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Effect of donor impurity dislocation in elliptical quantum rings

Hojjatollah Khajeh Salehani [a,*], Khosrow Shakouri [b,c], Mahdi Esmaeilzadeh [c]

[a] Department of Physics, Damavand Branch, Islamic Azad University, Damavand 39718-78911, Iran
[b] Young Researchers and Elites Club, Damavand Branch, Islamic Azad University, Damavand 39718-78911, Iran
[c] Department of Physics, Iran University of Science and Technology, Narmak, Tehran 16846, Iran

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ABSTRACT

We investigate the effect of an off-center donor impurity on the electronic properties of a two-dimensional quantum ring with a deformed geometrical structure in the form of an ellipse. It is shown that the dislocation of impurity from the center of elliptical quantum ring opens sizable gaps in the energy spectrum and largely deforms the eigenenergies near the ground state. As a result, the Aharonov–Bohm oscillations are quenched and the persistent electron current decreases intensely. Moreover, we show that the ground state energy exhibits a local extremum when the donor impurity is located on semi-minor (or -major) axis of the elliptic ring. The effects of the eccentricity of elliptical ring on the energy spectra and persistent current are also studied.

1. Introduction

After realization of nanoscale quantum rings with only a few electrons [1,2] a wide attention has been devoted to their intriguing quantum effects, in particular the Aharonov–Bohm oscillations [3] and persistent electron current [4]. Many potential applications have been proposed for quantum rings especially in opto-electronics, high-density memory and spintronic devices (see Ref. [5] and references therein). Similar to many nanoscale materials, the electronic properties of quantum rings strongly depend on the geometrical structure, or in other words, on the quantum confinement. The simplest geometrical structure used to model a quantum ring is an ideal circular ring, or a ring with a constant average radius, whereas in grown or even etched quantum rings the imperfections often deform its circular shape. So far, several attempts have been made to study the properties of quantum rings with elliptical geometrical structure [6–11].

Doping quantum rings with both the donor and acceptor impurities influences quantum confinement of the electron because the ionized impurities induce repulsive or attractive electrostatic potential that couples with the quantum ring confinement. Thus far, a few theoretical and experimental studies have paid attention to the effects of on-center and off-center donor impurities in circular quantum rings [12–21]. For example, in Ref. [16] the electronic states of a two-dimensional quantum ring in the presence of on-center donor impurity are studied. It has been shown that, due to electron localization around the donor impurity, the electronic structure can abruptly change at a critical magnetic field. In Ref. [19], the effect of a geometrical structure deformation on the Aharonov–Bohm oscillations in a two-dimensional GaAs/AlGaAs quantum ring with an embedded on-center donor impurity has been studied. Salehani et al. investigated the effects of on-center charged impurities on the persistent current and energy spectrum of two interacting electrons confined in a circular two-dimensional quantum ring [21]. It was shown that when the ratio of the ring width to its average radius is large, the donor impurity increases the persistent current considerably while the effect of acceptor impurity is negligible.

Recently, a few theoretical studies have focused on the effect of charged impurities in elliptical quantum rings [22,23]. However, in these studies, the position of charged impurity is assumed to be fixed and no attention has been paid to persistent current. In the present paper, we study the electronic properties of a two-dimensional quantum ring in the form of an ellipse in the presence of a dislocated donor impurity and of an infinite magnetic flux penetrating the ring. For a given eccentricity of elliptical structure, we consider different impurity-dislocations relative to the ring axes and calculate the energy spectra and persistent current. It is shown that the impurity dislocation from the center of quantum ring introduces an asymmetric electrostatic potential, leading to attenuation of the Aharonov–Bohm oscillations and as a result, the persistent current decreases significantly. It is also demonstrated that the minima and maxima of ground state energy occur whenever the dislocated impurity lies on semi-major or

* Corresponding author. fax: +98 2176327000.
E-mail address: hksalehani@damavandiau.ac.ir (H. Khajeh Salehani).

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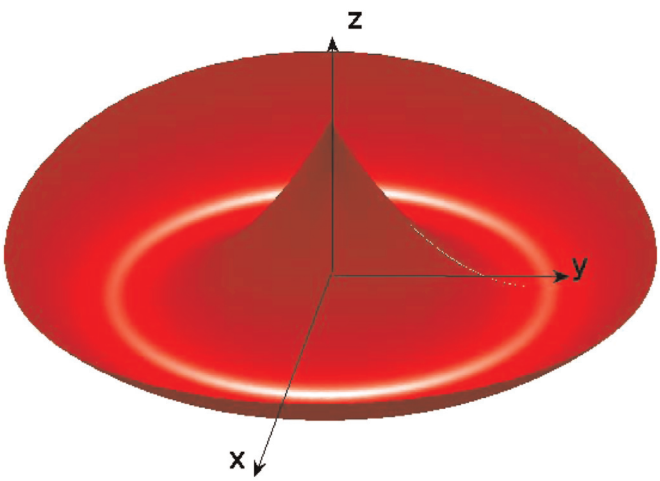

Fig. 1. Schematic view of a parabolic confinement potential for a two-dimensional quantum ring. The geometrical distribution of the potential minima draws an ellipse so that the average radius is a function of θ.

