provide a reasonable representation of real DQRs obtained in Ref. [36] by choosing appropriate values of Gaussian parameters.

2. Theory

Let us consider a three dimensional superlattice composed of $GaAs/Al_{0.33}Ga_{0.67}As$ DQRs. Before the influence of RTA on the distribution of Al and Ga atoms at the heterojunction one can assume that there is an exact interface between the DQR and the surrounding area. The shape of DQR can be taken as a superposition of two shifted Gaussian functions [37] with the introduction of the shape function as follows:

$$f(\rho,z)=\begin{cases}1, & 0\le z\le z_0(\rho),\\ 0, z<0 & \text{or } z>z_0(\rho),\end{cases} \tag{1}$$

where

$$z_0(\rho)=A\exp\left(-\alpha^2(\rho-\rho_1)^2\right)+B\exp\left(-\beta^2(\rho-\rho_2)^2\right) \tag{2}$$

In Fig. 1 the image of surface of $GaAs/Al_{0.33}Ga_{0.67}As$ SFDQR structure [36] (left) and a model of DQR corresponding to Eqs. (1) and (2) (right) are presented. The values of parameters in Eq. (2) are taken to be $A=B=\rho_2=2\rho_1=a/3$, $\alpha=\beta=25/a$, where a has the dimension of length and in further calculations is assumed to be the period of DQRSL in x and y directions ($a_x=a_y=a$). As is seen from the figure, Eqs. (1) and (2) provide a good description of real DQRs and the agreement can be improved choosing appropriate values of the parameters. It should be mentioned that the difference of the suggested model from the DQR model with rectangular profile used by most of authors is mainly expressed by the fact that the potential barrier between the concentric rings exists not for all values of z. It

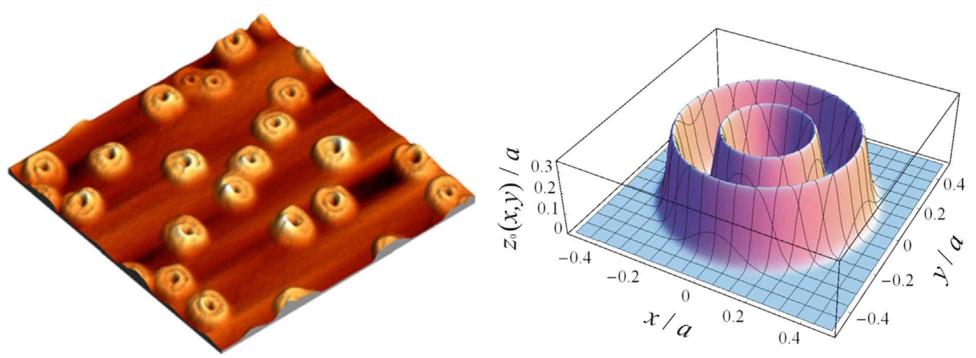

Fig. 1. The atomic force microscopy image of DQR obtained by Wu et al. [36] (left) and the model of DQR obtained by using of two shifted Gaussians (the lengths are presented in the unites of a).

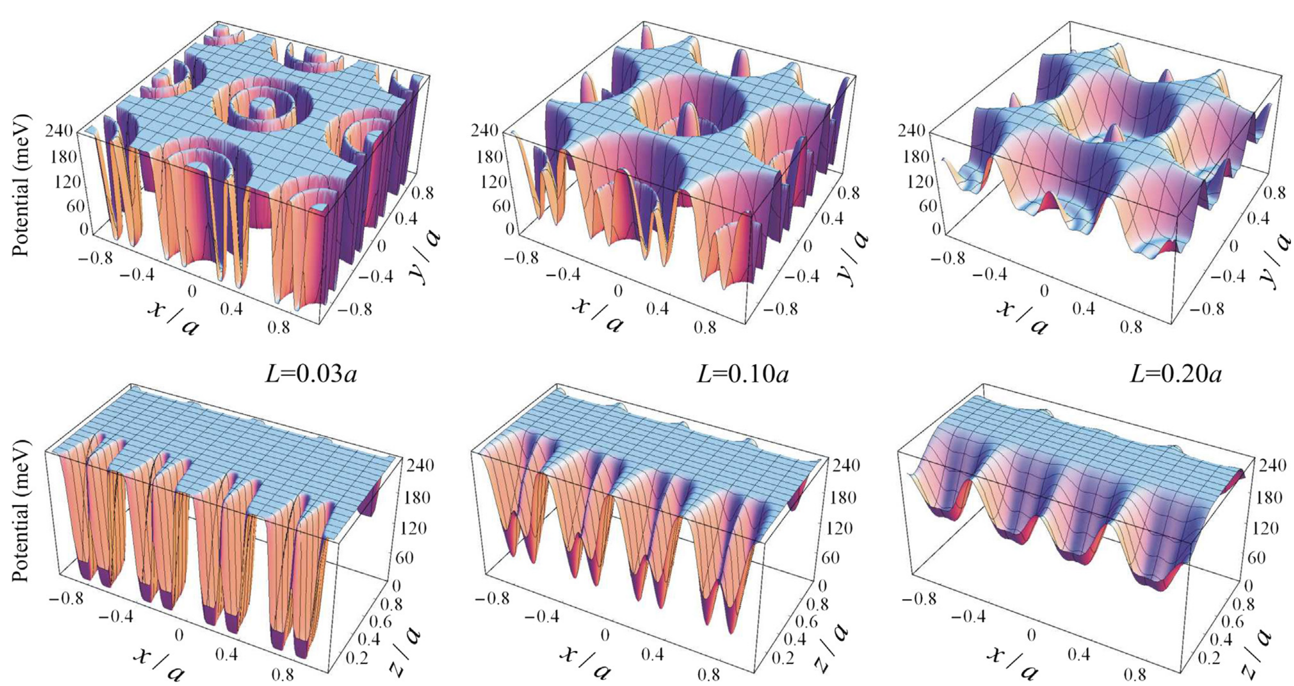

Fig. 2. The dependences of potential in conduction band on x and y coordinates for $z=0.1a$ (the upper row of graphics) and on x and z coordinates for $y=0$ (the lower row).