2. Theoretical model

Consider an elliptical quantum ring with a two-dimensional quantum confinement lying on the x–y plane. The radial profile of the confining potential is parabolic, but the angular distribution of the potential minima draws an ellipse. The confinement potential is shown schematically in Fig. 1.

In the presence of an embedded donor impurity and an infinite thin magnetic flux (ϕ) passing through the ring, the Hamiltonian of a single electron is given by

$$H = \frac{\hbar^2}{2m^*}\left(-\frac{\partial^2}{\partial\rho^2} - \frac{\partial}{\rho\partial\rho} - \frac{\partial^2}{\rho^2\partial\theta^2} - \frac{2i\phi\partial}{\rho^2\phi_0\partial\theta} + \frac{\phi^2}{\phi_0^2\rho^2}\right) + V_{conf}(\rho,\theta) + V_d(\rho,\theta), \quad (1)$$

where $\hbar = h/2\pi$, h is Planck's constant, $\phi_0 = h/e$ the flux quantum, $-e$ the electron charge, m^* the effective mass of electron, $i = \sqrt{-1}$, and ρ and θ are the radial and angular components in polar coordinates, respectively. The second term in the Hamiltonian is

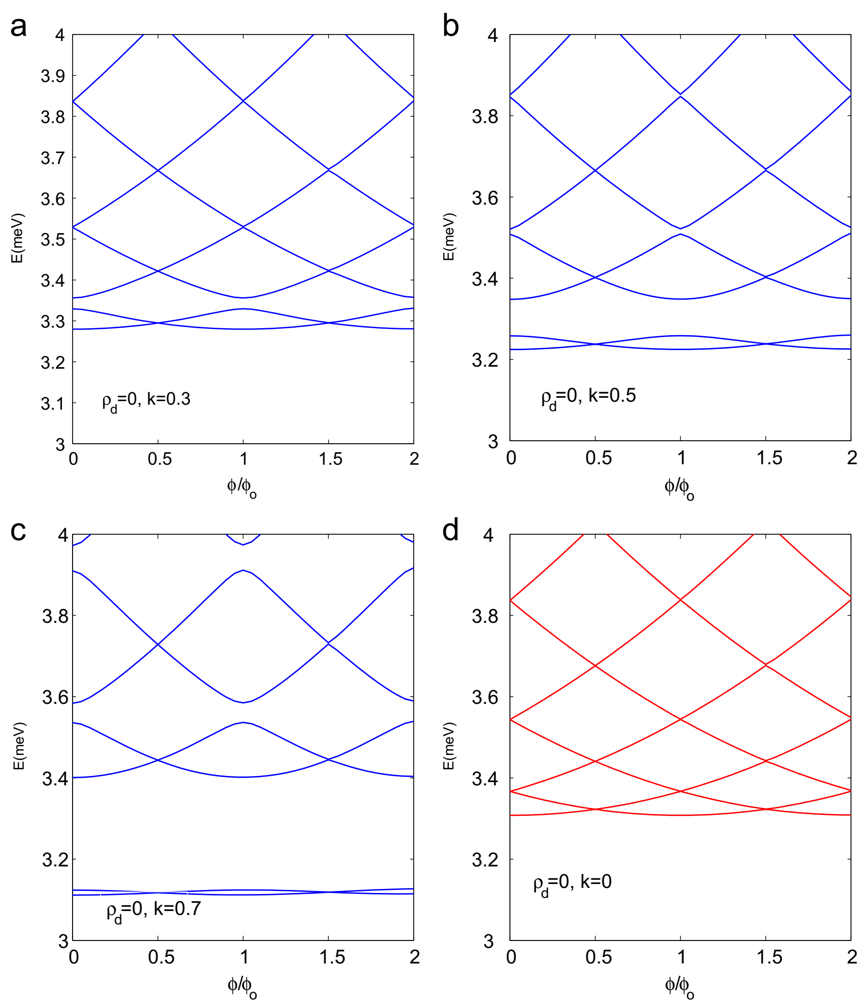

Fig. 2. Energy spectra of a single electron in the presence of an on-center donor impurity as a function of dimensionless magnetic flux for different eccentricities as follows: (a) k=0.3, (b) k=0.5, (c) k=0.7 and (d) k=0 (circular ring).

semi-minor axis of the elliptic ring. This paper is organized as follows. In Section 2, we present the details of our theoretical model. The results of a numerical study are presented and discussed in Section 3. Finally, we summarize our results in Section 4.

known as the lateral confinement potential and is described by

$$V_{conf}(\rho,\theta) = \frac{1}{2}m^*\omega^2(\rho - \rho_o(\theta))^2, \quad (2)$$

where ω is the confinement potential strength, and ρ_o is the radius of ring at which the confinement potential has its minimum value.